Cable Laying Vessel Design under Deep Market Uncertainty

A DAPP-Based Approach to Mission-Equipment Selection

MSc Marine Technology - Thesis

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Boskalis

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Thesis for the degree of Master of Science (MSc) in Marine Technology
in the specialization of Ship Design

Cable Laying Vessel Design under Deep Market Uncertainty

A DAPP-Based Approach to Mission-Equipment Selection

by

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Preface

I am proud to present this master's thesis, which marks the completion of my studies in Marine Technology at Delft University of Technology.

When I started the bachelor's programme in Marine Technology, all I really knew was that I liked boats and had an appetite for physics and mathematics. Over the years that followed, this interest developed into a genuine passion for ships, the technology behind them, and the operational and commercial systems in which they operate. Alongside my studies, my experiences at Allseas, N-Sea, and Zuyderzee Capital enabled me to connect and apply the theory taught in Delft with the realities of the maritime industry.

These experiences took me beyond the lecture halls of Delft and showed me that ship design is not only about technical performance. Design decisions are closely connected to how a vessel will be operated, how it creates value, and how it can remain relevant as markets and technologies change. This combination of engineering, operations, and commercial decision-making eventually led me to the central challenge of this thesis: how to design the right cable laying vessel not only for current requirements, but also for the uncertain conditions it may face throughout its operational life.

I would especially like to thank my academic supervisor, Austin Kana, for his guidance, constructive feedback, and continued support throughout the project. His questions and suggestions kept steering me in the right direction and were essential in shaping both the research and this thesis.

I am also grateful to Boskalis for giving me the opportunity to conduct my graduation research in such an inspiring environment. In particular, I would like to thank Ruud Beindorff and Onno Peters for their support, and Louis Nieuwenhuis for the many insightful and enjoyable conversations over coffee at the Living. Their practical experience helped connect the academic research to the realities of the offshore industry.

Finally, I would like to thank my family and friends for their encouragement, support, and the much-needed relaxation outside thesis work.

This thesis marks the end of my time as a student and the beginning of a new chapter. I look forward to continuing in the maritime industry and taking on the opportunities, challenges, and experiences that lie ahead.

Gijs P. Verloop
Delft, June 2026

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AI Acknowledgement

For this MSc graduation thesis, the author used generative AI tools, mainly ChatGPT (OpenAI, `https://chatgpt.com`) and, to a more limited extent, Claude (Anthropic, `https://claude.ai`) and Gemini (Google, `https://gemini.google.com`), to:

- support the development, debugging, refactoring, and vectorisation of Python code used for scenario generation, vessel-configuration evaluation, data processing, plotting, and output generation;
- improve the efficiency, readability, and robustness of scripts, while keeping the modelling logic and implementation decisions under the author's control;
- obtain inspiration for the overall structure, flow, and positioning of the report;
- support the drafting, rewriting, grammar, style, layout, and spelling improvement of selected parts of the text;
- support consistency checks between the computational model, the written methodology, the reported results, and the stated limitations;
- formulate critical feedback questions and alternative phrasings during the iterative writing and revision process.

Generative AI was not used as an autonomous source of data, literature, engineering judgement, model assumptions, or final conclusions. All AI-assisted code, text, interpretations, and suggested revisions were reviewed, checked, edited, and approved by the author. The author remains fully responsible for the content, implementation, results, and conclusions of this thesis.

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Summary

The offshore wind sector is developing rapidly under the influence of climate targets, technological change, regulatory pressure, and market volatility. Cable laying vessels (CLVs) are essential for installing offshore wind export cables, but their early-stage design is challenging because they are capital-intensive, long-lived assets whose required capability depends on uncertain future project conditions. Longer export routes, deeper water, heavier cables, changing voltage-system choices, and floating offshore wind may all affect the required storage capacity, tensioner capacity, lay-line arrangement, fuel performance, and investment cost of future CLV concepts.

This thesis investigates how deep uncertainty can be addressed in the early-stage design of a cable laying vessel to support future-resilient design decision making. Dynamic Adaptive Policy Pathways (DAPP) is selected as the main methodological framework because it supports adaptive decision-making without relying on one forecasted future or assigned probabilities. In this thesis, deterministic project-portfolio evaluations are used within synthetic scenario stress tests, while DAPP provides the structure for identifying vulnerabilities, interpreting adaptation tipping points, and translating design insights into possible future upgrade pathways.

A parametric CLV evaluation model is developed around a fixed reference platform hull. The model generates a mission-equipment design library by combining discrete carousel configurations with discrete tensioner configurations, resulting in 11,304 candidate configurations. Each configuration is evaluated against synthetic offshore wind export-cable project portfolios generated from an internal Boskalis dataset. The project-evaluation model checks storage feasibility, campaign count, line-layout compatibility, required tension, loaded stability, transit constraints, duration, fuel consumption, and infeasibility reasons. These results are aggregated into design-level performance measures, including feasible cable-kilometre share, campaign-limited performance, average fuel consumption per installed kilometre, utilisation, and mission-equipment capital expenditure.

Two main scenario families are used to stress-test the design library. The first increases cable length and distance from shore while also increasing the share of high-voltage direct-current export-cable projects. This mainly stresses carousel capacity, campaign requirements, transit effort, and two-line capability. The second increases water depth while also increasing the floating-project share, mainly stressing tensioner capacity and deep-water feasibility. The main pathway-performance reference is the share of portfolio cable kilometres that can be completed within at most three campaigns, with a 60% threshold used as an indicative acceptability level.

The results show that no single mission-equipment configuration is best under all future conditions. Lower-cost configurations can perform well in less demanding portfolios, but become vulnerable as project requirements increase. Larger carousel capacity improves campaign-limited market capture under longer, more remote, and high-voltage direct-current-oriented project portfolios, while higher tension capacity improves performance under deeper-water and floating-project portfolios. Two-line capability becomes especially important as the share of high-voltage direct-current export-cable projects increases. These findings are translated into adaptive pathway maps that show how initial configurations could be upgraded as future project portfolios become more demanding.

The thesis concludes that DAPP can be adapted usefully as an early-stage design-support framework for CLV mission-equipment decisions under deep uncertainty. The proposed approach does not replace detailed vessel design, supplier engineering, installation planning, or business-case analysis. Instead, it provides a transparent way to compare candidate configurations, identify capability vulnerabilities, and make under-specification, over-specification, and adaptability trade-offs explicit before major design decisions are locked in.

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Nomenclature

Abbreviations and Acronyms

Abbreviation	Definition
ABS	American Bureau of Shipping
AC	Alternating Current
AD/BD	Above deck / below deck
ATP	Adaptation Tipping Point
CAGR	Compound Annual Growth Rate
CAPEX	Capital Expenditure
CFS	Central Fleet Support
CFD	Contract for Difference
CII	Carbon Intensity Indicator
CLV	Cable Laying Vessel
CPS	Cable Protection System
DAP	Dynamic Adaptive Planning
DAPP	Dynamic Adaptive Policy Pathways
DC	Direct Current
DNV	Det Norske Veritas
DP	Dynamic Positioning
DP2/DP3	Dynamic Positioning Class 2 / Class 3
DS	Decision Scaling
EEA	Epoch–Era Analysis
EEXI	Energy Efficiency Existing Ship Index
EOA	Engineering Options Analysis
ETS	EU Emissions Trading System
EU	European Union
FIT	Feed-in Tariff
GHG	Greenhouse Gas
HVAC	High-Voltage Alternating Current
HVDC	High-Voltage Direct Current
IG	Info-Gap Decision Theory
IMO	International Maritime Organization
KPI	Key Performance Indicator
LARS	Launch and Recovery System
LCOE	Levelized Cost of Energy
MCR	Maximum Continuous Rating
MDP	Markov Decision Process
MORDM	Many-Objective Robust Decision Making
OCV	Offshore Construction Vessel
OD	Outer Diameter
OE-SC	Offshore Energy – Subsea Cables
OPEX	Operating Expenditure
RDM	Robust Decision Making
ROA	Real Options Analysis
ROV	Remotely Operated Vehicle
RSC	Responsive Systems Comparison
SBD	Set-Based Design
SC-MDP	Ship-Centric Markov Decision Process
SFC	Specific Fuel Consumption

Abbreviation	Definition
SP	Stochastic Programming
SQ	Sub-question
TSO	Transmission System Operator
VCG	Vertical Centre of Gravity
WACC	Weighted Average Cost of Capital

Symbols

Symbol	Definition
A_{cable}	Cable cross-sectional area
A_{current}	Underwater side-area proxy
A_{wind}	Above-water side-area proxy
b	Campaign bucket
C_i	Mission-equipment CAPEX of configuration i
$\text{CAPEX}_{\text{mission}}$	Total mission-equipment CAPEX
D_{shore}	Distance from shore
d_{max}	Maximum project water depth
d_{min}	Minimum project water depth
Δd	Project water-depth range
E	Energy consumption
F	Fuel consumption
$F_{i,p}$	Fuel consumption of configuration i for project p
$\mathcal{F}_{i,b}$	Feasible project set for configuration i and bucket b
FR_i	Project feasibility rate of configuration i
$f_{\text{DP,min}}$	Minimum DP power fraction
$f_{\text{DP,max}}$	Maximum DP power fraction
f_{sea}	Sea-margin factor
f_{WOW}	Workability allowance factor
GM_T	Transverse metacentric height
H	Carousel height
$\bar{h}$	Average project water depth
$h_{\text{proj,max}}$	Maximum project depth
I_{current}	Current-exposure index
I_{exp}	Combined exposure index
I_{wind}	Windage-exposure index
$K_{i,b}$	Cable-kilometre share for configuration i and bucket b
KG	Centre-of-gravity height above keel
KM_T	Transverse metacentre height above keel
L_{cable}	Total installed cable length
L_p^{inst}	Installed cable length of project p
$L_{\text{lay},i}$	Laying length in campaign i
L_{route}	Route length per physical cable
m_x	Scenario multiplier for variable x
N_{base}	Number of base-dataset projects
N_{cables}	Number of physical cables
N_{carousel}	Number of carousel configurations
$N_{\text{configurations}}$	Number of mission-equipment configurations
$N_{\text{feasible},i}$	Number of feasible projects for configuration i
N_{projects}	Number of projects in a portfolio
N_{scenario}	Number of projects in a scenario portfolio
$N_{\text{tensioner}}$	Number of tensioner configurations
n_{camp}	Number of campaigns
n_{series}	Number of tensioner units in series

Symbol	Definition
P	Power demand
P_B	Brake power
$P_{DP,i}$	DP-related power in case i
P_E	Effective propulsion power
P_{inst}	Installed vessel power
P_{project}	Project capacity
$P_{\text{ten,total},i}$	Total tensioner power in campaign i
$R_{\text{cable,dist}}$	Cable-length-to-distance ratio
R	Carousel outer radius; transit resistance where applicable
r	Carousel core radius
s_{cable}	Cable-specification score
SFC	Specific fuel consumption
T_{config}	Corrected configuration draft
T_{lay}	Estimated laying tension per line
T_{line}	Tension capacity per lay line
T_{raw}	Raw hydrostatic draft
T_{req}	Required line tension
T_{unit}	Rated tensioner-unit capacity
$t_{\text{lay},i}$	Laying time in campaign i
$t_{\text{load},j,i}$	Loading time of carousel j in campaign i
$t_{\text{project,total}}$	Total project duration
$t_{\text{transit,total}}$	Total transit time
V	Volume
$V_{\text{alloc},j,i}$	Volume allocated to carousel j in campaign i
V_{car}	Gross carousel volume
V_j	Available carousel volume
V_{req}	Required storage volume
v_{lay}	Cable laying speed
v_{load}	Cable loading speed
W_{cable}	Total cable weight
$W_{\text{load},i}$	Cable weight loaded in campaign i
W_{LS}	Lightship weight
W_{mission}	Mission-equipment weight
w_{sub}	Submerged cable weight per metre
x_{donor}	Donor-project value
x_{syn}	Synthetic project value
$\bar{f}_{i,b}$	Average fuel per installed cable kilometre
Δ	Vessel displacement
ϵ_x	Noise factor for variable x
η_{fill}	Carousel fill factor
η_{prop}	Propulsion efficiency
η_{ten}	Tensioner efficiency
γ	Tension safety factor
ρ_{cable}	Cable density
ρ_{sw}	Seawater density
σ	Lognormal noise standard deviation

1
Introduction

1.1. Project Background

The offshore energy sector is undergoing rapid transition under ambitious sustainability targets, geopolitical developments and evolving regulation. For offshore wind in particular, future build-out rates, support schemes and technology pathways remain highly uncertain. Zwaginga and Pruyn [147] describe this as a situation of *deep uncertainty*, in which key drivers such as market demand, fuel prices, regulatory requirements and technological developments cannot be reliably predicted or assigned probabilities. For ship owners and designers, this means that traditional point-forecast approaches are no longer sufficient: methods are needed that allow robust early-stage design choices despite incomplete and ambiguous information.

Cable laying vessels (CLVs) play a critical role in this context by constructing the subsea power-cable infrastructure that connects offshore wind turbines, substations and onshore grids. These vessels have distinct operational requirements, including dynamic positioning, large deck capacities and specialised cable-handling systems, which make their design problem highly constrained and strongly coupled to future project portfolios and technological developments. Their design can be characterised as a wicked [5] or ill-structured [126] problem, with many interdependent parameters and stakeholders pursuing partly conflicting objectives such as performance, flexibility, risk and cost. Balancing these objectives is further complicated by continuously evolving technology, market and regulatory standards.

(a) Boka Ocean **(b)** Giant 7 (Barge) **(c)** Ndurance

Figure 1.1: Overview of Boskalis' cable laying fleet (*Koninklijke Boskalis Westminster N.V.* [77])

At the time of writing, Boskalis is exploring the possibility of adding a new-build cable laying vessel to its existing fleet (Figure 1.1) in order to strengthen its capability in offshore wind cable installation. It is not straightforward, however, to determine what vessel concept and mission-equipment arrangement can remain effective and competitive across a wide range of uncertain future conditions over its decades-long lifetime. This decision is complicated by deep uncertainty in future project environments, requirements, and market development. The vessel must operate for decades, while many of these requirements are still unknown today.

Consequently, the challenge for Boskalis is not merely to identify an "optimal" design for a single forecasted future, but to understand which CLV mission-equipment configurations remain suitable across a range of plausible futures, and how design choices made today may preserve or limit future adaptation options. Addressing this challenge requires an approach that explicitly acknowledges deep uncertainty and evaluates how different configuration choices may perform under diverse, long-term external conditions.

1.2. Stakeholders

Early-stage design choices for a new-build CLV affect a wide range of actors in the offshore wind value chain and the wider vessel approval ecosystem. The most relevant stakeholders for this research and their perspectives on CLV design are summarised below.

- **Ship owner – Boskalis Central Fleet Support (CFS):** CFS acts as the owner's representative and fleet manager. Its main interests are lifecycle cost, fleet commonality, maintainability, operational flexibility, and high long-term vessel utilisation.
- **Ship operator – Boskalis Offshore Energy Subsea Cables (OE-SC):** OE-SC operates the vessel during cable-installation projects and translates project requirements into functional needs. Its main drivers are safe execution, high lay rates, cable integrity, workability, robust station-keeping, and competitive project performance.
- **Transmission System Operators (TSOs):** TSOs such as TenneT and 50Hertz commission offshore grid-connection projects and define many technical and contractual requirements. Their main concerns are reliability, safety, technical compliance, low project risk, reduced offshore joints, and increasingly low-emission operations.
- **Governments:** Governments shape the offshore wind market through regulation, permitting, subsidies, and energy-transition policy. Their interests include safe operations, environmental protection, protection of critical subsea infrastructure, and timely delivery of offshore energy targets.
- **Classification societies:** Classification societies such as DNV, Lloyd's Register, ABS, or Bureau Veritas verify whether the vessel and its systems comply with applicable class rules and safety standards. Their influence is especially relevant for structural design, stability, dynamic positioning, redundancy, machinery systems, and cable-handling equipment.
- **Financiers:** Shipping banks, leasing houses, and infrastructure funds provide capital and assess investment risk. They favour designs that support predictable cash flows, residual value, technical robustness, long-term employability, and manageable downside risk.
- **Research organisations and universities:** Research organisations and universities, including TU Delft, are concerned with the methodological soundness, transparency, and academic grounding of the applied design approach.

1.3. Research Gap

Despite growing recognition that ships must be designed to perform reliably under uncertain future conditions, the practical application of deep-uncertainty methods in ship design remains limited. Existing studies have explored uncertainty-handling and adaptive decision-making approaches for several maritime design problems, but their application to cable laying vessels is still largely unexplored.

For Boskalis, this gap manifests directly in the current fleet expansion question: not simply whether to acquire a new vessel, but what type of CLV capability can remain effective and competitive across a wide range of uncertain future project environments. Early design decisions in this context lock in large, long-lived investments, while future project requirements remain uncertain. There is therefore room for a method that structures the early-stage CLV design process and makes the consequences of alternative design choices more transparent under uncertainty. This thesis addresses this gap by investigating which uncertainty-handling method is suitable for the CLV case and by adapting it into a scenario-based evaluation framework for early-stage mission-equipment design decisions.

1.4. Research Objective and Research Questions

The primary objective of this thesis is to select, adapt, and evaluate a design-support method for dealing with deep uncertainty in the early-stage design of a cable laying vessel. The focus is on mission-equipment configuration choices, such as cable storage capacity, carousel arrangement, number of lay lines, and tensioner capacity, evaluated on a fixed reference platform hull. While various uncertainty-handling methods have been proposed for other ship-design problems, their application to CLV mission-equipment decisions remains largely unexplored. The project therefore aims to develop a structured framework that helps organisations such as Boskalis evaluate CLV design decisions under uncertain project-market conditions.

This leads to the following main research question:

How can deep uncertainty be addressed in the early-stage design of a cable laying vessel to support future-resilient design decision making?

To structure the work, this main question is decomposed into the following sub-questions (SQs):

1. What are the distinctive characteristics and key design drivers of cable-laying vessels, and why is uncertainty particularly challenging for their early-stage design?
2. Which uncertainty-handling and decision-making method is most suitable for early-stage cable-laying vessel design under deep uncertainty?
3. How can the selected method be adapted to evaluate CLV mission-equipment decisions under uncertain future project conditions?
4. Which configuration characteristics and project variables determine whether a CLV mission-equipment setup is technically and operationally suitable?
5. How can uncertain future offshore wind project portfolios be represented, and which performance measures are needed to compare CLV configurations across them?
6. How can the computational model be verified and validated before it is used for scenario evaluation?
7. How do different CLV mission-equipment configurations perform under changing project length, distance from shore, water-depth, floating-share, and cable-system conditions?
8. How can the identified design trade-offs and vulnerabilities be translated into adaptive design pathways for early-stage CLV decision-making?

1.5. Thesis Outline

The remainder of this thesis is structured as follows.

Chapter 2 addresses SQ 1 by introducing cable laying vessels, their main systems and operational requirements, and the market, technology, and policy uncertainties that influence CLV design. Chapter 3 addresses SQ 2 by reviewing uncertainty in ship design, comparing decision-making methods under deep uncertainty, and motivating the use of Dynamic Adaptive Policy Pathways (DAPP).

Chapter 4 addresses SQ 3 by translating DAPP into the methodology used for early-stage CLV mission-equipment design. Chapter 5 addresses SQ 4 by developing the parametric vessel model and project-evaluation logic, including hull, carousel, tensioner, cable, operational, fuel, and CAPEX modelling.

Chapter 6 addresses SQ 5 by defining the project dataset, synthetic scenario generation, KPI framework, screening logic, and Pareto comparison approach. Chapter 7 addresses SQ 6 by verifying implementation consistency and assessing engineering plausibility, while clarifying the limits of the validation.

Chapter 8 addresses SQ 7 by evaluating configuration performance across the base-like scenario and stress-test scenarios for length, distance, depth, floating share, and cable-system changes. Chapter 9 addresses SQ 8 by translating these results into adaptation actions, retrofit-compatibility rules, tipping points, signposts, pathway maps, and scorecard comparisons.

Finally, Chapter 10 answers the research questions, summarises the main contributions and limitations, and provides recommendations for further research and practical application.

2
Problem Background

Chapter 2 provides the technical, market, and policy context for cable laying vessel design under uncertainty. It addresses the first sub-question:

What are the distinctive characteristics and key design drivers of cable-laying vessels, and why is uncertainty particularly challenging for their early-stage design?

The chapter first introduces cable laying vessels and the mission systems that shape their design, including cable storage, station-keeping, cable-handling equipment, and supporting subsea systems (Section 2.1). It then discusses major technological trends in offshore wind and how these developments influence required CLV capabilities (Section 2.2). The chapter also reviews market volatility and its implications for vessel utilisation and investment decisions (Section 2.3). Finally, it discusses how changing policy, subsidies, and financing conditions affect the timing and attractiveness of CLV investments (Section 2.4). Together, these sections explain why CLV design is strongly coupled to uncertain external developments and why a structured uncertainty-handling approach is needed.

2.1. Cable Laying Vessels

A Cable Laying Vessel is a ship or barge "built for the sole purpose of laying and/or repairing subsea cables" [137]. These cables may include high-voltage export cables transmitting power from offshore wind farms to shore, interconnectors linking different electricity grids or substations, inter-array cables connecting individual turbines, or long-distance telecommunications cables [34, 86, 123]. Boskalis offers installation and burial services for power-cable systems, including export cables, interconnectors, and inter-array cables [10]. The scope of this thesis is therefore limited to power-cable installation. Within this broader power-cable scope, this thesis focuses primarily on export-cable installation.

2.1.1. Defining Characteristics and Considerations

The following content on cable laying vessels draws primarily on *Submarine Power Cables: Design, Installation, Repair, Environmental Aspects* by Thomas Worzyk [145], supplemented by additional sources referenced throughout the text.

Cable-laying operations differ strongly by cable type, project scale, water depth, distance from shore, and installation strategy [34, 86, 123]. As a result, cable laying vessels are rarely generic assets. Instead, they are typically configured around a specific operational niche, such as large export-cable installation, inter-array cable installation, shallow-water pull-in work, or cable repair. Figure 2.1 illustrates this range displaying four distinct vessel examples. Large export-cable vessels prioritise storage capacity and long continuous lay capability, while inter-array, shallow-water, and repair vessels are configured around different combinations of productivity, access, manoeuvrability, and intervention capability. This diversity highlights that CLV design is strongly mission-dependent, and that equipment choices involve trade-offs between capability, flexibility, and cost.

(a) XL Cable-laying vessel (Jan De Nul Group [73])

(b) Inter-array cable lay vessel (Royal IHC [119])

(c) Beached Shallow Water cable lay vessel (Navingo [97])

(d) Cable Repair Vessel (Neptune Marine [99])

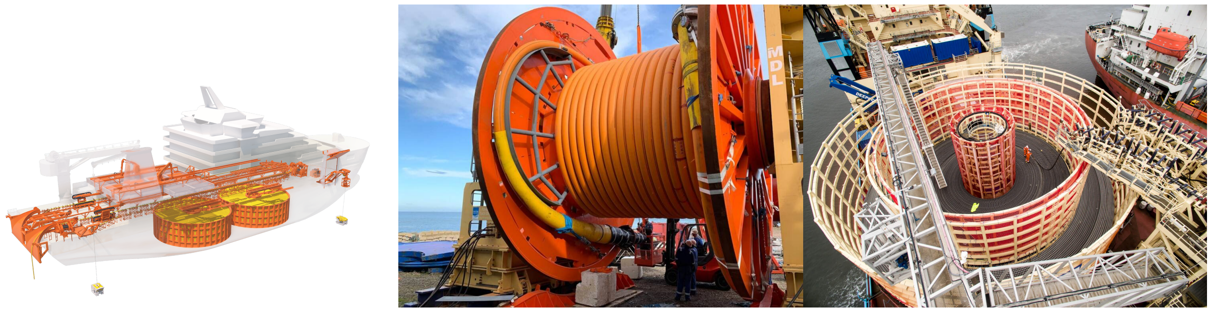
Figure 2.1: Examples of cable-lay and repair vessels.

The viability of any CLV concept is constrained by the integration of storage capacity, station-keeping capability, deck space, cable-handling equipment, power and thrust, seakeeping behaviour, and safe working conditions. Depending on the project scope, ROVs, cranes, burial equipment, and other subsea intervention tools may also be required. However, the mission-equipment trade-offs most relevant to this thesis are cable-storage capacity, carousel arrangement, lay-line configuration, and tensioner capacity. These are the design dimensions that are varied in the later fixed-platform model, while hull dimensions, accommodation, detailed deck layout, and support systems are left outside the design scope of this thesis.

Load-carrying Capacity

In CLV operations, subsea-cable storage is essential for protecting the cable and enabling controlled deployment under tension. Storage capacity may be limited by volume or weight, depending on the cable design. Carrying more cable per campaign can reduce the number of offshore joints and installation campaigns, but requires larger storage systems and greater vessel integration effort. The most common storage concepts are static tanks, cable drums or reels, and turntables or carousels, as illustrated in Figure 2.2.

Static tanks store non-torsion-stiff cables in fixed circular or oblong tanks using an overhead coiling spreader. They are relatively simple and cost-effective, but require careful control of minimum bending radius, stacking behaviour, and cable support. Cable drums or reels are used mainly for shorter cable lengths, umbilicals, or flexible products, and are practical for specialised short-length installations. Turntables or carousels are rotating storage systems capable of holding large power cables and enabling controlled loading and pay-out. They may be divided into sections or installed as multiple independent systems to support parallel cable operations.



(a) Static tanks (Evotec AS [38]) **(b)** Cable reel system (Maritime Developments Ltd [91]) **(c)** Turntable/carousel (Parkburn Ltd [108])

Figure 2.2: Overview of different cable storage and deployment systems.

The choice of storage system is therefore not only a layout decision, but also a strategic capacity decision. Larger carousel arrangements can reduce offshore joints and campaign requirements, but increase equipment weight, deck or below-deck space demand, installed drive power, and cost. This creates an early-stage trade-off between operational capability and capital intensity.

Manoeuvrability

Accurate manoeuvrability is essential for a CLV because the vessel must maintain position and heading along the planned cable corridor. Deviations can compromise cable integrity, reduce placement accuracy, or cause the cable to land outside the intended route. Position control can be achieved using anchor spreads or dynamic positioning (DP). Anchor-based positioning remains useful in some shallow-water operations, but is slower, labour-intensive, and can interfere with existing subsea infrastructure. Large offshore cable-installation projects therefore commonly rely on DP systems, which maintain vessel position and heading using navigation sensors, control systems, and coordinated thruster action. DP capability is classified by redundancy level, with DP2 commonly used for large submarine cable projects [105].

Cable Handling

Cable-handling equipment must match the intended installation capability and ensure that allowable bending radii and cable tension limits are respected during loading, laying, and recovery. The most important handling components include tensioners, cable haulers, chutes, and cable-protection-system handling equipment.

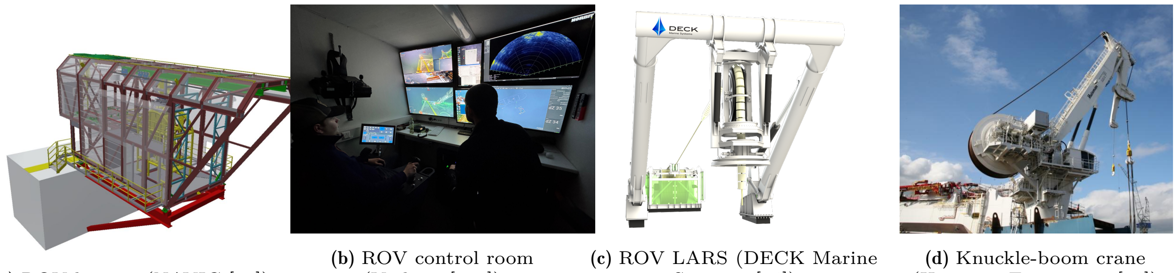
Tensioners are central to CLV capability because they move the cable on board and apply controlled tension during installation or recovery. Most systems use wheel pairs or belt-driven tracks and can operate in pulling or braking mode. Effective friction between the tracks or wheels and the cable is required to avoid slippage without over-pressurising the cable. Reported tensioner capacities generally range from about 5 t to 65 t [65, 85], while tandem or series arrangements can provide higher line pull.

Figure 2.3: Tracked tensioner (IHC [65]).

Tensioner selection introduces an important design trade-off. Higher line capacity improves the ability to handle heavier cables and deeper-water projects, while additional lay lines enable parallel or dual-cable operations. However, larger or duplicated tensioner systems increase equipment weight, installed power, deck integration requirements, and CAPEX.

ROV equipment

Remotely operated vehicles (ROVs) support cable-laying operations through seabed inspection, cable touchdown monitoring, subsea pick-up, jetting, trenching, and cable-retrieval tasks. Their use requires dedicated vessel facilities, such as a hangar or workshop, control room, launch-and-recovery system (LARS), and suitable crane or handling equipment. These systems influence deck layout, access routes, clearances, lifting arrangements, and integration of the main working deck.



(a) ROV hangar (NAVIC [96]) **(b)** ROV control room (Verloop [139]) **(c)** ROV LARS (DECK Marine Systems [24]) **(d)** Knuckle-boom crane (Huisman Equipment [64])

Figure 2.4: Representative ROV-related vessel facilities: hangar, control room, launch-and-recovery system, and handling crane.

ROV and subsea-tooling requirements are relevant for the overall arrangement of a cable-laying vessel, but they are not varied parametrically in this thesis. They are therefore treated as fixed contextual requirements rather than as adaptive design variables.

2.2. Evolving Technology

Technological developments in offshore wind are rapidly increasing demands on cable laying vessels. Larger turbines, greater distances to shore, and deeper installations require higher-capacity, more advanced, and versatile vessels. The following subsections outline how these trends drive changes in vessel capabilities and design.

2.2.1. Turbine Size

Over the past decade, offshore wind turbines have grown rapidly in capacity and physical size, reflecting a broader trend toward larger and more powerful installations (see Figure 2.5). Within one year, the average turbine capacity increased from around 7.7 MW in 2022 to approximately 9.7 MW in 2023 [23]. Industry leaders are already constructing prototypes of 21-26 MW, testing models of 20 MW, and have installed 16 MW-class turbines commercially offshore [16]. Some manufacturers, such as Vestas, have however argued for slowing the pace of turbine upscaling and instead consolidating existing platforms, emphasising longer product lifecycles, proven technology and a more sustainable, scalable supply chain [25].

Figure 2.5: Offshore wind farm evolution (RWE [120])

While the steady increase in turbine size can improve energy yield and reduce project-level cost, it also affects the supporting electrical infrastructure. Larger turbines are often associated with larger project capacities, higher export-system ratings, and more demanding cable specifications. As cable diameter, mass, and required handling tension increase, installation operations become more demanding. For CLVs, this increases the importance of storage capacity, deck load, cable-handling capability, and station-keeping performance. Conversely, excessively large or over-specified vessel concepts may become economically unattractive if the expected high-capacity project pipeline does not materialise.

2.2.2. Distance to Shore and Water Depth

Offshore wind parks are also being developed at increasing distances from shore and in deeper waters. This trend is evident in Europe, where developers seek stronger wind resources and less conflict with coastal uses. For example, in Germany the majority of projects are now at least 40 km offshore (some up to 120 km), with existing installations averaging about 70 km from shore [46]. Similar trends are observed in the UK, where large projects such as Dogger Bank are situated as far as 125-290 km offshore [32]. These increasing distances from shore are closely tied to rising water depths at project sites: global fixed-bottom offshore wind projects now average 35–40 m in depth, compared to just 15–20 m a decade ago, with future projects expected to push beyond 50 m in some regions [95] (see Fig. 2.6).

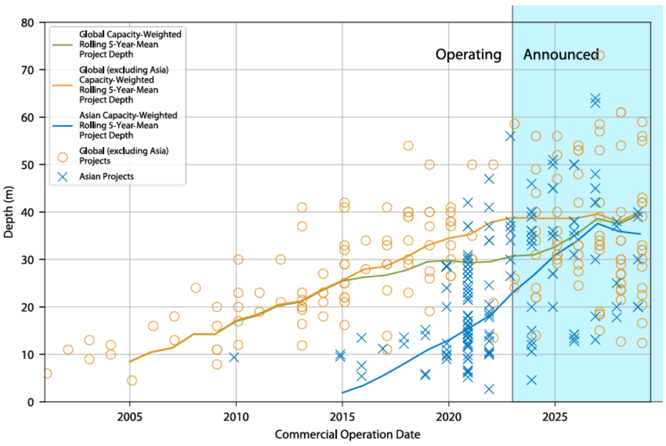


Figure 2.6: Maximum water depths for global fixed-bottom offshore wind energy projects (Musial et al. [95])

The shift toward deeper, harsher offshore environments poses new challenges for cable laying vessels. Longer distances to shore require the deployment of heavier and longer high-voltage export cables, including HVDC systems. The emergence of floating offshore wind further reinforces this development, as it enables projects in deeper waters and increases the importance of cable tension, dynamic cable behaviour, and subsea installation support. The industry is responding with larger, more capable CLVs to handle greater loads and rough conditions. Modern vessels like Prysmian's Leonardo da Vinci carry up to 600 km of cable and use advanced station-keeping (DP3) and heavy-duty tensioners to install cables in deep waters [71].

2.2.3. Congested Seabeds

Growing offshore wind development is also leading to increasingly congested seabed corridors, particularly near landfall zones and along export routes shared with telecommunications cables and pipelines [69]. This complicates route engineering and increases the number of crossings and proximity operations required during installation. For CLVs, this drives higher demands on positioning accuracy, survey integration and ROV-based inspection, as well as the need for deck capacity to store and deploy crossing materials such as mattresses and rock bags [63]. More technically complex seabeds also require robust retrieval and intervention capabilities, reinforcing the importance of versatile cranes and ROV launch-and-recovery systems [60].

2.2.4. Implications for CLV Capability

Taken together, these technological developments create uncertainty in the required capability envelope of future CLVs. Longer export routes, larger cable systems, deeper water, floating offshore wind, congested seabeds, and stricter environmental requirements may each favour different combinations of storage capacity, tension capacity, lay-line arrangement, station-keeping capability, and fuel performance. This makes it difficult to define a single future-proof specification and instead motivates the evaluation of multiple configurations across a range of plausible future project conditions.

2.3. A Volatile Market

This section provides an overview of recent developments in the offshore wind market and highlights key influencing factors, as well as analytical tools used to characterize the sector.

2.3.1. Levelized Cost of Energy

The levelized cost of energy (LCOE) is a widely used metric for comparing energy projects and technologies. It represents the discounted lifetime cost of producing electricity per unit of energy generated and is therefore important for tender outcomes, investor interest, and the required level of public support. LCOE decreases when lifetime costs such as CAPEX, operating expenditure (OPEX), decommissioning, and financing costs are reduced, when lifetime energy production increases, or when the discount rate decreases.

In the simplified formulation used here, tax and inflation are neglected and the discount rate is interpreted as the weighted average cost of capital (WACC) [51]. The LCOE is defined as:

$$LCOE = \frac{\sum_{t=1}^{n} \frac{I_t + M_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}} \tag{2.1}$$

where I_t is the investment expenditure in year t, M_t is the operation, maintenance, and service expenditure in year t, E_t is the energy generation in year t, r is the discount rate or WACC, and n is the project lifetime.

For CLV design, LCOE is relevant because cable installation contributes to offshore wind cost, while cable damage, installation delays, and repair work can create significant project risk [105, 125]. A vessel concept that reduces offshore joints, installation duration, or operational uncertainty can therefore help reduce installation-related cost and risk. This thesis does not calculate LCOE directly, but uses this logic to motivate why CLV capability, CAPEX, fuel consumption, utilisation, and operational feasibility must be considered together.

Offshore wind LCOE has decreased substantially over the past decade and is approaching competitiveness with fossil-fuel generation in several regions [22, 21]. However, continued cost pressure also means that additional vessel capability should not be treated as automatically beneficial: higher capability must be balanced against investment cost and expected utilisation.

2.3.2. Offshore Wind Driving CLV Demand

The global offshore wind CLV market, valued at about $2.8 billion in 2024, is projected to reach $8.4 billion by 2033, corresponding to a compound annual growth rate (CAGR) of 12.9% [23]. This growth is driven by the continued expansion of offshore wind projects, rising renewable energy investment, and the increasing need for vessels capable of installing and maintaining high-capacity export and inter-array cables [23]. More recent analysis on the offshore wind construction vessel (OCV) market shows a similar trend, with a market value of USD 9.31 billion in 2024 and a forecast of USD 16.91 billion by 2030, growing at a CAGR of around 10.3% [115]. This broader vessel-market growth reinforces that demand pressures are not limited to CLVs, but extend across the entire offshore wind construction system.

Recent sector analyses show that CLV demand is shaped by both strong long-term offshore wind growth potential and short-term turbulence in the global market. Despite a six-fold increase in offshore wind capacity between 2015 and 2024 [132], the industry experienced a slowdown in 2024: new installations fell to 8 GW, a 26% year-on-year decline, driven by cost inflation, higher interest rates, permitting delays, and policy instability in several key markets [45]. These challenges have contributed to a downgrade of short-term global offshore wind forecasts by roughly 24% compared to earlier estimates [45].

Nevertheless, medium-term indicators remain fundamentally positive for CLV demand. A record 56 GW of offshore wind capacity was awarded in auctions in 2024, with Europe and China leading and emerging markets such as South Korea, Taiwan, Japan, and the Philippines demonstrating accelerating policy support [45]. Globally, 48 GW of offshore wind capacity is currently under construction, providing a robust pipeline for cable installation over the second half of this decade [45].

Europe remains a central driver of CLV activity, supported by ambitious long-term targets such as 300 GW of offshore wind by 2050 [35] and continued tendering across the North Sea basin. China, accounting for roughly 46% of global installed capacity in 2024, continues to expand rapidly and anchors Asia-Pacific demand [132]. Emerging offshore wind markets in Asia and Latin America are also poised to contribute meaningfully to future CLV demand as policy frameworks mature and permitting accelerates [45].

Overall, while the offshore wind sector still appears to be heading for substantial medium- and long-term growth, the impact of short-term volatility should not be underestimated. Subsea cables remain essential to every offshore wind project, but the timing and consistency of demand can fluctuate sharply. For vessel owners, this market uncertainty creates a risk of both under-specification and over-specification. A vessel with insufficient storage or tension capacity may miss future high-value projects, while an excessively capable vessel may carry unnecessary capital cost if the expected project pipeline is delayed or does not materialise. For CLVs, these variations therefore create a serious design and deployment challenge and reinforce the need to assess configurations not only for technical capability, but also for robustness across uncertain demand conditions.

2.4. Changing Government Policy

Government policy strongly influences the pace, location, and timing of offshore wind development. Permitting rules, subsidy design, auction conditions, local-content requirements, grid planning, and broader energy policy can accelerate or delay project pipelines. For CLV owners, these policy-driven changes matter because vessel demand depends not only on long-term offshore wind targets, but also on whether projects reach final investment decision and installation within expected timeframes. Policy uncertainty can therefore affect long-term utilisation, investment timing, and return on investment.

2.4.1. Policy and Subsidies

Subsidy mechanisms have been particularly important in reducing financial risk for offshore wind projects and enabling early market growth. By improving revenue certainty or adding financial support to wholesale electricity revenues, these instruments helped make capital-intensive offshore wind projects bankable. Key subsidy mechanisms have included:

- **Feed-in Tariffs (FITs):** Fixed, above-market remuneration for renewable output; often used internationally to de-risk investment by guaranteeing revenue for new renewable generation [93].
- **Renewable Certificates / Tax Credits:** Tradable certificates or fiscal credits layered on top of

wholesale revenues; commonly applied in quota-based systems overseas to incentivise renewable deployment by providing an additional revenue stream [93].

- **Contracts for Difference (CFDs):** Pay-as-produced support when market prices fall below a pre-agreed strike price; highlighted as a tool used abroad to reduce investor exposure to wholesale price volatility and to accelerate new renewable build [93].

These mechanisms lowered financing costs and enabled learning-by-doing, driving significant cost reductions over the past decade. Conversely, insufficient or poorly indexed support has recently exposed project economics: the UK's 2023 CFD round attracted no bids after the maximum strike price rose only ∼15% while LCOE pressures increased by roughly 40%. More recently the Dutch government similarly received zero bids for the Nederwiek offshore wind development zone [15, 42].

Governments have in response adjusted policy to restore bankability and stabilize pipelines. In the United States, the 2022 Inflation Reduction Act introduced substantial tax credits and bonus incentives linked to domestic content and labor, while several states reopened or renegotiated Power Purchase Agreements to reflect higher costs [28]. At the same time, regulatory uncertainty has re-emerged under recent executive actions pausing federal wind approvals, and Jones Act constraints continue to necessitate U.S.-built CLVs or feeder-barge workarounds, affecting schedule and vessel logistics [92].

In Europe, offshore wind remains central to decarbonization strategies. Following auction setbacks, policy responses have included inflation indexation, longer contract tenors, and targeted support for grid and port infrastructure. An example of this is the EU's Net Zero Industry Act which aims to improve investment certainty and asset utilization [42].

Across Asia–Pacific, approaches vary. China continues rapid expansion via state-led programs and growing international activity [40]. Japan, South Korea, and Taiwan are progressing with structured auctions and enabling legislation to attract foreign expertise and accelerate capacity additions [41, 107, 138].

Overall, coherent, inflation-aware support schemes and clear permitting regimes are pivotal for predictable project pipelines. These policies directly govern the pace, sequencing, and localization of offshore wind projects. As a result, they shape CLV demand profiles by influencing vessel numbers, capabilities such as DP class and carousel size, and the timing of new-build or charter decisions.

2.4.2. Financing

High Capital Costs & Entry Barriers

Despite growing demand for subsea cables, the cable-laying sector is characterized by high entry barriers and limited supply, leading to a chronic shortage of CLVs relative to global needs [106]. CLVs are capital-intensive and built in very limited numbers. A brand new specialized cable layer can cost on the order of $200-300+ million USD to construct and may take 2-4 years to build [23]. For instance, in early 2024 the Danish company NKT ordered a new cable ship for an estimated $218–270 million USD, scheduled for delivery in 2026 [90]. These exceptionally high capital requirements indicate that shipowners are inherently cautious when considering new-build CLVs. Rather than engaging in speculative fleet expansion, investments are typically made only when long-term project visibility or secure contractual commitments are in place. This aligns with recent assessments that the business case for new cable-installation vessels is "challenging" without long-term off-take certainty, and that high fixed costs require stable demand to justify new capacity [37, 66]. As Takahisa Ohta neatly captured: "Owning a vessel is a huge fixed cost – that's all well when the market is growing, but when the tech bubble bursts like it did in 2000, then it becomes simply a big cost" [66].

Financing Challenges

The offshore wind and CLV markets have both faced growing financing pressures since 2020. Inflation in commodities, labour, vessel costs, and higher interest rates have eroded project economics and weakened investor confidence. Reuters reports that offshore wind project costs increased by roughly 30–40% over two years, reaching an average of about 230 US dollars per megawatt hour in 2023, compared with about 75 US dollars per megawatt hour for onshore wind [48]. These rising costs have contributed to project cancellations and renegotiations, particularly in the United States, and to major write-downs by developers such as Ørsted and Equinor [28, 47].

Increased capital costs have also complicated vessel financing. Newbuild CLVs typically require investments of 200–300 million euros, yet payback periods have lengthened as charter rates lag behind inflation. In order to reflect increased project risk lenders may now demand higher returns. These pressures directly influence vessel design: owners and financiers favour cost-efficient, versatile ships that can serve multiple markets, ensuring higher utilization and predictable cash flow.

Without financial stabilization, global offshore wind capacity may fall short of climate targets; The International Renewable Energy Agency (IRENA) estimates a one-third gap by 2030 [28]. Improving capital conditions therefore remains critical for sustained sector growth and future CLV demand.

These financing pressures increase the importance of transparent early-stage design comparisons. Since new-build CLVs require large upfront investments and long payback periods, decision-makers need to understand why one configuration is preferred over another, which future conditions make it vulnerable, and whether future upgrades could preserve its usefulness. Interpretability is therefore not only an academic requirement, but also a practical requirement for investment and fleet-planning decisions.

2.5. Implications for CLV Design

The combination of volatile offshore wind deployment, shifting policy frameworks, and tightening financing conditions creates a highly uncertain environment for CLV investment and design. As Section 2.3 showed, offshore wind has strong long-term growth potential, but short-term turbulence in auction outcomes, cost inflation, project cancellations, and forecast revisions can strongly affect the timing of vessel demand [21, 28, 48]. At the same time, government support schemes are being reconfigured, while capital costs and lender requirements have increased [22, 42]. Together with the high entry barriers and long payback periods discussed in Section 2.4.2, this means that CLV concepts must be judged not only on technical capability, but also on their ability to remain attractive under different future market and policy conditions.

These conditions favour vessel concepts that are robust enough for current market requirements while preserving options for later adaptation. In design terms, this can translate into adaptable deck layouts, reserved space or structural provisions for larger tensioners, additional carousel capacity, and arrangements that do not unnecessarily block future upgrades of power, station-keeping, or mission equipment [19, 100, 122]. Such measures may increase initial complexity and cost, but they can reduce downside risk if project sizes, cable weights, water depths, or regulatory standards evolve differently than expected [88, 144].

At the same time, financing constraints and competitive tenders limit the scope for over-specified solutions. Owners must balance flexibility against capital intensity, since very large or highly customised vessels are harder to finance and may be vulnerable if the expected project pipeline does not materialise [37, 66, 106]. This reinforces the importance of disciplined early-stage trade-offs between storage capacity, tension capacity, lay-line arrangement, technical novelty, and standardisation.

Within this context, CLV design is not only a naval-architectural problem, but also a strategic decision about how much capability, flexibility, and upgrade potential to embed in a capital-intensive asset that must operate for several decades. Because these decisions are made under deep uncertainty and involve multiple stakeholders, the design rationale must be transparent, traceable, and easy to communicate. Low-fidelity parametric models are therefore appropriate for early-stage exploration, provided their assumptions and limitations are made explicit. This motivates the use of a structured uncertainty-handling method in the following chapters.

2.6. Conclusion

This chapter described the cable laying vessel in its technical, market, and policy context and addressed the first sub-question: what are the distinctive characteristics and key design drivers of cable-laying vessels, and why is uncertainty particularly challenging for their early-stage design?

CLVs are specialised work vessels whose primary mission is the safe and accurate installation of subsea power cables. They combine large cable-storage systems, dedicated cable-handling equipment, precise station-keeping capability, and, depending on project scope, subsea intervention systems such as ROVs and cranes. Their layout is therefore strongly driven by the integration of mission equipment, which distinguishes them from more generic offshore construction vessels.

The main design drivers follow directly from this mission. Cable storage capacity and deck load determine how much cable can be transported and how many installation campaigns are required. Tensioner capacity and lay-line arrangement determine whether heavy cables, deep-water projects, and dual-cable systems can be handled safely. Manoeuvrability, DP capability, seakeeping, and subsea tooling affect the ability to install cables accurately in increasingly remote, congested, and technically demanding offshore environments. In addition, fuel performance, capital cost, and expected utilisation increasingly influence whether a CLV concept is commercially attractive.

Uncertainty is particularly challenging because many of these drivers are shaped by external developments over which the vessel designer has limited control. Turbine ratings, export-system choices, cable dimensions, water depths, floating-wind deployment, seabed congestion, subsidy schemes, and financing conditions may all change significantly during the multi-decade lifetime of a CLV. At the same time, CLVs are capital-intensive assets ordered in small numbers and strongly dependent on offshore wind project pipelines. This combination of high investment stakes, long asset life, and strong coupling to uncertain external drivers makes early-stage CLV design highly path dependent.

The chapter therefore shows that an appropriate design method for this thesis must be able to:

- address deep, non-probabilistic uncertainty in external drivers such as market development, technology trajectories, policy regimes, and financing conditions;
- compare multiple CLV mission-equipment configurations across a wide range of plausible future project portfolios;
- evaluate trade-offs between mission capability, market capture, fuel-related performance, and capital intensity;
- support the analysis of robustness, vulnerability, and upgrade potential over the lifetime of a capital-intensive vessel; and
- provide transparent and interpretable results for early-stage design and investment decision-making.

These requirements form the basis for the assessment of uncertainty-handling and adaptive decision-making methods in Chapter 3.

3
Dealing with Uncertainty in Ship Design

This chapter examines how uncertainty is handled in ship design and addresses the second sub-question:

SQ2: Which uncertainty-handling and decision-making method is most suitable for early-stage cable-laying vessel design under deep uncertainty?

The chapter first outlines how ship-design practice has evolved toward more flexible and exploratory approaches in response to increasing uncertainty (Section 3.1). It then introduces the main forms and levels of uncertainty and situates the CLV design problem within the deep-uncertainty context (Section 3.2). Finally, it reviews and compares a range of decision-making methods and selects the framework used in the remainder of the thesis (Sections 3.3 and 3.4).

3.1. Evolution of Ship Design

Historically, ship design relied on evolving existing concepts. The classic **design spiral** model formalized an iterative process to refine a single design through successive cycles [104, 136]. This point-based approach provides structure but can overlook novel configurations. Some argue that the spiral is too simplistic for today's complex projects, potentially blinding designers to innovation [4]. In the cable laying vessel design problem, a strict spiral process risks cementing assumptions that may prove invalid. A CLV optimized for current turbine sizes, cable specs, and practices could falter if future projects demand larger cables, deeper installations, or new techniques. Thus, while the spiral ensures systematic refinement, it must be supplemented by methods that explore alternative concepts and keep the design flexible for changing requirements.

Advanced analytical methods and high-performance computing have enabled naval architects to pursue more innovative and unconventional design solutions. It allowed **optimization-based design** to adopt multi-objective algorithms that can evaluate numerous design variants to find balanced trade-offs across conflicting objectives, yielding a Pareto set of viable solutions instead of one "optimal" point. Recent work by J.F. Schuitemaker [122] demonstrates this approach for offshore vessels, by integrating multi-objective cost and environmental impact optimization into conceptual design. In CLV design, optimization can automate the exploration of hull parameters and equipment combinations to identify concepts that best reconcile cost, capacity, and operability. It makes trade-offs explicit (e.g. a larger carousel boosts laying capacity but increases cost) and reveals designs that remain effective under different assumptions. By casting a wide net, designers avoid over-specializing for a single forecast. A concept explored across multiple objectives may therefore reveal more balanced trade-offs, although its robustness under future market or environmental change still needs to be tested explicitly.

The adoption of **systems engineering** provides a top-down framework to manage complexity and stakeholder diversity [4]. It starts by defining all stakeholder requirements and the vessel's functions in its broader context. For a CLV, this means designing the ship as part of the broader offshore wind installation system, taking into account installation processes, maintenance, port logistics, and regulations. By basing the design on clear, traceable requirements from owners, operators, regulators, and clients, the chance of overlooking critical criteria is reduced. A systems engineering mindset keeps the design aligned with its intended mission throughout development. Grimstad and Hagen note that a ship and its mission must be designed together [56]. In practice, this means that early CLV concepts must be developed and assessed with a clear understanding of their mission profiles, operational contexts and stakeholder needs, ensuring that design choices remain consistent with the vessel's intended role as the project evolves.

Set-Based Design (SBD) is a strategy to preserve flexibility by deferring design decisions [127]. Instead of committing to one concept, the design team explores a broad set of alternatives in parallel and gradually narrows the field. Multiple CLV configurations would be developed concurrently, and only clearly infeasible or inferior options are eliminated as more information becomes available. Under deep uncertainty, SBD ensures that if requirements change or new constraints emerge, a viable concept likely remains among the options. For example, if industry trends shift toward heavier cables or floating wind installations, a CLV design accommodating those needs would still be "in the running" rather than having been discarded prematurely. By delaying lock-in, SBD greatly reduces the risk of committing to a concept that later proves inadequate. Although it requires more upfront work and careful management of alternatives, it provides a powerful hedge against uncertainty in the design stage.

Another evolution is designing for adaptability from the outset. **Configuration-based design** flips the process by starting with the ship's internal arrangement [4]. For CLVs, this means laying out critical mission systems first, then shaping the hull around those needs. This inside-out approach ensures the vessel can accommodate specialized equipment without compromise, which is crucial for such complex vessels to sucessfully perform their mission.

In tandem, a **modular design** philosophy keeps the vessel flexible. Major subsystems are treated as modules, and space and connections are reserved for future upgrades or reconfiguration. For instance, the design might include foundations for an extra carousel or a higher-capacity tensioner to be added later. Worzyk highlights that the load-carrying capacity, deck space, and structural strength required for large turntables and cable-handling equipment are primary drivers in the design of cable-laying vessels [145]. Similarly, Gijsberts shows that, in practice, the deck layout of a converted CLV is developed around the main cable-handling modules from the conceptual design stage onward [44].

An inside-out, modular approach naturally facilitates this. This approach trades some initial optimization for long-term adaptability. A modular CLV might be slightly larger or have some unused capacity built in, but that extra margin is a hedge against obsolescence. The ship can be adapted to new tasks (laying larger cables, operating in harsher environments, serving different markets) with minimal structural changes. In an industry of rapidly evolving requirements, designing a CLV as a versatile platform rather than a single-mission tool can be an effective way to manage deep uncertainty.

Together, these developments show why early-stage ship design is increasingly moving beyond the refinement of a single point design. Optimisation broadens the exploration of trade-offs, systems engineering keeps the design linked to stakeholder needs and mission context, and Set-Based Design helps avoid premature lock-in. Configuration-based and modular design further highlight how adaptability can be embedded in the vessel arrangement itself. However, in the CLV context, these approaches mainly support the structuring and exploration of the design space. They do not fully address how configurations should be evaluated across deeply uncertain future project conditions, when they become vulnerable, or how possible adaptation actions could be structured. This creates the need for an additional uncertainty-handling method.

3.2. Uncertainty

Uncertainty refers to the state of knowledge in which outcomes, future conditions, or system behaviours cannot be predicted with absolute confidence. Walker et al. describe it as "any deviation from the unachievable ideal of completely deterministic knowledge of the relevant system" [140]. In other words, uncertainty arises whenever our information or models are incomplete or when systems are too complex to predict exactly.

This section outlines the main forms and sources of uncertainty relevant to early-stage CLV design, distinguishing between aleatory and epistemic uncertainty and between endogenous and exogenous drivers. It then introduces the concept of deep uncertainty and explains how the levels-of-uncertainty framework is used to position the CLV design problem on a spectrum from complete determinism to total ignorance. Finally, it identifies the major external uncertainties shaping CLV performance over time, including technology development, market dynamics and regulatory change.

3.2.1. Types of Uncertainty

Uncertainty within ship design manifests in different ways. A first distinction can be made between **aleatory** uncertainty, which arises from inherent variability in the system and cannot be reduced, and **epistemic** uncertainty, which stems from incomplete knowledge and may be reduced as data, models, and understanding improve [33]. Epistemic uncertainty is typical of early-stage CLV design, where assumptions about behaviour, loads, and operational limits are based on imperfect information and modelling. Aleatory uncertainty, by contrast, persists even with perfect knowledge and must be managed rather than eliminated.

Uncertainties can also be classified by their origin. **Endogenous** uncertainties arise within the design process and are partly manageable by decision-makers, such as estimates of propulsion power, steel weight, or equipment integration. **Exogenous** uncertainties are external to the design process, such as fuel prices, market demand, regulatory change, or future project requirements [2]. A more detailed taxonomy of uncertainty sources in ship design distinguishes context, agent, input, model, and process uncertainty [1]. For this thesis, the most relevant distinction is between early-stage technical and model uncertainty, which affects the fidelity of the CLV performance model, and long-term contextual uncertainty, which determines whether a vessel remains suitable under changing market, technology, and regulatory conditions.

This distinction is important because the dominant uncertainty sources shift over the CLV design timeline. During early concept development, input and model uncertainties influence the accuracy of vessel performance estimates. Over the multi-decade lifetime of the vessel, however, contextual uncertainties become more important. Future offshore wind project characteristics, market demand, regulatory trajectories, and technology pathways cannot be predicted reliably and may be interpreted differently by different stakeholders [148]. The design problem therefore shifts from only reducing technical uncertainty to ensuring strategic robustness against changing external conditions.

This leads to the concept of **deep uncertainty**. Under deep uncertainty, decision-makers may be unable to know or agree upon the external context, the system model and boundaries, or the outcomes of interest and their relative importance [84]. In the CLV design case, deep uncertainty is primarily present in the external context. The vessel's core mission, system boundaries, and main functional requirements are relatively well defined, because CLVs have an established operational role and are described in industry practice and technical literature [49, 89, 145]. The CLV design problem is therefore not deeply uncertain in every respect. Rather, it combines a relatively well-defined engineering system with deeply uncertain future operating conditions.

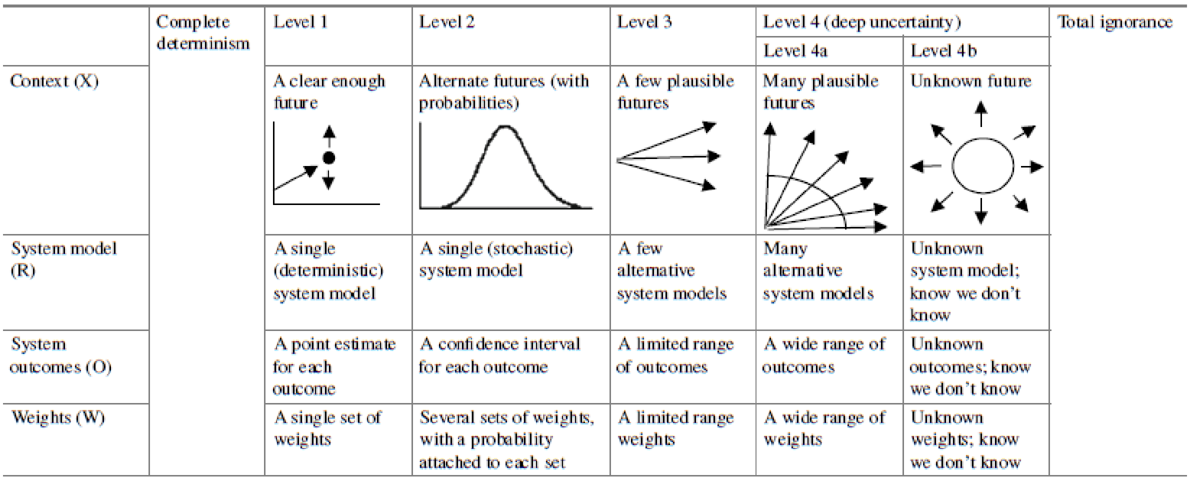
3.2.2. Levels of Uncertainty

Decision-making under uncertainty requires recognising that knowledge exists along a broad continuum. At one extreme lies the unattainable state of perfect, deterministic understanding; at the other lies total ignorance. Most real-world situations fall somewhere in between, where varying degrees of information and confidence shape the choices that can be made. To describe these intermediate states, this section uses the widely adopted levels-of-uncertainty framework from Marchau et al.'s *Decision Making Under Deep Uncertainty: From Theory to Practice* [88], which has also been applied in related maritime and engineering-design studies [131, 133, 144]. The framework is shown in Figure 3.1.

- *Level 1:* represents situations where uncertainty is acknowledged but not quantified, and future outcomes are reasonably predictable based on historical data
- *Level 2:* represents situations where uncertainty can be expressed probabilistically, allowing decisions to be based on expected outcomes and quantified risks.
- *Level 3:* represents situations with several plausible futures to which no probabilities can be

assigned, requiring scenario analysis to identify robust decisions that perform well across them.

- *Level 4a:* represents situations where the range of possible futures can be broadly outlined, but insufficient knowledge or data prevents reliable modelling or probability estimation.
- *Level 4b:* represents situations of near complete ignorance, where future developments are inherently unpredictable and no plausible bounds or models can be established



	Complete determinism	Level 1	Level 2	Level 3	Level 4 (deep uncertainty)		Total ignorance
					Level 4a	Level 4b	
Context (X)		A clear enough future	Alternate futures (with probabilities)	A few plausible futures	Many plausible futures	Unknown future	
System model (R)		A single (deterministic) system model	A single (stochastic) system model	A few alternative system models	Many alternative system models	Unknown system model; know we don't know	
System outcomes (O)		A point estimate for each outcome	A confidence interval for each outcome	A limited range of outcomes	A wide range of outcomes	Unknown outcomes; know we don't know	
Weights (W)		A single set of weights	Several sets of weights, with a probability attached to each set	A limited range weights	A wide range of weights	Unknown weights; know we don't know	

Figure 3.1: Progressive transition of levels of uncertainty (Marchau et al. [88])

Level 1 and Level 2 uncertainties can, respectively, be characterized through historical data and probabilistic assessment. Such approaches, however, prove inadequate for addressing the long-term contextual uncertainties inherent in CLV design. While some general trends such as the expansion of offshore wind energy, are seemingly evident, the strategic landscape is defined by factors that defy reliable probabilistic modelling. It is infeasible to assign reliable probabilities to the wide range of possible future paths or structural shifts. Key drivers, such as public policy and technological innovation, are illustrative: policy is often subject to volatile political dynamics rather than stable statistical patterns, and technological progress typically emerges through non-linear, disruptive advancements.

Consequently, this project focuses on how higher levels of uncertainty can be effectively managed. Fundamental to Level 3 uncertainty is the recognition that the multitude of possible future scenarios and design configurations can be represented by a limited set of plausible alternatives. Even when the broader design problem is imperfectly understood, it is still feasible to define a bounded scenario set or a small number of candidate CLV concepts that capture the essential characteristics of the problem.

Level 4a uncertainty extends beyond the structured, scenario-based reasoning of Level 3 by acknowledging that both the set of possible futures and the parameters defining them may themselves be unknown or contested. At this level, stakeholders may hold fundamentally different perceptions of the system's boundaries, relevant variables, and causal mechanisms. For CLV design, this might manifest in diverging assumptions about the future evolution of marine infrastructure networks, supply chain structures, or market demand drivers. Addressing Level 4a uncertainty thus requires an adaptive and exploratory design approach, where learning, stakeholder dialogue, and iterative reframing are integral components of the process.

Level 4b uncertainty, in contrast, refers to situations of deep ambiguity or partial ignorance, where even the nature of the problem or the existence of key influencing factors is unknown. While such conditions may arise in socio-technical transitions, they are not fully applicable to CLV design. The CLV domain is bounded by established naval-architectural principles, identifiable stakeholders, and a well-defined operational mission. As highlighted earlier (Section 3.2), the vessel's functions, system boundaries, and performance outcomes are largely agreed upon in the engineering community. Thus, although CLV design is shaped by significant contextual uncertainty, it does not exhibit deep uncertainty across all dimensions.

CLV design must deal with several levels of uncertainty, but the most critical challenges arise at Levels 3 and 4a, where long-term market, regulatory, and installation developments cannot be predicted probabilistically. At the lower Levels 1 and 2, the behaviour of a specific design can be quantified with reasonable confidence using established engineering tools. The real difficulty therefore lies not in estimating a vessel's physical performance in real operating conditions, but in determining whether it will remain the right vessel under future conditions that are far more uncertain. Since these contextual uncertainties shape a CLV's long-term relevance, the main opportunity for improvement, and the focus of this project, lies in developing approaches that better address Levels 3 and 4a.

3.2.3. Exogenous Uncertainties Shaping CLV Design

While the previous sections introduced general uncertainty taxonomies and levels of uncertainty, the CLV design problem is shaped most strongly by a narrower set of external, exogenous uncertainties. These uncertainties lie largely outside the control of designers or shipowners, but directly affect whether a vessel remains competitive across future offshore wind project portfolios. Building on the distinction between commercial, operational, and technical uncertainty in offshore ship design [2], this thesis groups the dominant exogenous uncertainties for CLV design into technical, market, and regulatory uncertainty.

Technical Uncertainty

Technical uncertainty refers to unpredictable changes in offshore wind technology and installation requirements. Future projects may involve larger turbines, longer export cables, heavier cable systems, deeper sites, floating foundations, and stricter dynamic-positioning or cable-handling requirements. As a result, future CLVs may require greater storage capacity, higher line tension, increased deck space, and more capable mission equipment, but the rate and extent of these changes are uncertain [31].

A traditional response is to add design margins, but this provides only a partial solution. Fixed margins may be insufficient if future requirements exceed the assumed range, while excessive margins can increase cost, reduce utilisation, and make the vessel less competitive in markets where standardised or lower-cost designs are preferred [109, 43]. Technical uncertainty therefore supports the need for design approaches that compare alternative technology trajectories and reveal the trade-off between initial overcapacity and future upgrade potential.

Market Uncertainty

Market uncertainty concerns the future demand for cable-laying services and the economic conditions under which the vessel will operate. Unlike conventional shipping markets, CLV demand is closely linked to offshore wind development pipelines, project timing, policy support, financing conditions, and competition. These factors make it difficult to predict how many vessels, and what type of vessels, will be required over a multi-decade design lifetime [148].

This creates a strategic design dilemma. Building for a high-demand future may lead to overcapacity and underutilisation if projects are delayed, while a conservative design may miss future opportunities if offshore wind deployment accelerates or project requirements increase. Since long-term market forecasts can deviate substantially from realised developments [134], CLV concepts should be evaluated across multiple plausible market trajectories rather than against a single expected demand scenario.

Regulatory Uncertainty

Regulatory uncertainty refers to changes in policies, laws, and standards that may affect both future offshore wind demand and vessel design requirements. One source is the policy framework that shapes offshore wind deployment, including renewable-energy targets, subsidy schemes, auction designs, permitting processes, and local-content rules [7, 124, 36]. These policies influence the volume, timing, and attractiveness of offshore wind projects and therefore affect demand for CLV capacity.

A second source is the regulatory framework that the vessel itself must satisfy throughout its lifetime. Changes in class rules, safety standards, environmental requirements, flag-state requirements, and offshore operational standards may alter the requirements for CLV design and operation [68, 146]. This could affect vessel layout, redundancy, cable-handling arrangements, station-keeping capability, or operational procedures. Regulatory drivers should therefore be treated as dynamic boundary conditions rather than fixed design constraints, since future changes may require additional compliance margins or later adaptation.

3.3. Candidate Decision-Making Methods

This section provides a concise overview of candidate decision-making methods for addressing uncertainty in early-stage CLV design. The purpose is not to describe each method in full detail, but to position the available approaches according to the level of uncertainty they primarily address and to identify which methods are most relevant for the CLV design problem. A more detailed review of the individual methods, including their usefulness and limitations, is provided in Appendix A.

The candidate methods are selected primarily from the framework discussed by Wirooks [144], with Stochastic Programming and Responsive Systems Comparison added because they are relevant to scenario-based engineering decision-making. Table 3.1 groups the methods according to the level of uncertainty they primarily address.

Table 3.1: Overview of decision-making methods grouped by level of uncertainty

Level	**Considered Decision-Making Methods**				
2	Ship-Centric Markov Decision Process (SC-MDP)	Real Options Analysis (ROA)	Stochastic Programming (SP)		
3	Engineering Options Analysis (EOA)	Epoch–Era Analysis (EEA)	Responsive Systems Comparison (RSC)		
4a	Decision Scaling (DS)	Robust Decision Making (RDM)	Many-Objective Robust Decision Making (MORDM)	Dynamic Adaptive Planning (DAP)	Dynamic Adaptive Policy Pathways (DAPP)
4b	Info-Gap Decision Theory (IG)				

The Level 2 methods are mainly suited to situations where uncertainty can be represented probabilistically. Methods such as Ship-Centric Markov Decision Processes, Real Options Analysis, and Stochastic Programming can support sequential or flexible decision-making, but they require probability distributions or transition structures that are difficult to justify for long-term CLV market and technology uncertainty.

The Level 3 methods are more suitable when several plausible futures can be defined without assigning probabilities. Engineering Options Analysis, Epoch–Era Analysis, and Responsive Systems Comparison can support scenario-based comparison of alternatives and can help identify designs that remain valuable across changing conditions. However, these methods provide less direct support for translating scenario insights into concrete early-stage design choices.

The Level 4a methods are most relevant to the CLV design problem, because they address situations where future conditions are deeply uncertain and cannot be represented by a single forecast or reliable probability distribution. Decision Scaling, RDM, and MORDM are useful for stress-testing designs across large scenario spaces and identifying robust alternatives. Dynamic Adaptive Planning and Dynamic Adaptive Policy Pathways go one step further by explicitly linking present decisions to future adaptation actions.

These differences indicate that the CLV design problem requires a method that can combine non-probabilistic scenario evaluation with explicit reasoning about future adaptation. The following section therefore assesses the reviewed methods against the CLV design requirements and selects the most suitable framework.

3.4. Method Selection

This section provides a qualitative assessment of the candidate methods reviewed in Section 3.3 and completes the answer to SQ2 by selecting the method most suitable for the CLV design problem.

3.4.1. Qualitative Assessment

Selecting a suitable decision-making approach for the CLV design problem requires evaluating how well each method can address the dominant sources of uncertainty identified in Chapter 2 and the levels of uncertainty discussed in Section 3.2. The methods summarised in Section 3.3 and described in more detail in Appendix A are therefore assessed qualitatively against a set of requirements that reflect the long asset lifetime, strong contextual uncertainty, multi-objective trade-offs, and early-stage modelling constraints of the CLV design context.

The ratings indicate the degree of alignment between each method and the CLV design requirements defined in Section 2.5: ++ denotes strong alignment, + partial or conditional alignment, − weak alignment, and −− very limited or fundamentally incompatible alignment.

- R1: Capability to address deep, non-probabilistic uncertainty in external drivers such as market development, technology trajectories, policy regimes, and financing conditions.
- R2: Ability to support robustness, vulnerability analysis, and upgrade potential over the multi-decade CLV lifetime.
- R3: Ability to incorporate multiple performance objectives, including mission capability, project feasibility, performance, and capital intensity.
- R4: Interpretability and clarity for decision-making stakeholders, including transparent, communicable, and explainable results.
- R5: Suitability for early-stage design using low-fidelity parametric CLV models and large exploratory ensembles.
- R6: Capability to analyse large sets of future scenarios and explore a wide space of plausible external developments.

Table 3.2: Qualitative assessment of decision-making methods against CLV design requirements.

	Level 2			**Level 3**			**Level 4a**					**Level 4b**
	SC-MDP	ROA	SP	EOA	EEA	RSC	DS	RDM	MORDM	DAP	**DAPP**	IG
R1: Deep uncertainty	- -	- -	- -	+	+	+	++	++	++	++	++	++
R2: Robustness/adaptability	++	++	+	++	+	-	-	+	+	++	++	- -
R3: Multiple objectives	+	+	+	+	+	++	+	+	++	+	+	- -
R4: Interpretability	+	+	-	++	++	++	+	+	+	+	++	+
R5: Early-stage design	-	+	- -	++	++	++	++	++	++	++	++	+
R6: Scenario analysis	+	+	-	+	+	+	++	++	++	+	++	- -

Legend: ++ strong alignment; + partial alignment; − weak alignment; −− very limited or fundamentally misaligned.

Table 3.2 highlights clear differences in how decision-making methods align with the requirements for early-stage CLV design under deep uncertainty. Probabilistic optimisation methods such as SC-MDP, ROA, and SP are less suitable as primary frameworks in this context. Because they depend on well-defined probability distributions or stochastic transition structures, they struggle to represent the deep uncertainty characterising future CLV operating environments (R1). Their limited suitability for broad scenario exploration (R6) and weaker compatibility with low-fidelity, exploratory early-stage modelling (R5) further limit their usefulness for the main uncertainty framing of this thesis.

Level 3 approaches such as EOA, EEA, and RSC provide a noticeable improvement. By evaluating designs across several plausible futures, they offer strong interpretability (R4) and good alignment with early-stage modelling needs (R5). However, they mainly support separate parts of the CLV design-decision problem: valuing flexibility, structuring future contexts, or comparing alternatives across epochs. They are therefore useful supporting methods, but less complete as standalone frameworks for combining scenario-based performance assessment, vulnerability identification, and adaptive design decision-making.

Deep-uncertainty methods such as DS, RDM, MORDM, DAP, and DAPP show the strongest overall alignment with the CLV requirements. Decision Scaling is effective for diagnosing vulnerabilities, while RDM and MORDM are strong for stress-testing and multi-objective exploration across many futures. However, these methods are less directly focused on constructing clear adaptive sequences of design actions. In contrast, DAP and especially DAPP combine high scenario capacity (R6), transparent decision logic (R4), and strong support for adaptive, pathway-based decision-making (R2).

The CLV design problem requires a method that can move from robustness testing to staged design action. RDM and MORDM are useful for stress-testing alternatives, but do not directly show how a vessel configuration could be adapted over time. EEA and RSC help structure and compare different futures, but are less focused on adaptation points and transition logic. ROA and EOA address flexibility more explicitly, but require assumptions about option value, probabilities, or investment timing that are difficult to justify in this early-stage CLV case. DAPP is therefore selected as the main structure because it supports non-probabilistic scenario testing, identifies when configurations become vulnerable, and presents possible upgrade routes in a form that is suitable for fleet-level design reasoning.

Among the reviewed methods, DAPP exhibits the most comprehensive alignment with the CLV design problem. It provides a structured way to compare initial actions, identify adaptation tipping points, and construct pathways of future actions. This is especially relevant for a long-lived CLV asset, where the key question is not only which mission-equipment configuration performs best under current assumptions, but also when that configuration may require an upgrade as future project requirements become more demanding. The potential suitability of DAPP for ship design under deep uncertainty is also supported by Zwaginga and Pruyn, who identify Dynamic Adaptive Policy Pathways as a promising framework for future-proof ship design under uncertain long-term conditions [147].

3.5. Conclusion

This chapter addressed the second sub-question by reviewing uncertainty-handling and decision-making methods for early-stage ship design under deep uncertainty, and by selecting the method used in the remainder of the thesis.

The review showed that ship-design practice has moved beyond purely point-based design toward more exploratory and flexible approaches. Optimisation-based design, systems engineering, Set-Based Design, configuration-based design, and modular design can all help broaden the design space and reduce premature lock-in. However, these approaches mainly support the structuring and exploration of design alternatives; they do not by themselves provide a complete framework for evaluating CLV configurations across uncertain future project conditions.

The uncertainty review positioned the CLV design problem primarily at Levels 3 and 4a of the uncertainty framework. The vessel's mission and technical system boundaries are relatively well defined, but the future project environment is deeply uncertain. Project characteristics such as cable length, distance from shore, water depth, voltage technology, foundation type, market timing, and regulation cannot be represented reliably by a single forecast or probability distribution. This makes scenario-based and adaptive decision-making methods more appropriate than deterministic or purely probabilistic approaches.

The comparison of candidate methods showed that several approaches can support parts of the CLV design problem. Probabilistic methods such as SC-MDP, ROA, and SP are less suitable as primary frameworks because they require probability assumptions that are difficult to justify. EOA, EEA, RSC, DS, RDM, and MORDM offer useful support for flexibility assessment, scenario comparison, stress-testing, or robustness analysis. However, Dynamic Adaptive Policy Pathways provides the strongest overall fit because it combines non-probabilistic scenario reasoning with the identification of vulnerabilities and possible adaptation over time.

DAPP is therefore selected as the overarching decision framework for this thesis. It is suitable for the CLV design problem because it supports structured reasoning about when a mission-equipment configuration may become vulnerable under changing future project conditions, and how alternative design choices or upgrades can be considered. The next chapter translates this framework into the research methodology used for early-stage CLV mission-equipment evaluation.

4
Research Methodology and DAPP Framework

This chapter translates the method selected in Chapter 3 into the research methodology used in this thesis. Chapter 3 concluded that Dynamic Adaptive Policy Pathways (DAPP) is suitable for the early-stage CLV design problem because it supports decision-making under deep uncertainty, focuses on vulnerabilities and adaptation tipping points, and enables the construction of adaptive strategies rather than relying on a single forecast. The present chapter explains how this logic is adapted to the cable-laying vessel case.

The chapter primarily addresses the third sub-question:

How can the selected method be adapted to evaluate CLV mission-equipment decisions under uncertain future project conditions?

The approach developed in this thesis combines a parametric mission-equipment design model, synthetic project portfolio generation, project-level simulation, portfolio-level performance evaluation, and adaptive pathway construction. The purpose is to create a structured method for comparing design alternatives, understanding their vulnerabilities, and identifying when future upgrades may become necessary.

4.1. DAPP Framework and CLV Translation

Dynamic Adaptive Policy Pathways (DAPP) is used in this thesis as the overarching methodological framework for structuring CLV mission-equipment decisions under uncertain future project conditions. DAPP was developed for long-term planning problems in which a single static plan may become inadequate as external conditions change. Rather than selecting one fixed solution for one forecasted future, DAPP compares how actions perform across different future conditions and identifies when adaptation may become necessary [26].

A central concept in DAPP is the adaptation tipping point: the condition under which an existing action no longer meets the required performance objective. Once such a tipping point is reached, the decision-maker can transition to a follow-up action that restores acceptable performance. By connecting initial actions, follow-up actions, and their validity ranges, DAPP produces adaptation pathways: sequences of decisions that can remain effective under different future developments.

This logic fits the CLV design problem because a cable-laying vessel is a long-lived and capital-intensive asset, while future project requirements are uncertain. A mission-equipment configuration that is adequate for current export-cable projects may become constrained if future projects require longer cables, deeper installation, higher tension capacity, or dual-cable HVDC capability. Conversely, selecting a very high-capacity configuration from the start may create unnecessary investment and underutilisation if demanding futures do not materialise.

4.2. Decision Context and System Boundary

The first step in applying DAPP is to define the decision context, including the system boundary, relevant uncertainties, and performance objective. In this thesis, this step translates the general CLV fleet-investment problem into a specific early-stage mission-equipment design problem.

The central decision problem addressed in this thesis is how to select an initial CLV mission-equipment configuration while keeping possible future upgrades in view. More specifically, the method supports the question of which carousel and tensioner arrangement should be selected initially, how its performance changes as future project portfolios evolve, and under which future conditions upgrades may be needed to retain acceptable performance. Throughout this chapter, the term configuration therefore refers to the mission-equipment configuration.

The operational scope is narrowed to export-cable installation for offshore wind projects. Compared with inter-array installation, export-cable installation places stronger emphasis on large cable-storage capacity, high cable-handling tension, reduced offshore jointing, and the ability to handle dual-cable HVDC projects. These requirements are sensitive to future project developments, since longer, deeper, more remote, and more HVDC- or floating-oriented portfolios can change storage demand, campaign count, required tension, transit effort, and lay-line requirements. The mission-equipment focus of this thesis is therefore limited to carousel and tensioner systems, as these systems most directly shape the storage, handling, and lay-line capabilities considered in the methodology.

Applying DAPP to CLV design also requires an explicit starting point. In the water-management domain, where DAPP was originally developed, the physical system often already exists. The current state of a river basin, delta, or infrastructure system can therefore act as the baseline for evaluating future adaptation actions. In early-stage CLV design, this is different: there is no pre-existing vessel configuration that automatically serves as the baseline, and the designer still has substantial freedom in defining the platform from which adaptation pathways may evolve.

In the Boskalis context, early-stage vessel development is not necessarily limited to a fully new-build design problem. Fleet-development decisions quite often start from an existing or acquired platform that is considered suitable for conversion. The fixed-hull assumption used in this thesis therefore represents a practically relevant design situation: the platform hull is treated as a given boundary condition, while the mission-equipment configuration remains open to variation. Hull dimensions, hydrostatic relations, baseline lightship properties, and installed vessel power are kept constant, while carousel and tensioner systems are varied parametrically. The design model generates a fixed library of candidate configurations, each combining one carousel arrangement with one tensioner arrangement. The same design library is evaluated across all scenario portfolios, so that changes in performance are caused by changes in the project environment rather than by changes in the available design set.

This modelling choice follows from the decision focus of the thesis. Rather than optimising a complete vessel design from first principles, the method investigates how different cable-storage and cable-handling configurations perform under uncertain project portfolios. The main effects considered are storage capacity, campaign requirements, cable-handling tension, dual-lay capability, mission-equipment weight and cost, and fuel consumption. Detailed hull-form optimisation, structural integration, DP system layout, general arrangement design, cable-chute geometry, ROV integration, and retrofit engineering are outside the quantitative scope.

The method is intended for Boskalis decision-makers involved in early-stage CLV design, fleet development, engineering assessment, and strategic investment discussions. It may also be relevant for other CLV owners or designers, but the primary context of this thesis remains the Boskalis case. The method does not prescribe a single investment strategy. A lean strategy may favour lower initial CAPEX and accept the possibility of later upgrades, while a conservative strategy may favour a higher-capacity initial configuration to reduce future infeasibility risk. The method supports such choices by making performance differences, trade-offs, and possible upgrade directions more transparent.

4.3. Adapted DAPP Workflow for CLV Design

After defining the decision context and system boundary, the remaining DAPP logic is translated into a CLV-specific workflow. In this thesis, DAPP policy actions are interpreted as mission-equipment choices or upgrade options, external conditions are represented by synthetic project portfolios, and adaptation tipping points occur when a configuration no longer meets the selected performance threshold. This translation is summarised in Table 4.1.

Table 4.1: Translation of DAPP concepts to the CLV design methodology.

DAPP concept	General meaning	Translation in this thesis
Objectives, constraints, and uncertainties	Define what the plan should achieve, which limits apply, and which future developments are uncertain.	Performance objectives, fixed-hull boundary, mission-equipment variables, and uncertain project requirements.
Action or option	Decision, intervention, or measure available to the decision-maker now or later.	Initial mission-equipment choice or later upgrade option.
External condition	Uncertain future state of the world that affects the performance of an action.	Scenario-based project portfolios with varying cable length, distance from shore, water depth, HVDC share, and floating share.
Adaptation tipping point	Condition under which an action no longer meets the required performance level.	Scenario state where performance falls below the selected threshold.
Adaptation pathway	Sequence of actions that maintains acceptable performance as external conditions change.	Sequence of configurations and logical mission-equipment upgrades.
Pathway comparison	Evaluation of alternative pathways using costs, benefits, risks, and other decision criteria.	Scorecard-based comparison supported by KPIs, Pareto plots, and pathway maps.
Signpost	Observable development indicating that reassessment or adaptation may be needed.	Conceptual monitoring indicators, such as HVDC share, project scale, water depth, and floating share.

The adapted method consists of five practical steps. First, the decision context and system boundary are defined. Second, candidate configurations are stress-tested against alternative future project portfolios to identify vulnerabilities and adaptation tipping points. Third, possible design actions and upgrade options are identified. Fourth, logical design actions are connected into adaptive pathways. Finally, configurations and pathways are compared using performance indicators, design-space plots, pathway maps, and qualitative scorecards.

To make the pathway logic more tangible, Figure 4.1 shows the general visual form of an adaptation pathway map. Each horizontal line represents an action or configuration state that remains valid over a certain range of external conditions. Transfer points indicate where a decision-maker can move from one action to another, while adaptation tipping points indicate where an action no longer satisfies the required performance objective. The accompanying scorecard is used to compare alternative pathways on criteria such as target effect, cost burden, and side effects.

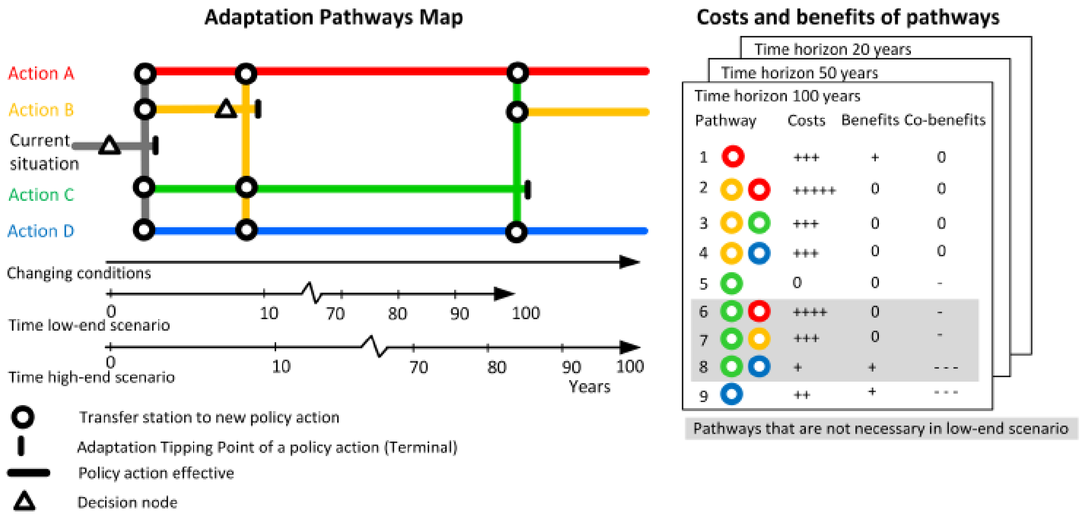


Figure 4.1: Example DAPP adaptation pathway map and pathway scorecard. Source: Deltares [26]

In this thesis, this visual logic is adapted to CLV mission-equipment design. The horizontal axis is not interpreted as a fixed timeline, but as increasing project-portfolio stress across scenario families. The pathway maps developed in Chapter 9 therefore show how configurations may remain valid, become vulnerable, or be upgraded as cable length, distance from shore, HVDC share, water depth, or floating-project share increase.

Transitions between configurations are interpreted as plausible capability-development directions. Detailed retrofit feasibility, layout integration, upgrade cost, and downtime are addressed qualitatively in the pathway analysis rather than modelled directly. Similarly, signposts and monitoring are included conceptually rather than implemented as an operational monitoring system. Since the scenarios are not linked to fixed points in time, the pathway maps should not be read as time-explicit investment schedules. If future market forecasts or fleet-planning timelines become available, indicators such as HVDC share, project scale, distance from shore, water depth, and floating-project share could be used as signposts for reassessing whether mission-equipment upgrades are required.

4.4. Scenario Logic and Adaptation Tipping Points

The uncertainty considered in this thesis is primarily contextual and exogenous. Future offshore wind projects may differ from current projects in terms of distance from shore, cable length, water depth, voltage technology, and foundation type. These developments are difficult to predict with confidence over the lifetime of a CLV, and assigning reliable probabilities to them would create a false sense of precision. This thesis therefore uses scenario-based stress testing instead of probabilistic forecasting.

Five uncertainty drivers are carried into the quantitative scenario framework:

- project cable length;
- distance from shore;
- installation water depth;
- share of HVDC projects;
- share of floating-foundation projects.

These drivers are selected because they have a direct influence on the vessel capabilities modelled in this thesis. Longer cable lengths and greater distances from shore are expected to increase storage demand, campaign requirements, transit time, and fuel consumption. Greater water depth is expected to increase required installation tension, making tensioner capacity a potential limiting factor. A higher HVDC share is expected to increase the number of dual-cable projects, making two-line tensioner capability increasingly important. Floating share is used mainly as a scenario indicator associated with deeper-water portfolios, rather than as an independent vessel-design driver.

The scenario framework is organised around two coupled stress-test families. The first family increases cable length and distance from shore while also increasing the HVDC share. This family primarily tests storage capacity, campaign count, transit effort, and the relevance of dual-lay capability. The second family increases water depth while also increasing the floating-foundation share. This family primarily tests tensioner capacity and the ability of configurations to remain feasible in deeper-water project portfolios.

Other uncertainties discussed earlier in the thesis, such as regulation, alternative fuels, financing conditions, seabed congestion, project timing, and regional market composition, are treated as contextual drivers. The quantitative scenario model focuses on the drivers most directly linked to carousel and tensioner sizing. Future applications could add further scenario dimensions to capture a broader uncertainty space.

The scenarios provide controlled and repeatable project portfolios for testing how candidate CLV configurations respond to increasingly demanding project requirements. This is consistent with the DAPP logic, where the objective is to identify vulnerabilities, tipping points, and possible adaptation actions across a range of plausible futures.

Identifying adaptation tipping points requires performance criteria that define when a configuration is considered adequate and when adaptation may be required. In this thesis, performance is evaluated through a set of indicators selected to match the decision focus of the study, rather than through a single optimisation objective. The main indicators are project feasibility, feasible share of total portfolio cable kilometres, number of required campaigns, fuel consumption per installed kilometre, and mission-equipment CAPEX.

The distinction between project count and cable-kilometre capture is important. A vessel may be able to complete many small projects while failing a smaller number of large projects that represent a substantial share of the portfolio's cable-kilometre demand. For this reason, the feasible share of total cable kilometres is used as a core market-capture indicator. Campaign count is included as an operational-efficiency indicator, since a theoretically feasible project may become unattractive if it requires too many separate installation campaigns.

In DAPP terminology, an adaptation tipping point occurs when a design no longer meets the required performance level under a given future condition. In the CLV case, this means that a configuration may become insufficient when project length, distance from shore, water depth, HVDC share, or floating share increases beyond the point at which the vessel can still capture an acceptable share of the project portfolio. The exact performance thresholds are operationalised in the KPI and screening framework described in Chapter 6, where feasible cable-kilometre capture within a limited number of campaigns is used as a main indicator.

In this thesis, the adaptation tipping point is scenario-based rather than time-based: it indicates the project-portfolio condition under which a design becomes vulnerable. The value of the tipping-point concept lies in comparing designs, since some configurations fail early as project requirements increase, while others retain acceptable performance over a wider uncertainty range.

4.5. Research Workflow

The overall research workflow is shown conceptually in Figure 4.2. The workflow starts with the problem background and method selection developed in Chapters 2 and 3. The selected DAPP logic is then translated into a parametric CLV design and evaluation framework.

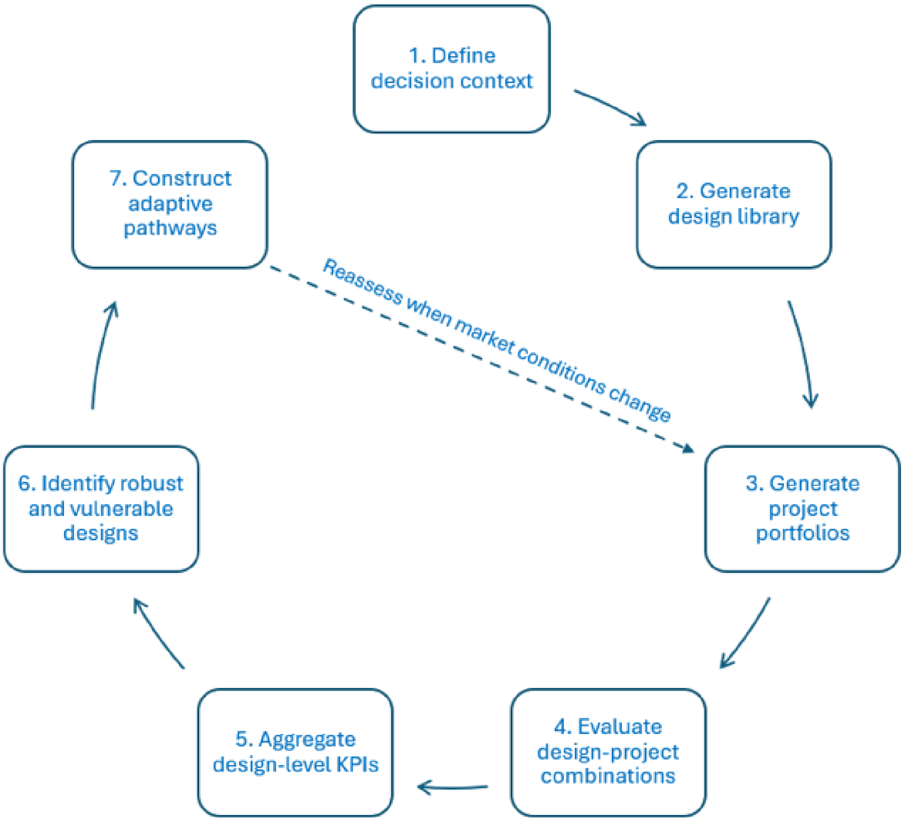


Figure 4.2: Adapted DAPP workflow for early-stage CLV mission-equipment design. The dashed reassessment link indicates that project portfolios, performance evaluation, and pathway choices can be revisited when market conditions change.

The workflow consists of the following steps:

1. **Define the decision context.** The fixed reference platform hull defines the system to which design actions are applied. Within this boundary, the decision concerns which mission-equipment configuration should be selected initially to support acceptable performance across uncertain future project portfolios.
2. **Generate a design library.** A fixed set of candidate configurations is generated by combining carousel and tensioner options on a common reference platform hull.
3. **Generate project portfolios.** Synthetic offshore wind project portfolios are generated from an internal base dataset. Scenario families are used to represent increasingly demanding future project conditions.
4. **Evaluate project-design combinations.** Each configuration is evaluated against each project in a portfolio. The model checks storage feasibility, tension feasibility, line-layout feasibility, campaign requirements, loaded stability, transit validity, and operational fuel consumption.
5. **Aggregate design performance.** Project-level outputs are aggregated into design-level KPIs, including feasibility rate, feasible cable-kilometre share, campaign-bucket performance, mission-equipment CAPEX, fuel intensity, utilisation, and infeasibility reasons.
6. **Identify robust and vulnerable designs.** Designs are compared across scenarios to identify which configurations remain successful, which become vulnerable, and which technical constraints dominate their performance.
7. **Construct adaptive pathways.** Candidate configurations and logical upgrade actions are combined into pathway maps. These maps show how an initial mission-equipment configuration could be upgraded if future project requirements become more demanding.

The final reassessment link reflects the adaptive nature of the method: as new market or project information becomes available, the scenario portfolios, performance evaluation, and pathway choices can be updated.

The detailed implementation of the parametric vessel model and project-evaluation logic is described in Chapter 5. The construction of the synthetic project portfolios, scenario families, performance measures, and Pareto-screening logic is described in Chapter 6. Verification and validation of the model behaviour are addressed in Chapter 7. The results of the scenario evaluations are discussed in Chapter 8, while the resulting adaptive pathways are discussed in Chapter 9.

4.6. Methodological Boundaries

The methodology is designed for early-stage comparative analysis and has the following boundaries.

First, the method is non-probabilistic. The scenarios are structured stress tests rather than probability-weighted forecasts.

Second, the analysis is not time-explicit. Scenario steps represent increasing levels of future project demand rather than specific years. If external market forecasts are available, the scenario states could be linked to an expected timeline, but this is outside the current implementation.

Third, the model focuses on mission-equipment capability. The fixed reference platform hull is not optimised, and detailed structural integration, general arrangement, DP system design, cable routing, ROV integration, and retrofit engineering are not modelled.

Fourth, the pathway analysis does not provide a detailed retrofit feasibility or cost assessment. Upgrades are interpreted as logical transitions between design-library configurations, but practical implementation would require further engineering, cost estimation, downtime assessment, and planning.

Fifth, financial business-case elements are outside the quantitative scope. Revenue, charter rates, utilisation forecasts, financing structure, net present value, and payback period are not modelled quantitatively. The CAPEX indicator is used only as a relative mission-equipment cost measure for comparing configurations.

Sixth, this thesis applies DAPP as an early-stage design-support framework, but it does not develop the full organisational process required to implement and monitor adaptive pathways in practice. Signposts are identified conceptually as relevant indicators to monitor, but detailed trigger values, decision rules, governance responsibilities, and implementation procedures are outside the scope of the research.

Finally, the method supports decision-making by making trade-offs explicit and traceable, while the final selection of a design strategy remains dependent on risk appetite, expected market development, investment strategy, and operational priorities.

4.7. Conclusion

This chapter has translated the DAPP framework selected in Chapter 3 into a CLV-specific research methodology. The central decision is framed as the selection of an initial mission-equipment configuration and the identification of future upgrade conditions under uncertain project requirements. DAPP is adapted by interpreting actions as mission-equipment choices and upgrade options, external conditions as alternative project portfolios, and adaptation tipping points as scenario conditions under which a configuration no longer meets the required performance level.

The resulting methodology follows a clear sequence: define the decision context and system boundary, generate a fixed design library, create synthetic project portfolios, evaluate each design against each project, aggregate portfolio-level performance, identify robust and vulnerable configurations, and construct adaptive design pathways. This structure provides the link between the theoretical uncertainty framework and the computational model developed in the following chapters.

The next chapter describes the parametric vessel model and project-evaluation logic in detail. It explains how candidate CLV configurations are generated, how project requirements are estimated, and how feasibility, campaign count, duration, fuel consumption, and mission-equipment cost indicators are calculated and stored for subsequent portfolio-level evaluation.

5

Parametric Vessel Model and Project Evaluation Logic

This chapter develops the parametric vessel model and project-evaluation logic used in this thesis. It addresses the fourth sub-question:

Which configuration characteristics and project variables determine whether a CLV mission-equipment setup is technically and operationally suitable?

The chapter first describes the model architecture and fixed reference platform hull. It then explains how the carousel and tensioner design libraries are generated, how vessel-level properties such as weight, draft, stability, power, and CAPEX are estimated, and how each configuration is evaluated against project-specific cable-installation requirements. Detailed supporting reference data, fitted equipment-scaling relations, and transit-resistance model inputs are provided in Appendix B

5.1. Model Architecture

The computational model is structured as a fixed-platform mission-equipment evaluation framework. It does not optimise a complete cable-laying vessel from first principles. Instead, the hull dimensions, general platform characteristics, installed vessel power, and main arrangement are kept fixed, while the cable-storage and tensioner arrangements are varied. Vessel-related calculations are used to assess whether each mission-equipment configuration remains technically plausible on the reference platform, rather than to optimise the platform itself. Figure 5.1 summarises the resulting model architecture.

The model first generates a design library of candidate mission-equipment configurations. This library is built from two component libraries: a carousel library representing alternative cable-storage arrangements, and a tensioner library representing alternative lay-line and tension-capacity arrangements. These libraries are combined through a full factorial cross-combination, so that each carousel arrangement is paired with each tensioner arrangement. The result is a fixed set of candidate CLV mission-equipment configurations.

Each combined configuration is then enriched with reference-platform attributes, including mission-equipment weight, total displacement, estimated empty draft, simplified stability properties, installed mission-equipment power, and indicative mission-equipment CAPEX. Separately, the operational modules use a fixed installed vessel power for transit and DP-related power estimates. This distinction is important: the mission equipment is varied, while the vessel platform and installed vessel power are not.

The resulting design library is kept constant across all scenario evaluations. This ensures that differences in model outcomes are caused by changes in the project portfolio, rather than by changes in the available design alternatives. The approach is therefore suited to comparing how the same candidate configurations perform under different structured future project conditions.

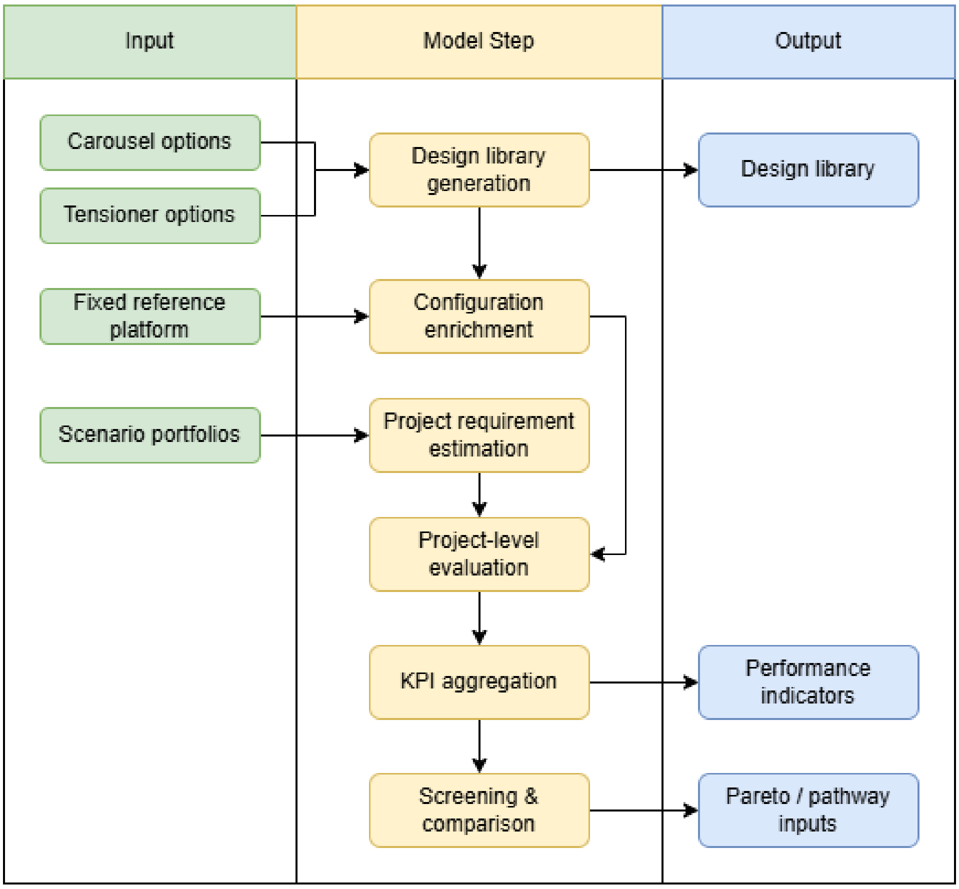


Figure 5.1: High-level architecture of the fixed-platform mission-equipment evaluation framework.

The model is implemented as a sequential evaluation pipeline. Candidate mission-equipment configurations are first generated from discrete carousel and tensioner variables and then enriched with technical and cost attributes on the fixed reference platform. Each enriched configuration is subsequently evaluated against every project in a scenario-specific offshore wind project portfolio. At project level, the model estimates cable requirements, campaign requirements, technical feasibility, loaded stability, transit performance, installation duration, and fuel consumption. These project-level outputs are then aggregated into design-level and portfolio-level performance measures, which are used for screening, Pareto comparison, and pathway analysis in the subsequent chapters.

5.1.1. Reference Platform Hull

The mission-equipment design space is generated around a fixed reference platform hull provided by Boskalis. The hull itself is not varied in this study. Instead, it provides the common platform boundary conditions for comparing alternative carousel and tensioner arrangements. Hull form, hydrostatic properties, main deck height, baseline lightship weight, and propulsion-related hull functions are therefore treated as fixed inputs. This allows the analysis to isolate how mission-equipment choices affect storage capability, tension capacity, weight, draft, stability, indicative cost, and operational performance.

The principal particulars of the reference platform hull are shown in Figure 5.2. Only the hull properties required for the model are used directly in the calculations.

主要技术参数	PRINCIPAL PARTICULARS	
船长_总长	LENGTH _OVER ALL	[redacted]
船长_设计水线	LENGTH _DESIGN WATER LINE	[redacted]
船长_规范	LENGTH _RULE	[redacted]
船长_载重线	LENGTH _LOAD LINE	[redacted]
型宽	BREADTH MOULDED	[redacted]
型深	DEPTH MOULDED	[redacted]
结构吃水	SCANTLING DRAUGHT	[redacted]
设计吃水	DESIGN DRAUGHT	[redacted]
载重量 (结构吃水)	DWT, SCANTLING DRAUGHT	[redacted]
载货甲板载荷	CARGO DECK DESIGN LOAD	[redacted]
载货甲板面积	CARGO DECK AREA	[redacted]
服务航速	SPEED, service at design draught	[redacted]
定员	COMPLEMENT	[redacted]

Figure 5.2: Principal particulars of the Deck Carrier concept used as reference platform hull [12].

Based on these particulars, the 3D hull model, and the general arrangement drawings, additional hull-related modelling assumptions are defined for the weight, draft, and stability calculations. These assumptions are summarised in Table 5.1.

Table 5.1: Additional hull-related particulars used in the parametric model.

Parameter	Value	Unit
Derived lightship weight	15,400	t
Main deck height above keel	14.0	m
Tank top height above keel	2.0	m
KM_T draft interpolation range	4–11	m
Resistance draft interpolation range	4–10	m
Minimum operational draft	7.86	m
Total installed power used in operational model	16	MW

Hull dimensions, deck structural capacity, machinery arrangement, DP class, accommodation, ROV facilities, and detailed general-arrangement constraints are not treated as design variables. Their influence is represented only through the fixed hull properties and simplified performance functions used later in this chapter. The minimum operational draft is introduced here as a model input and is further covered in the draft and stability calculation logic in Section 5.2.4.

5.2. Design Space Generation

The design space is generated by varying the two mission-equipment systems most directly linked to export-cable installation capability: carousel storage and tensioner handling capacity. Carousel volume determines the amount of cable that can be carried and therefore affects the number of campaigns required to complete a project. Tensioner capacity determines whether heavier cables can be handled in deeper water.

The model is intentionally limited to these two mission-equipment systems, as they most directly determine operational capability. Other CLV subsystems, including the DP and propulsion arrangement, ROV and crane systems, accommodation, and auxiliary systems, are not varied parametrically in this study. They are represented only through the fixed reference-platform assumptions where relevant, or otherwise left outside the design scope. This keeps the design space suitable for early-stage comparison while focusing on the capability choices most relevant to storage, campaign count, deep-water capability, and future upgrade potential.

5.2.1. Carousel Configuration Generation

The carousel generator defines the cable-storage design space using three predefined slots: two above-deck slots (AD1 and AD2) and one below-deck slot (BD1). Each slot has a fixed core diameter of 6 m and a discrete set of allowable outer diameters and heights, as summarised in Table 5.2.

Table 5.2: Carousel slot constraints and dimension ranges used in the design generator.

Slot type	Slot names	Outer diameter options [m]	Height options [m]	Core diameter [m]
Above deck	AD1, AD2	24, 32, 40	4, 6, 8	6
Below deck	BD1	20, 25, 30	4, 6, 8	6

The selected dimensions are based on the reference platform geometry and the collected carousel reference data. The 40 m above-deck diameter limit is linked to the 43 m breadth of the reference hull, while the 30 m below-deck limit reflects the more constrained integration environment below deck. The maximum height of 8 m is based on the largest carousel height found in the reference data listed in Appendix B.2. The common 6 m core diameter is used as a practical handling assumption to avoid unrealistically tight cable paths.

For each slot, the generator creates a set of possible carousel options, including the option that no carousel is installed. Options are filtered using the slot-specific dimensional limits and a minimum gross volume requirement of 2000 m^3, which removes small storage options that are inconsistent with the export-cable installation focus of the study. Since AD1 and AD2 are treated as functionally interchangeable, mirrored above-deck arrangements are counted only once. After filtering, excluding configurations without any installed carousel, and removing mirrored AD1–AD2 duplicates, 314 unique carousel configurations are retained.

For each remaining carousel option, gross storage volume is calculated as the annular cylindrical volume between the outer diameter and the fixed core diameter:

$$V_{car} = \pi H \left(R^2 - r^2\right) \tag{5.1}$$

where H is the carousel height, R is the outer radius, and r is the core radius. This volume represents geometric gross storage volume. Usable cable storage is treated separately through the fill factor in the project-evaluation model.

Each carousel is then assigned indicative weight, vertical centre of gravity, cable capacity, CAPEX, and installed drive power. These quantities are estimated using simplified scaling relations derived from the collected carousel reference data and experience-based cost input. Empty weight is estimated from a constant volume-based scaling factor, while the empty-carousel VCG is approximated as 40% of the carousel height above its base level. Above-deck carousels are placed at main deck height and the below-deck carousel is placed above the tank top. These assumptions are applied consistently across all generated carousel configurations.

Because the generated carousels are defined geometrically, an empirical volume-to-capacity relation is used to estimate indicative cable capacity before applying the CAPEX relation. Installed drive power is estimated directly from gross carousel volume. For configurations with multiple installed carousels, total carousel weight, CAPEX, installed power, and storage volume are obtained by summing over the active slots. The equations, underlying data, and fitted relations used for these carousel scaling assumptions are provided in Appendix B.2.

5.2.2. Tensioner Configuration Generation

The tensioner generator defines the cable-handling design space from a base catalogue of CEMAC offshore track tensioners [87]. The unit models used in the generator are shown in Table 5.3. The rated tension capacity of each unit is used as the primary scaling parameter.

Table 5.3: Tensioner unit catalogue used in the design generator [87].

Unit model	Capacity [t]	Speed [m/h]	Max. pull force [kN]	Weight [t]	No. Tracks [-]
5T	5	1200	50	6.8	2
10T	10	1200	100	13.0	2
15T	15	1200	150	17.0	2
20T	20	1200	200	21.0	2
25T	25	900	250	42.0	3
50T	50	900	500	75.0	4

For each unit model, the generator considers one or two parallel lay lines and one, two, or three identical tensioner units installed in series per line. Mixed-unit series arrangements are not generated, because unequal unit capacities would introduce additional load-sharing assumptions and reduce comparability between configurations. With six unit models, two line options, and three series options, this results in 36 possible tensioner configurations.

The line capacity is calculated from the unit capacity and the number of identical units installed in series:

$$T_{line} = n_{series} \cdot T_{unit} \tag{5.2}$$

where T_{line} is the tension capacity per line, n_{series} is the number of units in series per line, and T_{unit} is the rated capacity of one unit. Increasing the number of series units therefore increases the available tension per lay line, while increasing the number of parallel lines enables dual-lay operation.

At vessel level, the model assigns total tensioner weight, installed tensioner power, vertical centre of gravity, and indicative CAPEX to each generated arrangement. Installed power is estimated from the maximum pull force, specified line speed, and an assumed drive efficiency of 0.85. CAPEX is estimated using an experience-based linear relation with unit capacity. The tensioner VCG is estimated from the unit height and assumed deck-foundation level. These simplified scaling relations are applied consistently across all generated configurations and are summarised in Appendix B.2.

5.2.3. Formation of the Full Design Library

After the carousel and tensioner libraries have been generated independently, they are combined using a full factorial cross-merge. This means that every retained carousel configuration is combined with every generated tensioner-system configuration. The resulting design library therefore represents all combinations of the generated storage arrangements and tensioner arrangements:

$$N_{configurations} = N_{carousel} \cdot N_{tensioner} \tag{5.3}$$

where $N_{configurations}$ is the total number of generated mission-equipment configurations, $N_{carousel}$ is the number of retained carousel configurations, and $N_{tensioner}$ is the number of generated tensioner-system configurations. The generation counts are summarised in Table 5.4.

Table 5.4: Design-library generation counts.

Generation step	Count
Retained carousel configurations	314
Generated tensioner-system configurations	36
Full factorial carousel–tensioner combinations	11,304

Each row in the resulting design library represents a unique CLV mission-equipment configuration and is assigned a unique `config_id`. After generation, no scenario-specific changes are made to the design library: the same fixed set of configurations is evaluated in every project portfolio. This ensures that differences in performance can be attributed to changes in the project environment rather than to changes in the candidate design set. The design library therefore forms the basis for comparing configurations on storage capacity, line capacity, mission-equipment weight, draft, simplified stability, installed mission-equipment power, and mission-equipment CAPEX.

5.2.4. Weight, Draft, and Stability Enrichment

After the full design library has been formed, each mission-equipment configuration is enriched with weight, draft, and simplified stability properties. The total mission-equipment weight is obtained by summing the empty carousel weights and installed tensioner weights. This weight is added to the reference-platform lightship weight to estimate the empty configuration displacement. The lightship weight is derived from the principal particulars of the reference platform hull as the difference between the estimated displacement of 57,365 t at a scantling draft of 9.3 m and the corresponding deadweight of 42,000 t, resulting in $W_{LS} \approx 15{,}400$ t. The supporting weight, draft, and stability relations are summarised in Appendix B.3.

The raw hydrostatic draft of each configuration is estimated from a linear displacement–draft relation fitted to the reference hull hydrostatic data. The fit is based on draft points between 4 m and 11 m and gives a close representation of the available hydrostatic data. The fitted relation and supporting plot are provided in Appendix B.3. The resulting draft is retained as the unconstrained hydrostatic draft of the generated configuration.

A minimum operational draft is then imposed for subsequent performance calculations. This draft is used as a reference-platform constraint to maintain sufficient immersion of the aft propulsion units in the simplified operational model. It is not the result of a propeller or thruster design process. Based on the general arrangement drawings, the aft propulsor centreline is located approximately 2.61 m above the keel and the propeller diameter is estimated as 3.5 m [11]. Applying a minimum immersion requirement of 1.5 times the propeller diameter [129] gives a minimum operational draft of 7.86 m. The configuration draft used in later calculations is therefore:

$$T_{config} = \max\left(T_{raw}, 7.86\right) \tag{5.4}$$

where T_{raw} is the raw hydrostatic draft obtained from the displacement–draft relation. Configurations with $T_{raw} < T_{config}$ would require ballast in practice to reach the minimum operational draft. In this model, the minimum draft is enforced for performance calculations, but ballast mass, ballast moments, tank arrangement, trim effects, and ballast operations are not explicitly modelled. Detailed ballast effects on displacement, KG, GM, trim, and resistance are therefore outside the model scope.

The stability enrichment uses a first-order transverse metacentric-height estimate. The mission-equipment VCG is calculated from the weight moments of the carousel and tensioner systems. The lightship KG is represented by a fixed weight distribution consisting of hull structure, superstructure, and deckhouse contributions. Since the same lightship KG is applied to all configurations, the stability calculation primarily captures the relative effect of different mission-equipment weights and vertical positions.

Table 5.5: Hydrostatic KM_T values used for stability interpolation.

Draft [m]	KM_T [m]
4.0	40.34
5.0	33.99
6.0	29.87
7.0	27.07
8.0	25.04
9.0	23.41
10.0	22.10
11.0	21.07

For each configuration, the combined KG is calculated as the weight-averaged vertical centre of gravity of the lightship and installed mission equipment. The transverse metacentric height is then estimated by interpolating KM_T from Table 5.5 at the configuration draft and subtracting the combined KG:

$$GM_T = KM_T - KG_{config} \tag{5.5}$$

The resulting empty-condition GM_T is stored as a diagnostic property of each generated configuration. It provides a first-order indication of how mission-equipment weight and vertical position affect the reference platform hull, but it is not used as the main project-level feasibility screen. Loaded stability is evaluated later at campaign level, after project-specific cable loads have been allocated to the carousel system, as described in Section 5.3.3. The hull module also provides the resistance, side-area, and propulsion-power functions used later in the operational performance model.

5.3. Project Evaluation Logic

The generated design library is evaluated against project portfolios using a project-by-project simulation logic. For each vessel-configuration and offshore-wind-project combination, the model estimates cable requirements and compares them with the storage, line-layout, tension, stability, and transit capabilities of the configuration.

The feasibility checks are applied in a fixed order: input validity, line-layout compatibility, tension capacity, storage allocation, campaign splitting, loaded stability, and transit validity. This ensures that each project-design pair receives a consistent feasibility classification and, where relevant, a dominant infeasibility reason. The construction of the project portfolios themselves is described in Chapter 6; the present section focuses only on how a given portfolio is evaluated by the vessel model.

5.3.1. Project Input Variables

Each project is represented by a set of project variables that determine the required cable storage volume, tension capacity, campaign count, transit distance, and installation duration. The evaluation model does not generate the project portfolio itself; it only enriches and uses the project data provided by the scenario framework.

The main project input variables used in the simulation are summarised in Table 5.6.

Table 5.6: Main project variables used in the project-evaluation model.

Variable	Use in evaluation model
`WindfarmId`	Unique project identifier used for project-design matching
`CableLengthKm`	Total installed cable length used for storage and cable-weight estimation
`DistanceFromShore`	Proxy for one-way transit distance between port and project site
`WaterDepthMinM`	Used together with maximum depth to estimate average laying depth
`WaterDepthMaxM`	Used to estimate maximum required tension
`VoltageLevel`	Used to distinguish single-cable AC and dual-cable DC projects
`ModelledCapacity_MW`	Used to estimate relative cable size within the export-cable range

The required input columns are checked before simulation, and relevant project variables are converted to numeric values. Input consistency checks and missing-data handling are discussed further in Chapter 7.

The voltage level is used to determine the number of physical cables. For AC projects, the model assumes one physical cable and treats the reported cable length as the route length. For DC projects, the reported cable length is interpreted as the total installed length of two physical cables. The route length per physical cable is therefore taken as half of the reported cable length:

$$N_{cables} = \begin{cases} 1, & \text{for AC projects} \\ 2, & \text{for DC projects} \end{cases} \tag{5.6}$$

$$L_{route} = \begin{cases} L_{cable}, & \text{for AC projects} \\ \frac{1}{2} L_{cable}, & \text{for DC projects} \end{cases} \tag{5.7}$$

where L_{cable} is the reported total installed cable length and L_{route} is the route length per physical cable. This distinction is important because storage demand depends on total installed cable length, while transit and installed-kilometre performance metrics use the route length and number of physical cables.

5.3.2. Cable Requirement Estimation

The project input data do not contain detailed cable designs. Therefore, representative cable diameter and linear weight are estimated from a simplified export-cable envelope. Since this thesis focuses on export-cable installation, all projects use a diameter range of 0.20–0.30 m and a linear weight range of 70–150 kg/m, based on Offshore Wind Scotland reference data [123]. This range is summarised in Table 5.7.

Table 5.7: Export-cable specification range used in the model, based on Offshore Wind Scotland cable reference data [123].

Cable type	Diameter range [m]	Weight range [kg/m]
Export cable	0.20–0.30	70–150

Because project-specific cable parameters are unavailable, the model uses a relative cable-specification score to position each project within this export-cable range. The score is based on two normalised indicators: route length and capacity per physical cable. Capacity per cable is calculated as the modelled project capacity divided by the number of physical cables. Both indicators are normalised within the evaluated project portfolio, so the resulting cable-size estimate should be interpreted as a within-scenario proxy rather than an absolute cable design.

Capacity per physical cable is used as the dominant proxy because export-cable size is primarily related to required power transfer. Route length is included as a secondary proxy because longer export routes can influence cable-system requirements through losses, voltage level, reactive-power effects in AC systems, and transmission-system choices [67, 6, 52]. The cable-specification score is therefore defined as:

$$s_{cable} = \begin{cases} 0.30\tilde{L}_{route} + 0.70\tilde{P}_{cable}, & \text{for AC projects,} \\ 0.20\tilde{L}_{route} + 0.80\tilde{P}_{cable}, & \text{for DC projects.} \end{cases} \tag{5.8}$$

where $\tilde{L}_{route}$ is the normalised route length and $\tilde{P}_{cable}$ is the normalised capacity per physical cable. The higher route-length weight for AC projects reflects the stronger effect of distance on AC export-system requirements, while DC cable size is assumed to be more strongly driven by power transfer per cable. The numerical weights are simplified comparative assumptions, not validated cable-design coefficients.

The cable diameter and linear weight are then obtained by linearly interpolating between the minimum and maximum values of the export-cable range using s_{cable}. The resulting diameter is used to calculate the circular cable cross-sectional area, while the resulting linear weight is used for cable-weight and tension-related calculations.

The required gross carousel storage volume is estimated from the total installed cable length, the cable cross-sectional area, and a storage fill factor:

$$V_{req} = \frac{L_{cable} \cdot 1000 \cdot A_{cable}}{\eta_{fill}} \tag{5.9}$$

where V_{req} is the required gross carousel storage volume, L_{cable} is the total installed cable length in km, A_{cable} is the circular cable cross-sectional area, and $\eta_{fill} = 0.8$ is the assumed fill factor. The fill factor accounts for non-ideal packing, clearances, and practical handling limitations. The corresponding cable weight is calculated consistently from the selected linear weight and total installed cable length. This proxy is sufficient for comparing configurations, but it does not replace detailed project-specific cable design data.

5.3.3. Storage and Campaign Requirement

For each project-design combination, the model compares the required gross cable-storage volume with the available carousel volume of the vessel configuration. The available single-cable campaign capacity is calculated by summing the gross storage capacity of the active AD1, AD2, and BD1 carousel slots. If no carousel capacity is available, the project-design combination is classified as infeasible.

For single-cable projects, the number of required campaigns is obtained by dividing the required gross cable volume by the available campaign capacity and rounding up to the next integer. The required project volume is then split over these campaigns, with each campaign limited by the available carousel capacity. Within each campaign, cable volume is allocated over the active carousels using a deterministic greedy allocation rule, filling the largest available carousel first.

For dual-cable projects, the storage logic is more restrictive. A DC project is assumed to require two physical cables installed in parallel as part of a dual-lay concept. The total required storage volume is therefore split into two equal per-cable volumes. In each paired loading stage, a carousel may be assigned to cable A or cable B, but not to both simultaneously. The model searches over possible disjoint carousel assignments and determines the maximum equal per-cable storage capacity that can be achieved in one paired loading stage. The number of paired dual-cable campaigns is then obtained by dividing the required per-cable volume by this paired-stage capacity and rounding up.

These allocation rules are not intended to optimise the detailed loading plan. They are used as deterministic and reproducible modelling rules so that campaign count, carousel utilisation, loaded stability, and implied joint count can be compared consistently across configurations.

The number of implied cable joints is estimated from the number of cable sections required to complete the project. The section count includes both sections loaded from different carousels within a campaign and sections created by splitting the installation over multiple campaigns. For a single physical cable, the number of implied joints is approximated as the number of sections minus one, with a lower bound of zero. For dual-cable projects, this estimate is applied separately to both cable strings and then summed. The resulting joint count is used only as an operational complexity indicator and does not represent a detailed offshore jointing schedule.

For each campaign, the allocated gross cable volume in each carousel is converted into cable weight using the storage fill factor and cable density. The loaded cable vertical centre of gravity is estimated from the filled stack height in each carousel. The model assumes that stored cable lies above the carousel base structure, rotating platform, drive components, and lower handling arrangement, represented by a fixed vertical offset of 1.0 m above the carousel base. This provides a consistent first-order estimate of cable weight moments for the loaded-stability check.

The loaded cable weights and vertical moments are combined with the empty vessel and mission-equipment weight moments to estimate the loaded campaign displacement and KG. The campaign-level transverse metacentric height is then calculated as:

$$GM_{T,i} = KM_{T,i} - KG_i \tag{5.10}$$

where $GM_{T,i}$ is the transverse metacentric height of campaign i, $KM_{T,i}$ is the interpolated transverse metacentric height above keel at the campaign draft, and KG_i is the loaded vertical centre of gravity. If any campaign has a negative GM_T, the project-design combination is classified as infeasible due to insufficient initial transverse stability. This remains a first-order stability screen only. Passing the check does not imply compliance with intact or damage stability regulations, since trim, ballast distribution, free-surface effects, righting-arm curves, and regulatory loading conditions are outside the model scope.

5.3.4. Tension and Line-Layout Requirement

The model evaluates whether the installed tensioner system can handle the required installation tension of each project. The submerged cable weight per metre is estimated by subtracting seawater buoyancy from the cable weight in air, using the cable cross-sectional area and a seawater density of $\rho_{sw} = 1.025$ t/m^3. This submerged weight is then combined with the maximum project water depth to estimate the required line tension:

$$T_{req} = \gamma \cdot w_{sub} \cdot h_{proj,max} \tag{5.11}$$

where T_{req} is the required line tension in tonnes-force, w_{sub} is the submerged cable weight in t/m, $h_{proj,max}$ is the maximum project water depth in metres, and $\gamma = 1.5$ is the dynamic and installation allowance factor introduced earlier. The project-design combination is classified as infeasible due to insufficient tensioner capacity if the required line tension exceeds the installed tension capacity per line of the vessel configuration.

The model also checks whether the installed line layout is compatible with the number of physical cables required by the project. Single-cable AC projects can be executed with one tensioner line. Dual-cable DC projects are assumed to require simultaneous handling of two physical cables and therefore require two parallel tensioner lines. Sequential installation of the two DC poles with a single line is not considered.

As a result, one-line configurations are classified as infeasible for DC projects, even when their tension capacity per line would otherwise be sufficient. This infeasibility mode is recorded separately from pure tension-capacity infeasibility, because it reflects a lay-line layout limitation rather than insufficient pull capacity. The effect of this constraint is scenario-dependent: it does not remove scenarios from the analysis, but it reduces the feasible design-project combinations for scenarios with a higher DC or HVDC share. Consequently, HVDC-heavy scenarios make the number of installed tensioner lines a binding design feature.

5.3.5. Project Feasibility Classification

The project-evaluation model combines the storage, campaign, tension, line-layout, loaded-stability, and transit-validity checks into one feasibility classification for each design-project pair. A pair is classified as feasible only if sufficient storage capacity, tensioner line layout, and per-line tension capacity are available, all loaded campaigns have non-negative simplified GM_T, and the loaded and return transit drafts remain within the valid range of the resistance model. Transit power exceedance is retained as a diagnostic indicator, but is not used as a feasibility constraint.

Feasibility refers to technical executability within the simplified model. It does not imply that a project-design pair is commercially attractive or operationally preferred. For this reason, campaign count is retained as a separate performance variable and later used to distinguish efficient project execution from technically possible but operationally unattractive cases.

The main infeasibility modes recorded by the model are:

- insufficient storage capacity;
- insufficient tensioner-line layout or per-line tension capacity;
- missing or unsupported project input data required by the model;
- negative loaded GM_T in one or more campaigns;
- loaded or return transit draft outside the valid resistance-model range.

For feasible design-project pairs, the model estimates campaign count, carousel utilisation, implied joints, loaded draft and stability indicators, and the duration and fuel-consumption components for loading, laying, and transit. Projects requiring many campaigns are not removed at this stage. Instead, campaign count is retained for the portfolio-level performance metrics, where projects completed in one, two, three, or more campaigns are distinguished. This allows later evaluation to separate technical feasibility from operational attractiveness.

5.4. Operational Performance Estimation

For project-design combinations that pass the feasibility checks, the model estimates installation duration and fuel consumption. These estimates are used later to compare configurations not only by technical feasibility, but also by operational efficiency. The estimates remain simplified and are intended for relative comparison between configurations.

5.4.1. Loading and Installation Duration

The installation-duration model consists of cable loading time, offshore cable laying time, and transit time. Cable loading is evaluated at carousel level for each campaign. The loading time of carousel j in campaign i is calculated from the allocated gross cable volume:

$$t_{load,j,i} = \frac{V_{alloc,j,i} \cdot \eta_{fill}}{A_{cable} \cdot v_{load} \cdot 60} \tag{5.12}$$

where $t_{load,j,i}$ is the loading time in hours, $V_{alloc,j,i}$ is the gross stored volume allocated to carousel j, A_{cable} is the cable cross-sectional area, and $v_{load} = 10$ m/min is the assumed cable loading speed. This loading speed is based on expert judgement from a cable-lay specialist within the Boskalis OE BSC Engineering Knowledge Centre [103]. The factor 60 converts minutes to hours.

The campaign loading time is taken as the maximum loading time across the active carousels. This assumes simultaneous loading of all active carousels within a campaign, so the duration is governed by the slowest-loaded carousel. The total loading time of a project is then obtained by summing the campaign loading times. This is a favourable but consistent loading approximation; sequential loading, port infrastructure constraints, loading tower arrangement, and supplier logistics are not explicitly modelled.

Offshore laying time is calculated from the cable length installed during each campaign. The model reconstructs this length from the campaign cable load, cable density, and cable cross-sectional area. For dual-cable projects, the loaded campaign weight represents two physical cables installed simultaneously. The elapsed laying distance is therefore the length per cable, rather than the summed length of both cables:

$$L_{lay,i} = \frac{W_{load,i}}{\rho_{cable} \cdot A_{cable} \cdot N_{cables}} \tag{5.13}$$

where $L_{lay,i}$ is the laying length per physical cable during campaign i, $W_{load,i}$ is the total cable weight loaded in that campaign, $\rho_{cable} \cdot A_{cable}$ is the cable weight per metre, and N_{cables} is the number of physical cables. For dual-cable projects, $N_{cables} = 2$, so the total loaded cable weight is divided over the two simultaneously laid cables.

The campaign laying time is calculated from the laying length, the assumed laying speed, and a workability and operational allowance factor:

$$t_{lay,i} = \frac{L_{lay,i}}{v_{lay} \cdot 60} \cdot f_{WOW} \tag{5.14}$$

where $v_{lay} = 10$ m/min is the assumed cable laying speed and $f_{WOW} = 1.15$ is the allowance factor. The factor accounts in simplified form for workability losses and operational effects that are not modelled explicitly. This is consistent with offshore installation models in which weather limits, operation durations, vessel resources, and delay effects are treated as key planning inputs [125]. The total laying time is obtained by summing the laying times over all campaigns.

The total project execution duration used in the later evaluation combines loading, laying, and transit time:

$$t_{project,total} = t_{load,total} + t_{lay,total} + t_{transit,total} \tag{5.15}$$

5.4.2. Transit and Mobilisation Assumptions

Transit is modelled as a sequence of loaded outbound legs and unloaded return legs between port and project site. The project's distance from shore is used as a proxy for the one-way transit distance between the loading port and the offshore site. This avoids assigning project-specific ports, but it means that absolute transit duration and fuel consumption should be interpreted as approximate. Since the assumption is applied consistently across all configurations, its main role is to differentiate projects with shorter and longer offshore distances. Distances are converted from kilometres to nautical miles using 1 NM = 1.852 km.

Each project is assumed to start in port. For every campaign, the vessel sails loaded to the project site and, except after the final campaign, returns unloaded to port for reloading. The final demobilisation return leg is not included. The reported transit duration and fuel consumption therefore represent installation execution up to completion at site, rather than a full port-to-port project estimate. For a project requiring n_{camp} campaigns, this gives n_{camp} loaded outbound legs and $\max(0, n_{camp} - 1)$ unloaded return legs.

The transit time of each one-way leg is calculated from the one-way distance and an assumed transit speed of 12 kn, based on the service speed reported for the reference platform hull in Figure 5.2. Loaded outbound legs are evaluated using the baseline vessel displacement plus the campaign cable load, while return legs are evaluated using the baseline vessel displacement without cable load. For each leg, displacement is converted to draft using the reference hull displacement–draft relation, with the minimum operational draft of 7.86 m enforced.

Transit resistance is estimated using pre-calculated calm-water resistance curves for the reference platform hull at drafts of 4.0 m, 6.75 m, and 10.0 m. During simulation, resistance at the imposed transit speed of 12 kn is obtained by interpolation between these draft-dependent curves. The underlying Holtrop–Mennen inputs, polynomial coefficients, resistance curves, and propulsion-efficiency assumptions are provided in Appendix B.6.

The effective propulsion power is calculated from resistance and speed:

$$P_E = R \cdot V \tag{5.16}$$

where P_E is the effective power in kW, R is the resistance in kN, and V is the vessel speed in m/s. The required engine brake power is then calculated using the total propulsion efficiency and a sea-margin factor:

$$P_B = \frac{P_E}{\eta_{prop}} f_{sea} \tag{5.17}$$

where $\eta_{prop} = 0.648$ is the total propulsion efficiency and $f_{sea} = 1.15$ is the sea-margin factor. The model records whether the estimated transit power demand exceeds the installed vessel power of 16,000 kW. This exceedance is treated as a diagnostic check rather than an expected governing constraint, since DP-capable offshore vessels typically have substantial installed-power reserve for positioning and redundancy.

No separate mobilisation, demobilisation, port waiting, bunkering, weather routing, or offshore standby time is included. Port-side cable loading is represented explicitly by the loading model, while all other non-installation time components are outside the scope of the current early-stage evaluation.

5.4.3. Fuel Consumption Estimation

Fuel consumption is estimated from the energy demand of the loading, laying, and transit phases using a constant specific fuel consumption. The specific fuel consumption is set to $SFC = 180.4$ g/kWh, based on Sustainable Ships' medium-speed diesel-engine reference values derived from IMarEST engine data [130]. The selected value corresponds to operation at 85% maximum continuous rating and is used as a representative early-stage approximation. The model does not simulate part-load behaviour, generator scheduling, redundancy requirements, or mode-specific engine efficiency. Fuel results should therefore be interpreted primarily as relative energy-based comparisons rather than absolute fuel predictions.

For each energy-consuming process, fuel consumption is calculated from energy demand as:

$$F = \frac{E \cdot SFC}{10^6} \tag{5.18}$$

where F is fuel consumption in tonnes and E is energy consumption in kWh. The factor 10^6 converts grams to tonnes.

During cable loading, carousel-drive power demand is estimated from the installed carousel drive power and the average fill level during loading. Since no manufacturer-specific power curve is available, the power fraction is assumed to increase linearly from 20% at empty condition to 90% at full condition. For each carousel and campaign, the average fill level is approximated as half of the assigned campaign fill fraction. Loading energy is then calculated from the installed carousel power, the resulting average power fraction, and the carousel loading time, and summed over all active carousels and campaigns.

During cable laying, three power components are considered: DP-related propulsion power, tensioner power, and carousel payout power. DP-related propulsion power represents low-speed track-following, station-keeping, and compensation of environmental loads during cable installation. In the absence of vessel-specific DP power logs, it is approximated as a bounded fraction of the fixed installed vessel power:

$$P_{DP,i} = P_{inst} \left[f_{DP,min} + (f_{DP,max} - f_{DP,min}) \, I_{exp,i} \right] \tag{5.19}$$

where $P_{inst} = 16{,}000$ kW, $f_{DP,min} = 0.25$, $f_{DP,max} = 0.35$, and $I_{exp,i}$ is a normalised exposure index for campaign i. The exposure index combines a windage component and a current component, weighted 60% and 40%, respectively. The windage component is based on the draft-dependent above-water hull side area plus the side-projected area of the above-deck carousel arrangement, while the current component is based on the draft-dependent underwater hull side area. The underlying hull side-area strips are provided in Appendix B.4.

The windage and current indices are min–max normalised across the evaluated campaign cases within each scenario run and clipped to the interval $[0, 1]$. The resulting DP power estimate is therefore a relative within-run proxy used to distinguish compact configurations from configurations with higher windage and current area. It is not a vessel-specific DP capability or thruster-allocation calculation. Supporting DP literature is used only to justify the general modelling logic that DP power demand depends on operating conditions, environmental exposure, control settings, and redundancy requirements [30, 135, 57, 59].

Tensioner power during laying is estimated from the mechanical pulling power. The average project water depth is used for the operational power estimate, and the average laying tension per line is obtained from the submerged cable weight, this average depth, and the installation allowance factor introduced earlier. The total tensioner power is then:

$$P_{ten,total,i} = N_{cables} \frac{T_{lay,i} \cdot v_{lay}}{\eta_{ten}} \tag{5.20}$$

where $P_{ten,total,i}$ is the total tensioner power during campaign i, N_{cables} is the number of physical cables installed simultaneously, $T_{lay,i}$ is the average laying tension per line, v_{lay} is the laying speed in m/s, and $\eta_{ten} = 0.85$ is the assumed tensioner efficiency. For dual-cable projects, $N_{cables} = 2$, so the total tensioner power reflects the simultaneous handling of both physical cables.

Transit fuel consumption is calculated from the engine brake power and duration of each transit leg, as derived in Section 5.4.2. Transit energy is summed over all loaded outbound and unloaded return legs and converted to fuel using Equation 5.18.

During laying, the carousels also rotate while cable is paid out. Because no separate carousel payout power curve is available, and because the model uses similar cable-transfer speeds for loading and laying, carousel-drive fuel during offshore payout is approximated as equal to the carousel-drive fuel calculated for port loading. This is a simplified proxy, but it avoids introducing an unsupported second carousel power model.

The total project fuel consumption is obtained by combining the fuel components from loading, laying, and transit:

$$F_{total} = F_{load,total} + F_{DP,total} + F_{ten,total} + F_{car,payout,total} + F_{transit,total} \quad (5.21)$$

where $F_{load,total}$ represents port-side loading fuel, $F_{DP,total}$ and $F_{ten,total}$ represent DP-related and tensioner fuel during cable laying, $F_{car,payout,total}$ represents carousel-drive fuel during offshore payout, and $F_{transit,total}$ represents transit fuel. These project-level fuel estimates are later normalised by installed cable length to compare configurations on fuel consumption per installed kilometre.

5.5. Cost Representation

Cost differences between generated configurations are represented through mission-equipment CAPEX only, because the reference platform hull is kept constant. The total mission-equipment CAPEX of a configuration is calculated as the sum of the installed carousel and tensioner system costs:

$$CAPEX_{mission} = CAPEX_{carousels} + CAPEX_{tensioners} \quad (5.22)$$

where $CAPEX_{carousels}$ and $CAPEX_{tensioners}$ are the aggregated component-cost estimates stored in the design library. This value is used as the cost indicator in the later design comparison and screening.

The indicator should be interpreted as a relative mission-equipment cost index, not as a full vessel, integration, or retrofit cost estimate. Hull costs, structural integration, auxiliary systems, and downtime are excluded. Retrofit and integration effects are considered qualitatively in the adaptive pathway analysis.

5.6. Model Assumptions and Simplifications

The project-evaluation model is intended as an early-stage comparative simulation model. It is designed to be transparent, reproducible, and computationally efficient rather than to represent a detailed installation-engineering tool. Some assumptions mainly affect the absolute magnitude of the calculated duration, fuel, or cost values, while others may influence the relative ranking of configurations across scenarios. Assumptions expected to affect design ranking most strongly, such as cable sizing, fill factor, dual-lay logic, DP power, stability screening, and mission-equipment CAPEX, are therefore highlighted in the verification, validation, limitations, and discussion sections where relevant. The main assumptions and modelling boundaries are summarised in Table 5.8.

Table 5.8: Main model assumptions and simplifications.

Model area	Simplification	Main implication
Reference platform hull	Hull form, hydrostatics, propulsion-related functions, installed vessel power, and baseline lightship properties are fixed.	Results isolate the effect of mission-equipment choices, but do not compare alternative hull designs.
Design library	A fixed set of carousel–tensioner configurations is generated once and evaluated across all scenario portfolios.	Differences in performance can be attributed to project-portfolio changes rather than changes in the available design set.
Cable representation	Cable diameter and weight are estimated from a simplified export-cable range using a relative cable-specification score.	Results capture relative cable-demand differences, but not detailed project-specific cable design.
Storage and campaign logic	Required storage volume uses a fixed fill factor of $\eta_{fill} = 0.8$, and cable allocation uses deterministic carousel-allocation rules.	Campaign count and utilisation are comparable across designs, but detailed packing, routing, and loading optimisation are not modelled.
Line layout and tension	DC projects require two lay lines, and required tension is estimated from submerged cable weight, water depth, and a fixed installation allowance factor.	HVDC and depth vulnerabilities are represented explicitly, but detailed cable mechanics, layback, and dynamic cable behaviour are excluded.
Draft and ballast	A minimum operational draft is imposed, but ballast mass, moments and tank arrangement are not explicitly modelled.	The draft constraint is included consistently, but detailed ballast effects on displacement, KG, GM, trim, and resistance are excluded.
Stability	Loaded stability is screened using a first-order transverse GM_T calculation.	Negative GM_T is treated as infeasible, but positive GM_T does not imply intact or damage stability compliance.
Operational timing	Loading and laying speeds, workability allowance, simultaneous carousel loading, and campaign sequencing are represented with simplified deterministic assumptions.	Duration estimates are suitable for relative comparison, but not for detailed installation planning or port-logistics assessment.
Transit	Transit distance is approximated using distance from shore, with repeated port-to-site trips and no final return leg.	Transit time and fuel are suitable for relative comparison, but not full port-to-port mobilisation and demobilisation estimates.
Power and fuel	DP power is estimated using a bounded exposure proxy, carousel payout power is approximated from loading power, and a constant SFC is used for all operating modes.	Fuel results are best interpreted as relative energy-based indicators rather than absolute fuel predictions.
Cost	Quantitative CAPEX includes only carousel and tensioner CAPEX, estimated through early-stage scaling relations.	CAPEX is a mission-equipment cost index, not a full vessel, integration, or retrofit cost estimate.

These assumptions are consistent with the exploratory purpose of the thesis. The model is used to compare many candidate configurations across uncertain project portfolios and to identify relative capability, efficiency, and vulnerability patterns. The outputs should therefore be interpreted as early-stage comparative results, not as final engineering, supplier-level, or project-execution estimates.

5.7. Conclusion

This chapter described the parametric vessel model and project-level evaluation logic used in the thesis. A fixed reference platform hull is combined with generated carousel and tensioner configurations to form a reproducible mission-equipment design library. Each configuration is enriched with simplified indicators for mission-equipment weight, draft, stability, installed power, and mission-equipment CAPEX. The same fixed design library can then be evaluated against different project portfolios, allowing changes in performance to be interpreted as responses to changing project requirements rather than changes in the candidate design set.

The project-evaluation model tests each configuration against each project individually. It estimates cable requirements, storage demand, campaign count, line-layout compatibility, required tension, loaded stability, transit feasibility, installation duration, and fuel consumption. These outputs define the project-level information needed for later portfolio-level aggregation, but the scenario portfolios and performance measures themselves are introduced in Chapter 6.

The model should be interpreted as an early-stage comparative simulation model. It supports the identification of relative capability, efficiency, and vulnerability patterns across many mission-equipment configurations, but it does not replace detailed vessel design, supplier engineering, installation planning, or retrofit assessment.

6 Scenario Framework and Performance Measures

This chapter defines the scenario framework used to evaluate the parametric CLV design library under alternative offshore wind project portfolios. Chapter 5 described how a mission-equipment configuration is evaluated against an individual project. The present chapter extends this logic to portfolio-level evaluation by defining the base project dataset, synthetic portfolio-generation method, scenario families, performance measures, and screening logic used in the subsequent analysis.

The chapter addresses the fifth sub-question:

How can uncertain future offshore wind project portfolios be represented, and which performance measures are needed to compare CLV configurations across them?

6.1. Scenario-Framework Logic

The scenario framework uses offshore wind project data as the empirical basis for generating synthetic future-oriented project portfolios. The filtered base dataset is therefore not treated as a direct forecast of the future offshore wind market. Instead, it functions as a donor pool from which internally consistent project combinations can be sampled and then modified through controlled stress-test settings.

This distinction is important for interpreting the analysis. The thesis does not evaluate one fixed list of existing projects and assume that this represents the future. Rather, it generates alternative synthetic portfolios that preserve realistic relationships between project variables while systematically increasing selected drivers that are relevant for CLV capability. The scenario families vary cable length, distance from shore, water depth, HVDC share, and floating-foundation share, because these variables directly affect storage demand, campaign count, line-layout requirements, tension capacity, transit duration, and fuel consumption.

The resulting scenarios are structured what-if cases, not probability-weighted forecasts. They are used to expose design vulnerabilities and performance trade-offs under progressively more demanding project conditions. In this implementation, the scenario framework represents a limited set of plausible future portfolio states. It does not yet explore a full many-futures uncertainty space, but it provides a transparent basis for comparing configurations and identifying where storage capacity, line layout, or tension capacity may become binding.

The final scenario set consists of one base-like reference portfolio and two stress-test families: a length–distance/HVDC family and a depth/floating family. The base-like case represents a synthetic portfolio sampled from the filtered base dataset without additional stress settings. The length–distance/HVDC scenarios represent increasingly long and remote export-cable projects with a rising HVDC share. The depth/floating scenarios represent increasingly deep-water portfolios with a rising share of floating projects.

6.2. Base Project Dataset as Donor Pool

The market data used as input for the scenario-generation stage was provided by Boskalis and is treated as internal project data. The dataset contains offshore wind project characteristics relevant for export-cable installation, including project location, water depth, distance from shore, modelled capacity, number of turbines, cable length, foundation type, and voltage level. Due to confidentiality, the individual records from the original Boskalis dataset are not reproduced or disclosed in this thesis.

Before scenario generation, the dataset is filtered to create a consistent donor pool. Only export-cable projects are retained, because the vessel model focuses on export-cable installation rather than inter-array cable work. Projects classified as MVAC, projects with mixed fixed/floating foundation descriptions, and rows with insufficient information in the required project variables are removed. After filtering, the global base dataset contains 364 projects.

The filtered dataset should not be interpreted as a complete or fully accurate representation of the global offshore wind export-cable market. It is incomplete, dependent on available data fields, and shaped by the filtering choices described above. Its role in this thesis is methodological: it provides a structured and industry-relevant donor pool from which synthetic project portfolios can be generated.

Several helper variables are derived before scenario generation. These include the water-depth range, the cable-length-to-distance-from-shore ratio, and the average modelled capacity per turbine. These variables help preserve realistic relationships between project characteristics when synthetic values are generated. A spread bucket is also assigned to each base project using rank-normalised cable length, distance from shore, minimum water depth, and maximum water depth. The resulting quantile-based bucket is used during donor sampling to retain broad differences in project scale and remoteness.

Geography and country are used only for donor matching and category-share preservation. They are not direct CLV performance variables. Their purpose is to avoid creating unrealistic synthetic portfolios by sampling project characteristics without regard to their observed regional context. Median profiles are calculated for selected project variables because the dataset contains skewed variables and outliers. These medians are used mainly for diagnostic comparison, not as direct inputs to the vessel-performance model.

6.3. Synthetic Project Portfolio Generation

Synthetic project portfolios are generated using a donor-based sampling approach. Instead of drawing each project variable independently, the model samples donor projects from the filtered base dataset and modifies selected characteristics according to the scenario settings. This preserves realistic combinations of project variables while allowing relevant future stress dimensions to be varied systematically.

Each synthetic scenario contains half the number of projects in the filtered base dataset:

$$N_{\text{scenario}} = \left\lfloor \frac{N_{\text{base}}}{2} \right\rfloor \tag{6.1}$$

With $N_{\text{base}} = 364$, this gives $N_{\text{scenario}} = 182$ projects per synthetic portfolio. This size is used to limit computational effort while retaining sufficient portfolio variation. A fixed random seed of 42 is used to make the sampling procedure reproducible.

The synthetic portfolio generation consists of five main steps:

1. **Set target category counts.** Scenario-specific category shares are translated into project counts. If no target is imposed, the observed distribution in the filtered base dataset is used. If a target is imposed, such as an HVDC or floating-foundation share, the required number of projects in that category is calculated before donor sampling.
2. **Sample donor projects.** Each synthetic project is assigned a donor project from the filtered base dataset. Donors are first sampled from projects matching the target combination of region, country, spread bucket, voltage type, and foundation type. If this group is unavailable or too small, the algorithm progressively relaxes the matching criteria until a suitable donor pool is obtained.

3. **Apply scenario stress settings.** Scenario multipliers are applied to the stressed variables. The length–distance/HVDC scenarios increase distance from shore and cable length and impose a higher HVDC share. The depth/floating scenarios increase water depth and impose a higher floating-foundation share. Variables not stressed use a multiplier of one.
4. **Generate numerical project variables.** Numerical variables are generated from the selected donor project, the relevant scenario multiplier, and a small multiplicative noise term:

$$x_{\text{syn}} = x_{\text{donor}} \cdot m_x \cdot \epsilon_x \tag{6.2}$$

where x_{syn} is the generated value, x_{donor} is the donor value, m_x is the scenario multiplier for variable x, and ϵ_x is a lognormal noise factor. In the current implementation, the noise factor uses $\sigma = 0.05$ for capacity, turbine rating, depth, distance, and cable-to-distance ratio. For example, a variable with a nominal +20% stress setting uses $m_x = 1.20$, while unstressed variables use $m_x = 1.00$.

Some variables are derived rather than varied independently. Cable length is calculated from the generated distance from shore, the donor-specific cable-to-distance ratio, the cable-length multiplier, and a small noise term:

$$L_{\text{cable,syn}} = D_{\text{shore,syn}} \cdot R_{\text{cable/distance,donor}} \cdot m_L \cdot \epsilon_L \tag{6.3}$$

where $L_{\text{cable,syn}}$ is the generated cable length, $D_{\text{shore,syn}}$ is the generated distance from shore, $R_{\text{cable/distance,donor}}$ is the donor-specific cable-length-to-distance ratio, m_L is the scenario multiplier for cable length, and ϵ_L is the cable-length noise factor. This keeps cable length linked to distance from shore while allowing the length–distance scenarios to increase cable demand.
5. **Export and validate the generated portfolio.** The generated projects retain the column structure of the base input dataset and are passed to the vessel-evaluation model. For each scenario, validation outputs compare realised category shares and numerical project-variable distributions with the intended scenario settings.

Figure 6.1 shows an example base-versus-scenario validation plot. The base-like case is shown to illustrate the randomness introduced by donor sampling and noise: the synthetic portfolio remains close to the filtered base dataset, but is not an exact copy of it. For the stress-test scenarios, comparable validation plots are used to check whether distance, cable length, and water depth shift in the intended direction; these supporting plots are provided in Appendix C.

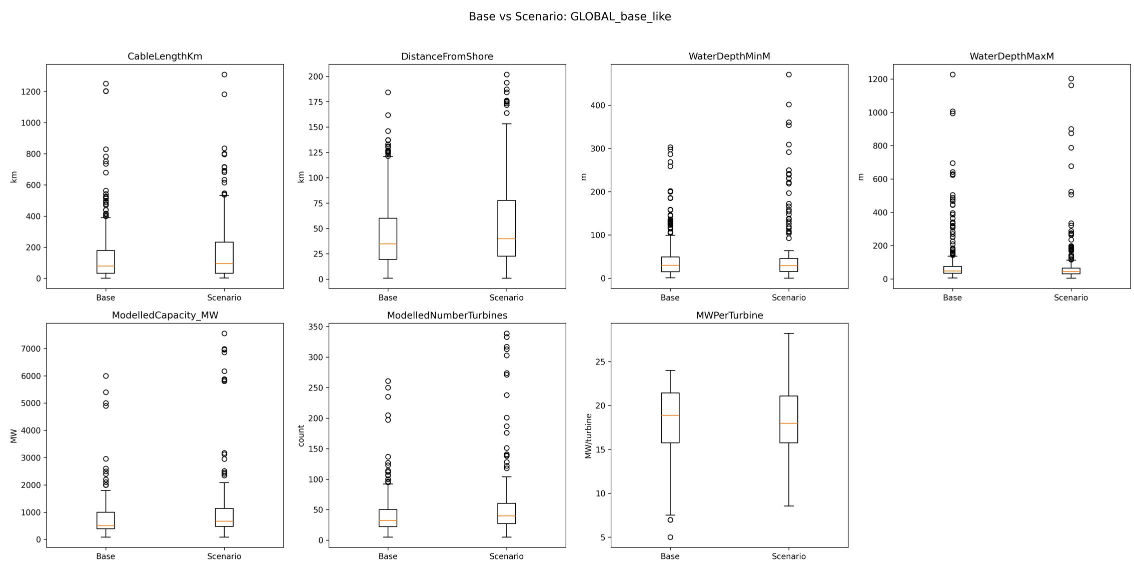


Figure 6.1: Base-versus-scenario validation boxplots for the global base-like synthetic portfolio.

6.4. Scenario Families

The scenario framework is designed to stress-test CLV configurations against project portfolios that become progressively more demanding. The scenarios are not forecasts and are not assigned probabilities. Instead, they are ordered stress states that isolate project developments relevant to export-cable installation. Table 6.1 summarises the final scenario set. The stress levels are labelled as mild, moderate, strong, and severe. The percentage values in the table refer only to nominal input multipliers or target category shares. The realised portfolio characteristics also depend on donor sampling, category targeting, scenario scaling, and small stochastic variation.

Table 6.1: Synthetic scenario families used in the global-scope evaluation.

Scenario state	Model code	Input stress setting	Category target
Base-like reference	`base_like`	No numerical scaling	Base dataset shares
Mild length–distance/HVDC	`len_dist_10`	Nominal multiplier +10%	HVDC share 20%
Moderate length–distance/HVDC	`len_dist_20`	Nominal multiplier +20%	HVDC share 35%
Strong length–distance/HVDC	`len_dist_30`	Nominal multiplier +30%	HVDC share 50%
Severe length–distance/HVDC	`len_dist_40`	Nominal multiplier +40%	HVDC share 65%
Mild depth/floating	`depth_50`	Nominal multiplier +50%	Floating share 25%
Moderate depth/floating	`depth_100`	Nominal multiplier +100%	Floating share 40%
Strong depth/floating	`depth_150`	Nominal multiplier +150%	Floating share 55%
Severe depth/floating	`depth_200`	Nominal multiplier +200%	Floating share 70%

The scenario states are generated independently. They are ordered by increasing stress severity, but they are not nested modifications of the same project list. Differences in design performance between scenario states may therefore reflect both the imposed stress settings and changes in the sampled project mix, capacity distribution, donor selection, and total portfolio cable-kilometre denominator.

This is especially important for the length–distance/HVDC family. Cable length is calculated from generated distance from shore, the donor-specific cable-to-distance ratio, the nominal cable-length multiplier, and a small noise term. Simultaneously, the HVDC share is increased to the scenario-specific target. Since HVDC projects in the donor data are generally associated with larger and more remote export-cable projects, this portfolio-composition change can amplify the realised increase in mean cable length. The length–distance scenarios are therefore interpreted as combined length–distance–HVDC stress cases rather than uniform percentage increases applied to a fixed base portfolio.

The same logic applies to the depth/floating family. The water-depth multiplier is a nominal input setting, while the realised depth distribution also depends on donor sampling, the imposed floating-foundation share, and the characteristics of floating projects in the donor data. These scenarios are therefore interpreted as combined depth–floating stress cases rather than isolated uniform depth increases.

Within the DAPP framing, the scenario families are used as stress-test dimensions rather than time-explicit forecasts. Their ordered steps provide conditions under which design vulnerabilities can be observed and later interpreted as indicative adaptation tipping points, for example when additional carousel capacity, tensioner capacity, or line capability may become necessary.

For transparency, the scenario generator exports validation outputs for each generated portfolio, including category-share comparisons and base-versus-scenario boxplots. These outputs are used to check whether the realised HVAC/HVDC and grounded/floating shares match the intended scenario settings, and whether the numerical variables shift in the expected direction. The realised project-variable indicators are summarised in Table 7.2, while the supporting base-versus-scenario boxplots are provided in Appendix C.

6.5. Performance Measures

Each mission-equipment configuration is evaluated against every project in a given portfolio using the project-level simulation logic described in Chapter 5. The integrated simulation enriches each project with cable-related quantities, evaluates storage, tension, line layout, loaded stability, transit, duration, and fuel components, and returns project-level outputs for each design-project pair.

The portfolio-level evaluation uses four main types of indicators: project feasibility, captured cable-kilometres, campaign-bucket performance, and operational efficiency. Because HVAC and HVDC projects differ in the number of physical cables, the installed cable length of each project is first calculated as:

$$L^{\mathrm{inst}}p = L_{\mathrm{route},p} \cdot N_{\mathrm{cables},p} \tag{6.4}$$

where $L^{\mathrm{inst}}p$ is the installed cable length of project p, $L\mathrm{route},p$ is the route length per physical cable, and $N_{\mathrm{cables},p}$ is the number of physical cables. HVAC projects are treated as one physical cable, while HVDC projects are treated as two physical cables. The route-length, cable-sizing, storage-volume, and fill-factor assumptions used to obtain these quantities are defined in Section 5.3.2.

The first design-level indicator is the project feasibility rate:

$$FR_i = \frac{N_{\mathrm{feasible},i}}{N_{\mathrm{projects}}} \tag{6.5}$$

where FR_i is the feasibility rate of design i, $N_{\mathrm{feasible},i}$ is the number of feasible projects for that design, and N_{projects} is the number of projects in the scenario portfolio.

Because project count does not account for project size, the central portfolio-coverage KPI is defined as *portfolio cable-kilometre capture*. This represents the share of total portfolio cable kilometres that a design can complete technically feasibly within a specified campaign bucket. The model evaluates four cumulative campaign buckets, denoted by $b \in \mathrm{all}, \leq 1, \leq 2, \leq 3$. The first bucket includes all technically feasible projects, while the remaining buckets include only projects completed within at most one, two, or three campaigns.

For each design i and campaign bucket b, portfolio cable-kilometre capture is defined as:

$$K_{i,b} = \frac{\sum_{p \in \mathcal{F}i,b} L^{\mathrm{inst}}p}{\sum_{p \in \mathcal{P}} L_p^{\mathrm{inst}}} \tag{6.6}$$

where $\mathcal{P}$ is the full project portfolio, $\mathcal{F}i,b$ is the set of projects feasible for design i within campaign bucket b, and $L^{\mathrm{inst}}p$ is the installed cable length of project p. The denominator represents all cable kilometres in the evaluated portfolio, while the numerator represents the part of that portfolio that can be completed by design i within the selected campaign bucket.

Operational efficiency is measured using the average project-level fuel consumption per installed cable kilometre:

$$\bar{f}i,b = \frac{1}{|\mathcal{F}i,b|} \sum_{p \in \mathcal{F}i,b} \frac{Fi,p}{L_p^{\mathrm{inst}}} \tag{6.7}$$

where $F_{i,p}$ is the total fuel consumption for design i on project p, including loading, laying, and transit fuel. This metric is an unweighted average of project-level fuel intensities: each feasible project contributes equally, regardless of project size. It is therefore interpreted together with the portfolio cable-kilometre share, so that fuel efficiency is not considered separately from the share of the portfolio captured by a design. A similar metric is available for duration per installed cable kilometre.

Together, these KPIs describe both technical coverage and operational efficiency under a specific project portfolio. They form the basis for design comparison, screening, shortlisting, and pathway analysis. The main design-level performance measures are summarised in Table 6.2.

Table 6.2: Main design-level performance measures used in the scenario evaluation.

KPI	Meaning	Role in analysis
Total CAPEX	Combined carousel and tensioner CAPEX	Relative mission-equipment cost indicator.
Feasibility rate	Share of projects completed by the design	Indicates broad project coverage.
Portfolio cable-km capture	Share of total portfolio cable kilometres feasible within the selected campaign bucket	Main portfolio-coverage KPI, reported for all feasible projects and the ≤ 1, ≤ 2, and ≤ 3 campaign buckets.
Fuel per installed km	Average fuel use per installed cable kilometre	Main operational efficiency indicator.
Duration per installed km	Average project-level duration per installed cable kilometre	Indicates time efficiency.
Carousel utilisation	Average use of available storage volume	Diagnostic for storage sizing.
Tensioner utilisation	Average use of available tension capacity	Diagnostic for cable-handling capacity.
Average joints	Average number of implied offshore joints	Indicates campaign fragmentation.
Infeasibility shares	Share of projects limited by storage, tension, line layout, stability, or transit constraints	Identifies dominant technical bottlenecks.

6.6. Screening and Pareto-Front Selection Logic

The screening and Pareto-front selection logic reduces the large generated design library to a smaller set of relevant candidate configurations. Pareto fronts are used to identify non-dominated trade-offs between mission-equipment CAPEX and fuel intensity, while portfolio cable-kilometre capture is used as an additional screening and interpretation criterion. This prevents low-cost and low-fuel designs from being interpreted as attractive without considering how much of the project portfolio they can serve.

The evaluation script first aggregates the project-level simulation results by configuration identifier. For each design, it stores the main cost and capability indicators, including mission-equipment CAPEX, carousel volume, and maximum tension per line, together with the feasibility, campaign, fuel, utilisation, and infeasibility metrics introduced in Section 6.5. The main feasibility control is then applied before identifying the Pareto front for the ≤ 3 campaign bucket.

For the Pareto plots, designs are compared on two objectives: minimising mission-equipment CAPEX and minimising average fuel consumption per installed cable kilometre. A design is Pareto-efficient if no other design can reduce either CAPEX or fuel consumption without increasing the other objective.

For the ≤ 3 campaign Pareto front, an additional portfolio cable-kilometre capture threshold is applied to $K_{i,\leq 3}$, which denotes the share of total portfolio cable kilometres that design i can complete within at most three campaigns:

$$K_{i,\leq 3} \geq 0.60 \tag{6.8}$$

The 60% threshold is used as a practical portfolio cable-kilometre capture screen. It prevents designs that appear attractive in CAPEX–fuel space from being selected if they cannot serve a substantial share of the portfolio within an operationally acceptable number of campaigns. The threshold is a modelling choice, not a universal industry requirement, and is used as a consistent reference level for comparing vulnerability patterns across scenarios. If no designs satisfy this threshold in an extreme scenario, it is reduced in steps of 10 percentage points to allow the remaining trade-off structure to be visualised.

Trade-off plots with Pareto fronts are generated for the total feasible set and for the ≤ 1, ≤ 2, and ≤ 3 campaign buckets. The scatter plots use mission-equipment CAPEX on the horizontal axis and fuel consumption per installed kilometre on the vertical axis. The Pareto front is based on these two objectives, while the colour scale shows the captured portfolio cable-kilometre share. This makes it possible to distinguish low-cost and low-fuel designs from designs that also capture a substantial share of the project portfolio.

Several diagnostic plots are also generated, including CAPEX versus portfolio cable-kilometre share, carousel volume versus carousel utilisation, and maximum tension per line versus tensioner utilisation. These plots are not used as formal selection criteria, but help explain why certain designs perform well or poorly. In the pathway analysis, configurations highlighted by the screening and Pareto-front analysis are compared with technically compatible upgrade candidates to construct adaptive mission-equipment pathways.

6.7. Scenario Framework Boundaries

The scenario framework has several boundaries that should be considered when interpreting the results. The generated portfolios are synthetic and depend on the structure, completeness, and filtering of the internal Boskalis base dataset. The imposed scenario levels are stress-test settings rather than forecasts, and the scenario families vary only a limited set of project drivers: cable length, distance from shore, water depth, HVDC share, and floating-foundation share. Project timing, regional market differences, policy uncertainty, financing conditions, port availability, seabed congestion, and vessel charter-market dynamics are not explicitly modelled.

A further limitation is that the scenario portfolios are generated independently. The scenario states are ordered by increasing stress severity, but they are not nested versions of the same project portfolio. Changes in design performance between scenario states may therefore reflect both the imposed stress settings and differences in sampled project mix, capacity distribution, donor selection, and total cable-kilometre denominator. Scenario-based vulnerability points should therefore be interpreted as indicative thresholds for the sampled portfolios, not as precise continuous boundaries.

These boundaries are consistent with the purpose of the scenario framework. The scenarios are designed to create structured project portfolios for comparing CLV mission-equipment configurations, not to forecast the offshore wind market. The current implementation represents a limited set of structured future portfolio states. A broader deep-uncertainty exploration would require larger scenario ensembles, more uncertainty drivers, and a wider set of market and design variables.

6.8. Conclusion

This chapter defined the scenario framework and performance measures used to evaluate the generated CLV design library across structured future offshore wind project portfolios. The filtered Boskalis base dataset is used as a donor pool rather than as a direct forecast. Synthetic project portfolios are generated through donor-based sampling, controlled scenario multipliers, target category shares, and small stochastic variation. The final scenario set consists of a base-like reference case and two ordered stress-test families: a length–distance/HVDC family and a depth/floating family, each labelled using mild, moderate, strong, and severe stress states.

The chapter also defined the main design-level KPIs: feasibility rate, portfolio cable-kilometre capture, campaign-bucket performance, fuel and duration per installed kilometre, utilisation indicators, average joints, and infeasibility shares. These metrics distinguish configurations that are technically feasible from configurations that capture a substantial share of the portfolio within an operationally attractive number of campaigns.

Finally, the screening and Pareto-front logic was introduced to identify relevant candidate configurations from the generated library. Pareto fronts are used to identify non-dominated CAPEX–fuel trade-offs, while feasible portfolio cable-kilometre capture is used as an additional portfolio-capture screen and interpretation variable. The following chapters use this framework to verify model behaviour, evaluate CLV design performance across scenarios, and construct adaptive mission-equipment pathways.

7 Verification and Validation

This chapter evaluates whether the computational model is internally consistent and sufficiently plausible for its intended use. The model is not intended to predict the exact installation performance of a specific vessel on a specific offshore wind project. It is an early-stage comparative model that evaluates a fixed library of CLV mission-equipment configurations across synthetic project portfolios. Verification and validation are therefore interpreted as fit-for-purpose checks: the model should be reproducible, internally consistent, and directionally credible for comparing relative design performance under different scenario conditions.

The chapter addresses the sixth sub-question:

> *How can the computational model be verified and validated before it is used for scenario evaluation?*

7.1. Verification and Validation Approach

The validation approach is informed by the purpose-oriented view of validation proposed by Pedersen et al. [110]. Their Validation Square distinguishes between structural validity, which concerns the logical consistency of a method, and performance validity, which concerns whether the method produces useful results for its intended purpose. This distinction is used here to structure the assessment of the computational model. The full Validation Square is not applied as a complete validation of the broader DAPP-based design-support approach; that broader methodological usefulness is assessed later through the scenario results, pathway analysis, and discussion.

Verification addresses whether the model has been implemented correctly according to its own logic. This includes checking required input columns, deterministic design-library generation, output completeness, scenario-run traceability, and explicit handling of infeasible cases. Validation is interpreted more narrowly as engineering face validity: whether the model behaviour is plausible and useful for early-stage comparison of mission-equipment configurations. Since detailed operational benchmark data are not available, the model is assessed against consistency expectations, plausible equipment ranges, selected reference-vessel comparisons, and expected directional responses to changes in storage demand, tension demand, and scenario severity.

The procedure consists of five check types, summarised in Table 7.1.

Table 7.1: Verification and validation checks applied to the computational model.

Check type	Evidence used	Expected behaviour
Implementation and structural checks	Structural tests, run traceability, and output completeness.	Reproducible runs, complete outputs, and retained infeasible cases.
Design-library checks	Distributions of draft, CAPEX, storage, tension capacity, and simplified stability.	Plausible equipment ranges and expected discrete design bands.
Project-evaluation behaviour checks	Feasibility, infeasibility, campaign, and utilisation trends.	Capability changes produce expected feasibility and utilisation responses.
Scenario-input checks	Target-share checks and base-versus-scenario validation plots.	Scenario variables shift in the intended stress-test direction.
Engineering face-validity checks	Reference-vessel comparison and diagnostic trade-off plots.	Equipment ranges and performance trade-offs are directionally plausible.

Together, these checks provide structural evidence that the model has been implemented consistently and performance evidence that the model behaves plausibly for comparing CLV mission-equipment configurations. They do not establish predictive validity for detailed subsea cable project execution.

7.2. Implementation and Structural Consistency Checks

The computational model is implemented as a deterministic batch simulation. The design library is generated or loaded once and then evaluated against every scenario project file, so that differences between scenario outcomes result from changes in the project portfolio rather than changes in the candidate design space.

Structural checks are embedded throughout the workflow. The carousel and tensioner libraries are checked for non-empty outputs before being combined through a factorial cross-merge. The resulting design-library size is checked against the expected product of the component-library sizes. Under the current settings, this gives 314 retained carousel arrangements and 36 tensioner-system arrangements, resulting in 11,304 mission-equipment configurations. Each configuration is assigned a unique `config_id`, and the saved or loaded design library is checked for required columns, duplicate identifiers, and empty critical fields.

Input consistency is also checked in the loading, laying, transit, and evaluation modules to reduce the risk of silent errors from missing, renamed, or incompatible variables. Run traceability is preserved through saved input copies, run summaries, row counts, runtimes, and batch summaries for each evaluated scenario. Infeasible design–project combinations are retained rather than dropped, with explicit infeasibility reasons such as insufficient lay lines, insufficient tension capacity, invalid campaign loading, loaded-stability failure, or transit draft exceedance. This is important because infeasibility is itself a model output.

The design-level KPI aggregation was checked against the definitions introduced in Chapter 6. Campaign-bucket metrics are calculated cumulatively, feasible cable-kilometre share uses the full project portfolio as denominator, and fuel and duration intensities are calculated only over feasible design–project combinations. The HVAC/HVDC distinction is also preserved consistently: HVAC projects are treated as one physical cable, while HVDC projects are treated as two physical cables and require two lay lines.

Together, these checks provide structural verification that the model components are connected consistently and that outputs remain traceable from scenario input files to design-level KPI tables.

7.3. Design-Library Consistency Checks

The generated design library was inspected before applying it to the scenario project portfolios. The purpose of this check is not to validate every individual equipment combination, but to verify that the generated design space is internally consistent and covers a plausible range of mission-equipment configurations for early-stage comparison.

The design-library verification script produces distributions for raw hydrostatic draft, mission-equipment

CAPEX, total carousel volume, maximum line tension, and empty transverse metacentric height. The raw draft shown in Figure 7.1 is calculated from the fixed lightship weight and generated mission-equipment weight, before applying the minimum operational draft of 7.86 m used in the operational modules. It should therefore be interpreted as a consistency check on the relative mission-equipment weight range, not as the final operating draft of the vessel.

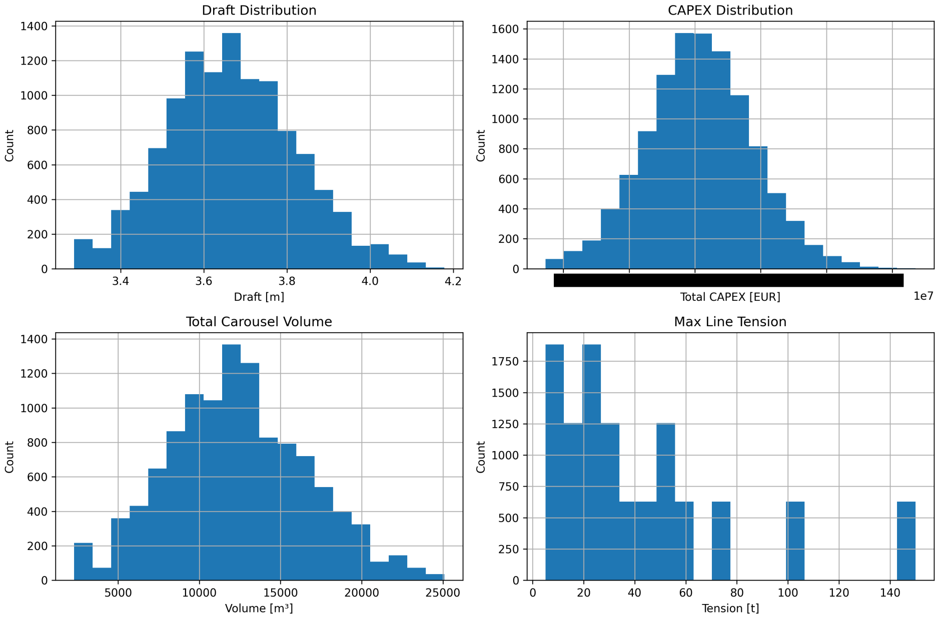
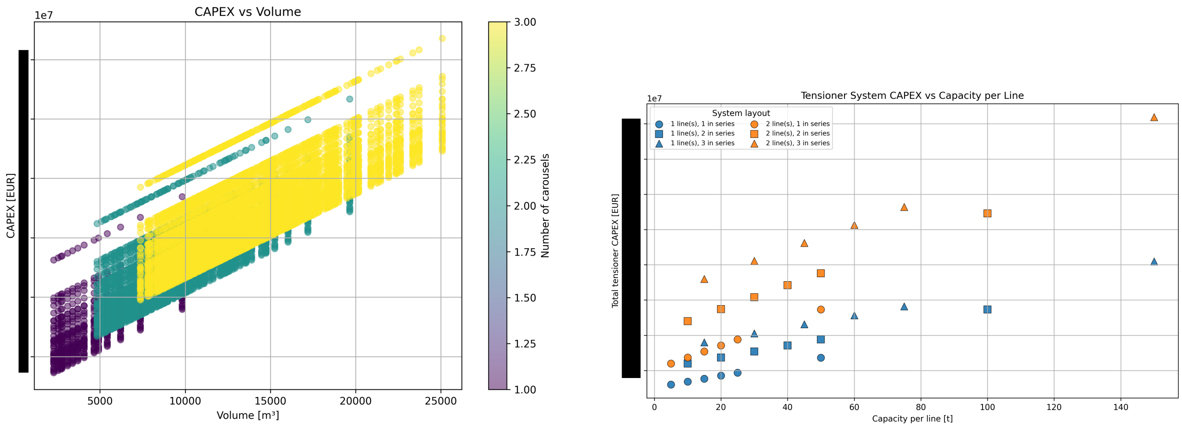


Figure 7.1: Verification distributions for the generated design library: raw hydrostatic draft, mission-equipment CAPEX, total carousel volume, and maximum line tension. The raw draft is calculated before applying the minimum operational draft.

Figure 7.1 shows the expected structure of a combinatorial design library. Draft, CAPEX, and carousel-volume values are concentrated around intermediate ranges because more component combinations lead to moderate aggregate values than to extreme low or high values. The maximum line-tension distribution is more discrete because it is generated from a finite tensioner catalogue, one- or two-line layouts, and a limited number of identical units in series. This confirms that the generated alternatives form a structured set of discrete mission-equipment combinations rather than a continuously optimised design space.

Additional design-library checks are shown in Figure 7.2. The plots confirm that larger storage capacity and higher line capacity correspond to higher mission-equipment CAPEX, with the expected banded and stepwise patterns caused by the discrete carousel and tensioner options. In the carousel plot, the vertical bands reflect the finite set of carousel dimensions and slot combinations, while the colour scale shows the increasing number of installed carousels. In the tensioner plot, the separate point groups reflect different combinations of line count, series units, and unit tension capacity. These patterns support the implementation check that the cost and capacity calculations respond consistently to the generated equipment choices.



(a) Mission-equipment CAPEX versus total carousel volume. **(b)** Tensioner-system CAPEX versus capacity per line.

Figure 7.2: Design-library cost and capacity checks. The plots verify that larger storage and higher line-capacity configurations correspond to higher mission-equipment CAPEX, with banded and stepwise patterns caused by the discrete carousel and tensioner options.

The empty GM distribution is shown in Figure 7.3. The model calculates empty GM using the fixed lightship KG, mission-equipment VCG, and interpolated transverse metacentric height at the minimum-draft-corrected empty draft. Configurations with a raw hydrostatic draft below 7.86 m are therefore assessed as if ballast or equivalent weight-management measures bring the vessel to the minimum operational draft. The ballast mass, position, and free-surface effects are not explicitly modelled, so the values should be interpreted as simplified diagnostic indicators rather than detailed ballast-condition stability results.

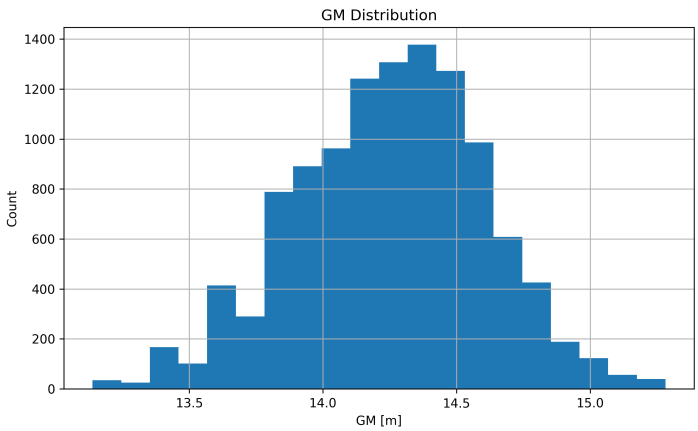


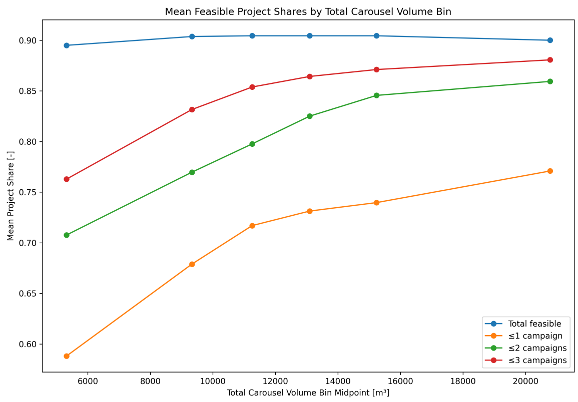
Figure 7.3: Empty transverse GM distribution for the generated design library, evaluated at the minimum-draft-corrected empty draft. The simplified stability check shows positive empty GM values for the generated configurations.

All generated configurations have positive empty-condition GM_T values in the simplified stability check. Together with the other design-library checks, this supports the internal consistency of the generated mission-equipment design space. The library therefore provides a consistent basis for comparing relative performance across structured equipment configurations, but should not be interpreted as a detailed vessel-design optimisation.

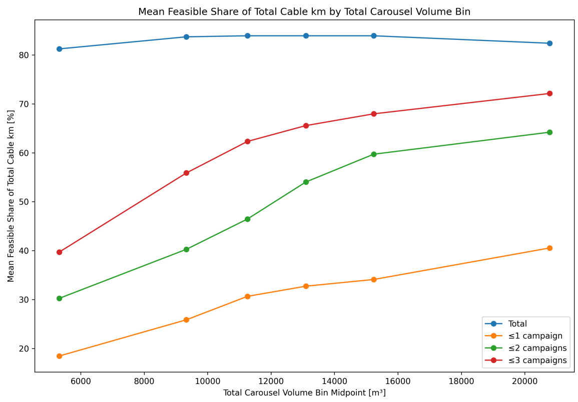
7.4. Project-Evaluation Behaviour Checks

The project-evaluation logic was checked by examining whether the model produces the expected behaviour when project requirements exceed specific design capabilities. The main represented failure modes are insufficient storage capacity, insufficient tension capacity, insufficient number of lay lines, loaded-stability failure, and transit draft exceedance. In the evaluated runs used for this thesis, no design–project combinations failed due to the simplified loaded-stability criterion. This is likely related to the large beam and high transverse stability margin of the reference hull, although the check remains useful as a safeguard against high-VCG loading cases. A supporting distribution of minimum loaded campaign GM_T values is provided in Appendix B, Section B.5, Figure B.6.

Storage behaviour was checked by grouping designs by total carousel volume. As expected, designs with low carousel volume often complete projects only in multiple campaigns, while larger carousel configurations complete a larger share of projects within one, two, or three campaigns. This behaviour is visible both for project-count metrics and for installed cable-kilometre metrics, as shown in Figure 7.4. The cable-kilometre metric is especially relevant for portfolio capture because larger projects contribute more installed cable length than smaller projects.



(a) Feasible project share by carousel-volume bin.



(b) Feasible cable-kilometre share by carousel-volume bin.

Figure 7.4: Storage-capacity behaviour checks for the base case. Larger carousel volume improves campaign-limited feasibility across project-count and cable-kilometre measures.

The plateau below full feasibility in Figure 7.4 should not be interpreted as a storage effect alone. Because the volume bins include configurations with different line layouts and tension capacities, some remaining infeasibility is caused by non-storage constraints. In particular, HVDC projects are treated as requiring two physical cables and therefore two lay lines; under this simultaneous dual-lay assumption, one-line designs are classified as infeasible before storage allocation is evaluated.

Tension behaviour was checked by grouping designs by maximum tension capacity per line. Figure 7.5 shows the expected directional response: mean feasible project share increases with line capacity, with diminishing returns once most base-case project requirements are covered.

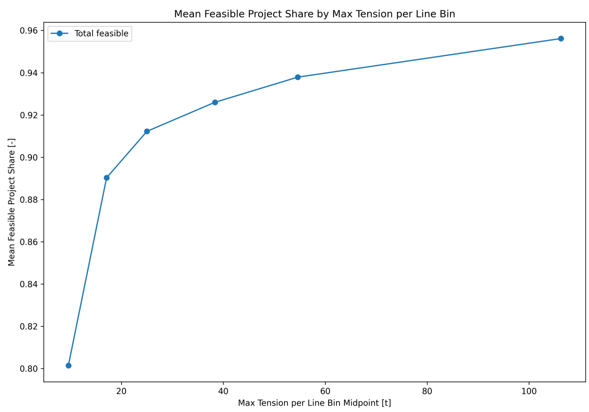
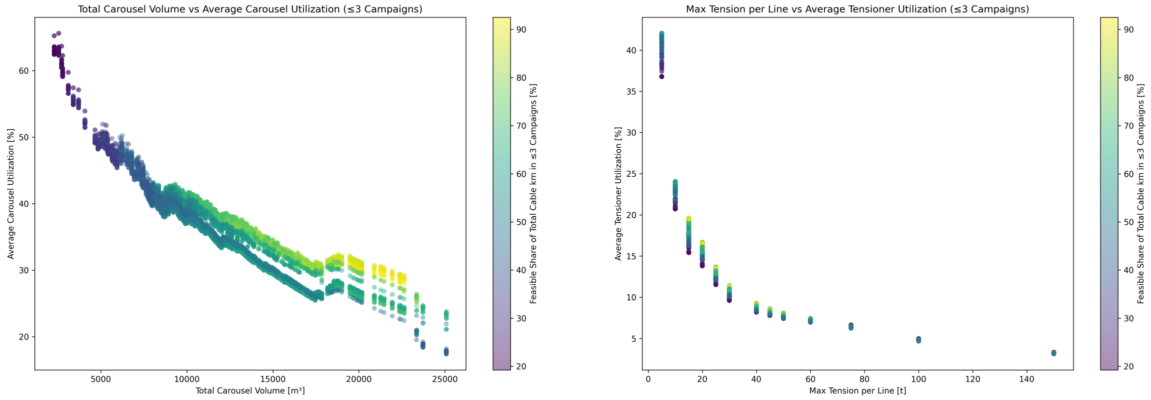


Figure 7.5: Tension-capacity behaviour check for the base case, showing improved feasibility with higher line capacity.

A further behaviour check concerns utilisation. If installed storage or tension capacity increases while the project portfolio remains fixed, average utilisation should generally decrease because the same project demand is spread over more installed capability. This behaviour is shown in Figure 7.6. Larger storage and higher tension capacity can improve project capture, but they also reduce average utilisation.



(a) Carousel volume versus carousel utilisation.

(b) Line capacity versus tensioner utilisation.

Figure 7.6: Utilisation behaviour checks for the base case. Higher installed storage or tension capacity can improve feasible cable-kilometre share, but generally reduces average utilisation.

Finally, the transit model checks whether loaded and unloaded transit drafts remain within the valid draft range of the hull resistance relation. In the current evaluation, this range was not exceeded. The check is nevertheless retained to prevent a design from being counted as feasible when the loading mode is feasible but the resulting transit condition falls outside the valid hydrodynamic model range.

7.5. Scenario-Input Consistency Check

The generated project scenarios were checked before being used in the vessel-evaluation model. The purpose of this check is to verify that the scenario portfolios shift the project variables that drive storage demand, transit distance, tension requirement, line-layout feasibility, and cable-size estimation. The detailed scenario-generation method is presented in Chapter 6, while the full base-versus-scenario validation plots are provided in Appendix C. The base-like, length–distance/HVDC, and depth/floating validation plots are shown in Sections C.1, C.2, and C.3, respectively.

Table 7.2 summarises the realised scenario means for the core project variables used by the evaluation model.

Table 7.2: Realised core project-variable indicators for the generated global-scope scenarios. Values are scenario means, except for HVDC and floating shares.

Scenario	Cable length (km)	Distance from shore (km)	Min depth (m)	Max depth (m)	HVDC share (%)	Floating share (%)	Project Capacity (MW)
base_like	183	56	57	96	8	20	1080
len_dist_10	302	71	62	119	20	20	1252
len_dist_20	459	98	60	101	35	20	1476
len_dist_30	635	129	62	111	50	20	1581
len_dist_40	900	161	58	89	65	20	1940
depth_50	207	54	106	205	8	25	1056
depth_100	207	60	159	320	8	40	1020
depth_150	192	54	271	507	8	55	945
depth_200	161	57	417	812	8	70	690

Table 7.2 should be interpreted as a realised-output check of the synthetic portfolios, not as evidence that the nominal percentage labels in Table 6.1 correspond to realised mean changes from one fixed project list. Each scenario is independently sampled and combines donor selection, target category

shares, scenario multipliers, and small stochastic variation. The realised means can therefore shift more strongly than the nominal input multipliers alone suggest.

This is especially visible in the length–distance/HVDC family. The increasing HVDC share changes the donor composition toward larger and more remote projects, while cable length is derived from generated distance from shore, donor-specific cable-to-distance ratios, the cable-length multiplier, and noise. The realised increase in mean cable length therefore reflects the combined length–distance–HVDC stress setting, rather than a uniform percentage increase applied to the base-like portfolio.

With this interpretation, Table 7.2 confirms that the scenario inputs move in the intended stress-test direction. The length–distance/HVDC family increases cable length, distance from shore, and HVDC share, while the depth/floating family increases water depth and floating-foundation share. These realised shifts provide suitable inputs for testing CLV storage demand, transit distance, tension demand, and lay-line requirements. The appendix boxplots provide the corresponding distributional check and show that these shifts are not limited to the scenario means reported in the table.

7.6. Engineering Face Validity and Reference-Vessel Comparison

Engineering face validity was assessed by checking whether the model produces plausible mission-equipment ranges and directionally credible trade-offs for early-stage CLV configuration comparison. In addition to the internal behaviour checks discussed above, a small set of existing or announced cable-laying vessels was compared with the generated design library.

The purpose of this comparison is not to recreate these vessels in full detail. The model uses the fixed reference platform hull introduced earlier, corresponding to the Boskalis 24,000 t CLV concept, and does not vary vessel length, breadth, deadweight, installed propulsion power, deck arrangement, or hull-form characteristics. The comparison is therefore limited to high-level mission-equipment characteristics: carousel storage volume, approximate carousel layout, and tension capacity.

(a) Jan De Nul *Connector* [72]

(b) *NKT Victoria* [121]

(c) *Prysmian Monna Lisa* [94]

(d) Boskalis 24,000 t CLV concept [17]

Figure 7.7: Example cable-laying vessels used as external reference cases for comparison with modelled configurations.

Figure 7.7 shows the selected reference cases. The first three vessels provide external equipment-range reference points, while the Boskalis 24,000 t CLV concept provides an upper-end platform reference aligned with the fixed reference hull used in the model. For each case, the closest model configuration was selected based on storage volume, carousel layout, and tension-system similarity. The comparison is summarised in Table 7.3.

Table 7.3: Indicative equipment comparison between selected reference vessels and matched model configurations.

Reference vessel	Config ID	Storage [m^3]	Ref. carousel layout	Model carousel layout	Tension match per line
NKT Victoria [121]	538	4,225 / 4,832	AD1: 26.2 × 5; BD1: 21.5 × 5	AD1: 24 × 6; BD1: 20 × 8	Ref: 45 t; Config: 50 t
Connector [72]	922	6,115 / 6,169	AD1: 25 × 8; BD1: 23.6 × 5.9	AD1: 24 × 8; BD1: 25 × 6	Ref: 20 t; Config: 20 t
Monna Lisa [94]	1691	8,093 / 8,049	AD1: 28 × 8: AD2: 24 × 8;	AD1: 32 × 6: AD2: 24 × 8	Ref: 100 t; Config: 100 t
Boskalis CLV [17]	3514	19,654 / 19,654	AD1: 40 × 8; AD2: 40 × 8;	AD1: 40 × 8; AD2: 40 × 8;	Ref: 20 t; Config: 20 t

Note: Carousel dimensions are shown as outer diameter × height in metres, and storage values as reference vessel / matched model configuration. The 6 m core diameter is omitted because it is shared by the model and selected comparison data. Reference vessels are indicative only.

Table 7.3 shows that the generated design library contains configurations with storage volume, carousel arrangement, and tension capacity that are broadly comparable to selected reference vessels. This supports the plausibility of the modelled mission-equipment range. The matched configurations are not digital replicas of the reference vessels, since hull size, deck layout, installed power, DP capability, supplier-specific equipment, structural integration, and retrofit feasibility are not represented.

The matched configurations were then evaluated using the same project-evaluation model as the rest of the design library. Table 7.4 reports selected model outputs for configurations with mission-equipment characteristics comparable to the reference vessels. The comparison therefore indicates how reference-like equipment configurations perform within the model framework.

Table 7.4: Model performance indicators for the configurations matched to reference vessels.

Reference case	Config ID	Storage [m^3]	Line Tension [t]	CAPEX [MEUR]	Fuel avg. [t/km]	Cable-km capture
NKT Victoria [121]	538	4,832	50	[redacted]	1.58	35%
Connector [72]	922	6,169	20		1.62	42%
Monna Lisa [94]	1691	8,049	100		1.74	56%
Boskalis CLV [17]	3514	19,654	20		[redacted]	[redacted]%

Note: Performance indicators refer to the matched model configurations evaluated against the base-like project portfolio. Cable-km capture is the feasible share of total portfolio cable kilometres associated with projects completed within at most three campaigns.

Across these matched examples, the model results are broadly in line with expectations for reference-like equipment configurations. The lower-capacity reference cases capture a relatively limited share of the base-like portfolio cable kilometres within at most three campaigns, while the largest upper-end configuration captures a substantially larger share. At the same time, higher-capability equipment packages carry higher mission-equipment CAPEX. This pattern is consistent with the expected trade-off between capital intensity and operational capability. The reference-vessel comparison therefore strengthens the engineering face-validity argument by showing that the generated design library overlaps with recognisable CLV equipment arrangements and produces plausible relative portfolio-capture behaviour, while detailed vessel validation, performance prediction, and retrofit assessment remain outside the scope of the thesis.

7.7. Scope of Validity and Validation Limitations

The validation performed in this chapter is limited by the early-stage and comparative purpose of the model. Following the purpose-oriented view of validation, the model can only be considered valid for the purpose for which evidence has been provided: comparing CLV mission-equipment configurations on a fixed reference platform across synthetic project portfolios. The checks in this chapter therefore do not establish predictive validity for detailed cable-laying operations, vessel operability, project execution cost, retrofit feasibility, or final vessel design.

The model is not validated against detailed operational data from real cable-laying campaigns or vessel performance logs. Actual installation performance depends on vessel-specific operability, route- and installation-specific constraints, and logistical or environmental conditions that are outside the model scope. Technical components are therefore assessed through internal consistency and directional behaviour only. Cable size is estimated from simplified project-level proxies, storage is represented geometrically with a fixed fill factor, tension demand is estimated from submerged cable weight and water depth, and stability is limited to first-order KG, KM_T, and GM_T calculations rather than full intact or damage stability assessment. The operational minimum draft is imposed by clipping the calculated draft, while ballast mass, ballast distribution, and free-surface effects are not explicitly modelled.

The operational and cost models are also simplified. Transit fuel is based on interpolated resistance polynomials, constant speed, a fixed propulsion-efficiency chain, and a sea margin. Laying fuel is based on simplified DP, carousel, and tensioner power estimates, with DP power represented through a normalised exposure proxy rather than a full station-keeping or thruster-allocation analysis. Fuel consumption uses constant specific fuel consumption. CAPEX is limited to mission-equipment CAPEX and excludes broader vessel conversion, integration, financing, downtime, and retrofit execution costs. It should therefore be interpreted as a relative mission-equipment cost indicator, not as a complete investment estimate.

Scenario validation is distributional and directional. The generated scenarios are stress-test inputs, not forecasts of future offshore wind project portfolios. The results should therefore be used to compare relative robustness and identify pathway-relevant vulnerabilities, not to make deterministic claims about future market demand or absolute project performance. The broader usefulness of the adapted DAPP-based design-support approach is also not fully validated in this chapter; it is assessed later through the scenario interpretation, pathway construction, and final discussion.

7.8. Conclusion

The verification and validation checks indicate that the computational model is internally consistent and directionally plausible for its intended early-stage comparative purpose. The implementation checks confirm that the model workflow is reproducible, traceable, and able to retain infeasible design–project combinations as explicit outputs. The design-library checks further show that the generated carousel and tensioner configurations form a structured and plausible mission-equipment design space.

The project-evaluation behaviour is consistent with the implemented engineering logic. Increasing storage capacity, line tension capacity, and line capability produces the expected changes in portfolio capture, infeasibility, CAPEX, and utilisation. The scenario-input checks confirm that the generated portfolios shift the project variables relevant to storage demand, transit distance, tension requirement, and lay-line feasibility. The reference-vessel comparison further supports engineering face validity by showing that the design library contains mission-equipment arrangements broadly comparable to selected existing or announced CLVs, and that reference-like configurations produce plausible relative portfolio-capture behaviour within the model framework.

Overall, the model provides a consistent basis for scenario stress-testing, Pareto-based design comparison, and adaptive pathway construction in the following chapters. Its outputs should be interpreted as relative early-stage indicators, not as detailed predictions of installation cost, fuel consumption, vessel operability, or retrofit feasibility.

8 Evaluation of CLV Design Performance Across Scenario Stress Tests

This chapter addresses the seventh sub-question:

How do different CLV mission-equipment configurations perform under changing project length, distance from shore, water-depth, floating-share, and cable-system conditions?

This chapter applies the computational model from Chapter 5 to the global-scope scenario set introduced in Chapter 6. The evaluation is deterministic for each design–scenario combination; changing project-portfolio conditions are used as structured stress tests rather than probabilistic forecasts. The chapter first introduces the evaluation scope and design-interpretation logic, then analyses base-like CAPEX–fuel trade-offs, and finally compares configuration performance across the two scenario families to identify the vulnerability patterns used in the adaptive pathway analysis in Chapter 9.

8.1. Evaluation Scope and Design Interpretation

This chapter evaluates the fixed CLV mission-equipment design library across the global-scope scenario set introduced in Chapter 6. The same configurations are evaluated in every scenario run, so differences in performance reflect changes in the project portfolio rather than changes in the candidate design space. The scenario portfolios are independently generated stress-test states, not nested modifications of one fixed project list. Performance values are therefore interpreted as directional scenario evidence rather than as exact project-by-project causal trajectories.

The main performance indicator used in this chapter is portfolio cable-kilometre capture within at most three campaigns. It represents the share of total portfolio cable kilometres associated with technically feasible projects within this campaign limit. This metric combines technical feasibility, portfolio coverage, and a practical campaign-count constraint. A 60% value is used as a consistent reference threshold for meaningful campaign-limited portfolio coverage, following the screening logic introduced in Section 6.6. It is a modelling threshold, not a universal industry requirement. The interpretation also considers mission-equipment CAPEX, average fuel consumption per installed cable kilometre, utilisation, and dominant infeasibility mechanisms.

The scenario results are interpreted through the design characteristics that most directly affect CLV performance: carousel volume, lay-line capability, tension capacity per line, and mission-equipment CAPEX. Table 8.1 summarises the expected influence of these characteristics under the two scenario families.

Table 8.1: Design characteristics used to interpret the scenario results.

Characteristic	**Low-capability interpretation**	**High-capability interpretation**	**Main affected scenario family**
Carousel volume	More loading campaigns; lower portfolio cable-km capture	Fewer campaigns; higher portfolio cable-km capture	Length–distance/ HVDC
Number of lay lines	Limited dual-cable capability	Compatible with dual-cable projects	Length–distance/ HVDC
Tension capacity per line	Vulnerable in deeper water	Greater deep-water capability	Depth/floating
Mission-equipment CAPEX	Lower cost, but less capability margin	Higher capability, but greater overcapacity risk	Both families

The most capable configuration is not automatically the preferred design. Higher storage, higher tension capacity, and two lay lines improve technical robustness, but also increase CAPEX and may reduce utilisation in milder portfolios. The following sections therefore evaluate both performance levels and the capability increments responsible for that performance.

8.2. Pareto Trade-Off Analysis

The Pareto analysis is used to identify configurations that offer attractive trade-offs between mission-equipment CAPEX and average fuel consumption per installed cable kilometre. A configuration is Pareto-efficient if no other configuration achieves both lower CAPEX and lower fuel intensity. The feasible share of portfolio cable kilometres completed within at most three campaigns is shown as an additional portfolio cable-kilometre capture indicator, rather than as a Pareto objective. This keeps the trade-off analysis focused on cost and fuel efficiency, while still showing whether a configuration serves a substantial part of the portfolio within a practical campaign limit.

Figure 8.1 shows the resulting CAPEX–fuel trade-off for the base-like scenario.

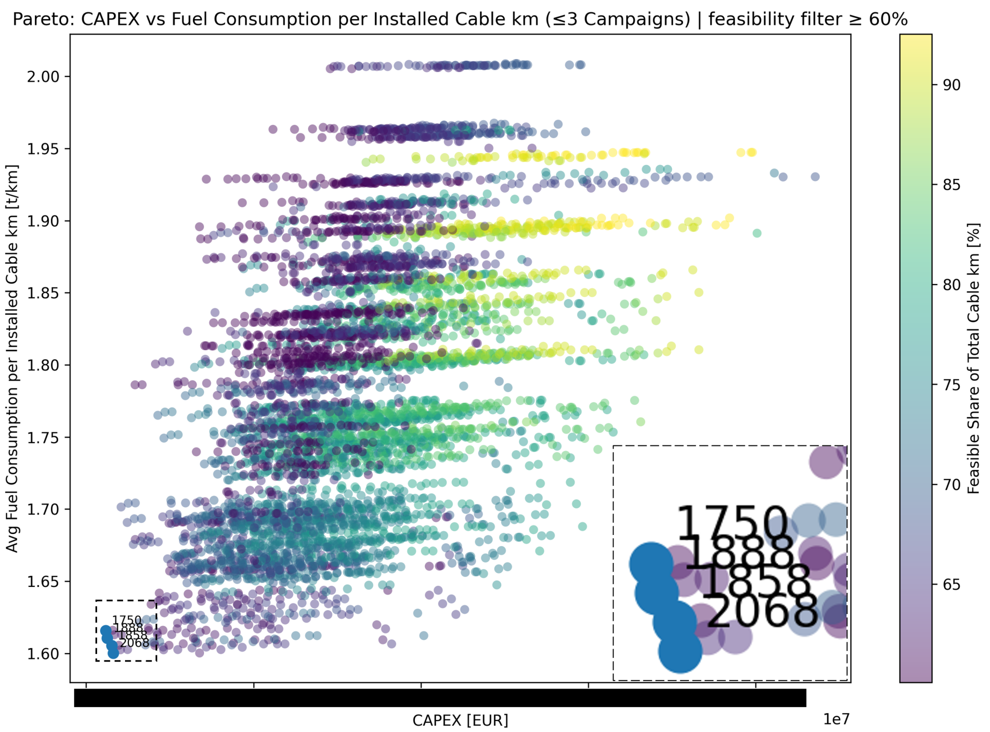


Figure 8.1: Base-like scenario Pareto trade-off between mission-equipment CAPEX and average fuel consumption per installed cable kilometre for projects completed within at most three campaigns.

The Pareto-efficient configurations are concentrated at relatively low CAPEX compared with the full design library. This indicates that very large mission-equipment configurations are not required to obtain attractive CAPEX–fuel performance under base-like portfolio conditions. However, the colour scale shows that low-cost and low-fuel configurations do not necessarily capture the largest share of portfolio cable kilometres. The plot therefore illustrates why CAPEX–fuel efficiency and campaign-limited portfolio capture need to be interpreted together.

The same Pareto-identification procedure is applied consistently to the other scenario states and scenario families. This makes it possible to observe how the set of relevant trade-off configurations changes as project portfolios become more demanding. These scenario-specific Pareto sets are not treated as final design selections. Instead, they are used to expose potential pathway candidates, which are later compared in terms of capability, compatibility, and upgrade logic in Chapter 9. A comparison of alternative campaign buckets is provided in Appendix D.1.

8.3. Scenario Stress-Test Results

The stress-test scenarios show how relevant design trade-offs change as project portfolios become more demanding. The analysis focuses on which configurations become Pareto-efficient in CAPEX–fuel space, the portfolio cable-kilometre capture they achieve within the ≤ 3 campaign bucket, and which design characteristics become valuable in each scenario state.

8.3.1. Length, Distance, and HVDC Scenario Family

The length, distance, and HVDC family stresses carousel storage capacity, campaign count, and compatibility with dual-cable installation. As discussed in Section 6.4, the scenario states are ordered by increasing stress severity, while the realised portfolio characteristics also depend on HVDC-share targeting, donor selection, and resampling. Table 8.2 summarises which configurations become Pareto-efficient in each stress state. The main pattern is a progressive shift from low- and mid-storage configurations in the base-like and mild cases toward substantially larger carousel volumes in the moderate, strong, and severe cases.

Table 8.2: Pareto-efficient configurations across the length, distance, and HVDC scenario family.

Scenario	Pareto-efficient config. IDs	Storage range	Interpretation
Base-like	1750, 1888, 1858, 2068	8,357–8,985 m^3	Low/mid storage is sufficient in the reference case
Mild	2794, 5350, 5746	8,614–11,636 m^3	Additional storage begins to enter the front
Moderate	3328, 7900, 7936, 7972	14,313–14,740 m^3	Medium-large storage becomes necessary
Strong	10168, 10312	17,800–18,359 m^3	High storage dominates the relevant trade-off
Severe	3508, 10708, 10744, 10924	19,654–20,169 m^3	Very large storage remains competitive

The shift in Table 8.2 is mainly driven by storage volume rather than tension capacity. All Pareto-efficient configurations in this family use a two-line tensioner arrangement, while line capacity varies only between 15 and 20 t per line and becomes uniform at 15 t per line from the moderate state onward. This indicates that increasing cable length, campaign limitation, and dual-cable compatibility dominate the length–distance/HVDC family, rather than increasing tension demand.

The full CAPEX–fuel trade-off plots with Pareto fronts for the individual stress states are provided in Appendix D.2.1, Figure D.2. Table 8.3 then tests how the Pareto-efficient configurations from each stress state perform across the full length–distance/HVDC family. The first column indicates the stress state in which each configuration was selected as Pareto-efficient. The remaining columns show the campaign-limited portfolio cable-kilometre share achieved by that same configuration when evaluated against each scenario state. Values at or above 60% meet the selected campaign-limited portfolio-capture reference level.

Table 8.3: Stress-test performance matrix for Pareto-efficient configurations in the length–distance/HVDC family. Values show feasible portfolio cable-kilometre share within at most three campaigns.

Selection set	Config. ID	Base-like	Mild	Moderate	Strong	Severe
Base-like	1750	61%	29%	18%	9%	5%
	1888	61%	30%	18%	9%	6%
	1858	61%	31%	18%	10%	5%
	2068	62%	31%	18%	9%	6%
Mild	2794	74%	62%	32%	13%	7%
	5350	74%	62%	31%	12%	7%
	5746	74%	62%	32%	13%	7%
Moderate	3328	81%	69%	69%	42%	20%
	7900	81%	69%	62%	34%	15%
	7936	81%	69%	66%	37%	18%
	7972	81%	69%	68%	37%	18%
Strong	10168	83%	72%	76%	62%	30%
	10312	85%	76%	78%	63%	46%
Severe	3508	87%	78%	89%	71%	61%
	10708	87%	78%	89%	71%	61%
	10744	87%	78%	89%	71%	61%
	10924	87%	78%	89%	71%	61%

Table 8.3 shows that configurations selected under base-like and mild conditions lose campaign-limited portfolio capture quickly as the length–distance/HVDC stress increases. The moderate and strong selection sets extend the range of acceptable performance, but still fall below the 60% reference level in the severe state. Only the configurations selected from the severe state remain above the threshold across the full scenario family. This pattern indicates that increasing carousel capacity is the main adaptation direction exposed by the length–distance/HVDC stress test, while the repeated appearance of two-line configurations also reflects the importance of dual-cable compatibility.

8.3.2. Depth and Floating Scenario Family

The depth/floating family primarily stresses cable-handling capability. As discussed in Section 6.4, the scenario states are ordered by increasing stress severity, while the realised portfolio characteristics also depend on floating-share targeting, donor selection, and resampling. Table 8.4 summarises which configurations become Pareto-efficient in each stress state. The main pattern is a progressive shift toward higher line tension capacity, while the storage range remains much narrower than in the length–distance/HVDC family.

Table 8.4: Pareto-efficient configurations across the depth and floating scenario family.

Scenario	Pareto-efficient config. IDs	Storage range	Tension range	Interpretation
Base-like	1750, 1888, 1858, 2068	8,357–8,985 m^3	15–20 t/line	Low/mid tension is sufficient in the reference case
Mild	2110, 2182, 2290, 2398, 2542	9,312–10,342 m^3	20 t/line	Moderate tension capacity becomes preferable
Moderate	1900, 2080	8,727–8,985 m^3	25 t/line	Higher line tension enters the front
Strong	1906, 2086, 2075, 2543	8,727–10,342 m^3	40–50 t/line	Deep-water tension becomes a dominant constraint
Severe	500, 2086, 2070	8,985–9,827 m^3	45–100 t/line	High-tension options dominate, with line-layout trade-offs

The shift in Table 8.4 is mainly driven by tension capacity rather than storage volume. The Pareto-efficient storage range remains within approximately 8,357–10,342 m^3, while the tension range increases from 15–20 t/line in the base-like case to 40–100 t/line in the strong and severe states. This indicates that water depth and floating-project share primarily expose a cable-handling vulnerability, rather than the storage-capacity vulnerability observed in the length–distance/HVDC family.

The severe state also includes configuration 500, which combines high tension capacity with only one lay line. It appears on the Pareto front because the depth/floating family mainly rewards tension capacity, while the one-line layout keeps CAPEX relatively low. However, this does not make it a generally robust option: under scenarios with higher HVDC share, one-line configurations remain vulnerable because they cannot serve dual-cable projects.

Table 8.5 then tests how the Pareto-efficient configurations from each stress state perform across the full depth/floating family. The first column indicates the stress state in which each configuration was selected as Pareto-efficient. The remaining columns show the campaign-limited portfolio cable-kilometre share achieved by that same configuration when evaluated against each scenario state. Values at or above 60% meet the selected campaign-limited portfolio-capture reference level.

Table 8.5: Stress-test performance matrix for Pareto-efficient configurations in the depth and floating scenario family. Values show feasible portfolio cable-kilometre share within at most three campaigns.

Selection set	Config. ID	Base-like	Mild	Moderate	Strong	Severe
Base-like	1750	61%	49%	49%	41%	32%
	1888	61%	46%	50%	42%	31%
	1858	61%	50%	51%	41%	33%
	2068	62%	46%	50%	42%	31%
Mild	2110	69%	60%	55%	52%	35%
	2182	69%	62%	58%	52%	35%
	2290	69%	65%	58%	52%	36%
	2398	70%	63%	58%	52%	36%
	2542	70%	65%	58%	52%	36%
Moderate	1900	62%	55%	61%	45%	35%
	2080	64%	55%	61%	45%	36%
Strong	1906	64%	58%	64%	63%	65%
	2086	65%	58%	64%	63%	66%
	2075	65%	57%	63%	61%	56%
	2543	71%	69%	69%	71%	59%
Severe	500	54%	58%	59%	59%	61%
	2086	65%	58%	64%	63%	66%
	2070	65%	58%	64%	62%	65%

Table 8.5 shows that base-like and mild Pareto-efficient configurations lose campaign-limited portfolio capture as the depth/floating stress increases. Configurations selected in the strong and severe states generally maintain stronger performance because they provide higher line tension capacity. However, the trajectories are not strictly monotonic for every configuration. This does not necessarily indicate inconsistent model behaviour, because the scenario states are independently generated synthetic portfolios rather than a fixed set of projects scaled progressively. The feasible cable-kilometre share depends on both the projects that become feasible and the total cable-kilometre denominator in each generated portfolio.

The severe-state selection set illustrates the line-layout trade-off. Configuration 500 reaches the 60% reference level in the severe depth/floating state because of its high tension capacity and relatively low CAPEX, but it remains below the threshold in the base-like state and is vulnerable to HVDC-heavy futures because it has only one lay line. This is why Chapter 9 considers pathway compatibility rather than selecting designs solely from isolated scenario Pareto fronts.

Together, the two scenario families show why the pathway analysis cannot be based on a single best-performing configuration. The length–distance/HVDC family points toward storage capacity and two-line capability, while the depth/floating family points toward tension capacity. Chapter 9 therefore treats configurations as capability states that may need to be connected through adaptive upgrade pathways.

8.4. Robustness and Vulnerability Analysis

The stress-test results show that robustness is not a single design property. Different scenario families expose different bottlenecks. The length–distance/HVDC family mainly stresses storage capacity, campaign count, and lay-line compatibility, while the depth/floating family mainly stresses tension capacity. Table 8.6 summarises the resulting robustness and vulnerability patterns.

Table 8.6: Observed robustness and vulnerability patterns across the scenario families.

Design type	**Robustness strength**	**Main vulnerability**	**Most sensitive scenario family**
Low/mid storage, low tension	Low CAPEX and adequate base-like performance	Rapid loss under longer cable routes	Length–distance/ HVDC
High storage, low tension	Strong campaign-limited capture for long routes	Limited deep-water cable-handling capability	Depth/floating
Low/mid storage, high tension	Stronger deep-water capability	Limited campaign performance for long routes	Length–distance/ HVDC
One-line high-tension	Low-cost deep-water capability	Dual-cable HVDC incompatibility	Length–distance/ HVDC
High storage, high tension, two-line	Broad technical robustness	High CAPEX and possible overcapacity	Both families

These vulnerability patterns follow directly from the model logic. Storage vulnerability occurs when the required cable volume can no longer be installed within a limited number of campaigns. Tension vulnerability occurs when the required cable-handling tension exceeds installed line capacity. Line-layout vulnerability occurs when dual-cable HVDC projects require two lay lines, while the configuration has only one. The 60% feasible cable-kilometre threshold within at most three campaigns is therefore used as a consistent reference for identifying pathway-relevant vulnerability points. When a configuration falls below this level, it indicates a substantial loss of campaign-limited portfolio coverage under the tested scenario conditions. These losses motivate the storage, line-layout, and tension-capacity actions considered in Chapter 9.

8.5. Conclusion

This chapter evaluated the generated CLV mission-equipment design library across the structured scenario stress tests introduced in Chapter 6. The evaluation is deterministic for each design–scenario combination; uncertainty is represented through alternative synthetic project portfolios rather than probability-weighted simulation. Pareto-efficient configurations are identified consistently across scenario states to expose relevant trade-offs and pathway candidates.

The results show that scenario stress changes which capability dimensions become valuable. Under base-like conditions, moderate configurations can provide attractive CAPEX–fuel performance, although not always the highest portfolio cable-kilometre capture. In the length–distance/HVDC family, the Pareto-efficient set shifts toward larger carousel volumes, showing that storage capacity, campaign limitation, and dual-cable compatibility become dominant. In the depth/floating family, it shifts mainly toward higher line-tension capacity, showing that cable-handling capability becomes the dominant deeper-water vulnerability. No single capability dimension is sufficient: high storage does not solve deep-water tension limitations, high tension does not solve long-route campaign limitations, and one-line high-tension configurations remain vulnerable under higher HVDC share. These findings motivate the adaptive pathway analysis in Chapter 9, where candidate configurations are assessed in terms of capability, compatibility, upgrade logic, and pathway-relevant vulnerabilities.

9
Adaptive Pathway Analysis and Discussion

Chapter 8 evaluated how the fixed CLV mission-equipment design library performs across the global-scope scenario set introduced in Chapter 6. The results showed that different scenario families create different capability gaps. The length, distance, and HVDC scenario family mainly stresses carousel storage, campaign count, and lay-line capability. The depth and floating scenario family mainly stresses installed tension capacity per line.

This chapter addresses the eighth sub-question:

How can the identified design trade-offs and vulnerabilities be translated into adaptive design pathways for early-stage CLV decision-making?

The chapter translates the scenario-performance results into adaptive design pathways using the DAPP logic introduced in Chapter 4. The purpose is not to define a final vessel design or detailed retrofit plan, but to identify which configurations can act as starting points, which configurations can serve as later capability steps, and under which scenario-state conditions a configuration no longer meets the selected performance reference. The maps should therefore be interpreted as capability pathways. They show how a CLV mission-equipment concept could evolve across increasingly demanding scenario portfolios, provided that the necessary design provisions are made.

9.1. Pathway Construction Logic

The pathway analysis uses the same performance reference as Chapter 8: a configuration remains acceptable while it can technically install at least 60% of the total cable kilometres in the relevant scenario portfolio within at most three campaigns.

Each row in the pathway maps represents one complete mission-equipment configuration. This means that storage layout, lay-line capability, tension capacity, CAPEX, fuel use, and feasibility are evaluated as one combined design state, rather than as separate component choices. Adaptation is therefore shown as a move from one configuration state to another.

The pathway configurations are selected from the same design library evaluated in Chapter 8. The selection is not a direct copy of the results from the Pareto analysis. Instead, the pathway set is constructed in three steps. First, the scenario-performance results are used to identify which capability dimensions become valuable under increasing scenario stress. Second, configurations are selected that represent logical capability steps within the generated design library. Third, qualitative compatibility rules are applied to remove transitions that do not represent a logical upgrade within the same storage layout, line-layout concept, or below-deck arrangement.

The pathway interpretation considers scenario performance, upgrade compatibility, and investment burden together. A high-performing configuration is not automatically preferred if it requires a large upfront CAPEX commitment or leaves few credible upgrade options. Conversely, a lower-CAPEX starting configuration can be attractive if it remains acceptable in mild scenarios and can be linked to later capability steps. The pathway analysis therefore makes the trade-off between under-specification, over-specification, and staged investment explicit.

The pathway maps were drawn using the Deltares Pathway Generator [142], but the scenario ordering, validity ranges, and transition links are defined by the model results and compatibility rules in this chapter. In the maps, horizontal bars indicate the evaluated scenario states for which a configuration remains above the selected performance threshold, while transition markers indicate allowed moves between configurations. The horizontal axis should be read as an ordered sequence of scenario states, not as calendar time or as a continuous performance scale. The stress-test results translate into three main adaptation needs: additional carousel capacity for longer and more distant projects, two-line capability for increasing HVDC share, and higher tension capacity for deeper water and floating projects. These links are summarised in Table 9.1.

Table 9.1: Translation of observed performance vulnerabilities into candidate adaptation actions.

Observed vulnerability	**Main scenario driver**	**Capability gap**	**Candidate adaptation action**
Loss of campaign-limited portfolio cable-km capture	Longer cables and larger distances	Insufficient carousel capacity	Add or enlarge carousel storage
Infeasibility for dual-cable projects	Higher HVDC share	Insufficient number of lay lines	Select or reserve two-line capability
Tension-related infeasibility	Greater depth and floating share	Insufficient line tension	Upgrade tensioner capacity
Low utilisation in mild scenarios	Overcapacity relative to demand	Excess installed capability	Delay high-capacity investment

The final row highlights that adaptation is not only about avoiding under-capacity, but also about avoiding premature over-specification. A very large, high-tension configuration may remain feasible across many futures, but it requires higher initial investment and may be underutilised in mild portfolios. Adaptive pathways therefore provide a staged alternative between a low-CAPEX but fragile starting design and a high-CAPEX design that is robust but potentially over-specified.

9.2. Selected Upgrade Options, Compatibility Rules, and Scorecard Logic

Although the design library contains many combinations of carousel layout and tensioner arrangement, only transitions that represent a logical capability development are treated as plausible pathway steps. The compatibility assessment is qualitative and simplified: it identifies conceptually suitable transitions, while detailed integration, retrofit planning, and cost assessment would be required in later design stages.

Since the reference platform is assumed to have sufficient overall deck area and carrying capacity, the pathway assessment does not evaluate detailed layout, foundation, routing, or power-integration constraints. It instead checks whether each transition represents a logical upgrade within the same equipment family; where later upgrades require reserved space or interfaces, this is treated qualitatively as a credibility condition.

Table 9.2 summarises the selected pathway families and the conditions under which their transitions are treated as clean pathway steps.

Table 9.2: Selected pathway families and their upgrade logic.

Pathway family	Upgrade logic	Clean-pathway condition
Above-deck storage	Increase carousel capacity within the above-deck storage family.	Retain the same above-deck storage concept and avoid reducing installed capacity.
Mixed AD/BD storage	Combine an initial BD1 choice with later above-deck capacity growth.	Treat BD1 as an initial layout choice, not as a later clean retrofit.
Tensioner replacement	Increase line capacity by replacing units while keeping the same line layout.	Reserve sufficient layout, foundation, power, routing, and control margins.
Series tensioner addition	Increase line capacity by adding units in series.	Retain existing units, but accept higher integration complexity.
High-capability direct step	Move directly to a high-capability end state.	Useful as a benchmark or shortcut, but less representative of staged adaptation.

The compatibility rules used in the pathway maps are intentionally simple. Storage transitions must maintain or increase installed carousel capacity; reducing storage or removing an installed carousel is not treated as an adaptive upgrade. Above-deck storage growth is considered plausible when it follows a recognisable storage family, for example by increasing carousel height at fixed outer diameter or by adding capacity in a reserved above-deck slot. BD1 is treated as an initial design choice rather than a later retrofit option, because changing below-deck storage is assumed to require a major design alteration.

For tensioners, replacement with a higher-capacity unit is treated as a logical upgrade when the same line layout is retained and sufficient integration margins are assumed. Series addition is also considered because it allows existing tensioner units to be retained while increasing total line capacity. The pathway analysis focuses on two-line configurations only because the Pareto results indicate stronger portfolio performance under increasing HVDC share for a limited added CAPEX burden. This preserves compatibility with dual-cable projects and provides a more suitable basis for later storage or tension-capacity upgrades.

The pathway maps show validity ranges and possible transitions, but not the relative attractiveness of each action. Therefore, each pathway section includes a qualitative scorecard using a 0–5 scale. Higher target-effect scores indicate stronger contribution to the intended capability, while higher cost-burden and side-effect scores indicate greater CAPEX, implementation effort, integration complexity, downtime risk, overcapacity risk, or reduced future compatibility. The scores are comparative judgement scores, not precise engineering or economic estimates.

The CAPEX values in the scorecards refer to the final mission-equipment configuration state, not to cumulative pathway cost. They exclude additional retrofit engineering, yard-time, and downtime costs. The scorecards should therefore be read as relative pathway-attractiveness indicators, not as lifecycle retrofit-cost calculations.

9.3. Adaptation Tipping Points and Signposts

In DAPP terminology, an adaptation tipping point occurs when an existing strategy no longer meets the required performance objective. In this thesis, the existing strategy is represented by a selected CLV mission-equipment configuration. A transition toward a higher-capability configuration represents a possible response once that configuration no longer meets the selected performance objective. The performance objective is to retain at least 60% feasible capture of total portfolio cable kilometres within at most three campaigns.

Because the scenarios are independently generated and not time-explicit, the adaptation tipping points identified here should be interpreted as indicative scenario-state thresholds. The pathway maps show where a configuration meets or fails the selected 60% performance criterion in the evaluated portfolios, but they do not define exact continuous boundaries between scenario states.

The concept of signposts is used to connect the scenario states to observable market developments. Signposts are indicators that can be monitored over time to assess whether reassessment or adaptation may be needed. In the CLV context, the most relevant signposts are directly related to the scenario variables and the modelled capability limits. Table 9.3 links each vulnerability type to its tipping-point interpretation and corresponding signposts.

Table 9.3: Scenario-based adaptation tipping points and signposts.

Vulnerability type	Tipping-point interpretation	Relevant signposts
Storage/campaign limitation	Configuration falls below the 60% portfolio cable-kilometre capture threshold because too many campaigns are required.	Cable length, distance from shore, expected campaign count.
HVDC line-layout limitation	Configuration loses portfolio coverage because one-line layouts cannot serve dual-cable projects.	HVDC share, dual-cable project pipeline, demand for simultaneous dual-lay.
Tension limitation	Configuration falls below the threshold because required line tension exceeds installed capability.	Water depth, floating share, required line tension.
Overcapacity risk	Configuration remains technically valid but provides more capability than required by mild portfolios.	Project mix, expected project scale, share of demanding HVDC or floating projects.

The signposts are conceptual in this thesis. No operational monitoring system is developed, and no fixed trigger values are assigned beyond the scenario-based performance threshold. This corresponds to the monitoring logic in DAPP: signposts indicate when reassessment may be needed, but do not by themselves define detailed operational triggers. In practice, a company like Boskalis could periodically update the project portfolio and re-run the evaluation as new market information becomes available, turning the pathway maps into a living decision-support tool.

9.4. Length, Distance, and HVDC Pathway

The length, distance, and HVDC pathway addresses the vulnerability observed in Chapter 8: as cable routes become longer, projects move further from shore, and HVDC share increases, low-storage configurations lose portfolio cable-kilometre capture. The selected pathway options therefore focus on increasing carousel capacity while retaining two lay lines for HVDC compatibility.

All configurations shown in this pathway have two lay lines with one 15 t tensioner unit per line. This followed from the earlier scenario results, where two-line configurations provided stronger portfolio performance under increasing HVDC share for a limited added CAPEX burden. The pathway therefore starts from HVDC-compatible line layouts and isolates the effect of additional carousel capacity as the length–distance/HVDC family moves from base-like to severe.

Table 9.4 summarises the storage layout, total storage volume, and mission-equipment CAPEX of the configurations selected for the pathway map. The configurations are grouped into three storage families: an above-deck-only route, a mixed AD/BD route with a 30×8 BD1 carousel, and a limited mixed-storage branch with a 30×6 BD1 carousel.

Table 9.4: Storage particulars and CAPEX of configurations used in the length–distance/HVDC pathway map. Carousel cells report volume in m^3 with OD×H in metres in parentheses; all configurations use the `2L-1S-15T` tensioner setup.

Config.	Family	AD1 (m^3)	AD2 (m^3)	BD1 (m^3)	Total (m^3)	CAPEX
2284	AD-only	4,913 (40×4)	4,913 (40×4)	–	9,827	[redacted]
3328	AD-only	7,370 (40×6)	7,370 (40×6)	–	14,740	[redacted]
3508	AD-only	9,827 (40×8)	9,827 (40×8)	–	19,654	[redacted]
2536	AD/BD	4,913 (40×4)	–	5,429 (30×8)	10,342	[redacted]
3400	AD/BD side	9,827 (40×8)	–	5,429 (30×8)	15,256	[redacted]
9016	AD/BD	7,370 (40×6)	3,104 (32×4)	5,429 (30×8)	15,903	[redacted]
10312	AD/BD	9,827 (40×8)	3,104 (32×4)	5,429 (30×8)	18,359	[redacted]
10744	AD/BD	9,827 (40×8)	4,656 (32×6)	5,429 (30×8)	19,911	[redacted]
2068	BD1 30×6	4,913 (40×4)	–	4,072 (30×6)	8,985	[redacted]
7972	BD1 30×6	7,370 (40×6)	3,104 (32×4)	4,072 (30×6)	14,546	[redacted]

The clean-transition logic follows directly from the storage families in Table 9.4. The AD-only route 2284 → 3328 → 3508 keeps the same two above-deck carousel slots and increases capacity by raising carousel height at fixed 40 m outer diameter. The mixed AD/BD route treats BD1 as an initial layout choice; later growth is therefore limited to above-deck capacity. Configurations with a 30×6 BD1 carousel, such as 2068 and 7972, form a separate lean branch and are not treated as clean predecessors of the 30×8 BD1 family. The arrows represent logical capability steps, not costed retrofit actions; if severe length–distance/HVDC demand is already expected, a direct move to a final high-capacity state may be preferable to repeated carousel modifications.

Table 9.5 combines each pathway configuration with its total storage volume and scenario validity range. The table reports the feasible share of portfolio cable kilometres completed within at most three campaigns. Values at or above the selected 60% threshold indicate that the configuration remains valid for the corresponding scenario state.

Table 9.5: Feasible share of portfolio cable kilometres completed within at most three campaigns for configurations used in the length–distance/HVDC pathway map. All configurations have two lay lines with a capacity of 15 t per line.

Config. ID	Total V [m^3]	Base-like	Mild	Moderate	Strong	Severe
2284	9,827	67%	45%	25%	10%	6%
3328	14,740	81%	69%	69%	42%	20%
3508	19,654	87%	78%	89%	71%	61%
2536	10,342	69%	47%	25%	10%	6%
3400	15,256	76%	60%	34%	16%	8%
9016	15,903	81%	70%	69%	44%	20%
10744	19,911	87%	78%	89%	71%	61%
2068	8,985	62%	31%	18%	9%	6%
7972	14,546	81%	69%	68%	37%	18%
10312	18,359	85%	76%	78%	63%	46%

The performance values show a clear storage-driven validity pattern. Low-storage starting configurations such as 2284 and 2536 are valid only in the base-like state, while intermediate configurations such as 3328, 9016, and 7972 remain valid through the moderate state. Configuration 10312 extends the mixed AD/BD route through the strong state, but falls below the threshold in the severe state. Only the highest-storage end states, 3508 and 10744, remain valid across the full length–distance/HVDC family.

Combining the configuration characteristics in Table 9.4 with the validity ranges in Table 9.5 gives the pathway map shown in Figure 9.1. The map visualises the clean AD-only route, the mixed AD/BD route, and the limited 30×6 BD1 branch across the evaluated scenario states.

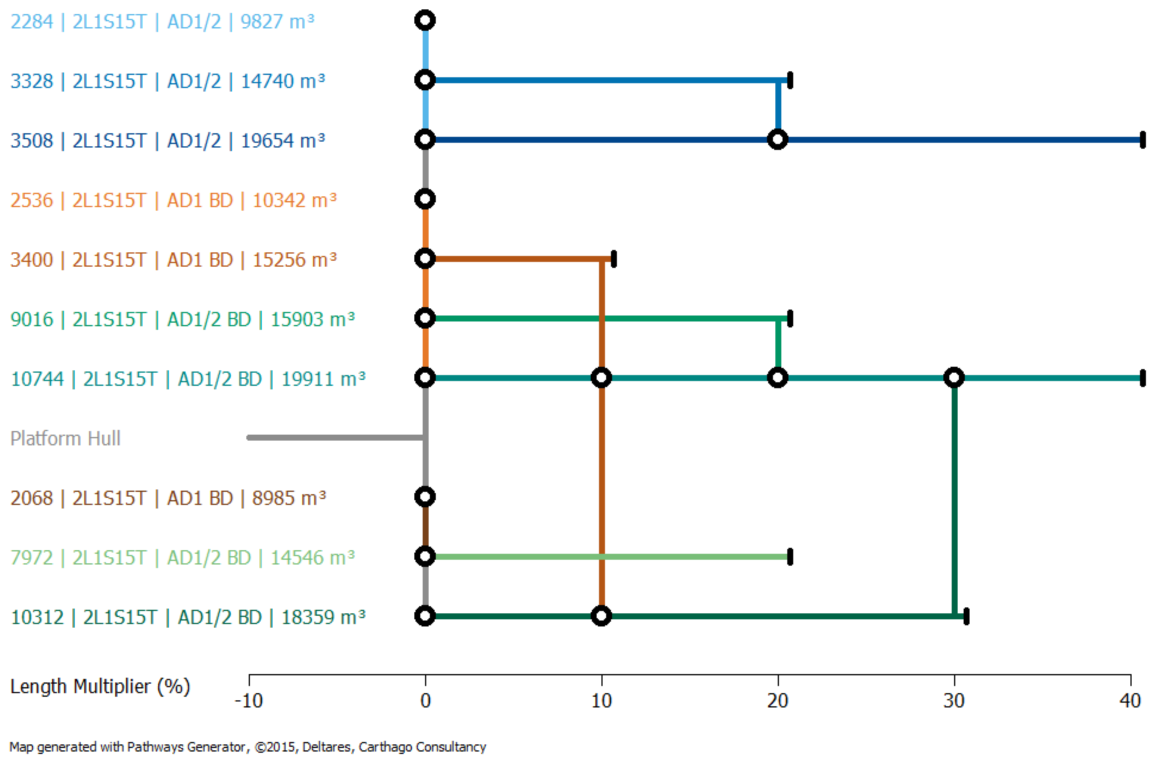


Figure 9.1: Adaptive pathway map for the combined cable-length, distance-from-shore, and HVDC-share scenario family. The horizontal axis orders the independently generated scenario states from base-like to severe; model codes are retained in the supporting tables for traceability. The visual map was generated using the Deltares Pathway Generator [142].

The pathway map should be read together with the clean-transition logic above. The AD-only route 2284 → 3328 → 3508 is the clearest staged storage-growth sequence because it retains the same two above-deck carousel slots. The mixed AD/BD family provides two related routes from 2536: one through 9016 toward 10744, and one through 3400 and 10312 toward 10744. The first adds AD2 capacity earlier, while the second first increases AD1 capacity and then adds AD2 capacity. The 30×6 BD1 branch, 2068 → 7972, is retained as a leaner alternative, but it remains separate from the 30×8 BD1 family.

The resulting length-pathway scorecard is shown in Table 9.6. The scorecard compares the main pathway actions in terms of target effect, cost burden, and side effects. It is not a retrofit-cost estimate; CAPEX values refer to the final mission-equipment configuration state.

Table 9.6: Scorecard comparison of length–distance/HVDC pathway options. Higher target-effect scores are favourable; higher cost-burden and side-effect scores indicate greater burden or complexity.

Pathway/action	Effect	Cost	Side	Interpretation
2284 → 3328 → 3508	5	4	3	Cleanest AD-only staged storage route; final-state CAPEX 36.7m.
2284 → 3508	5	5	4	Direct high-capacity step; strong effect, but higher upfront commitment and less staged decision flexibility.
2536 → 9016 → 10744	5	4	4	Strong mixed-storage route if BD1 is included initially; final-state CAPEX 39.6m.
2536 → 3400 → 10312 → 10744	5	4	3	Logical mixed-storage side route; first increases AD1 capacity before adding AD2 capacity.
2068 → 7972	3	4	4	Limited BD1 30×6 branch; useful as a leaner alternative but not a route to the 30×8 BD1 family.
10312 → 10744	4	2	2	Incremental final step within the BD1 30×8 family; increases AD2 capacity within the same storage architecture.

The scorecard confirms the main pathway trade-off. The AD-only route has the clearest upgrade logic because it increases above-deck carousel capacity within one storage family. Mixed AD/BD routes can achieve similar severe-state performance, but depend on selecting BD1 as part of the initial layout. The direct high-capacity step has a strong target effect, but represents a larger upfront commitment rather than staged adaptation.

9.5. Depth and Floating Pathway

The depth and floating pathway addresses the second main vulnerability observed in Chapter 8: as water depth and floating-project share increase, configurations with limited line tension lose feasible portfolio cable-kilometre capture. The selected pathway options therefore focus on increasing tension capacity while keeping storage layout constant where possible.

Unlike the length–distance/HVDC pathway, this pathway mainly varies the tensioner arrangement rather than carousel capacity. The main pathway family keeps the same AD1/BD1 storage layout and total storage volume, so the effect of increasing line tension can be isolated. Two additional branches are included to show that the same tension-upgrade logic can also be applied from other carousel-layout starting points.

Table 9.7 summarises the storage layout, tensioner setup, line capacity, and mission-equipment CAPEX of the configurations selected for the depth/floating pathway map.

Table 9.7: Configuration particulars of designs used in the depth/floating pathway map. Carousel cells show storage volume in m^3, with OD×H in metres shown in parentheses. Tensioner setup labels omit the TEN_ prefix. CAPEX is rounded to one decimal million euros.

Config.	Family	AD1 (m^3)	AD2 (m^3)	BD1 (m^3)	Total (m^3)	Tensioners	Line cap.	CAPEX
2536	Replace	4,913 (40×4)	–	5,429 (30×8)	10,342	2L-1S-15T	15 t	[redacted]
2542	Replace	4,913 (40×4)	–	5,429 (30×8)	10,342	2L-1S-20T	20 t	[redacted]
2548	Replace	4,913 (40×4)	–	5,429 (30×8)	10,342	2L-1S-25T	25 t	[redacted]
2554	Replace	4,913 (40×4)	–	5,429 (30×8)	10,342	2L-1S-50T	50 t	[redacted]
2537	Series add.	4,913 (40×4)	–	5,429 (30×8)	10,342	2L-2S-15T	30 t	[redacted]
2538	Series add.	4,913 (40×4)	–	5,429 (30×8)	10,342	2L-3S-15T	45 t	[redacted]
2284	AD-only alt.	4,913 (40×4)	4,913 (40×4)	–	9,827	2L-1S-15T	15 t	[redacted]
2302	AD-only alt.	4,913 (40×4)	4,913 (40×4)	–	9,827	2L-1S-50T	50 t	[redacted]
2392	AD1/BD1 alt.	4,656 (32×6)	–	5,429 (30×8)	10,085	2L-1S-15T	15 t	[redacted]
2410	AD1/BD1 alt.	4,656 (32×6)	–	5,429 (30×8)	10,085	2L-1S-50T	50 t	[redacted]

The clean-transition logic follows directly from the families in Table 9.7. The main replacement route 2536 → 2542 → 2548 → 2554 keeps the same AD1/BD1 storage layout and increases unit tension capacity from 15 t to 20 t, 25 t, and 50 t per line. The series-addition route 2536 → 2537 → 2538 keeps the same storage layout and retains the 15 t unit type, but adds identical units in series to increase line capacity. The AD-only pair 2284 → 2302 and the alternative AD1/BD1 pair 2392 → 2410 are included as additional starting-layout examples. They show that high-tension capability can also be reached from different carousel arrangements, rather than only from the main 2536–2554 storage family.

Table 9.8 combines each pathway configuration with its total storage volume, line capacity, and scenario validity range. The table reports the feasible share of portfolio cable kilometres completed within at most three campaigns. Values at or above the selected 60% threshold indicate that the configuration remains valid for the corresponding scenario state.

Table 9.8: Feasible share of portfolio cable kilometres completed within at most three campaigns for configurations used in the depth/floating pathway map.

Config. ID	Total V [m^3]	Line cap.	Base-like	Mild	Moderate	Strong	Severe
2536	10,342	15 t	69%	57%	56%	52%	33%
2542	10,342	20 t	70%	65%	58%	52%	36%
2548	10,342	25 t	70%	67%	67%	55%	38%
2554	10,342	50 t	71%	70%	70%	73%	73%
2537	10,342	30 t	70%	68%	67%	60%	40%
2538	10,342	45 t	71%	70%	70%	72%	72%
2284	9,827	15 t	67%	57%	56%	52%	33%
2302	9,827	50 t	70%	70%	70%	73%	73%
2392	10,085	15 t	69%	55%	56%	52%	33%
2410	10,085	50 t	71%	69%	70%	73%	73%

The performance values show a clear tension-driven validity pattern. The 15 t starting configurations remain acceptable in the base-like state but fall below the threshold as depth/floating stress increases. Intermediate line capacities improve the validity range: 2548 remains valid through the moderate state, while the series-addition configuration 2537 reaches the threshold in the strong state but fails in the severe state. The high-tension end states 2554, 2538, 2302, and 2410 remain valid across the full depth/floating family. Because these configurations use different storage layouts but similar high line capacity, the result supports the interpretation that line tension is the dominant adaptation lever in this pathway.

Combining the configuration characteristics in Table 9.7 with the validity ranges in Table 9.8 gives the pathway map shown in Figure 9.2. The map visualises the replacement route, the series-addition route, and the alternative starting-layout examples across the evaluated scenario states.

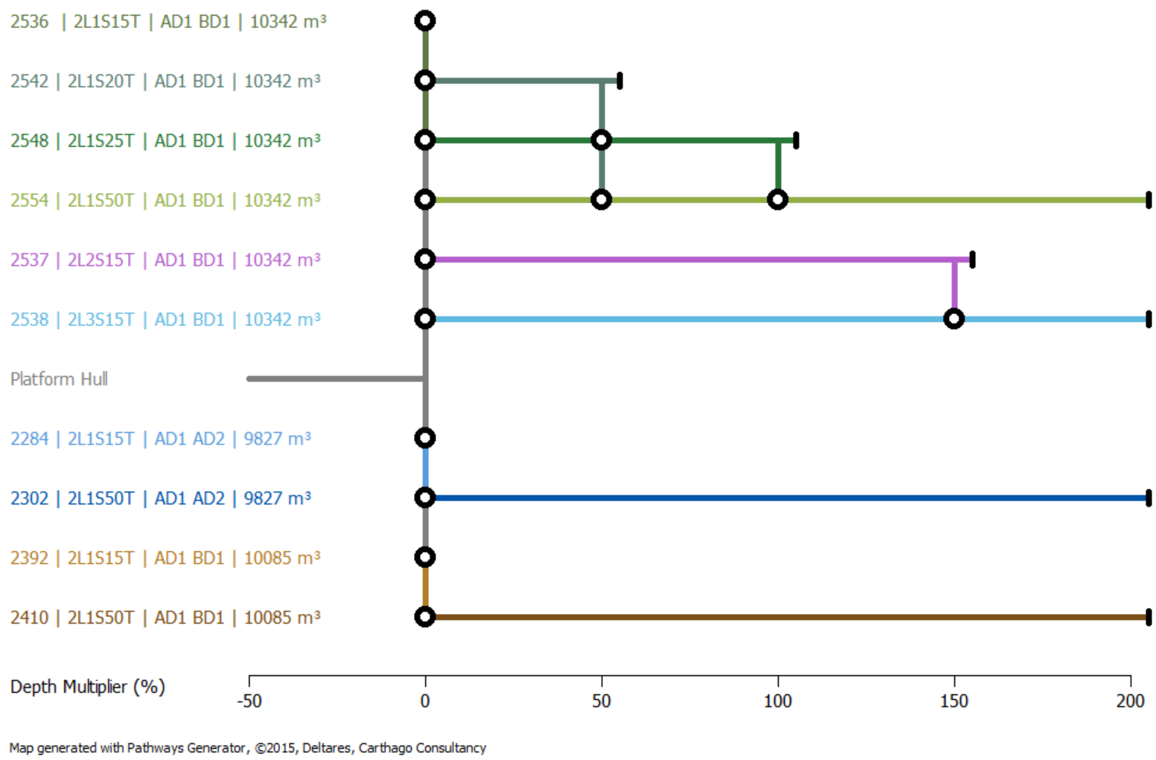


Figure 9.2: Adaptive pathway map for the combined water-depth and floating-project-share scenario family. The horizontal axis orders the independently generated scenario states from base-like to severe; model codes are retained in the supporting tables for traceability. The visual map was generated using the Deltares Pathway Generator [142].

The pathway map should be read together with the clean-transition logic above. The main replacement route provides a staged path from a 15 t starting point to a 50 t line-capacity end state while retaining the same storage layout and line arrangement. The series-addition route reaches a comparable severe-state validity range, but through a different equipment philosophy: it retains the 15 t unit type and adds units in series. The alternative 2284 → 2302 and 2392 → 2410 branches demonstrate that the same high-tension end-state logic can also be applied from different carousel layouts.

The resulting depth-pathway scorecard is shown in Table 9.9. The scorecard compares the main pathway actions in terms of target effect, cost burden, and side effects. It is not a retrofit-cost estimate; CAPEX values refer to the final mission-equipment configuration state.

Table 9.9: Scorecard comparison of depth/floating pathway options. Higher target-effect scores are favourable; higher cost-burden and side-effect scores indicate greater burden or complexity.

Pathway/action	Effect	Cost	Side	Interpretation
2536 → 2542 → 2548 → 2554	5	3	2	Clearest tensioner-replacement route; same storage and line layout, final-state CAPEX 26.5m.
2536 → 2537 → 2538	5	5	4	Strong severe-state validity and unit retention, but higher final-state CAPEX (31.2m) and greater layout burden.
2542 → 2554	5	3	3	Direct high-tension step; skips the intermediate 25 t state when stronger depth/floating demand is already expected.
2284 → 2302	5	3	3	AD-only starting layout demonstrating the same 15 t-to-50 t tension-upgrade logic.
2392 → 2410	5	3	2	Alternative AD1/BD1 starting layout demonstrating the same high-tension end-state logic.

The scorecard confirms the main pathway trade-off. The replacement route provides the cleanest route to higher depth/floating capability because it keeps storage and line layout constant while increasing unit tension capacity. The series-addition route reaches a comparable severe-state validity range and retains existing units, but has a higher final-state CAPEX and integration burden. The alternative storage-layout branches show that high-tension capability can be combined with different carousel arrangements, but they are included as examples rather than as preferred main pathways.

9.6. Discussion of Main Design Insights

The pathway analysis provides four main design insights. First, within the defined mission-equipment model, the two scenario families expose different capability bottlenecks. The length–distance/HVDC pathway mainly points toward carousel storage and campaign limitation, because longer cable routes and greater distance from shore increase the need for storage capacity to maintain portfolio capture within a limited number of campaigns. The depth/floating pathway mainly points toward line-tension capacity, because deeper-water and floating-oriented portfolios increase cable-handling demand. This distinction is useful for interpreting the pathway results, but should be read within the model scope: the analysis varies carousel and tensioner arrangements on a fixed reference platform, rather than jointly optimising vessel dimensions, deck layout, power capacity, and equipment integration.

Second, two-line capability is selected not only because it avoids HVDC incompatibility, but because the Pareto results indicated a favourable cost–performance relationship. Under increasing HVDC share, two-line configurations improve portfolio cable-kilometre capture for a relatively limited added CAPEX burden compared with one-line alternatives. Line layout is therefore treated as an early design choice rather than as a later pathway variable. This conclusion is linked to the selected portfolio-capture KPI and threshold; a different threshold or performance objective could shift the balance between one-line and two-line configurations.

Third, adaptive pathways make the trade-off between under-specification and over-specification explicit. A low-CAPEX starting configuration may perform well in the base case but reach an adaptation tipping point quickly. A high-capacity configuration can avoid early tipping points, but may carry unnecessary CAPEX and limited equipment utilisation if demanding futures do not materialise. The pathway perspective therefore highlights a staged design logic: an initial configuration can be selected for acceptable near-term performance while preserving credible upgrade options if future project conditions become more demanding.

Fourth, retrofit compatibility affects the cost and feasibility of later adaptation. Adding carousel capacity, preserving two-line capability, or upgrading tensioners can in principle be addressed after delivery, but the required engineering effort, downtime, and cost increase when layout space, structural support, and power/control integration have not been considered in early design. Adaptability is therefore not binary: early provisions make later upgrades cleaner and less disruptive, while unplanned retrofits remain possible but less attractive.

The value of the analysis is not that it identifies one universally optimal configuration, but that it clarifies which capability margins matter under which future conditions and how early design decisions can preserve or limit future adaptation options.

9.7. Reflection on DAPP for Early-Stage CLV Design

The application of DAPP to CLV mission-equipment design provides interesting insights because it shifts the analysis from static optimisation to adaptive decision-making. Instead of asking which configuration performs best in one scenario, the method asks over which scenario range a configuration remains acceptable, when it becomes vulnerable, and which actions could restore performance. This fits the CLV investment problem, where the vessel is a long-lived asset exposed to uncertain future project requirements.

This application also confirms the broader conclusion of Zwaginga and Pruyn [147]: DAPP is valuable for creating a clear strategic overview of possible adaptive pathways, but it does not by itself provide detailed vulnerability analysis, parameter sensitivity, or engineering feasibility assessment. Its usefulness in ship design depends strongly on the quality of the input provided to the pathway step. In this thesis, that input is supplied by the parametric CLV design library and scenario-evaluation model. The model translates uncertain project-portfolio conditions into storage, campaign, lay-line, tension, fuel, and CAPEX performance before the DAPP pathway logic is applied.

The level of uncertainty addressed by this implementation should therefore be interpreted carefully. In principle, DAPP is suited to deep uncertainty because it does not require probabilities for future states and because it allows strategies to be revised when new information becomes available [88]. As a method, it can support Level 4a uncertainty when many plausible futures are explored, and it can do so by continuous monitoring and reiteration of design options, scenarios and performance indicators through the asset lifetime. The implementation in this thesis is more limited. The scenario set consists of a bounded number of independently generated stress-test states, grouped into two scenario families. The model therefore does not explore an open-ended future space, nor does it generate many combinations of uncertain external drivers. The computational evaluation is best interpreted as a structured Level 3 application: it compares design performance across a limited set of plausible future conditions.

At the same time, the thesis goes beyond a simple Level 3 comparison of a few manually defined scenarios. First, it evaluates a large mission-equipment design library rather than a small number of predefined alternatives. Second, it uses performance loss across the scenario states to identify adaptation tipping points. Third, it translates these tipping points into capability pathways, signposts, and qualitative scorecards. The contribution is therefore not that the thesis fully implements a Level 4a exploratory uncertainty analysis, but that it shows how a Level 3 scenario-stress-test evaluation can be embedded in a DAPP structure to support adaptive design reasoning. This creates a bridge between scenario-based design comparison and a more mature adaptive planning approach.

The pathway maps provide an intuitive way to communicate this logic. They show that different initial choices imply different future options. A low-CAPEX starting design can be attractive if compatible upgrades are available, but risky if it reaches an early tipping point without a clean transition path. A high-capability starting design can be robust, but may commit capital before the future market direction is clear. The pathway representation therefore supports strategic discussion between technical, operational, and investment stakeholders.

The CLV case also adds a ship-design-specific insight to the DAPP discussion. In many DAPP applications, actions can be represented as relatively separable policy measures. In this thesis, each action is a complete mission-equipment configuration. Carousel storage, lay-line arrangement, tension capacity, weight, stability, CAPEX, fuel use, and future compatibility are coupled. A pathway step is therefore not simply an abstract decision to add capability, but a physical transition that may require layout space, structural and power integration, and yard-time planning. This makes the definition of clean transitions more restrictive than in applications where pathway actions can be treated as more separable policy measures.

A further insight is that adaptability is not binary. The pathway maps distinguish between configurations that remain technically valid, configurations that fail the selected performance threshold, and configurations that preserve credible next steps. In a practical vessel-design setting, this means that the value of an initial configuration is not only determined by its immediate scenario performance. It also depends on whether it leaves sufficient margins and interfaces for later adaptation. Early provisions for deck space, carousel foundations, lay-line routing, power supply, control interfaces, and access can make future upgrades cleaner and less disruptive. Without such provisions, later adaptation may remain technically possible, but become more costly, disruptive, or commercially unattractive.

The implementation remains simplified. The scenario states are not linked to specific years, transition costs and retrofit downtime are not quantified, and the compatibility rules are based on logical engineering interpretation rather than detailed general arrangement or structural assessment. The model also focuses on carousel and tensioner systems, while other vessel systems such as DP capability, power generation, emissions performance, ROV systems, cable chutes, and deck logistics are not varied.

The application also shows that DAPP does not remove judgement from the design process. The resulting pathways depend on the selected performance threshold, the scenario families considered, the configurations carried forward from the design library, and the qualitative compatibility rules used to define plausible transitions. A different threshold, a different metric to define success, alternative hull dimensions, or a broader set of mission systems could change the resulting pathway map. The method is therefore most useful as a transparent structuring tool for discussing adaptive design choices, rather than as an automatic procedure for identifying an optimal vessel concept.

The comparison with the broader uncertainty-methods literature also indicates how this work could be extended. Robust Decision Making or Decision Scaling could be used before the pathway step to explore a wider uncertainty space and identify vulnerability thresholds more systematically. Epoch–Era Analysis could be used to convert independent scenario states into time-explicit sequences of market development. Engineering Options Analysis could be used after the pathway step to value which design provisions are most effective in opening, preserving, or closing future pathways. In such an extended framework, the DAPP map would become the strategic organising layer, while other methods would provide deeper evidence on vulnerability, sequence, and option value.

The pathways should therefore be interpreted as early-stage decision-support outputs, not as directly executable retrofit plans. A practical implementation would require detailed layout and integration studies, retrofit cost and downtime estimation, and commercial evaluation of the expected project pipeline. Nevertheless, the DAPP structure is useful because it links performance thresholds, scenario-based vulnerabilities, signposts, and possible adaptation actions without requiring probabilistic forecasts. For this thesis, the main methodological insight is that DAPP can be meaningfully adapted to CLV mission-equipment design, provided that its uncertainty level, input dependence, and physical retrofit limitations are made explicit.

9.8. Conclusion

This chapter translated the scenario-performance results from Chapter 8 into adaptive pathway logic. The analysis showed that the main adaptation actions for CLV mission-equipment design are increasing carousel capacity, preserving two-line capability, and increasing tension capacity per line.

The length–distance/HVDC pathway showed that storage capacity becomes the dominant adaptation lever when cable routes become longer, projects move further from shore, and HVDC share increases. Low-storage configurations can perform acceptably in the base-like portfolio, but lose performance quickly as scenario stress increases. Higher-storage configurations such as 3508 and 10744 remain valid under the severe length–distance/HVDC state, but require higher investment and stronger integration assumptions.

The depth/floating pathway showed that tension capacity becomes the dominant adaptation lever when project portfolios move into deeper water and include a higher floating-project share. Constant-storage tension-upgrade sequences demonstrated that increasing line capacity from 15 t to 50 t can restore performance under severe depth/floating stress. The comparison between replacement and series-addition pathways also showed that similar capability gains can involve different CAPEX and integration implications.

Methodologically, the chapter showed that DAPP can be adapted to CLV mission-equipment design as a strategic structuring framework. In this thesis, the pathway maps should be interpreted as capability maps based on a structured Level 3 scenario-stress-test application, not as full Level 4a exploratory uncertainty analysis or executable retrofit plans. Their value lies in linking scenario-based vulnerabilities, adaptation tipping points, signposts, and possible capability steps without requiring probabilistic forecasts.

Overall, the pathway analysis confirms that adaptive CLV design should not focus only on selecting the largest initial configuration. It should consider which starting configurations provide acceptable current performance, which future stressors may create adaptation tipping points, and which upgrade options should be preserved through early design provisions. The resulting pathways provide a structured basis for discussing future-resilient CLV mission-equipment decisions, while making clear that practical implementation would require design-specific retrofit assessment, transfer-cost modelling, and commercial evaluation.

10 Conclusions and Recommendations

This chapter concludes the thesis by answering the research questions, summarising the main contributions, and translating the findings into practical and methodological recommendations. It does not introduce new results, but synthesises the findings from the method selection, parametric vessel model, scenario evaluation, and adaptive pathway analysis. It also clarifies how the proposed framework can support practical ship-design decision-making and where further development is needed.

10.1. Answers to the Research Questions

SQ1: What are the distinctive characteristics and key design drivers of cable-laying vessels, and why is uncertainty particularly challenging for their early-stage design?

Cable-laying vessels are specialised offshore work vessels whose performance is strongly determined by mission-equipment integration. For export-cable installation, the key design drivers are cable storage capacity, carousel arrangement, number of lay lines, tensioner capacity, stability, station-keeping capability, and transit performance. Uncertainty is challenging because CLVs are capital-intensive, long-lived assets, while future offshore wind projects may become longer, further from shore, deeper, more HVDC-oriented, or more floating-oriented. A vessel designed only for current project conditions may become under-specified, while an overly capable vessel may carry unnecessary investment cost if demanding futures do not materialise.

SQ2: Which uncertainty-handling and decision-making method is most suitable for early-stage cable-laying vessel design under deep uncertainty?

Dynamic Adaptive Policy Pathways (DAPP) was selected as the most suitable framework among the methods reviewed in this thesis. It is appropriate because it does not require one forecast or probability distribution for uncertain future conditions. Instead, it compares actions across plausible futures, identifies when an action no longer meets the required performance level, and links present decisions to possible future adaptations. Robustness and many-objective methods remain useful for wider stress-testing, but DAPP adds a clear structure for staged decision-making and pathway construction.

SQ3: How can the selected method be adapted to evaluate CLV mission-equipment decisions under uncertain future project conditions?

DAPP was adapted by translating its planning concepts into CLV mission-equipment design concepts. Actions were interpreted as mission-equipment configurations or upgrade options, external conditions as synthetic project portfolios, and adaptation tipping points as scenario states where a configuration no longer meets the selected performance reference. Because the CLV case involves multiple possible starting configurations, pathway states were treated as complete mission-equipment configurations rather than isolated component changes. This makes the method suitable for strategic design support, while detailed retrofit engineering and transfer-cost estimation remain outside the quantitative scope.

SQ4: Which vessel-configuration characteristics and project variables determine whether a CLV mission-

equipment configuration is technically and operationally suitable for a project portfolio?

Suitability is determined by the interaction between vessel capability and project demand. On the vessel side, the most important characteristics are total carousel volume, carousel layout, number of lay lines, tension capacity per line, mission-equipment weight, draft, and simplified stability margin. On the project side, the most relevant variables are cable length, distance from shore, water depth, voltage type, number of physical cables, and estimated cable diameter and weight. Cable length mainly drives storage and campaign requirements, water depth drives required tension, and HVDC projects make two-line capability important.

SQ5: How can uncertain future offshore wind project portfolios be represented, and which performance measures are needed to compare CLV configurations across them?

Uncertain project portfolios were represented through donor-based synthetic scenarios generated from an industry-relevant base dataset. The scenario framework included a base-like portfolio and two stress-test families: the length–distance/HVDC family and the depth/floating family. These scenarios are not forecasts, but controlled what-if cases used to reveal design vulnerabilities. The main performance measures are project feasibility rate, feasible share of portfolio cable kilometres, campaign-limited feasible cable-kilometre share, mission-equipment CAPEX, fuel consumption per installed kilometre, duration per installed kilometre, utilisation, and campaign count.

SQ6: How can the computational model be verified and validated before it is used for scenario evaluation?

The model was verified through implementation checks, design-library consistency checks, project-evaluation behaviour checks, scenario-input checks, engineering face-validity assessment, and comparison with selected reference CLVs. These checks confirmed that the model behaves in the expected direction: larger carousel volume improves storage-limited performance, higher tension capacity reduces tension-related infeasibility, and one-line configurations are vulnerable to dual-cable HVDC projects. The model is therefore suitable for comparative early-stage evaluation, but not as a detailed engineering, cost-estimation, or installation-planning tool.

SQ7: How do different CLV mission-equipment configurations perform under changing project length, distance from shore, water-depth, floating-share, and cable-system conditions?

The scenario evaluation showed that different future developments create different capability bottlenecks within the fixed-platform mission-equipment design space. In the length–distance/HVDC scenario family, the dominant vulnerabilities are storage capacity, campaign count, and two-line capability. In the depth/floating scenario family, the dominant vulnerability shifts toward tension capacity. Future-resilient CLV mission-equipment design therefore requires a balanced view of storage, line layout, and tension capacity, while recognising that different KPI thresholds or vessel-platform assumptions could change the preferred balance.

SQ8: How can the identified design trade-offs and vulnerabilities be translated into adaptive design pathways for early-stage CLV decision-making?

The identified vulnerabilities were translated into adaptive pathways by linking configurations that represent logical capability increases. The main adaptation actions are increasing carousel capacity, preserving two-line capability, and increasing tension capacity per line. The resulting pathways should be interpreted as strategic capability pathways, not as validated retrofit plans. The implementation is best understood as a structured Level 3 scenario-stress-test application embedded in DAPP; moving further toward Level 4a would require a wider exploratory uncertainty space, additional scenario combinations, and potentially multiple system or hull representations.

10.2. Answer to the Main Research Question

The main research question of this thesis is:

How can deep uncertainty be addressed in the early-stage design of a cable laying vessel to support future-resilient design decision making?

Deep uncertainty in early-stage CLV design can be addressed by combining adaptive decision-making logic with a transparent parametric evaluation framework. In this thesis, DAPP was adapted to the CLV mission-equipment problem by generating a design library of carousel and tensioner configurations on a fixed reference platform hull, evaluating these configurations against synthetic project portfolios, aggregating performance into portfolio-level KPIs, identifying scenario-based vulnerabilities, and translating these vulnerabilities into adaptive pathway options. The resulting approach does not aim to select one optimal vessel configuration for one expected future, but to assess under which uncertain future project conditions a configuration remains suitable, when it becomes vulnerable, and which upgrade options it preserves. Within the scope of this thesis, the implementation is best interpreted as a structured Level 3 scenario-stress-test application embedded in DAPP: the scenarios are controlled stress tests rather than forecasts, and the pathway maps are strategic capability maps rather than validated retrofit plans. At the same time, the framework provides a basis for moving toward a Level 4a exploratory uncertainty application, provided that the scenario space is expanded to include a wider range of uncertainty drivers and scenario combinations. The framework therefore supports future-resilient design decision-making by making under-specification, over-specification, and adaptability trade-offs explicit for early-stage CLV mission-equipment design.

10.3. Main Contributions

The contributions of this thesis are both methodological and practical. Scientifically, the thesis contributes to the application of adaptive decision-making methods in early-stage ship design under deep uncertainty. Practically, it provides a structured way to compare CLV mission-equipment configurations and discuss future adaptability in fleet-planning decisions.

10.3.1. Scientific Contribution

The scientific contribution consists of three elements. First, the thesis addresses the research gap between deep-uncertainty decision-making methods and practical offshore vessel design by adapting DAPP to an early-stage CLV mission-equipment problem. DAPP concepts are translated to the ship-design context by treating configurations as actions, scenario portfolios as external conditions, and performance losses as adaptation tipping points.

Second, the thesis contributes methodologically by integrating adaptive pathway logic with a parametric design and evaluation model. The workflow combines design-space generation, synthetic scenario construction, project-level feasibility simulation, KPI aggregation, Pareto analysis, and pathway construction. This provides a structured way to move from scenario stress-testing to adaptive design reasoning.

Third, the thesis provides CLV-specific design insight by showing that different uncertainty families activate different mission-equipment bottlenecks. Within the fixed-platform model, length–distance/HVDC uncertainty primarily exposes storage, campaign, and line-layout vulnerabilities, while depth/floating uncertainty primarily exposes tension-capacity vulnerability. This shows that future-resilient CLV mission-equipment design cannot be assessed through a single aggregate capability measure.

The thesis also identifies methodological challenges in applying DAPP to a coupled physical vessel system. A CLV configuration is not a separable policy measure, but an integrated equipment state involving layout, weight, stability, power, cable routing, CAPEX, and operational feasibility. This does not remove the usefulness of DAPP, but it shows that ship-design applications require explicit attention to model input quality, physical compatibility, and retrofit feasibility.

10.3.2. Practical Contribution

The practical contribution is a repeatable decision-support process for early-stage CLV fleet planning and concept development. For Boskalis, and for CLV design practice more broadly, the method helps compare mission-equipment configurations across uncertain project portfolios, identify capability bottlenecks, and link design choices to project executability, campaign count, portfolio cable-kilometre capture, utilisation, fuel-related performance, and mission-equipment CAPEX. Its main contribution is therefore not the set of configurations analysed, but the structured and repeatable process through which such configurations can be evaluated.

10.4. Synthesis for the Practical Ship Designer

For a practical ship designer or design manager, the main value of the framework is that it turns an uncertain market question into a structured design discussion. The method should not be used to select a final vessel concept automatically. Instead, it should be used to compare how different mission-equipment choices perform, where they become vulnerable, and which future options they preserve.

In practical use, the designer should first define the asset boundary: new-build, conversion, or upgrade of an existing fleet asset. This determines whether the design space should include only mission-equipment choices, or also hull size, deck layout, propulsion system, DP system, and other vessel-level variables. The designer should then define the relevant mission-equipment options and stress-test them against project portfolios that represent the intended market exposure.

The outcome should be interpreted as a design-management tool rather than a final design answer. It helps identify, for example, whether a concept is storage-limited, tension-limited, line-layout-limited, or over-specified. It also helps determine which provisions should be preserved, such as layout space, structural support, and power/control integration. This shifts the design discussion from identifying the best configuration to assessing which configuration is acceptable now, where it might fail, and what should be preserved to keep future choices open.

10.5. Recommendations

This section translates the thesis findings into recommendations for practical CLV design decision-making and for future applications of the proposed framework.

10.5.1. Practical Recommendations

The first practical recommendation is to use the proposed framework as a recurring early-stage fleet-planning tool. Its value increases when it is applied repeatedly with updated project data, alternative scenario assumptions, and different strategic priorities. Boskalis could build an internal library of scenario-performance results for regional portfolios, client-specific project sets, HVDC-heavy portfolios, floating-wind portfolios, shallow-water portfolios, or other strategically relevant input markets.

The second recommendation is to treat adaptability as a design requirement from the start. If future carousel expansion, two-line capability, or tensioner upgrading may become relevant, then layout space, structural support, and power and control integration should be considered during concept development. This does not mean that the largest equipment must be installed immediately; rather, the design should preserve credible options without unnecessarily increasing cost, weight, integration burden, or underutilisation risk.

The third recommendation is to use the pathway logic as a risk-based decision aid. Storage-oriented pathways are most relevant if future export projects become longer, more remote, and more HVDC-oriented, while tension-oriented pathways are most relevant if exposure to deeper-water and floating-wind projects becomes more important. These pathways should not be interpreted as universal prescriptions, but as structured ways to compare lean, conservative, and adaptation-ready strategies.

10.5.2. Methodological Recommendations

Future applications should preserve the modular structure of the model. Individual modules can then be replaced by more detailed alternatives when better data or models become available. This is important because the value of the DAPP layer depends directly on the quality of the model results used as input.

The framework should also be extended beyond the fixed reference platform and the two scenario families used in this thesis. A broader design space would allow hull size, deck layout, carrying capacity, power capacity, and mission-equipment integration constraints to vary together with carousel and tensioner choices. A broader scenario space could include regional market focus, cable-voltage development, port availability, weather-window limitations, emission requirements, supply-chain constraints, competitor vessel availability, and alternative contracting strategies. Together, these extensions would move the framework closer to a Level 4a exploratory uncertainty application.

A stronger economic layer should be added before the framework is used for investment decisions. The present CAPEX indicator only includes mission-equipment CAPEX, while practical decision-making would require full vessel CAPEX, integration cost, retrofit cost, downtime, charter revenue, utilisation, financing assumptions, payback period, net present value, and explicit transfer costs between pathway states.

Finally, future applications should connect scenario states to operational signposts and combine DAPP with complementary uncertainty-handling methods. Market indicators such as HVDC share, average export-route length, water depth, floating-project share, cable weight, and tender requirements could support reassessment over time. Robust Decision Making or Decision Scaling could support wider vulnerability exploration, Epoch–Era Analysis could represent time-explicit market sequences, and Engineering Options Analysis could help value design provisions that preserve future options.

10.6. Limitations

The first limitation is the fixed-platform scope. The thesis evaluates mission-equipment configurations on one reference platform hull. This isolates the effect of carousel and tensioner choices, but does not compare alternative hull forms, vessel sizes, propulsion arrangements, DP layouts, or complete general arrangements. It also means that possible correlations between vessel dimensions, carousel volume, tensioner capacity, and equipment integration constraints are not fully explored. The conclusions should therefore be interpreted as mission-equipment insights within a fixed-platform context, not as complete CLV concept-selection results.

The second limitation is the simplified technical modelling. Cable size, storage allocation, tension requirement, DP power, fuel consumption, transit, carousel power, and stability are represented at a level suitable for comparative screening, not detailed engineering. The model therefore supports relative comparison and vulnerability identification, but should not be used directly as a final design, cost, or installation tool.

The third limitation is the scenario and uncertainty scope. The synthetic portfolios are generated from a filtered base dataset and represent controlled stress tests rather than forecasts. The scenario families cover uncertainty drivers most directly linked to carousel and tensioner sizing, but not all market, policy, regulatory, supply-chain, emission, port, or commercial uncertainties relevant to CLV investment decisions. The implementation is therefore best interpreted as a structured Level 3 scenario-stress-test application embedded in DAPP, not as a full Level 4a exploratory uncertainty analysis at this stage.

The fourth limitation is the cost scope. Quantitative CAPEX includes only carousel and tensioner CAPEX. Hull cost, equipment integration, auxiliary systems, engineering cost, retrofit yard cost, downtime, and financing are not included. As a result, the CAPEX results are useful as a mission-equipment cost index, but not as a full investment estimate or lifecycle business case.

The fifth limitation concerns the adaptation and validation of DAPP for ship design. In a new-build CLV context, the initial state is still open, pathway states are coupled physical configurations, and transfer costs are difficult to quantify without detailed design work. A pathway that is logical in the configuration library may still be difficult, unattractive, or infeasible in a real general arrangement. The method has also not yet been applied to multiple independent vessel-design cases or systematically compared with alternative decision-support approaches.

10.7. Future Research

Future research should first apply the framework to more specific project sets and market scopes. This could include regional portfolios such as Europe or Asia, HVDC-heavy portfolios, floating-wind projects, shallow-water projects, or confidential tender pipelines. Such applications would make the method more directly useful for fleet-planning decisions and would test whether the same pathway logic holds under different portfolio assumptions.

A second research direction is to extend the model from a fixed-platform mission-equipment comparison to a coupled vessel-and-equipment design space. Future work should vary hull dimensions, deck layout, equipment arrangement, carrying capacity, power capacity, and integration margins alongside carousel and tensioner choices. This would allow the relationship between vessel size, storage capacity, tensioner capacity, and equipment integration constraints to be analysed explicitly.

A third research direction is to improve the technical and economic realism of the pathway evaluation. This includes detailed assessment of retrofit feasibility, transfer costs, downtime, shipyard implications, and the layout, structural, power/control, and stability consequences of specific transitions. It should also include a stronger techno-economic layer with full vessel CAPEX, retrofit cost, charter revenue, utilisation, financing assumptions, payback period, and net present value.

Finally, future research should extend and validate the adapted DAPP approach across broader uncertainty spaces and additional cases. A move toward Level 4a would require testing more combinations of uncertainty drivers, rather than using two bounded scenario families. Robust Decision Making, Decision Scaling, and Epoch–Era Analysis could support this step, while Engineering Options Analysis could help value adaptive design provisions such as reserved layout space, structural support, power/control capacity, or modular tensioner positions. Further validation should test whether the workflow remains useful across other offshore vessel types, project markets, and decision contexts.

10.8. Final Reflection

This thesis shows that early-stage CLV design under deep uncertainty benefits from an adaptive rather than purely deterministic design philosophy. The proposed framework does not predict the future or deliver a final vessel design, but makes uncertainty explicit and shows how mission-equipment choices remain useful, become vulnerable, or preserve future options across structured project-portfolio stress tests. This is particularly relevant for CLVs, because they are capital-intensive assets with long service lives, while the offshore wind projects they are expected to serve may change substantially in length, distance from shore, water depth, cable-system type, and foundation type.

The main value of the framework is therefore not that it identifies one configuration as universally best, but that it supports a more transparent discussion of design preparedness. It helps decision makers distinguish between current suitability, future vulnerability, and preserved adaptability. In doing so, it shifts early-stage CLV design from a static comparison of equipment capacity toward a structured assessment of how design choices may remain viable under changing project conditions. Within the scope of this thesis, that is the central contribution of applying adaptive pathway thinking to cable-laying vessel design.

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A

Detailed Review of Candidate Decision-Making Methods

A.1. Candidate Decision-Making Methods

This appendix provides the detailed method review that supports the concise overview and method selection in Section 3.3 and Section 3.4. The candidate methods are selected primarily from the framework discussed by Wirooks [144], with Stochastic Programming and Responsive Systems Comparison added because they are relevant to scenario-based engineering decision-making. Table A.1 groups the reviewed methods according to the level of uncertainty they primarily address.

Table A.1: Overview of decision-making methods grouped by level of uncertainty.

Level	**Considered Decision-Making Methods**				
2	Ship-Centric Markov Decision Process (SC-MDP)	Real Options Analysis (ROA)	Stochastic Programming (SP)		
3	Engineering Options Analysis (EOA)	Epoch–Era Analysis (EEA)	Responsive Systems Comparison (RSC)		
4a	Decision Scaling (DS)	Robust Decision Making (RDM)	Many-Objective Robust Decision Making (MORDM)	Dynamic Adaptive Planning (DAP)	Dynamic Adaptive Policy Pathways (DAPP)
4b	Info-Gap Decision Theory (IG)				

A.1.1. Ship-Centric Markov Decision Process

Ship-Centric Markov Decision Process (SC-MDP) adapts the Markov Decision Process framework to ship design by modelling decisions as transitions between probabilistic states [101]. This provides a structured way to incorporate life-cycle considerations into early-stage design [102].

Its main usefulness lies in supporting adaptive rather than static design choices. By representing design and operational decisions as sequential decision epochs, SC-MDP captures how variables such as policy or fuel prices may evolve over time [74]. This allows designers to compare how design alternatives perform under uncertain regulatory pathways [102] and, with Monte Carlo extensions, explore broader ranges of futures [74]. In CLV design, this could help identify which features should be fixed initially and which should remain flexible [122].

The method also has drawbacks. It requires specifying transition probabilities, which are often highly uncertain in long-term ship design [14]. SC-MDP therefore treats uncertainty as probabilistic risk and optimises expected outcomes, making results sensitive to assumptions [113]. Its computational burden also increases quickly with model detail, limiting the number of design variables that can be included [74].

In terms of uncertainty classification, SC-MDP is limited to Level 2 uncertainty, since it uses a single system model with probabilistic transitions. Although it can be applied to problems characterised by deeper uncertainty, the method itself converts these uncertainties into stochastic risk rather than explicitly addressing deep uncertainty.

A.1.2. Real Options Analysis

Real Options Analysis (ROA) evaluates the value of managerial flexibility by applying option-pricing concepts from finance to real assets and projects [20]. In this framework, decisions such as deferring, expanding, or abandoning an investment are treated as real options and valued using numerical techniques such as binomial lattices or Monte Carlo simulation [29]. ROA formalises the intuition that preserving the right, but not the obligation, to act later can add economic value when investments are large, irreversible, and subject to uncertain future conditions [20].

In ship design, ROA has been used to quantify the value of flexibility in early-stage concepts, for example for multi-purpose offshore vessels, by comparing designs with and without embedded upgrade options [70]. For offshore construction vessels, ROA has been combined with Epoch–Era Analysis to assess how flexible configurations perform across changing contract portfolios and market conditions [111]. These studies show how ROA can highlight which design provisions, such as reserved space, structural allowances, or modular interfaces, are worth implementing to keep future technical or market options open.

The approach also has important limitations. Applying ROA in practice requires stochastic models for key drivers such as prices, demand, or environmental conditions, and the resulting option values can be sensitive to these assumptions [76]. Under deep uncertainty, where probability distributions or even plausible model structures are contested, ROA's reliance on expected-value calculations and a single stochastic model makes it less suitable as the sole decision basis [79].

In the uncertainty taxonomy of Marchau et al., ROA corresponds to Level 2 uncertainty, where a single system model and quantified probabilities are assumed [88]. While it can be applied to problems that are conceptually characterised by deeper uncertainty, ROA itself represents these uncertainties as probabilistic risk rather than explicitly addressing Level 3 or Level 4 uncertainty.

A.1.3. Stochastic Programming

Stochastic Programming (SP) formulates design under uncertainty as an optimisation problem with first-stage decisions made before uncertainty is revealed and second-stage recourse actions taken afterward [9]. In this structure, first-stage variables represent committed design choices, while second-stage variables adapt to each scenario once uncertain parameters are known [3]. The objective typically minimises the sum of first-stage cost and expected second-stage cost, allowing designers to couple robust commitments with flexible operational adjustments [9].

In ship design, SP has been applied by explicitly partitioning variables before and after uncertainty realisation and solving the resulting two-stage optimisation problem [27]. This formulation enables the designer to evaluate how architectural decisions, taken in the first stage, influence operational performance across possible futures. For a CLV, first-stage decisions could define key configuration choices such as carousel size or DP class, while second-stage recourse could capture operational adjustments once weather, project duration, or resource availability become known.

Despite its usefulness, SP also has limitations. The method requires uncertainty to be represented by a finite set of scenarios with known probabilities, making the results sensitive to how these scenarios and likelihoods are defined [3]. Under deep uncertainty, where probability distributions are contested or unknown, SP may provide overconfident results and struggle to represent the full range of plausible futures [88].

In the uncertainty taxonomy, SP corresponds to Level 2 uncertainty, since it assumes a single model structure and known probability distributions. Although it can incorporate many scenarios, it does not explicitly address Level 3 or Level 4 uncertainty and instead reduces uncertainty to probabilistic risk.

A.1.4. Engineering Options Analysis

Engineering Options Analysis (EOA) evaluates flexibility in engineering systems by comparing staged development pathways rather than single fixed designs [100]. EOA considers how initial decisions influence the ability to adapt later, and values modularity or phased implementation through scenario-based performance assessment [141].

EOA is useful because it makes the consequences of flexibility explicit. By generating alternative development pathways and simulating their outcomes across uncertain futures, the method highlights how staged or modular strategies can outperform monolithic configurations [18]. EOA enables designers to identify early decisions that preserve adaptability and to quantify trade-offs between cost, capability, and risk [19]. In ship design, this supports evaluating phased technology adoption, such as deferring propulsion upgrades until operational or regulatory conditions justify them [1].

The method also has limitations. EOA requires extensive scenario generation and simulation, which can be computationally demanding and sensitive to modelling assumptions [141]. The approach depends on the quality of the defined pathways and scenarios, and results may overlook futures that were not explicitly represented [19]. Because outcomes are evaluated through scenario assessment rather than formal optimisation, identifying preferred pathways may rely strongly on expert judgement.

In terms of uncertainty classification, EOA aligns with Level 3 uncertainty, since it evaluates alternative strategies across multiple plausible futures without relying on precise probabilities [88]. The method is more suitable for deep uncertainty than Level 2 methods, but it does not fully address Level 4 uncertainty.

A.1.5. Epoch--Era Analysis

Epoch–Era Analysis (EEA) structures long-term uncertainty by dividing time into discrete epochs in which contextual conditions remain fixed, and by linking these epochs into eras that represent plausible sequences of future developments [116]. An epoch is defined by specific levels of key external drivers such as regulation, market demand, or technology state, and multiple epochs are combined to form era pathways that capture how external conditions may evolve over time [98].

EEA is useful because it represents both short-term and long-term uncertainty in a systematic and temporally explicit way. By enumerating epochs and forming diverse era sequences, the method enables designers to test system alternatives against structured future trajectories rather than isolated scenarios [116]. This helps identify designs that remain effective across changing external contexts and clarifies which capability or architectural features provide robustness to shifts in regulation, demand, or technology.

EEA also presents challenges. Constructing epochs and eras requires analysts to define contextual variables and plausible levels, which can be time consuming and dependent on expert judgement [98]. The number of possible eras can grow quickly as more variables are included, creating computational and analytical complexity. Evaluating system performance across these scenarios may require extensive simulation models, and insights can be sensitive to how epochs and transitions are defined.

In the Marchau uncertainty taxonomy, EEA aligns with Level 3 uncertainty, since it evaluates system performance across multiple plausible futures without assigning probabilities to transitions between epochs [88]. The method therefore supports decision-making under deep uncertainty, but does not fully address Level 4 uncertainty, where even the structure of plausible futures is contested.

A.1.6. Responsive Systems Comparison

Responsive Systems Comparison (RSC) evaluates alternative system designs across a wide range of plausible future contexts to understand how each performs under changing conditions [118]. The method constructs a structured scenario space, often informed by approaches such as EEA, and assesses each candidate design within every scenario using defined performance metrics [39]. RSC focuses on comparing the distribution of outcomes across futures rather than evaluating performance in a single forecast.

RSC is useful because it highlights which designs maintain acceptable performance across diverse contexts. By analysing many combinations of designs and scenarios, the method identifies concepts that remain valuable even as user needs, technologies, and operating environments evolve [117]. In ship design, this supports comparison of alternative hull forms or propulsion configurations under varying regulatory, economic, and environmental futures, making it possible to identify vessel concepts that are resilient to contextual change.

The approach also has limitations. Constructing the scenario space requires defining relevant contextual variables and plausible levels, which can be subjective and time consuming [39]. The number of required simulations may grow quickly with added scenarios or design variants, increasing computational demands. RSC does not inherently recommend a single preferred design, as results depend on how decision makers interpret performance distributions and acceptable thresholds.

In the Marchau uncertainty taxonomy, RSC corresponds to Level 3 uncertainty because it evaluates system designs across many plausible futures without assigning probabilities to them [88]. The method therefore supports decision-making under deep uncertainty, but does not fully address Level 4 uncertainty.

A.1.7. Decision Scaling

Decision Scaling (DS) evaluates system robustness by stress testing designs across a broad range of uncertain conditions before considering specific forecasts [13]. The method begins with formal decision framing that identifies objectives, performance metrics, and critical thresholds, and then explores how the system performs across a multidimensional space of varied input conditions [61].

DS is useful because it reveals the conditions under which a system becomes vulnerable without depending on any single projection or model. By mapping performance across the full uncertainty space, analysts obtain an unbiased view of sensitivities and identify which combinations of external drivers pose the greatest risk [112]. This provides decision makers with insight into which design modifications or operational strategies can reduce vulnerability and improve robustness.

The approach also has challenges. DS requires extensive simulation across many scenario variations, which can be computationally demanding for complex engineering models [61]. The method depends on the choice of stress-test ranges and metrics, and insights can be limited if the explored uncertainty space fails to capture relevant futures. DS also does not itself recommend an optimal design, but instead provides information that must be interpreted within broader decision processes.

In terms of uncertainty classification, DS corresponds to Level 4a uncertainty in the Marchau taxonomy, because it does not assume known probabilities or a single forecast and instead evaluates system behaviour across many plausible futures [88]. DS is therefore well suited for deep uncertainty, where the focus is on identifying vulnerabilities rather than forecasting a most likely future.

A.1.8. Robust Decision Making

Robust Decision Making (RDM) identifies strategies that maintain acceptable performance across a wide range of plausible futures rather than optimising for a single forecast [83]. RDM uses exploratory modelling to generate many scenarios by sampling key uncertainties, and then evaluates candidate strategies across the full ensemble to reveal their performance patterns [50].

RDM is useful because it directly targets robustness instead of optimality under a specific projection. By analysing hundreds or thousands of simulations, the method reveals which uncertainties most influence outcomes and which strategies perform reliably across divergent futures [82]. RDM provides diagnostic tools, including scenario discovery and regret analysis, that support understanding trade-offs between robustness, performance, and vulnerability [143]. In ship design, RDM has been applied to long-term fuel and technology decisions, showing how certain configurations remain viable across a broad range of market and regulatory scenarios [133].

The approach also has limitations. RDM requires extensive computational resources because it relies on large ensembles of simulations [50]. The method depends on the quality and breadth of the uncertainty sampling; poorly chosen uncertainty ranges or models may limit insights or overlook critical futures [82]. RDM does not by itself produce a single optimal solution, but instead generates robust candidates that must be interpreted within a broader stakeholder process.

In the Marchau uncertainty taxonomy, RDM corresponds to Level 4a uncertainty because it evaluates strategies across many plausible futures without assigning probabilities to them [88]. The method is therefore well suited for deep uncertainty, where the aim is to identify strategies that remain effective even when model structures, parameters, and future conditions are highly uncertain [131].

A.1.9. Many-Objective Robust Decision Making

Many-Objective Robust Decision Making (MORDM) extends RDM by combining exploratory scenario analysis with multi-objective optimisation to address problems with multiple competing objectives [55]. The method begins by generating a large ensemble of plausible futures and then applies an evolutionary multi-objective algorithm to produce candidate strategies that represent trade-offs across all objectives [75]. Each candidate is subsequently evaluated across the full scenario set to identify solutions that achieve good performance and maintain robustness under uncertainty [114].

MORDM is useful because it integrates Pareto-based search with robustness screening, enabling analysts to reveal solution sets that balance complex objectives while remaining resilient to uncertain futures. By jointly analysing trade-offs and uncertainty, the method helps decision makers understand how alternative strategies perform across conflicting goals, such as minimising cost, emissions, and construction time [55]. In ship design, where performance metrics inherently span many domains including safety, efficiency, emissions, and cost, MORDM offers a structured way to identify vessel concepts that preserve feasibility and competitiveness across diverse future conditions.

The approach also has limitations. MORDM can be computationally intensive because it combines large scenario ensembles with multi-objective evolutionary optimisation [75]. The method depends on careful specification of objectives, constraints, and uncertainty ranges, and poorly defined problem formulations may lead to misleading Pareto fronts or overconfident robustness estimates. Interpretation of high-dimensional Pareto sets can also be challenging, requiring additional visualisation and decision-support tools.

In the Marchau uncertainty taxonomy, MORDM corresponds to Level 4a uncertainty because it evaluates strategies across many plausible futures without assuming known probabilities [88]. MORDM is therefore suited to deep uncertainty, providing insight into which multi-objective trade-offs remain acceptable across a wide range of potential future states [114].

A.1.10. Dynamic Adaptive Planning

Dynamic Adaptive Planning (DAP) develops strategies that incorporate built-in mechanisms for adjustment as new information emerges [81]. Instead of relying on a single static plan, DAP specifies an initial short-term strategy alongside contingent actions and monitoring indicators that guide when and how the plan should adapt over time [58].

DAP is useful because it explicitly prepares for uncertainty by identifying assumptions, vulnerabilities, and potential future developments during the design phase. By linking these to predefined triggers, DAP allows decision makers to respond when conditions change, thereby maintaining progress toward long-term goals [54]. In ship design, this supports development strategies that preserve flexibility, such as allocating space for future propulsion upgrades and activating retrofit actions only when relevant regulatory or cost thresholds are reached.

The approach also has limitations. DAP requires detailed monitoring frameworks and well-calibrated signposts, and poor trigger design can lead to either delayed adaptation or unnecessary adjustments [78]. Implementation can be resource intensive, since it demands continuous evaluation of external developments and careful coordination across stakeholders.

In the Marchau uncertainty taxonomy, DAP corresponds to Level 4a uncertainty because it does not rely on probabilistic forecasts but uses adaptive strategies that evolve across many plausible futures [88]. The method is therefore well suited for deep uncertainty, providing a structured way to maintain robust performance as the operational environment of a vessel changes.

A.1.11. Dynamic Adaptive Policy Pathways

Dynamic Adaptive Policy Pathways (DAPP) integrates adaptive planning principles with the construction of explicit adaptation pathways to structure long-term decision making under deep uncertainty [54]. The method identifies adaptation tipping points at which a current strategy will no longer meet objectives and links these with possible subsequent actions, producing a network of alternative decision sequences [80]. These sequences are visualised as a pathways map that shows when strategies become inadequate and how decision makers can transition to new actions over time [53].

DAPP is useful because it provides a transparent representation of adaptive strategies, their timing, and the conditions under which they should change. By mapping alternative pathways, decision makers can compare near-term actions while understanding their long-term implications across multiple futures [54]. In ship design, DAPP can be used to evaluate sequences of investment decisions, such as adopting one technology or configuration initially while preserving the option to transition to another configuration when market, regulatory, or technical conditions justify it.

The approach also has limitations. Constructing pathways requires identifying tipping points, thresholds, and transition actions, which depend on expert judgement and may be sensitive to assumptions [80]. Creating high-quality pathway maps can be analytically demanding, and results may become complex when many strategies or uncertainties are included. Implementation also requires monitoring systems to detect when tipping points are being approached.

In the Marchau uncertainty taxonomy, DAPP corresponds to Level 4a uncertainty because it evaluates strategies across multiple plausible futures without relying on probabilistic forecasts [88]. DAPP is therefore appropriate for deep uncertainty, supporting the design of adaptive ship development strategies that evolve as conditions change.

A.1.12. Info-Gap Decision Theory

Info-Gap Decision Theory (IG) evaluates decision alternatives under severe uncertainty by identifying how much deviation from assumed conditions a system can tolerate while still meeting performance requirements [8]. Instead of using probability distributions, IG models uncertainty as nested sets of increasingly larger deviations from a nominal estimate and assesses decisions through a robustness function that quantifies the largest uncertainty horizon under which the performance criteria remain satisfied [128].

IG is useful because it focuses directly on robustness rather than expected outcomes. By quantifying how far uncertain parameters can vary before a design becomes unacceptable, the method highlights which alternatives provide the greatest immunity to unknown or poorly characterised conditions [8]. In ship design, this allows assessment of how fuel quality, cargo variability, or environmental loads can change before safety or range requirements fail, guiding designers toward concepts that maintain essential performance under extreme deviations [62].

The approach also has limitations. IG depends strongly on the choice of nominal estimates and the structure of the uncertainty sets, which can influence robustness assessments [128]. Because the method evaluates worst-case outcomes within expanding uncertainty horizons, it may be overly conservative compared to probabilistic or scenario-based methods. IG provides limited insight into trade-offs among competing objectives and does not specify how likely any particular deviation is.

In the Marchau uncertainty taxonomy, IG corresponds to Level 4b uncertainty, since it explicitly addresses situations with severe lack of knowledge and avoids probability assignments altogether [88]. IG is therefore suited for applications involving novel technologies or unprecedented conditions where reliable probability distributions cannot be defined.

B

Supporting Reference Data for the Parametric Vessel Model

This appendix collects the supporting reference data, equations, and fitted relations used in Chapter 5. The main chapter presents the modelling logic, while this appendix provides the underlying data tables, scaling equations, and diagnostic figures used to derive selected model assumptions.

B.1. Carousel Reference Data

Table B.1: Reference carousel characteristics used for capacity, volume, and line-speed comparison.

Capacity (t)	Outer D (m)	Core D (m)	Stacking Height (m)	Gross Volume (m^3)	Line Speed (m/min)
10000	32.0	4.0	6.50	4002	15.0
7000	30.0	4.0	6.50	3451	15.0
5000	25.0	4.0	6.50	2251	15.0
4000	23.0	4.0	6.50	1843	15.0
2500	18.0	4.0	6.50	1001	15.0
1500	14.0	2.5	6.50	675	15.0
9000	29.0	8.0	7.00	2425	15.1
7000	28.0	8.0	7.70	2419	16.7
5500	26.0	5.0	6.00	2078	10.0
2000	18.0	4.0	6.40	985	20.0
5000	23.0	6.0	8.00	1816	28.3
2750	18.0	6.0	8.00	905	28.3
1700	15.0	6.0	8.00	509	28.3
3000	23.0	3.6	5.00	1478	–
7000	28.0	8.0	6.50	2042	17.0
5500	26.0	5.0	6.50	2251	10.0
4750	23.0	8.0	6.50	1149	17.0
7000	27.4	–	7.50	–	20.0
2000	18.3	4.0	5.24	842	–
4000	23.3	7.6	7.90	1529	23.8
6000	26.0	6.0	6.50	2042	15.1
4000	23.0	4.0	6.00	1701	20.1
2000	20.0	5.6	8.00	1303	22.7
1800	14.0	3.6	5.00	425	17.0
2000	13.7	6.0	5.00	233	18.1
5000	23.0	4.5	6.00	1613	16.7

Source overview for the carousel entries in Table B.1.

Table B.1 entry or entries	Source document or supplier page	URL or source note
10,000 t EuroCarousel	Neptune Marine, EuroCarousel 10,000 specification sheet	`https://www.neptunemarine.com/wp-content/uploads/2022/04/EuroCarousel-10.000-spec-sheet-V.01.pdf`
7,000 t EuroCarousel	Neptune Marine, EuroCarousel 7,000 specification sheet	`https://www.neptunemarine.com/wp-content/uploads/2022/04/EuroCarousel-7000-spec-sheet-V.01.pdf`
5,000 t EuroCarousel	Neptune Marine, EuroCarousel 5,000 specification sheet	`https://www.neptunemarine.com/wp-content/uploads/2022/04/EuroCarousel-5000-spec-sheet-V.01.pdf`
4,000 t EuroCarousel	Neptune Marine, EuroCarousel 4,000 specification sheet	`https://www.neptunemarine.com/wp-content/uploads/2022/04/EuroCarousel-4000-spec-sheet-V.01-1.pdf`
2,500 t EuroCarousel	Neptune Marine, EuroCarousel 2,500 specification sheet	`https://www.neptunemarine.com/wp-content/uploads/2022/04/EuroCarousel-2500-spec-sheet-V.01-1.pdf`
1,500 t EuroCarousel	Neptune Marine, EuroCarousel 1,500 specification sheet	`https://www.neptunemarine.com/wp-content/uploads/2022/04/EuroCarousel-1500-spec-sheet-V.01-1.pdf`
9,000 t basket carousel	Dutch Offshore Contractors, 9,000 t basket carousel	`https://www.dutchoffshorecontractors.com/services/basket-carousel/9000t`
7,000 t basket carousel	Dutch Offshore Contractors, 7,000 t basket carousel	`https://www.dutchoffshorecontractors.com/services/basket-carousel/7000t`
5,500 t basket carousel	Dutch Offshore Contractors, 5,500 t basket carousel	`https://www.dutchoffshorecontractors.com/services/basket-carousel/5500t`
2,000 t basket carousel	Dutch Offshore Contractors, 2,000 t basket carousel	`https://www.dutchoffshorecontractors.com/services/basket-carousel/2000t`
5,000 t, 2,750 t, and 1,700 t carousel entries	Blue Offshore, carousel specification	`https://www.blueoffshore.com/wp-content/uploads/2016/09/Carousel-specification-rev2.pdf`
3,000 t cable carousel	Jan De Nul, cable carousel specification	`https://www.jandenul.com/sites/default/files/public/Cable%20carousel.pdf`
7,000 t basket carousel	Osprey Group, 7,000 t basket carousel specification	`https://osprey.group/wp-content/uploads/2021/10/osprey_7000t-basket-carousel_01_oct-21.pdf`
5,500 t basket carousel	Osprey Group, 5,500 t basket carousel specification	`https://osprey.group/wp-content/uploads/2021/10/osprey_5500t-basket-carousel_01_oct-21.pdf`
4,750 t basket carousel	Osprey Group, 4,750 t basket carousel specification	`https://osprey.group/wp-content/uploads/2021/10/osprey_4750t-basket-carousel_01_oct-21.pdf`
7,000 t and 2,000 t Maersk Connector carousel entries	Maersk Supply Service, *Maersk Connector Standard*	`https://www.maersksupplyservice.com/wp-content/uploads/2020/11/Maersk-Connector-Standard-2020-11.pdf`
[redacted] Boskalis carousel entry	Boskalis internal document, *BoD* [redacted] *carousel*	Internal Boskalis SharePoint document.
6,000 t carousel entry	*Spec of 6000T Carousel*	`https://www.scribd.com/document/724567125/Spec-of-6000T-Carousel`
4,000 t, 2,000 t, 1,800 t, 2,000 t, and 5,000 t carousel hire entries	*Carousel hire service and operation*	`https://www.scribd.com/document/740815281/Carousel-hire-service-and-operation`

Table B.2: Reference carousel power characteristics used for the installed-power relation.

Capacity (t)	Outer D (m)	Core D (m)	Stacking Height (m)	Available Volume (m^3)	No. of Drives (-)	Drive Power (kW)	Power (kW)
9000	29.0	8.0	7.0	2425	4	147	588
7000	28.0	8.0	7.7	2419	4	160	640
3000	23.0	3.6	5.0	1478	4	75	322
7000	28.0	8.0	6.5	2042	4	160	640
6000	26.0	6.0	6.5	2042	5	75	375
4000	23.0	4.0	6.0	1701	4	90	416
2000	20.0	5.6	8.0	1303	3	45	159
1800	14.0	3.6	5.0	425	2	86	172
5000	23.0	4.5	6.0	1613	3	140	430

B.2. Mission-Equipment Scaling Relations

This section provides the supporting data and figures for the mission-equipment scaling relations used in Section 5.2.1 and Section 5.2.2. These relations are used as early-stage comparative estimates rather than supplier-level design or procurement values.

Table B.3: Carousel scaling relations used in the design generator.

Quantity	**Relation**	**Note**
Gross volume	$V_{car} = \pi H \left(R^2 - r^2\right)$	Geometric annular volume, where H is carousel height, R is outer radius, and r is core radius.
Empty weight	$W_{car} = 0.25 V_{car}$	Empty carousel weight in tonnes, based on the average observed weight-to-volume ratio in Table B.5.
Empty VCG	$VCG_{car} = z_{base} + 0.4H$	Vertical centre of gravity above keel. The base height z_{base} is 14 m for above-deck carousels and 2 m for the below-deck carousel.
Indicative cable capacity	$C_{car} = 2.358 V_{car} + 535.93$	Indicative cable capacity in tonnes, fitted to the reference carousel data shown in Figure B.1.
Carousel CAPEX	$CAPEX_{car} = ($[redacted]$C_{car} +$ [redacted]$) \cdot 10^6$	Indicative carousel CAPEX in euros, based on experience-based cost input and shown in Figure B.2.
Installed drive power	$P_{car} = \max(0,\, 0.2508 V_{car} - 14.733)$	Installed carousel drive power in kW, fitted to the reference power data shown in Figure B.3.

Table B.4: Tensioner scaling relations used in the design generator.

Quantity	**Relation**	**Note**
Installed unit power	$P_{ten,unit} = \dfrac{Fv}{\eta}$	Installed tensioner power in kW, where F is pull force, v is line speed, and $\eta = 0.85$ is the assumed drive efficiency.
Line capacity	$T_{line} = n_{series} \cdot T_{unit}$	Tension capacity per lay line, based on the number of identical units installed in series.
Total number of units	$n_{units,total} = n_{lines} \cdot n_{series}$	Total number of installed tensioner units on the vessel.
Unit CAPEX	$CAPEX_{ten,unit} = ($[redacted]$T_{unit} +$ [redacted]$) \cdot 10^6$	Indicative unit CAPEX in euros, based on experience-based cost input and shown in Figure B.4.
Total tensioner CAPEX	$CAPEX_{tensioners} = n_{units,total} \cdot CAPEX_{ten,unit}$	Vessel-level tensioner CAPEX, obtained by multiplying unit CAPEX by the total number of installed units.
Tensioner VCG	$VCG_{ten} = 14 + 4 + \frac{1}{2} h_{ten}$	Vertical centre of gravity above keel, assuming a deck foundation 4 m above the 14 m main deck level.
Submerged cable weight	$w_{sub} = w_{air} - \rho_{water} \frac{\pi}{4} D^2$	Submerged cable weight per metre, where w_{air} is cable weight in air, $\rho_{water} = 1025$ kg/m^3, and D is cable diameter.
Indicative maximum operating depth	$h_{op,max} = \dfrac{1000 \cdot T_{line}}{\gamma \cdot w_{sub}}$	Diagnostic depth indicator using line capacity and submerged cable weight, with $\gamma = 1.5$ as installation allowance factor.

Table B.5: Carousel weight characteristics relative to storage volume.

Capacity (t)	Outer D (m)	Core D (m)	Height (m)	Gross Volume (m^3)	Weight (t)	W_{car}/V_{car} (t/m^3)
9000	29.0	8.0	7.0	2425	490	0.20
5500	26.0	5.0	6.0	2078	600	0.29
2000	18.0	4.0	6.4	985	230	0.23
5000	23.0	6.0	8.0	1816	680	0.37
3000	23.0	3.6	5.0	1478	370	0.25
4000	23.3	7.6	7.9	1529	370	0.24
4000	23.0	4.0	6.0	1701	375	0.22
2000	20.0	5.6	8.0	1303	280	0.21
					Average	0.25

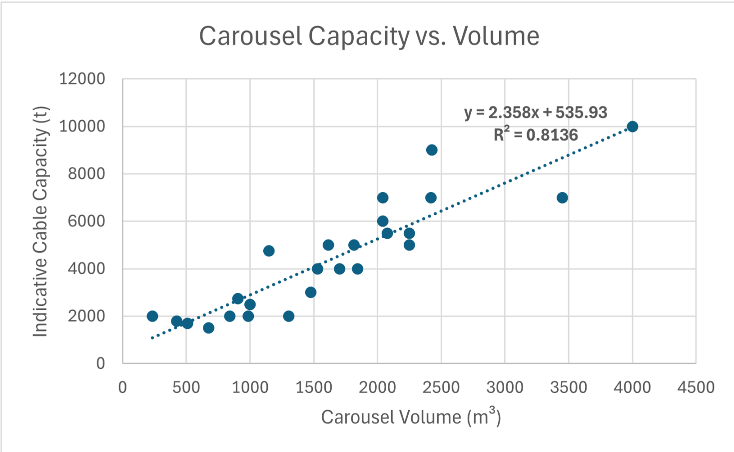


Figure B.1: Empirical relation between carousel gross volume and indicative cable capacity based on reference carousel data.

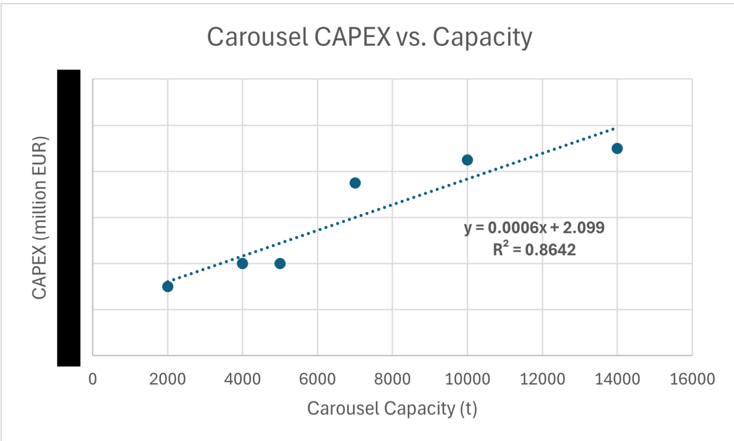


Figure B.2: Linear CAPEX estimation model fitted to experience-based carousel cost data.

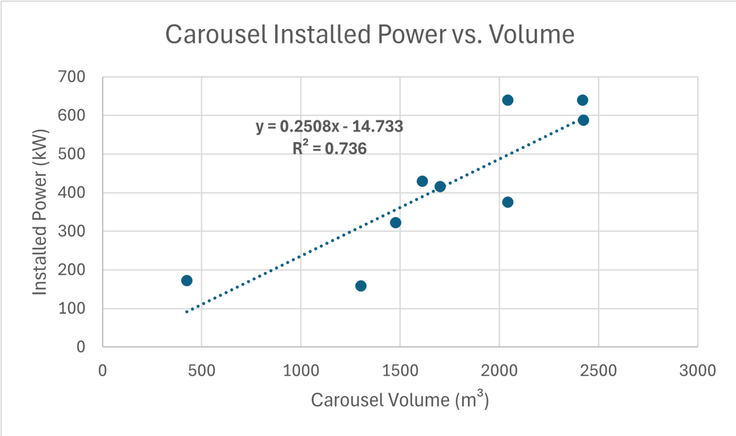


Figure B.3: Empirical relation between carousel volume and installed drive power based on reference carousel data.

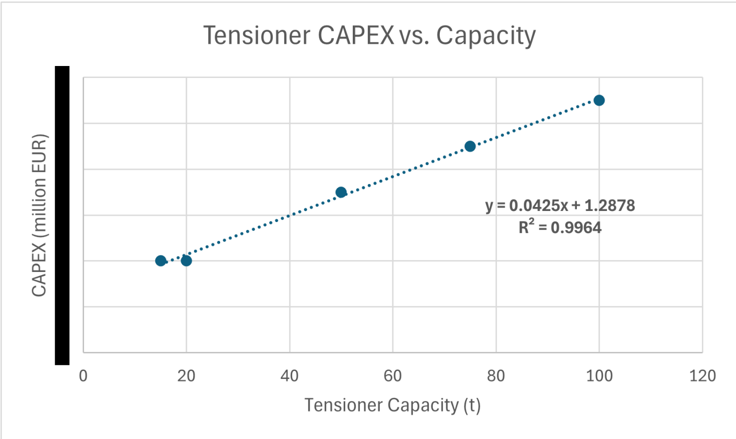


Figure B.4: Indicative tensioner CAPEX scaling relation based on experience-based cost input.

B.3. Reference Hull Hydrostatics

Figure B.5 shows the linear displacement–draft relation used to estimate the raw hydrostatic draft of generated configurations. The relation is fitted to hydrostatic data for the reference platform hull and is used in Section 5.2.4.

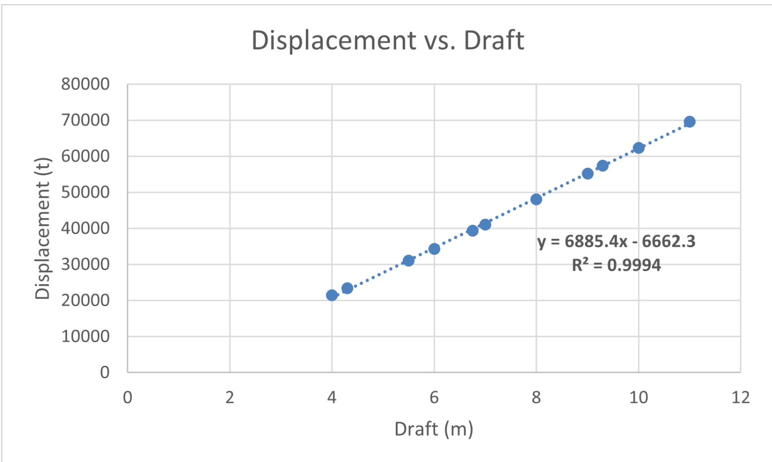


Figure B.5: Linear relation between draft and displacement based on hydrostatic data for the reference platform hull.

The main weight, draft, and simplified stability relations used for the design-library enrichment are summarised in Table B.6. These relations support the compact description in Section 5.2.4.

Table B.6: Weight, draft, and simplified stability relations used for design-library enrichment.

Quantity	**Relation**	**Note**
Mission-equipment weight	$W_{mission} = W_{carousels} + W_{tensioners}$	Sum of empty carousel weight and installed tensioner weight.
Empty configuration displacement	$\Delta = W_{LS} + W_{mission}$	Empty displacement of the reference platform with installed mission equipment.
Raw hydrostatic draft	$T_{raw} = \dfrac{\Delta - b_\Delta}{a_\Delta}$	Linear displacement–draft fit with $a_\Delta = 6885.4$ t/m and $b_\Delta = -6662.3$ t.
Minimum operational draft	$T_{min} = z_{prop,CL} + 1.5D_{prop} = 7.86$ m	Based on $z_{prop,CL} = 2.61$ m and $D_{prop} = 3.5$ m.
Configuration draft	$T_{config} = \max(T_{raw}, 7.86)$	Draft used in later performance calculations.
Lightship KG	$KG_{LS} = \dfrac{W_{hull}z_{hull} + W_{super}z_{super} + W_{deck}z_{deck}}{W_{LS}}$	First-order fixed lightship KG estimate using hull, superstructure, and deckhouse contributions.
Configuration KG	$KG_{config} = \dfrac{W_{LS}KG_{LS} + W_{mission}VCG_{mission}}{W_{LS} + W_{mission}}$	Combined vertical centre of gravity of the lightship and installed mission equipment.
Empty transverse GM	$GM_T = KM_T - KG_{config}$	KM_T is linearly interpolated from the reference hull hydrostatic data shown in Table 5.5.

B.4. Reference Hull Side-Area Strips

Table B.7 gives the side-projection strip areas used to estimate draft-dependent above-water and underwater hull side area in the operational performance model. The strip areas represent successive 1 m vertical bands above the keel and are used as fixed geometric input for the relative DP exposure proxy.

Table B.7: Reference hull side-projection strip areas used for the DP exposure proxy.

Vertical band above keel [m]	**Side area [m^2]**	**Vertical band above keel [m]**	**Side area [m^2]**
0–1	160.31	7–8	177.01
1–2	162.54	8–9	177.10
2–3	163.87	9–10	177.10
3–4	164.83	10–11	177.09
4–5	165.68	11–12	177.08
5–6	169.24	12–13	177.20
6–7	173.89	13–14	177.42

B.5. Loaded-Stability Diagnostic

This section provides supporting diagnostic figures for the simplified stability checks used in the design-library generation and project-evaluation model. These figures are not used as formal stability validation, but help verify that the generated configurations and loaded campaign conditions remain plausible within the first-order GM_T approximation.

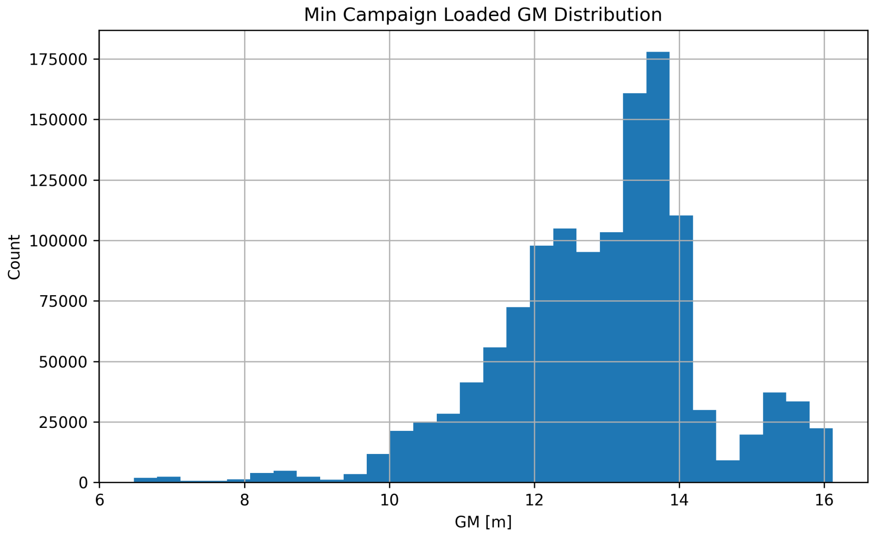


Figure B.6: Distribution of minimum loaded campaign GM_T values across simulated design–project campaign combinations.

Figure B.6 provides a supporting diagnostic for the simplified loaded-stability check used in the project-evaluation model. The figure shows the distribution of minimum loaded campaign GM_T values across simulated design–project campaign combinations.

B.6. Transit Resistance Model

This section provides the supporting resistance-model data used in Section 5.4.2. The main chapter describes how transit resistance is used in the project-evaluation model; the detailed Holtrop–Mennen input values, polynomial coefficients, resistance curves, and propulsion-efficiency factors are collected here to keep the main text focused on the modelling logic.

Table B.8: Main Holtrop–Mennen input parameters used for the transit-resistance estimate.

Parameter	$T = 4.00$ **m**	$T = 6.75$ **m**	$T = 10.00$ **m**	**Unit**
Waterline length, $L_{pp} = L_{wl}$	[redacted]			m
Breadth, B				m
Draft, T	4.00	6.75	10.00	m
Displacement, Δ	20990	38421	60878	t
Shell and appendage factor	1.005	1.005	1.005	–
Half angle of entrance	41.416	41.416	41.416	deg
Midship section area, A_m	170	289	428	m^2
Waterplane area, A_w	5981	6677	7033	m^2
Midship coefficient, C_M	0.990	0.994	0.996	–
Block coefficient, C_B	0.739	0.756	0.799	–
Prismatic coefficient, C_P	0.746	0.761	0.803	–
Waterplane coefficient, C_{WP}	0.842	0.887	0.924	–
Longitudinal centre of buoyancy, LCB	93.9	90.9	87.9	m
LCB as percentage of L_{wl}	6.85	1.91	-0.37	%
Wetted surface area	6794	8266	9749	m^2
Transom area	0.00	0.00	86.53	m^2
Afterbody form	Normal	Normal	Normal	–
Skeg volume	66.5	66.5	66.5	m^3

Table B.9: Polynomial coefficients for the draft-dependent calm-water resistance model.

Draft [m]	a_4	a_3	a_2	a_1	a_0
4.0	0.0459	-1.6416	22.370	-90.807	111.13
6.75	0.0606	-2.1848	29.434	-119.44	144.78
10.0	0.0721	-2.4634	31.679	-118.91	137.74

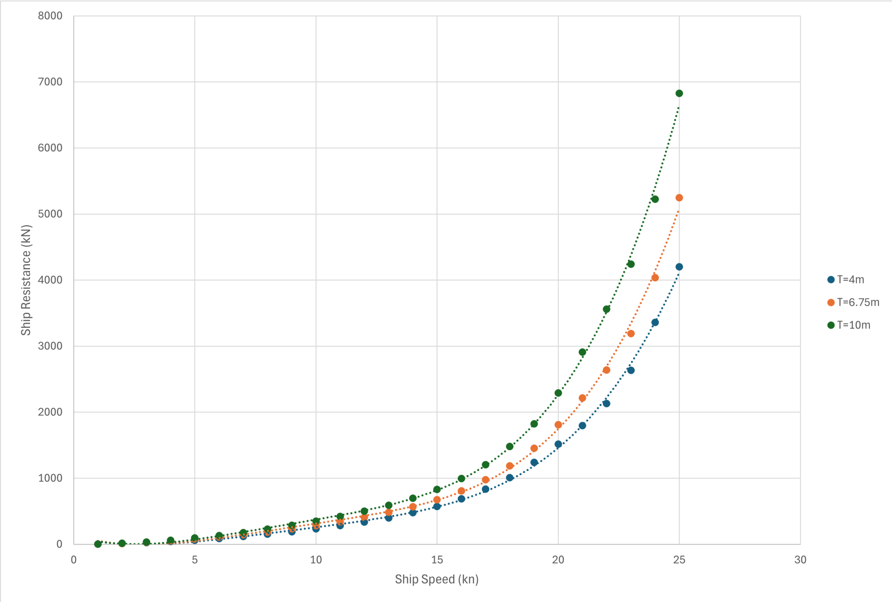


Figure B.7: Holtrop–Mennen calm-water resistance curves for the reference platform hull at drafts of 4.0 m, 6.75 m, and 10.0 m. Resistance at intermediate drafts is obtained by linear interpolation between the surrounding curves.

Table B.10: Propulsion efficiency factors used in the transit-power calculation.

Efficiency factor	Symbol	Value
Hull efficiency	η_H	1.03
Open-water propulsor efficiency	η_O	0.70
Relative-rotative efficiency	η_R	0.99
Pod mechanical efficiency	η_{pod}	0.99
Electric motor efficiency	η_{motor}	0.98
Converter efficiency	$\eta_{converter}$	0.985
Transformer efficiency	$\eta_{transformer}$	0.99
Generator efficiency	$\eta_{generator}$	0.96
Total propulsion efficiency	η_{prop}	0.648

C

Scenario-Generation Consistency Checks

This appendix presents the base-versus-scenario boxplots used to check the generated global-scope project portfolios. The figures support the scenario-generation procedure described in Section 6.3 and the scenario families defined in Section 6.4. They are used to verify that the base-like portfolio remains broadly comparable to the filtered donor dataset and that the stress-test portfolios shift the relevant project variables in the intended directions before being used in the vessel-evaluation model.

Because each portfolio is generated independently through donor sampling, category targeting, numerical scaling, and multiplicative noise, the realised distributional changes do not necessarily equal the nominal stress multipliers exactly.

C.1. Base-Like Reference Scenario

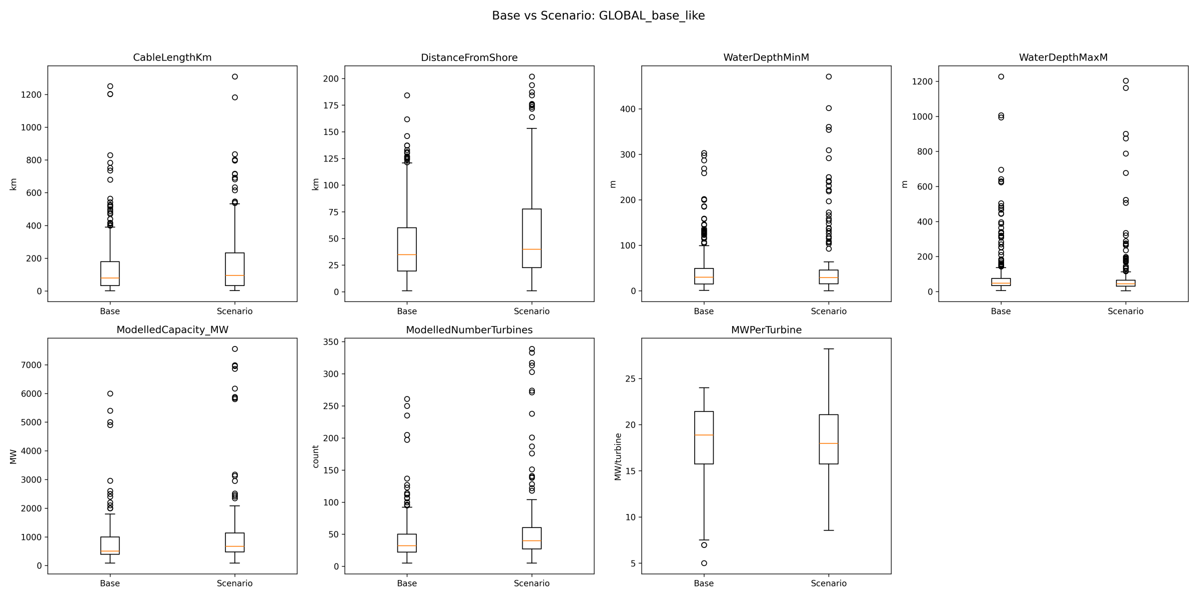


Figure C.1: Base-versus-scenario boxplots for the global base-like synthetic portfolio.

C.2. Length--Distance/HVDC Scenarios

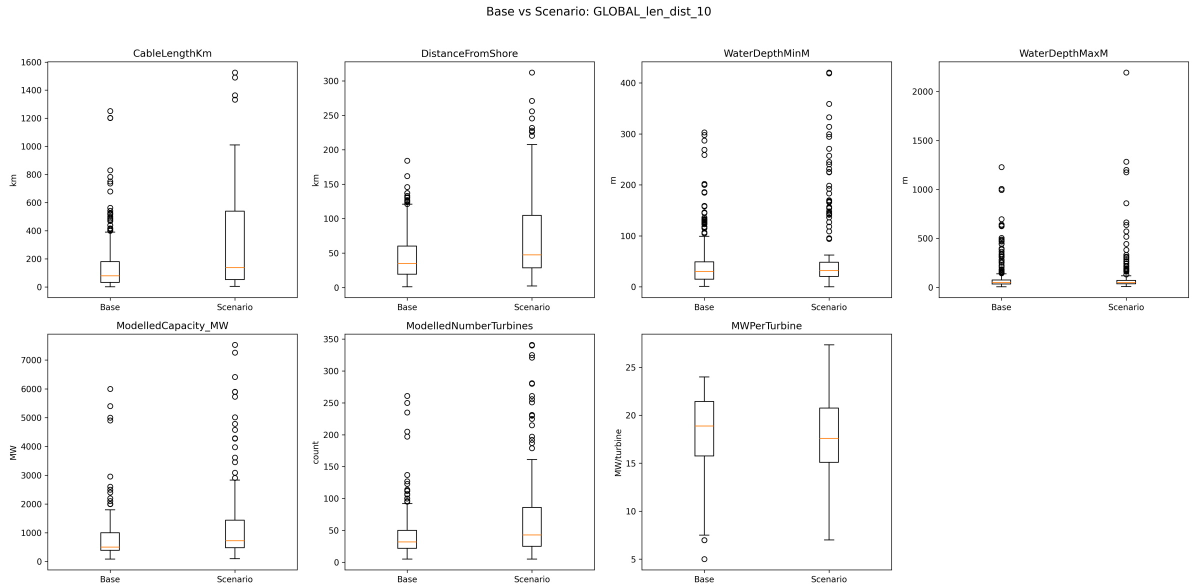


Figure C.2: Base-versus-scenario boxplots for the global `len_dist_10` scenario, using a nominal +10% length–distance multiplier and an HVDC-share target of 20%.

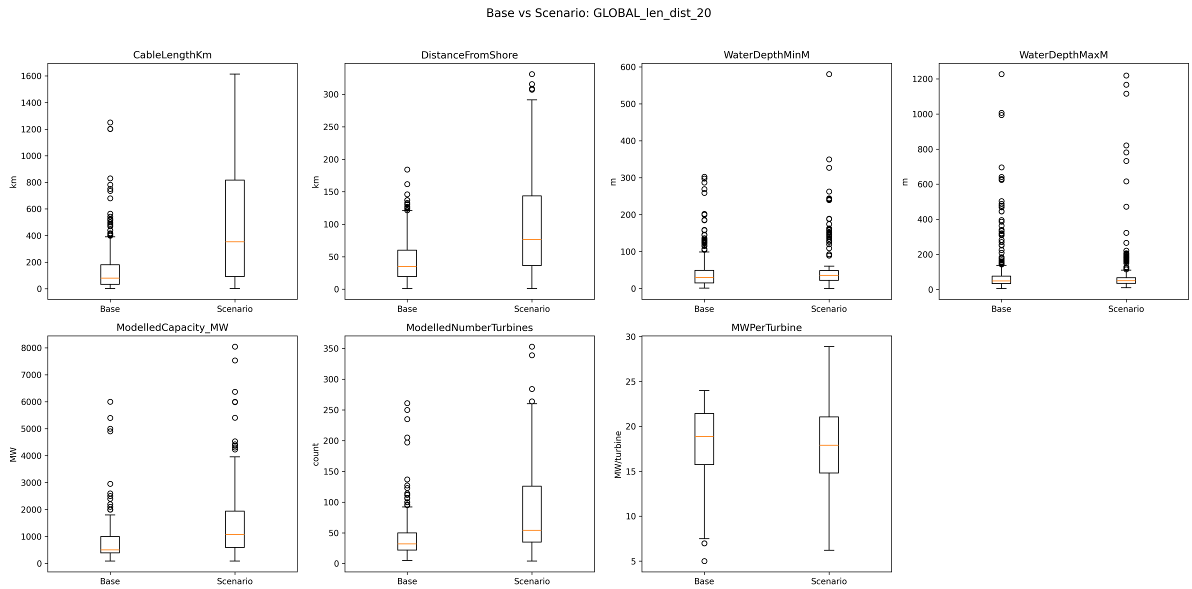


Figure C.3: Base-versus-scenario boxplots for the global `len_dist_20` scenario, using a nominal +20% length–distance multiplier and an HVDC-share target of 35%.

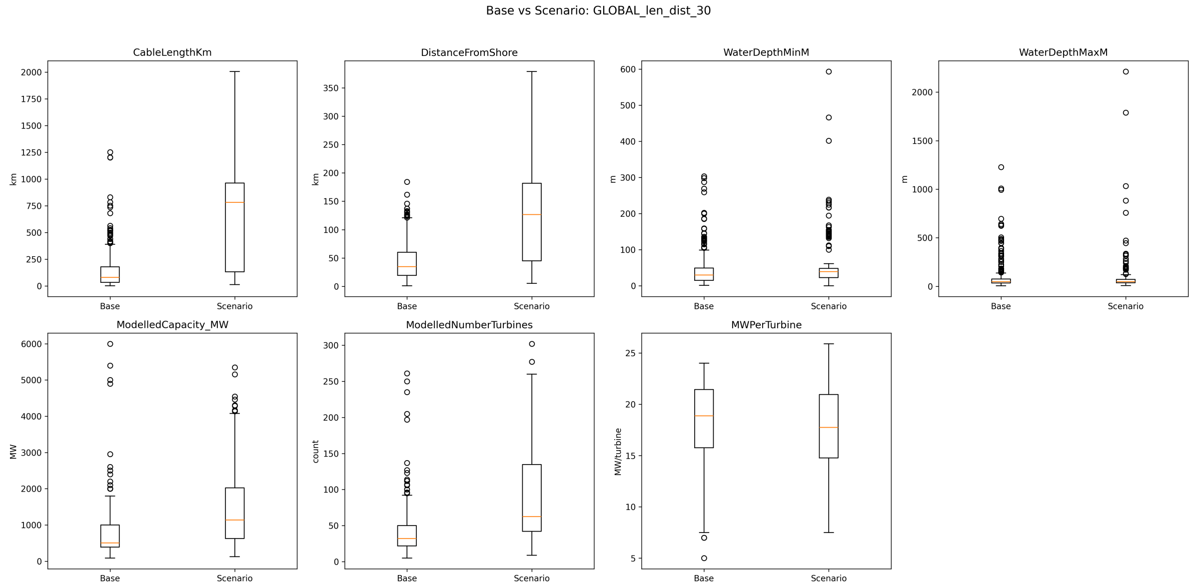


Figure C.4: Base-versus-scenario boxplots for the global `len_dist_30` scenario, using a nominal +30% length–distance multiplier and an HVDC-share target of 50%.

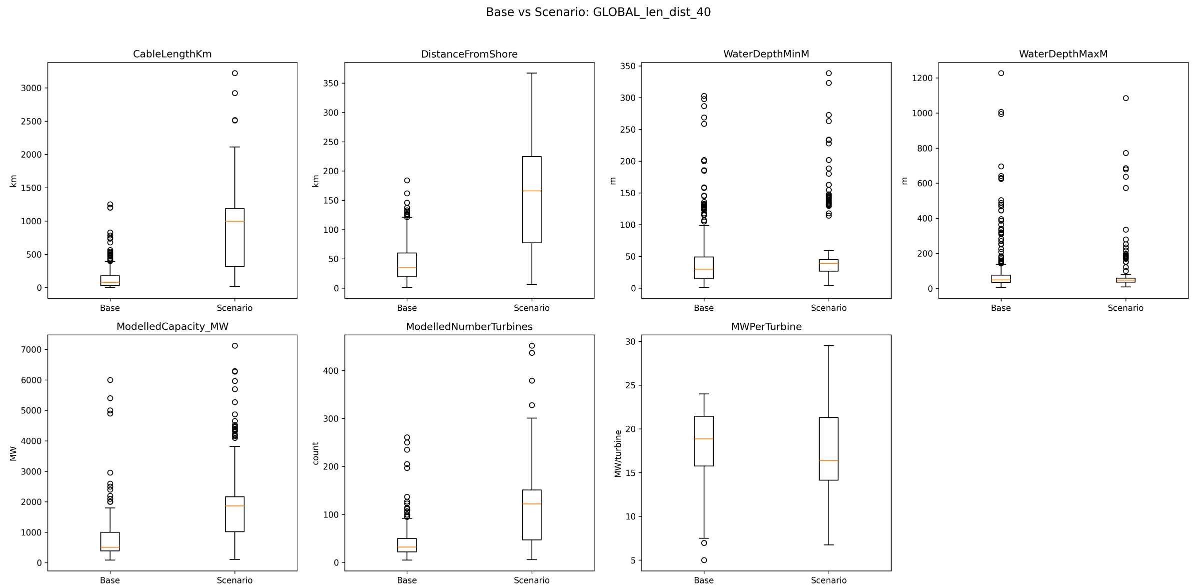


Figure C.5: Base-versus-scenario boxplots for the global `len_dist_40` scenario, using a nominal +40% length–distance multiplier and an HVDC-share target of 65%.

C.3. Depth/Floating Scenarios

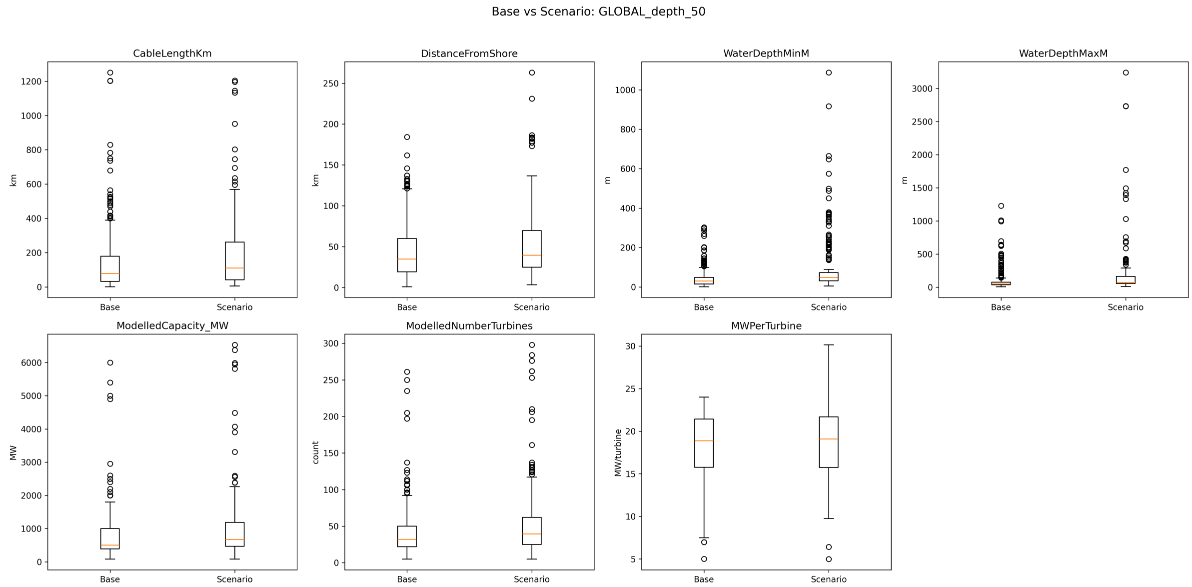


Figure C.6: Base-versus-scenario boxplots for the global `depth_50` scenario, using a nominal +50% water-depth multiplier and a floating-project-share target of 25%.

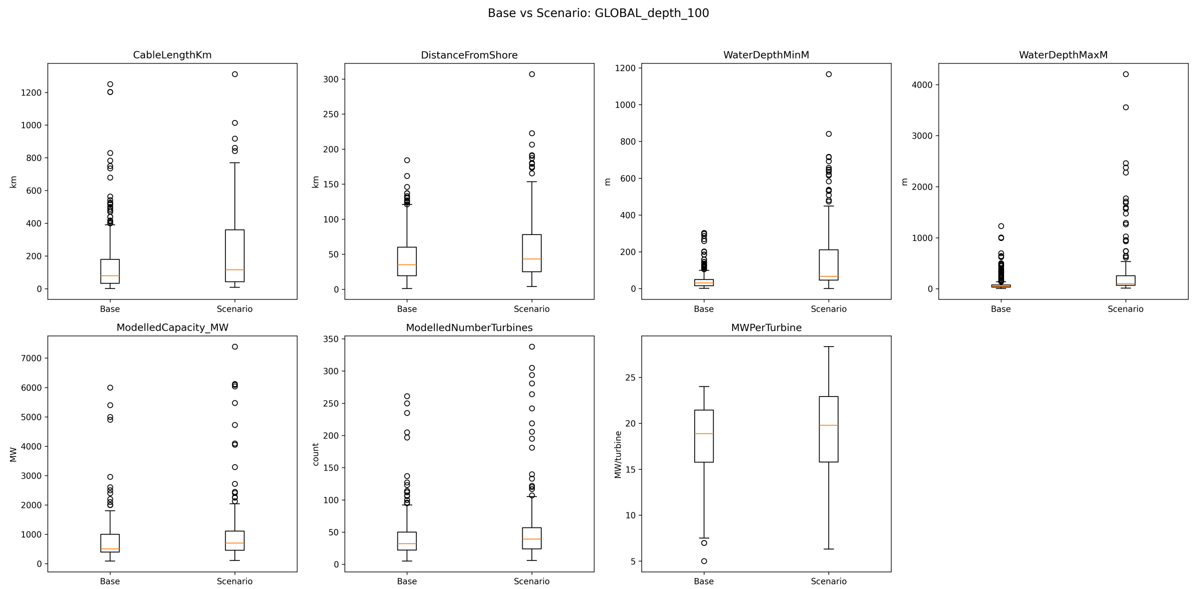


Figure C.7: Base-versus-scenario boxplots for the global `depth_100` scenario, using a nominal +100% water-depth multiplier and a floating-project-share target of 40%.

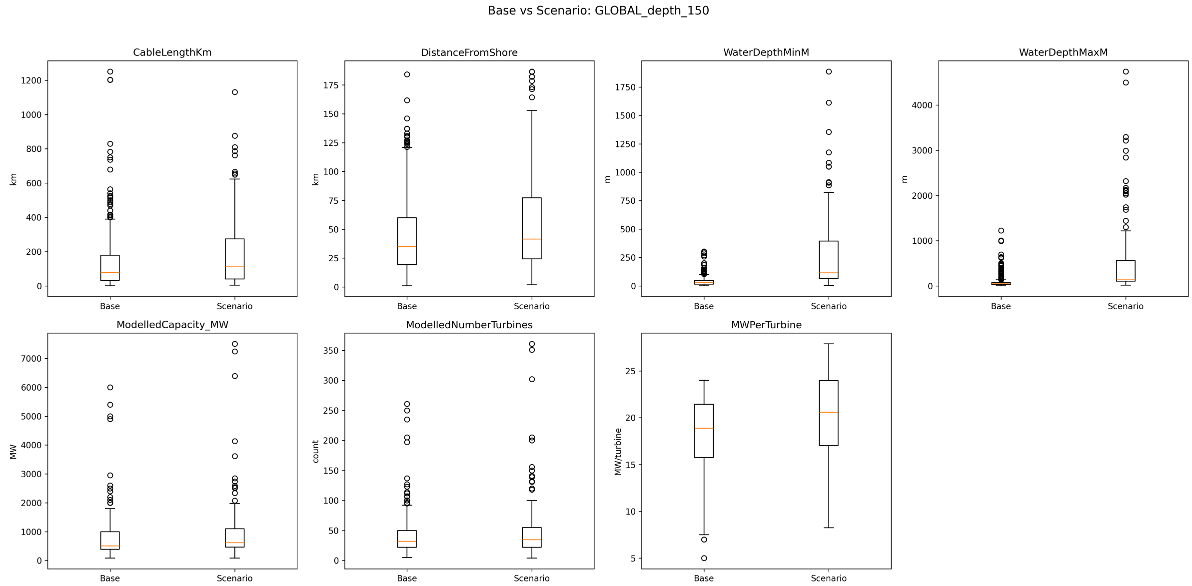


Figure C.8: Base-versus-scenario boxplots for the global **`depth_150`** scenario, using a nominal +150% water-depth multiplier and a floating-project-share target of 55%.

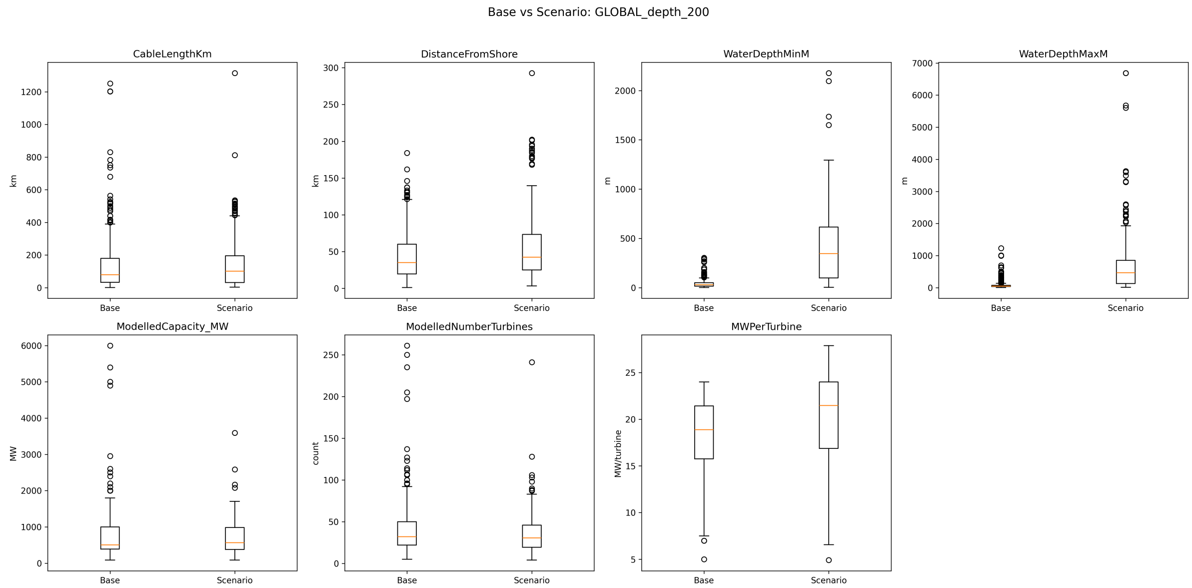


Figure C.9: Base-versus-scenario boxplots for the global **`depth_200`** scenario, using a nominal +200% water-depth multiplier and a floating-project-share target of 70%.

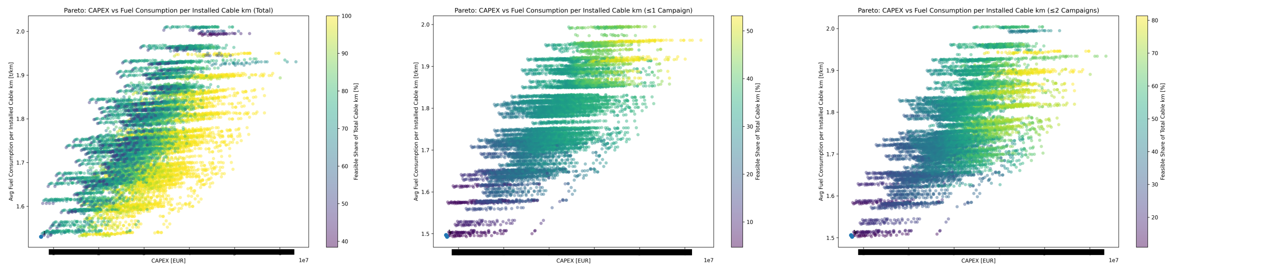
D

Supporting Results for Scenario Evaluation

This appendix provides supporting result figures for Chapter 8. The main chapter focuses on the figures and tables needed for the core argument, while the additional plots below provide supporting evidence for selected interpretation choices.

D.1. Campaign-Bucket Pareto Comparison

Figure D.1 compares the Pareto trade-offs for the total feasible set and the one- and two-campaign buckets in the base-like scenario. The corresponding at-most-three-campaign trade-off is presented in Figure 8.1 and is not repeated here. Together, these figures support the choice to use portfolio cable-kilometre capture within at most three campaigns as the principal campaign-limited performance metric.



(a) Total feasible

(b) ≤1 campaign

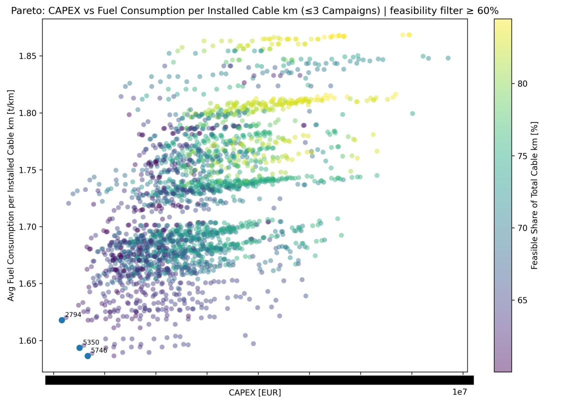
(c) ≤2 campaigns

Figure D.1: Comparison of base-like Pareto trade-offs for different campaign buckets.

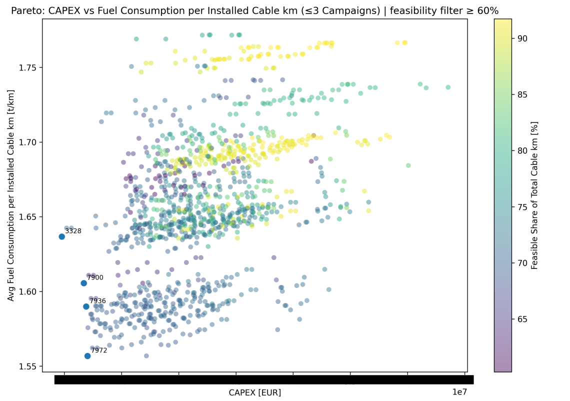
D.2. Scenario Pareto Plots for the Main Campaign-Limited Metric

This section provides the complete set of Pareto plots for the principal campaign-limited performance metric used in Chapter 8. Each plot compares mission-equipment CAPEX with average fuel consumption per installed cable kilometre for projects completed within at most three campaigns. The colour scale represents portfolio cable-kilometre capture within the same campaign limit. A 60% portfolio-capture threshold is applied where possible, following the screening logic introduced in Section 6.6. Because the colour scale is generated separately for each scenario plot, colours should be interpreted within each subplot rather than compared directly between subplots.

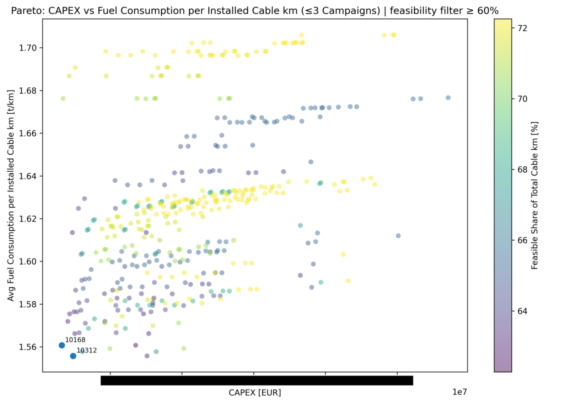
D.2.1. Length--Distance/HVDC Scenarios



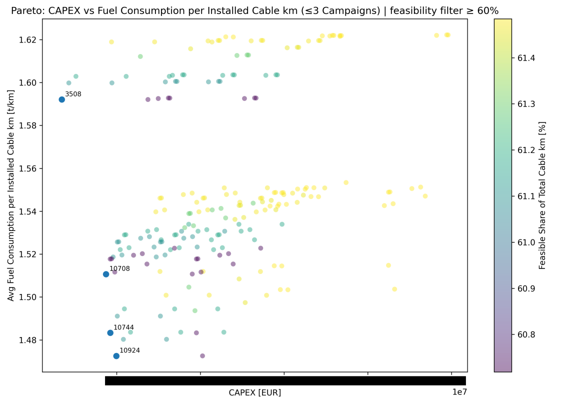
(a) `len_dist_10`: cable length and distance +10%, HVDC share 20%.



(b) `len_dist_20`: cable length and distance +20%, HVDC share 35%.



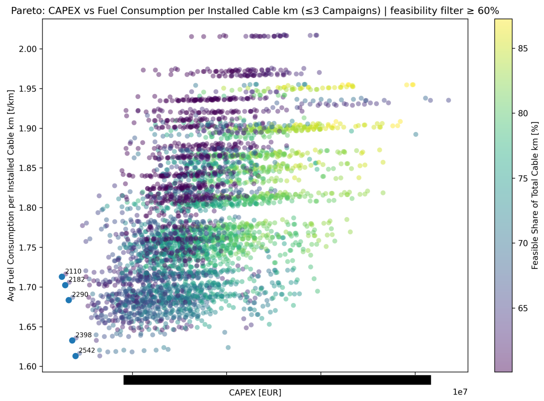
(c) `len_dist_30`: cable length and distance +30%, HVDC share 50%.



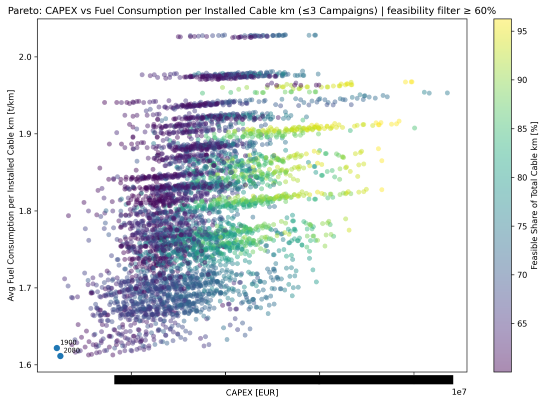
(d) `len_dist_40`: cable length and distance +40%, HVDC share 65%.

Figure D.2: CAPEX–fuel trade-off plots with Pareto fronts for the length–distance/HVDC scenario family, using portfolio cable-kilometre capture within at most three campaigns as the campaign-limited performance metric.

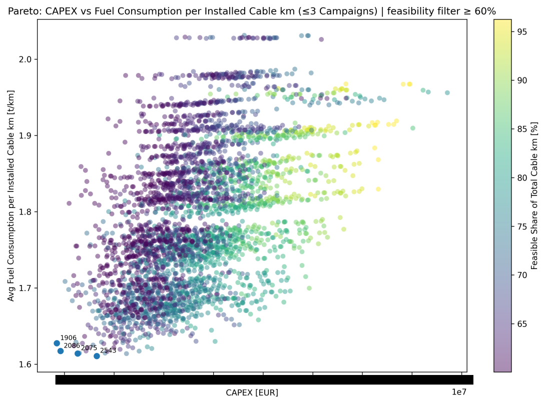
D.2.2. Depth/Floating Scenarios



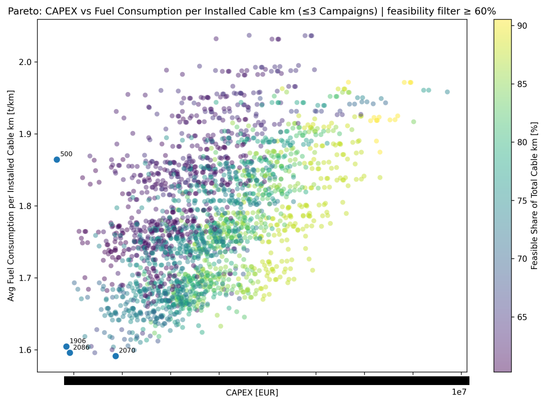
(a) `depth_50`: water depth +50%, floating share 25%.



(b) `depth_100`: water depth +100%, floating share 40%.



(c) `depth_150`: water depth +150%, floating share 55%.



(d) `depth_200`: water depth +200%, floating share 70%.

Figure D.3: Pareto plots for the depth/floating scenario family, using the at-most-three-campaign performance metric.