SEASTARS

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SUSTAINABLE EMISSION ABATEMENT STRATEGIES & TECHNOLOGIES
FOR ADVANCED REVOLUTION SHIPS

D1.1

Report on the Systems Engineering Methodology for the Modularization

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Abbreviations and Terminology

Partners - Abbreviations	
AMC	ALFA MARIN TECHNIKH SYMVOULEYTIKH MELETON KAI ERGON EPE
ATHINA	ATHINA KENTRO NAFTIKIS KATARTISIS KAI EXELIXIS ANONYMI ETAIREIA
AURELIA	AURELIA DESIGN B.V.
Bound4Blue	BOUND 4 BLUE SL
COMPOSITE RECYCLING	COMPOSITE RECYCLING SA
DG TWIN	DG TWIN SRL
Erma First	ERMA FIRST ESK ENGINEERING SOLUTIONS SA
HEMEXPO	ELLINES KATASKEVASTES NAFTILIAKOU EXOPLISMOU ASTIKI MI KERDOSKOPIKI ETAIREIA (HEMEXPO)
QUADRISE	QUADRISE INTERNATIONAL LIMITED
MARIN	STICHTING MARITIEM RESEARCH INSTITUUT NEDERLAND
MERCURIUS	MERCURIUS SHIPBUILDING BV
METACON	METACON MONOPROSOPI ANONYMI ETAIREIA
MINERVA	MINERVA MARINE INC. TRUST COMPANY COMPLEX,
NEPTUNE LINES	NEPTUNE LINES SHIPPING AND MANAGING ENTERPRISES S.A.
RINA	RINA HELLAS ETAIRIA PERIORISMENIS EVTHINIS NIOGNOMONAS
UoB	THE UNIVERSITY OF BIRMINGHAM
UOS	UNIVERSITY OF STRATHCLYDE
VERTORO	VERTORO BV
Voyex	Voyex B.V.

Abbreviations	
CAD	Computer aided Design
CAPEX	CAPital Expenditure
CCS	Carbon Capture and Storage
CFD	Computational Fluid Dynamics
CII	Carbon Intensity Indicator
CINEA	European Climate, Infrastructure and Environment Executive Agency
CSRD	Corporate Sustainability Reporting Directive
CTUe	Comparative Toxic Units for ecosystems
CTUh	Comparative Toxic Units for humans
DCF	Discounted Cash Flow
DMP	Data Management Plan
DP	Data Platform
DPP	Discounted Payback Period
DSCR	Debt Service Coverage Ratio
DT	Digital Twin
EEDI	Energy Efficiency Design Index
EFRAG	European Financial Reporting Advisory Group
EROEI	Energy Return on Energy Invested
ESG	E nvironmental, Social, and Governance
ETS	Emissions Trading System
HFO	Heavy Fuel Oil
IMO	International Maritime Organization
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LCOE	Levelised Cost of electricity
LOHC	Liquid Organic Hydrogen Carriers
MBSE	Model-Based Systems Engineering
MDO	Marine Diesel Oil
MEPC	Marine Environment Protection Committee
MGO	Marine Gas Oil
MRV	Monitoring, Reporting, and Verification
NAI	Net Annual Income
NFRD	Non-Financial Reporting Directive
OFB	Oil-Fired Boiler
OPEX	OPerational EXpenditure

OPS	Onshore Power Supply
POCP	Photochemical Ozone Creation Potential
RFNBOs	Renewable Fuels of Non-Biological Origin
RMSE	Root Mean Square Error
ROI	Return on Investment
SDG	Sustainable Development Goals
SFOC	Specific Fuel Oil Consumption
SOC	State of Charge
TCO	Total Cost of Ownership
TRUST	Transparency, Responsibility, User focus, Sustainability, and Technology
WMO	World Meteorological Organization
WTT	Well-to-Tank
TTW	Tank-to-Wake
WTW	Well-to-Wake

Terminology	
Digital Twin	A digital replica of a physical asset, process or system that can be used for various purposes including monitoring, simulation and optimization.
MBSE	A methodological approach that uses digital models as the primary means of information exchange and system development

Executive Summary

By **combining innovative decarbonization technologies for shipping applications**, the SEASTARS project has the main objective of **demonstrating a well-to-wake GHG emissions reduction of minimum 30% by 2030 (compared to 2008) as well as a 20% energy efficiency improvement (compared to 2022 reference performance) on 8 market-ready vessel designs (4 retrofits and 4 newbuilds)** operated over inland, short and high-seas routes. Emission reduction measures and efficiency enhancement are considered at different levels, both **directly related to the vessel's hydrodynamics**, through propeller-hull optimization and air lubrication implementation, **and to the energy conversion and use onboard**. In this respect, technologies such as fuel cells, electric motors, integrated solar panels, sails and electrochemical storage systems are contemplated, as well as alternative fuels such as biofuels, hydrogen, methanol, LNG, ammonia and energy treatment systems like fuel preparation, fuel reforming, cold ironing and Carbone Capture Storage (CCS).

The final project outcome is a **smart design tool suitable to support shipowners in achieving a concrete future-proof efficiency enhancement of their fleets while reducing operational costs and acknowledging capital expenditure**, thus providing a robust decision-making instrument for integrated sustainability and profitability purposes.

Shipowners' needs and modular technology integration are seamlessly aligned by the project, so as to ensure that every retrofit or new build delivers measurable efficiency gains, **finally accelerating the uptake of new technologies and the reduction of the environmental impact of the shipping industry**.

The most innovative aspect of SEASTARS lies in **the adopted approach**, which **fully accounts for the growing complexity of modern ship systems, as coupled with amplified industry demands** for cost-effectiveness, environmental sustainability and accelerated market entry.

Model-Based Systems Engineering (MBSE) is proposed by the Consortium as a methodology to be applied, a pivotal evolution from traditional document-centric methods towards a model-driven engineering paradigm. By establishing comprehensive system representations alongside domain-specific models, MBSE facilitates improved collaboration between multi-disciplinary Partners and the information exchange throughout the engineering lifecycle. It enhances various systems engineering functions, including requirements specification, architectural design, and downstream development activities, by centralizing system models as the primary engineering artifacts. **Models, indeed, play a crucial role as they not only provide structured system information and specifications but also serve to build a cross-disciplinary communication framework**.

The present **Deliverable examines the MBSE methodology and especially the adopted practices by the Consortium**, as defined in Work Package 1, to establish a strong foundation for the SEASTARS project's activities and provide a smart guideline to Partners for a collaborative and effective R&D action.

1 Introduction

*The SEASTARS project **is fully committed to driving decarbonization and energy efficiency** in the maritime industry, **ensuring compliance with evolving regulations** and fostering sustainable innovation.*

In the contemporary global landscape, sustainability has definitely transcended the dimension of a mere trend to become a critical imperative at all levels, especially for business. A multitude of environmental and also societal challenges have indeed emerged worldwide in the last decades, primarily related to climate change. Mitigation of this last has therefore become a core objective worldwide, compelling a reduction in greenhouse gas (GHG) emissions, particularly carbon dioxide (CO2), methane (CH4) and nitrous oxide (N2O), recognized as primary drivers of global warming (The Current State of the Climate).

Under the Paris Agreement (The Paris Agreement, s.d.), many Countries have in fact set the well-known aspirational goal of limiting long-term global warming to no more than 1.5 °C (2.7 °F) with respect to a pre-industrial level. The state of the climate in recent years, however, gave ominous new significance to the expression “off the charts”. Recent reports from the World Metereological Organization (WMO), in fact, show worrisome data for greenhouse gas levels, surface temperatures, ocean heat and acidification, sea level rise, Antarctic Sea ice cover and glacier retreat, especially in the latest 10 years, recognized as the warmest on record (State of Global Climate 2023).

Earth’s average surface temperature in 2024 was the warmest on record since recordkeeping began in 1880 (source: NASA/GISS). Overall, Earth was about 1.47 degrees Celsius warmer in 2024 than in the late 19th-century (1850-1900) preindustrial average.

A single year average Earth temperature getting so close to the set target of 1.5 °C is undoubtedly a unambiguous warning sign of how close the overall climate system has come to exceeding the Paris Agreement goal. With greenhouse gas emissions continuing to set record highs, it is likely that climate will regularly exceed 1.5 °C in the next decade, and, indeed, according to predictions, current climate change mitigation trajectories indicate a 2.7°C rise by 2100, if no significant changes are implemented (Climate Action Tracker, s.d.).

Impacts of climate change are indeed already far-reaching and are increasingly directly or indirectly affecting various sectors of the global economy. Extreme weather events damage infrastructure, displace populations, and strain resources, particularly affecting vulnerable communities. Rising temperatures impact agricultural yields, leading to food insecurity and economic instability. Coastal regions face rising sea levels, threatening coastal economies and livelihoods. These environmental disruptions may even trigger migration, social unrest, and geopolitical tensions, further complicating the socio-economic landscape. From a financial perspective, increased frequency and intensity of natural disasters create instability , due to significant risks to disrupt supply chains, damage infrastructure, leading to business interruptions, affecting productivity and profitability. Climate change-related regulations and carbon pricing also alter business models and investment decisions, affecting corporate profitability and economic growth. Quantifying these interrelated impacts is therefore a crucial aspect.

The maritime transport accounts for 2.9% of global emissions and 3-4% of EU's total CO_2 emissions (over 124 million tonnes in 2021). Without action, these emissions could increase by up to 130% by 2050, undermining Paris Agreement objectives.

The promotion of sustainable shipping and sustainable maritime development is one of the major priorities of the International Maritime Organization (IMO), a specialized agency of the United Nations responsible for regulating maritime transport. Established in 1948 following a UN conference in Geneva and officially operational since 1958, the IMO serves as the global standard-setting authority for the safety, security and environmental performance of international shipping. Headquartered in London, United Kingdom, the IMO currently has 176 Member States and three Associate Members as of 2024.

As part of the United Nations family, IMO is actively working towards the 2030 Agenda for Sustainable Development and the associated SDGs, with particular emphasis on SDG 14 (Life Below Water). Recent initiatives include developing mandatory marine fuel standards and greenhouse gas emissions pricing mechanisms to address climate change, demonstrating the organization's commitment to environmental stewardship alongside traditional safety and security concerns.

In Europe, the European Green Deal's "Fit for 55" package, complementary measures include the FuelEU Maritime Regulation setting greenhouse gas limits for ship energy use, the Alternative Fuels Infrastructure Directive mandating shore-side electricity targets, increased renewable energy targets to 40% by 2030, and removal of outdated tax exemptions for intra-EU maritime transport.The EU's dual strategy focuses on improving energy efficiency through reduced fuel consumption and promoting renewable and low-carbon fuels, creating a comprehensive ecosystem for cleaner maritime technologies. While pursuing regional action, the EU coordinates with global efforts through the IMO, supporting the 2023 IMO GHG Strategy targeting net-zero emissions by around 2050 with interim reductions of 20-30% by 2030 and 70-80% by 2040.

1.1 Regulatory changes and restrictions in the European maritime sector

In recent years, the maritime transport sector has experienced a tightening of environmental regulations both at the international level (IMO) and within the European Union (EU), aimed at achieving rapid decarbonization. In particular, the adoption of the IMO 2023 strategy and the European FuelEU Maritime Regulation has set binding targets and precise deadlines for reducing ship greenhouse gas (GHG) emissions. Both regulatory frameworks require concrete measures to improve energy efficiency, the adoption of alternative low- or zero-emission fuels, and a systemic review of ship design and operational management. These regulations not only address the urgency of the ecological transition but also aim to safeguard the competitiveness of the European maritime industry in a rapidly evolving global context.

1.1.1 IMO 2023 Strategy – Resolution MEPC.377(80)

In July 2023, the IMO Marine Environment Protection Committee (MEPC) adopted Resolution MEPC.377(80), updating the initial 2018 strategy for the reduction of GHG emissions from international maritime transport, which in 2018 accounted for approximately 2.89% of global GHG emissions. The new strategy, aligned with the goals of the Paris Agreement and the UN 2030 Agenda, sets out four main levels of ambition:

1. Reduce the carbon intensity (gCO_2/ton-mile) of international shipping by 40% by 2030 compared to 2008, through improved energy efficiency;

2. Reduce total annual GHG emissions by at least 20%, striving for 30%, by 2030 compared to 2008;

3. Ensure that at least 5% (striving for 10%) of the energy used comes from zero or near-zero GHG emission technologies or fuels by 2030;

4. Reach net-zero GHG emissions by or around 2050.

The strategy evaluates the impact of alternative fuels across their full lifecycle (well-to-wake), and foresees short- and mid-term measures to achieve emission reduction targets, while promoting energy transition and ensuring a fair transition for all countries, with a particular focus on developing nations. Technical and financial support is needed to facilitate participation from least developed countries and small island developing states. The strategy is subject to review every five years, with the first revision scheduled for 2028. These revisions will consider updated emissions estimates and available mitigation options, and assess the impact of measures on different states to allow for necessary adjustments.

1.1.2 FuelEU Maritime Regulation – Regulation (EU) 2023/1805

Regulation (EU) 2023/1805, part of the “Fit for 55” package, is the European Union’s main legislative tool to reduce the environmental impact of maritime transport by mandating the use of renewable and low-carbon fuels. The regulation pursues a dual goal: achieving climate neutrality in the sector by 2050 and preserving the competitiveness of European maritime transport, which accounts for 75% of the EU’s external trade and 31% of its internal trade, involving more than 400 million passengers annually.
The regulation sets progressive limits on the GHG intensity of fuels used onboard, calculated on a well-to-wake basis. The target is to reach mandatory reductions of up to 80% by 2050.
Key provisions of the regulation include:

- **Scope**: Applies to all commercial ships over 5,000 gross tonnage entering or leaving EU ports, regardless of flag.

- **Exemptions**: Temporary exemptions are provided for routes between ports on islands with fewer than 200,000 residents, outermost regions, and public service passenger ships.

- **Mandatory use of Onshore Power Supply (OPS)**: From 2030, ships moored in designated EU ports must use OPS to meet their power needs, with exceptions for short stops or ships using zero-emission technologies.

- **Promotion of alternative fuels**: Renewable fuels of non-biological origin (RFNBOs) are incentivized with a multiplier of 2 from 2025 to 2033. If their market share is below 1% in 2031, a mandatory sub-target of 2% will apply from 2034.

- **Monitoring, reporting, and verification (MRV)**: Shipping companies must annually monitor and report data on energy use, GHG emissions, OPS usage, and fuels used, both underway and at berth. This data will be verified by accredited independent bodies and registered in the FuelEU database.

- **Sanctions and compliance**: Ships that fail to comply with emission limits or lack a valid compliance document will be subject to dissuasive and proportionate penalties, enforced by national authorities. Compliance deficits may be offset through carry-overs, borrowing, or pooling across multiple vessels.

The FuelEU Maritime Regulation is consistent with the European Green Deal and Regulation (EU) 2021/1119 on climate neutrality. It represents a strategic pillar for the ecological transition of maritime transport. Its full implementation requires the collection and analysis of extensive, reliable, and standardized datasets, enabling transparent and traceable monitoring of emission intensity trends across the sector.

1.2 Alignment of SEASTARS objectives with the regulatory framework

According to the project proposal, SEASTARS aims to achieve the following by 2030:

- 30% reduction in well-to-wake GHG emissions, using 2008 as the reference year;

- 20% improvement in energy efficiency, using 2022 as the operational baseline.

These targets apply to eight market-ready ship concepts (four retrofits and four newbuilds) and are fully aligned with the IMO strategy. Specifically, the 30% GHG reduction target matches the IMO's highest level of ambition for 2030. The 20% energy efficiency improvement, although not explicitly defined in IMO terms, is a valuable project-specific metric that complements the carbon intensity reduction target.
SEASTARS is also consistent with the EU regulatory framework: the adoption of dual baselines (2008 and 2022) reflects the availability and quality of historical data. The year 2008 is recognized by the IMO as the standard reference year for emissions, while 2022 is a more realistic benchmark for efficiency due to the technologies currently in use and the increased availability of operational data.

The importance of a solid baseline and dataset requirements

Establishing accurate baselines and monitoring progress toward SEASTARS objectives requires access to a large volume of technical and operational data, collected in a standardized and interoperable format. These data are essential to evaluate the energy and environmental performance of the proposed solutions, compare retrofits with newbuilds, and measure actual impacts in terms of GHG reduction and efficiency gains. The reference datasets clearly must meet key requirements, such as:

- **Extended temporal coverage** (at least from 2008 onward);
- **Completeness and quality**;
- **Consistency** in formats and units of measurement to enable proper comparisons;
- **Sufficient granularity** (per ship, voyage, segment, condition);
- **Verified origin** (IMO DCS, EU MRV, operators, shipowners, technology providers);
- **Controlled accessibility**, governed by internal Consortium rules to ensure secure sharing and protection of sensitive data.

This need is even more critical in light of the adoption of **Model-Based Systems Engineering (MBSE)**, which is central to the SEASTARS project approach. MBSE implementation relies on both real-world data and results of accurate digital models built to simulate decarbonization sub-systems over actual use profiles, to link them and assess technological alternatives, optimize modular configurations, support investment decisions, monitor performance at the ship or fleet level, and possibly adapt to evolving regulatory contexts. Without a robust and coherent dataset, MBSE models cannot be properly validated or used for the flexible modular design foreseen in the project. For this reason, the strategic decision to **include shipowners and technology providers directly in the Consortium** has proven crucial. Their participation ensures access to authentic operational data representative of real-world conditions, including fuel consumption, route and speed data, load conditions, environmental and weather data, technical configurations of onboard systems and others.

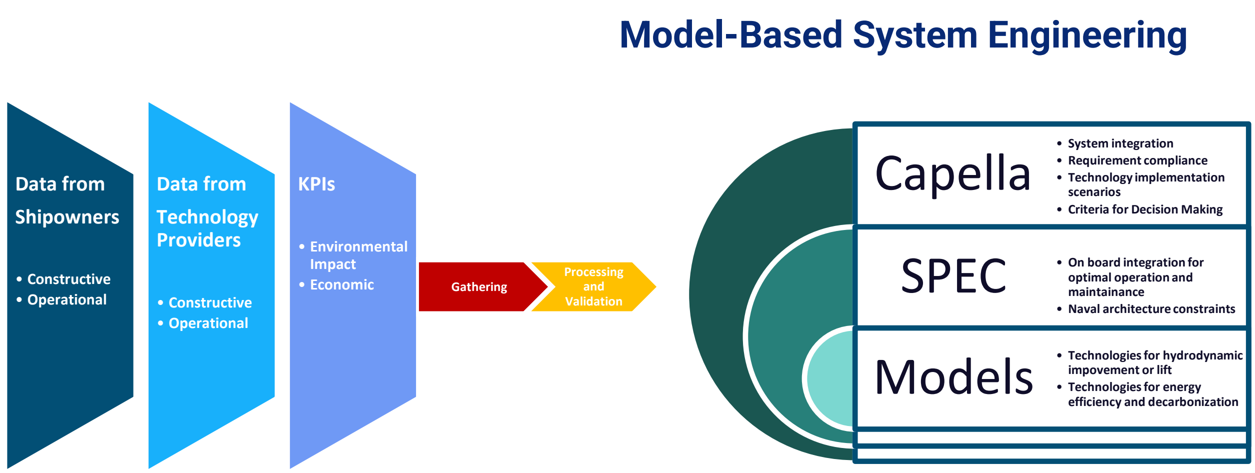

Figure 1. 1 - Schematic representation of the SEASTARS approach to shipping decarbonization.

The present Deliverable highlights the main aspects of the adopted methodology, whose schematization is provided in **Error! Reference source not found.** with a special focus on data gathering and management. In SEASTARS, **MBSE addresses sustainability challenges**, particularly in assessing and comparing different innovative technologies aimed at maritime transport decarbonization, through **a consistent modelling framework enabling to quantify environmental impacts alongside traditional performance metrics.**

By extremely simplifying the decided approach to the problem and with reference to the above figure, starting from **data collected by both shipowners (Sos) and technology providers (TPs)**, and having established proper **Key Performance Indicators (KPIs)**, processing and validation is first realized by the consortium Members in order to apply the chosen frameworks for decision making. In particular, the central role is given to the **ARCADIA/CAPELLA open source software** (Arcadia Capella, s.d.), dedicated to system integration and decision making, by also resorting to the **in-house code SPEC (Ships Power and Energy Concepts)** by the Partner MARIN to evaluate the dimension constraints and other issues relevant to the real implementation onboard of each considered ship. The chosen framework will integrate **properly developed numerical models of the selected innovative decarbonization technologies** by the University of Birmingham and DG Twin to deeply describe innovative decarbonization technologies and evaluate their potential to enable meeting the set decarbonization objectives. The **whole digital thread will be implemented on a proper data platform** whose features are better explained in the SEASTARS Data Management Plan.

After this first Chapter being the needed Introduction to the Deliverable D1.1, Chapter 2 deeply addresses the MBSE approach, Chapter 3 focuses on its application in the maritime ship design and the specifically adopted procedure by the Consortium, while Chapters 4 and 5 respectively present the data gathering processing and validation steps and the KPI definition relevant to the SEASTARS objectives.

2 Model-Based Systems Engineering

2.1 Definition and Scope

Systems Engineering is *"the process of managing requirements to include user and stakeholder requirements, concept selection, architecture development, requirement flowdown and traceability, opportunity and risk management, system integration, verification, validation and lessons learnt"* (Forsberg, Mooz, & Cotterman, 2005). This multidisciplinary engineering approach integrates complex "systems of systems" across their entire lifecycles, providing a structured and robust methodology that guides the design, development, production, and ongoing maintenance of complex products such as maritime vessels.

One of the most widely recognized frameworks for organizing and visualizing systems engineering activities is the Dual Vee model (Mooz & Forsberg, 2006), illustrating the systems engineering process as a V-shaped path that begins with user needs on the upper left, progresses downward through system requirements and design, and then moves upward to the right through integration, verification, and validation (Figure 2.1). The left side of the V represents the decomposition and definition activities, breaking down requirements from the system level to the component level. The bottom of the V represents the implementation phase, where detailed design and development occur. The right side represents the integration and verification activities, where components are progressively assembled and tested against the requirements defined on the corresponding left side. This approach ensures that each requirement is properly verified and validates that the final system meets the original user needs.

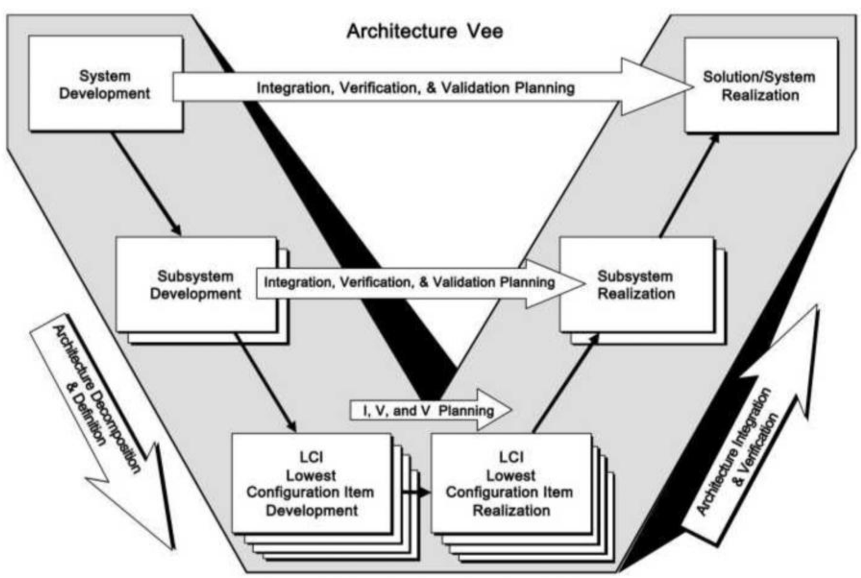

Figure 2.1 - The Systems Engineering Dual Vee Model (Mooz & Forsberg, 2006).

Within this context, the following definition of Model-Based Systems Engineering (MBSE) is introduced (INCOSE, s.d.).

> *"Model-Based Systems Engineering is the formalized application of modelling to support system requirements, design, analysis, verification, and validation activities beginning in the conceptual design phase and continuing throughout development and later lifecycle phases".*

In contrast to document-centric approaches, **MBSE gives role to models** in the specification, design, integration, validation, and operation of a complex system. It provides a structured approach where activities that support the engineering process are accomplished through the development of increasingly detailed models. Figure 2.2 schematizes advantages of virtualization by proper models in systems engineering, again by referring to the Vee model. **The representation of sub-components or processes within suitable modelling frameworks allows a faster verification of requisites and facilitates verification up to the final release of the system as a whole**.

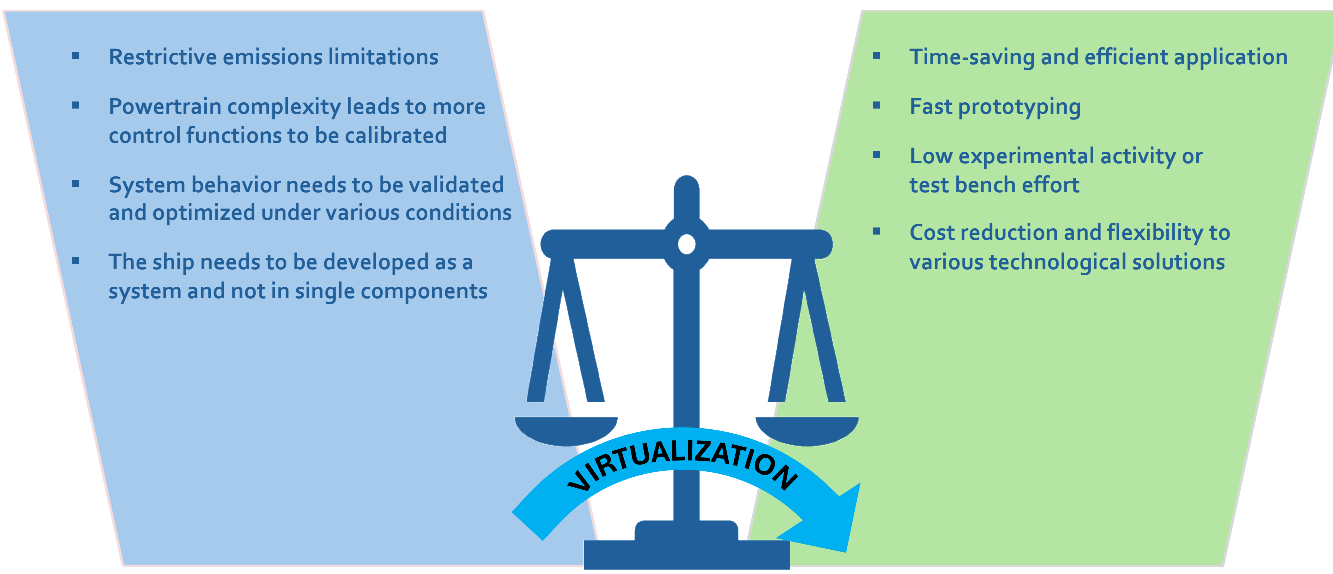

Figure 2. 2 - The virtualization approach in the Vee model, favoring the matching between prerequisites and solutions.

The main prerequisite for MBSE is a clear purpose agreed upon by all stakeholders, while models provide a key support throughout the entire development lifecycle - from initial concept formulation through trade-off evaluations, architectural decisions, detailed design, and ultimately system integration, verification, and validation across both hardware and software domains. The architectural phase of MSBE, therefore, needs the choice of specialized models addressing distinct aspects as functional capabilities, including interfaces, performance metrics. Beyond development, models serve as valuable knowledge repositories, maintaining information currency while ensuring change traceability (Wymore, 2018).

Generally speaking, and according to Friedenthal et al. (Friedenthal, Moore, & Steiner, 2008), modeling has four primary purposes: characterizing existing systems, specifying new or modified systems, evaluating system performance, and training system operators and maintenance personnel. A more recent interpretation sees models as knowledge generators, delivering specific outcomes such as discussion frameworks, formal specifications, or simulation foundations for progressive upgrades of products or processes. In fact, while model-based approaches aren't entirely novel, digital transformation has dramatically expanded their adoption by also opening the way to their use beyond the design phase, thanks to the connection enabled in Internet of Things (IoT) between any real object and its virtual counterpart.

Indeed, modeling gained prominence in mechanical and electrical engineering during the 1980s when 3D CAD tools began replacing traditional drafting boards (this transition established CAD as an indispensable methodology that enhanced design modularity, reduced development timelines, and created reusable, easily modifiable models usable also for stress analysis purposes) and in the 90s especially for Computational Fluid Dynamics (CFD) applications. Today's role of numerical models is by far increased, especially where high system complexity leads to misunderstandings, interpretive errors, and divergent objectives among stakeholders with different perspectives. The current reality necessitates a multidisciplinary approach that considers systems holistically while accommodating diverse disciplinary viewpoints. Within a problem-solving cycle, models facilitate this last requirement, since they allow performing analysis and synthesis at various detail levels - from a system-wide perspective to granular component views. Synthesis represents the constructive, creative process that produces system specifications from initial sketches to detailed models. Analysis provides the deconstructive, evaluative component that employs simulation to identify design strengths and weaknesses. These complementary approaches operate iteratively, as, say, exemplified in engineering methodologies like the VDI 2221 (Jänsch & Birkhofer, The development of the guideline VDI 2221, 2006) which structures problem-solving through sequential steps: problem analysis, problem formulation, system synthesis, system analysis, assessment, decision-making, and feedback implementation.

Given these reasons, it can be said that **MBSE strongly supports the systems engineering process** by:

- **capturing and analyzing requirements in structured, model-based formats;**
- **providing a consistent system representation across all lifecycle phases;**
- **enabling analysis and simulation of system behavior before physical implementation;**
- **supporting verification and validation through model-based testing;**
- **facilitating communication among multidisciplinary teams;**

- **enabling traceability from requirements to implementation.**

2.2 Models and Simulation in Systems Engineering

In the systems engineering context, numerical models serve dual functions as they support the description of activities, inputs, work items, and outputs through informal visual representations, while also enabling information processing in model-based development through more formal digital structures.

A model is fundamentally defined as a **physical, mathematical, or otherwise logical representation of a real system, entity, phenomenon, or process**. Models possess three essential properties, namely 1) mapping property – they represent something natural or artificial originals that might themselves be models; 2) reduction – they selectively include attributes of the original, focusing only on those deemed relevant by creators or users; 3) pragmatism - they function as replacements for specific purposes within defined time intervals.

Models can be categorized into three major types:

- **Schematic models:** represent system components, processes, workflows, requirements, constraints, and information flows through diagrams and charts.
- **Mathematical models:** employ mathematical notation to describe system behavior, with equations representing relationships or functions.
- **Physical models:** directly reflect the physical characteristics of actual systems, whether as scale models, mock-ups, or prototypes.

From a development perspective, the approach to models can further be differentiated into:

- **White-box modeling:** applies physics principles to derive mathematical equations for simulation, with both internal structure and input/output parameters known.
- **Black-box modeling:** focuses on input/output behavior based on measured data and mathematical approximation.

Models serve different functions depending on creator, observer, and technical discipline:

- Specification (describing systems);
- Design exploration (gaining knowledge);
- Documentation (storing/digitalizing information);
- Communication (making information available to others).

Generally speaking, the purpose determines the scope of the modeling effort in terms of model breadth, depth, and fidelity, which must be balanced against available computational resources.

The term simulation involves manipulating and executing models under specified conditions over defined periods. In the systems engineering context, simulation is a virtual method for manipulating digitalized models with defined inputs to generate outputs for subsequent processing. It serves to gain system knowledge through analysis and to verify behaviour as part of validation activities.

Common simulation approaches include computer-based simulation and x-in-the-loop (XiL) simulation. XiL encompasses various controller types (Function-in-the-Loop, Model-in-the-Loop, Software-in-the-Loop, Processor-in-the-Loop, Hardware-in-the-Loop) interacting with simulated environments through appropriate interfaces. Models and simulation are intrinsically linked - simulation requires models, while models without simulation offer limited proof of assumptions. Both share important characteristics including degree of fidelity, abstraction level, connectivity, processability, performance capabilities, resolution, accuracy, stability, and uncertainty. Understanding these characteristics is essential for effective systems engineering implementation across development processes, particularly in the context of MBSE (Kaelble, 2022).

2.3 Key Benefits of MBSE

The adoption of MBSE was chosen within the SEASTARS project due to the complexity of the ship system and its operational behaviour, and especially since it offers several advantages over traditional document-based approaches (Kapurch, 2010):

1. **Improved Communication:** provides a common language and representation for stakeholders across disciplines;
2. **Enhanced Quality:** reduces errors through consistent system representation and automated verification;
3. **Better Requirements Management:** Offers improved traceability and impact analysis capabilities
4. **Effective Knowledge Transfer:** captures design decisions and rationale in structured models;
5. **Reduced Development Time and Cost:** enables early verification and validation through simulation;
6. **Improved System Integration:** supports interface definition and management under various constraints.

The methodology is a collection of related processes, methods, and tools, specifically characterized as the integration of these elements to support systems engineering. In particular, under multi-objective optimization design, it offers a comprehensive, scientifically-grounded approach to conform to requirements and constraints. As for sustainability purposes, in the three dimensions of this last - environmental, social and economic - MBSE may concretely enable compliance and operational resilience, addressing the critical gap identified in current frameworks (Bajzek, et al., 2020).

2.4 Survey of MBSE Methodologies

More recently, attention towards MBSE methodologies focused on ARCADIA/Capella, that will be used within the SEASTARS context. ARCADIA (Architecture Analysis & Design Integrated Approach) is a structured systems engineering methodology supported by CAPELLA, an open-source platform specifically designed for complex systems engineering (Capella, s.d.). This will be discussed in a following chapter of this Deliverable. Based on a previous INCOSE survey of MBSE methodologies by Estefan (Estefan, 2007), the following leading approaches were applied early in time:

IBM Telelogic Harmony-SE

Harmony-SE is a subset of a larger integrated systems and software development process. It uses a "service request-driven" modeling approach with SysML artifacts and includes three main process elements:

- Requirements analysis;
- System functional analysis;
- Architectural design.

Harmony-SE defines clear workflows and deliverables for each phase and uses model transformation to move between levels of abstraction.

INCOSE Object-Oriented Systems Engineering Method (OOSEM)

OOSEM integrates a top-down, model-based approach using SysML to support specification, analysis, design, and verification of systems. Key objectives include:

- Capturing and analyzing requirements and design information;
- Integration with object-oriented software development methods;
- Supporting system-level reuse and design evolution.

OOSEM includes the following development activities:

- Analyze Stakeholder Needs;
- Define System Requirements;

- Define Logical Architecture;
- Synthesize Candidate Allocated Architectures;
- Optimize and Evaluate Alternatives;
- Validate and Verify System.

IBM Rational Unified Process for Systems Engineering (RUP SE)

RUP SE extends the Rational Unified Process to systems engineering, applying its discipline and best practices to system specification, analysis, design, and development. Key elements include:

- New roles for systems engineers;
- New artifacts and workflows addressing systems engineering concerns;
- Emphasis on business modeling;
- Architecture framework with model levels and viewpoints;
- Support for allocated versus derived requirements.

Vitech Model-Based System Engineering (MBSE) Methodology

Vitech's MBSE methodology is based on four primary concurrent SE activities:

- Source Requirements Analysis;
- Functional/Behavior Analysis;
- Architecture/Synthesis;
- Design Validation and Verification.

It uses an incremental "Onion Model" approach that allows complete interim solutions at increasing levels of detail and includes a System Definition Language (SDL) to manage model artifacts.

JPL State Analysis (SA)

State Analysis is a JPL-developed methodology that leverages a model- and state-based control architecture. It:

- Provides a process for capturing system requirements as explicit models;
- Distinguishes between system "state" and "knowledge" of that state;
- Focuses on state variables, commands, and measurements;
- Supports closed-loop commanding and autonomous systems.

Dori Object-Process Methodology (OPM)

OPM is a formal paradigm combining visual models (Object-Process Diagrams) with natural language sentences (Object-Process Language) to express system function, structure, and behavior in an integrated model. OPM:

- Uses objects and processes as primary building blocks;
- Provides visual and textual representations of the same model;
- Manages complexity through refinement mechanisms;
- Supports system lifecycle processes.

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3 Application of MBSE within the maritime transport industry

3.1 MBSE Advantages for the maritime industry

In the maritime industry, **MBSE may radically transform the traditional development paradigm by embedding modeling and simulation throughout the entire vessel lifecycle**. Activities can commence at project inception and persist beyond delivery, supporting operations, maintenance, and decommissioning. The modeling depth may vary from comprehensive ones during critical design phases to simplified representations during operational support but remains fundamental to modern shipbuilding practices.

In the complex world of maritime systems development, in fact, **requirements management forms the cornerstone of successful engineering practices**. As vessels become increasingly sophisticated with integrated navigation systems, autonomous capabilities, and alternative propulsion technologies, the shipping industry faces unprecedented challenges in organizing and tracking requirements throughout the product lifecycle. Sustainability compliance and profitability issues further exacerbate this scenario nd amplify the difficulty in converging to optimal solutions.

Within the SEASTARS Consortium, naval architects as AURELIA and ALPHA MARINE CONSULTING have proven being a valuable asset since they directly witness requirements journey beginning with high-level features and functions — even initially sketched on a napkin during a meeting with a shipowner discussing vessel specifications like cargo capacity, operational range, and maximum speed – to then progressively realise the final design. Broad concepts must evolve into hundreds or thousands of detailed, testable requirements that cascade through systems and subsystems. For example, a requirement for reduced emissions might drive specifications for hybrid propulsion systems, which in turn generate requirements for battery systems, power management, and software controls.

Maritime systems engineering, in other words, demands meticulous organization of this requirements hierarchy. Each requirement must maintain clear parentage, ensuring traceability from the top-level vessel down to individual components. This genealogy prevents "orphan requirements" (those lacking clear lineage) and identifies potential gaps where high-level requirements lack proper implementation details. Such structured management is particularly critical in the shipping industry, as mentioned above, also due to the regulatory compliance with IMO regulations, classification society rules, and environmental standards, which are mandatory.

Effective requirements must be specific, measurable, and verifiable. Rather than bundling multiple specifications together and each aspect should constitute a distinct requirement. Clear criteria for verification must be also provided since these become vital when managing international maritime certification processes.

The MBSE digital thread revolutionizes how the shipping industry handles these requirements. Rather than relying on static documents that quickly become outdated, MBSE enables storing requirements as individual objects within a database, linking them to the vessel's architectural models. This integration allows engineers to extract values from requirements directly into CAD models of hull structures or simulation environments, testing vessel performance in various operational conditions and sea states.

Parameters — defined targets with acceptable ranges — form critical connections within this digital thread. For navigation systems, parameters might specify required accuracy, update frequency, redundancy levels, and recovery times. The digital thread tracks these parameters in sets: the goal (target), minimum acceptable value, maximum acceptable value, and current measured result based on the latest model iteration.

In both new ship design and evaluation of retrofitting options, this comprehensive approach enables shipping companies to identify conflict points early, preventing costly late-stage integration problems. When requirements change, say due to new emissions regulations or operational needs, the digital thread can provide an impact analysis across all affected systems. The result is a more efficient development process where virtual testing validates requirements before physical construction begins, significantly reducing the risk of expensive modifications during sea trials.

By adopting MBSE for requirements management, maritime organizations can achieve greater agility in vessel development while maintaining rigorous compliance with industry standards. This modern approach enables shipbuilders to handle the increasing complexity of vessel systems while delivering more innovative ships in less time and at lower costs.

Two transformative advantages distinguish the MBSE approach in maritime development:

Enhanced System Maturity in Early Development Stages

Maritime system modeling initiates during conceptual design on the left side of the Vee model of **Error! Reference source not found.**, creating visual representations that facilitate deeper understanding. While this approach requires greater front-end investment, it yields substantially more thorough vessel system consideration. The maritime engineer's cognitive processes naturally align with visual representations rather than textual documentation. When designing complex propulsion systems or bridge layouts, visual models enable engineers to identify spatial constraints, flow patterns, and operational ergonomics that would remain obscure in text-based requirement documents.

For example, when designing a new LNG carrier's propulsion system, early-phase modeling enables shipbuilders to visualize interactions between cryogenic storage, gas processing systems, and dual-fuel engines long before physical construction begins. This visual approach helps stakeholders—from engineers to classification societies—comprehend system behaviors holistically rather than as abstract textual descriptions.

Superior Quality Through Continuous Verification

Beyond enhancing understanding, MBSE elevates vessel quality through ongoing simulation-based verification throughout development. Maritime engineers can employ models to predict vessel performance under various operating conditions—from standard operations to extreme weather scenarios. By conducting these simulations early and continuously, shipbuilders implement "frontloading" - shifting verification activities earlier in the development process when changes cost significantly less.

Simulations enable comprehensive trade-off analyses across interconnected systems. For instance, when designing an offshore support vessel, engineers can simultaneously evaluate how modifications to hull design affect fuel consumption, stability, and dynamic positioning capabilities. Such integrated assessments would be virtually impossible without model-based approaches.

The financial impact is also substantial - defects identified during sea trials typically cost 100-1000 times more to rectify than those caught during design phases. Fewer change orders during construction can be reached after implementing MBSE practices for requirements validation, as potential issues with power distribution systems can be identified during simulation rather than during commissioning.

By establishing a continuous verification environment, maritime MBSE creates a development trajectory where each design iteration benefits from accumulated knowledge rather than repeating historical errors. This approach yields vessels with higher reliability, improved operational efficiency, and reduced maintenance requirements, enhancing both initial quality and long-term value and sustainability throughout the ship's operational lifecycle.

3.2 MBSE as Foundation for Digital Twin Implementation and Data-Driven Optimization

Nowadays, thanks to the IoT development, evolution of MBSE today may extend far beyond traditional design and verification phases, positioning itself as the fundamental foundation for implementing advanced digital twin technologies and enabling data-driven optimization throughout the system operational lifecycle. This paradigm shift represents a natural progression from somehow “static” design models to “dynamic” ones, namely continuously updated digital representations that mirror real-world system behavior in real-time.

Digital twins, defined as dynamic digital replicas of physical systems that continuously synchronize with their real-world counterparts through operational data streams, find their most robust establishment in the structured modeling framework established by MBSE. The comprehensive system representations, requirement traceability, and architectural documentation developed during the MBSE process provide the essential digital infrastructure upon which digital twin capabilities can be built. Rather than creating digital twins as separate, isolated systems, MBSE-developed models serve as the authoritative baseline that evolves into “living” digital representations.

The maritime industry exemplifies this evolution particularly well. In the SEASTARS context, the detailed vessel models developed through MBSE methodologies using tools like CAPELLA and SPEC establish a foundational digital architecture that can seamlessly transition into operational digital twins. These twins can continuously ingest real-world operational data - fuel consumption patterns, engine performance metrics, environmental conditions, cargo loads - to refine and validate the original design models while enabling predictive maintenance, route optimization, and performance enhancement strategies. The synergy between MBSE and digital twin implementation, indeed, creates unprecedented opportunities for data-driven system optimization. Traditional systems engineering approaches relied on design-phase assumptions and periodic validation exercises. However, MBSE-enabled digital twins facilitate continuous learning loops where operational data feeds back into the system models, enabling:

- **Real-time performance validation** against original design requirements and specifications;
- **Predictive analytics**, especially of environmental KPIs, that anticipate system behavior under varying operational conditions;
- **Adaptive optimization** where system parameters are continuously tuned based on actual performance data;
- **Anomaly detection** that identifies deviations from expected behavior patterns before failures;
- **Scenario planning** that evaluates alternative operational strategies using validated models.

In other words, the data-driven approach transforms static design artifacts into dynamic optimization tools. For maritime applications, this means that vessel performance models developed during design can continuously evolve based on actual voyage data, weather patterns, and operational profiles. The digital twin becomes not just a monitoring tool, but an active optimization engine that recommends operational adjustments, maintenance schedules, and even design modifications for future vessels. The whole SEASTARS project has been conceived in the view of this future eveolution that can even reinforce the already ambituous sustianble goals by the Consortium.

Furthermore, the structured approach inherent in MBSE ensures that digital twin implementations maintain the same rigor in requirements traceability, system boundaries definition, and verification protocols that characterize effective systems engineering practices. This prevents digital twins from becoming isolated data processing systems and instead integrates them into a comprehensive engineering ecosystem where design intent, operational reality, and continuous improvement converge.

It must be stressed that the maritime sector's adoption of **MBSE-enabled digital twins represents a transformative shift toward intelligent, self-optimizing systems that learn from their operational environment**. As vessels equipped with comprehensive sensor networks generate vast amounts of operational data, the MBSE-developed models provide the structured framework necessary to transform this data into actionable insights for improved efficiency, reduced emissions, and enhanced safety performance.

The integration of MBSE with digital twin technology establishes a new paradigm where the traditional boundaries between design, operation, and optimization dissolve, creating a continuous cycle of improvement that extends throughout the entire system lifecycle.

3.3 Main components of the MBSE approach of SEASTARS

The SEASTARS project aims to achieve substantial reductions in maritime greenhouse gas (GHG) emissions while enhancing vessel design in terms of operational efficiency. Success depends on developing accurate, validated digital models for both existing and emerging decarbonization technologies. These models serve two critical purposes: they enable pragmatic evaluation of key performance indicators (KPIs) for each solution under real-world shipping conditions, and they facilitate the virtual integration necessary for informed investment and retrofit decisions during the design phase. In a future perspective, models will also serve as the baseline for digital twins of the ship, namely, to progressively improve performances once the operation in the real world has started, with the integration of decarbonization technologies.

Creating an effective digital framework for decision-making requires several vital components, particularly relevant data and sophisticated processing tools. The modeling process centers on collecting and utilizing real operational data from both Technology Providers (TPs) and Ship Owners (SOs), as detailed in Chapter 4. The information provided by SOs proves especially crucial to achieving the project's objectives, as it forms the foundation for testing digital models with authentic operational data. This typically proprietary information, rarely made accessible to the public, enables identification of optimal technology combinations and integration methods for real ship systems.

Evaluating new technologies such as fuel cells or carbon capture and storage (CCS) systems requires detailed performance specifications and component analysis to assess onboard integration feasibility. Chapter 4 provides comprehensive details on the motivation, methods, and objectives behind data collection from Ship Owners and Technology Providers, including the KPI definitions adopted throughout the project.

Within the Consortium's established framework, the primary tools for data utilization include the ARCADIA/CAPELLA and SPEC components, along with Technology Provider models that will be developed within Work Package 4. In the following, a brief introduction to these core chosen instruments is made, although their full explanation will be the matter of other Deliverables.

3.4 CAPELLA and the ARCADIA Methodology

In order to implement the MBSE approach, SEASTARS uses **CAPELLA**, an open-source platform specifically designed to support the engineering of complex systems.

CAPELLA is based on the **ARCADIA methodology (Architecture Analysis & Design Integrated Approach)**, a structured systems engineering framework that guides users through a rigorous workflow, independent of the application domain. The software provides visual tools and automatic traceability across layers, enabling effective management of complexity. It is composed of **four main levels**, as in Figure 3.1:

1. **Operational Analysis**
    - Identifies stakeholder needs and the operations to be supported, describing missions and use-case scenarios at an abstract level.
2. **System Analysis**
    - Defines functional requirements and system expectations, translating operations into high-level functionalities and main interfaces.
3. **Logical Architecture**
    - Structures the system into logical subsystems, representing internal functions and interactions without referring to physical implementation.
4. **Physical Architecture**
    - Maps logical elements to physical components (hardware/software), considering technological, performance, and environmental constraints.

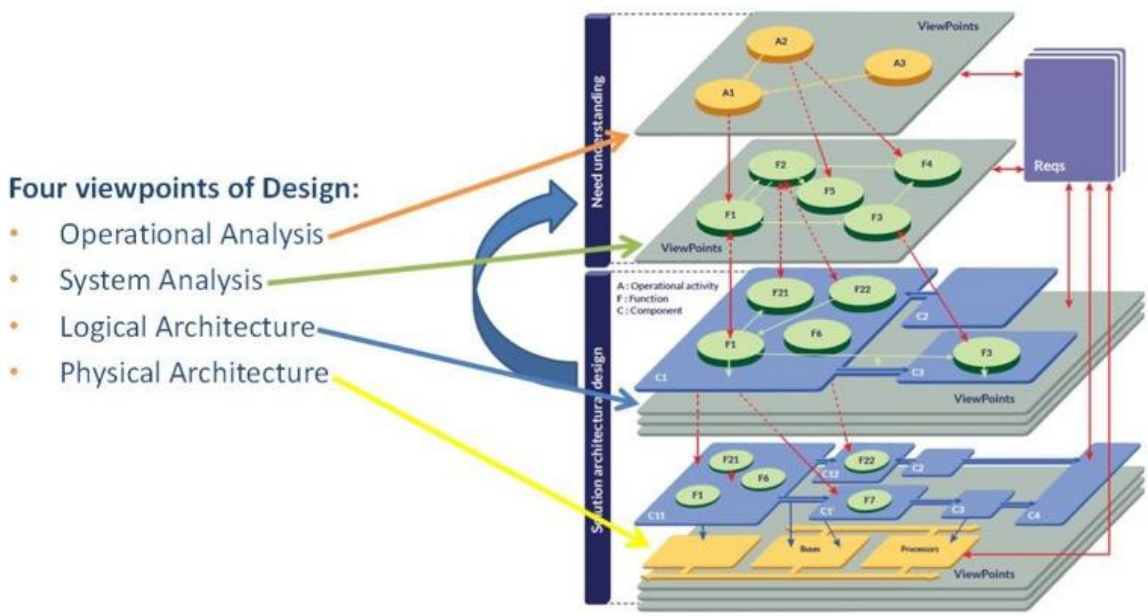


Figure 3. 1 - Four viewpoints of Design within the ARCADIA/Capella approach.

CAPELLA will be used here to:

- define modular ship architectures (retrofits and newbuilds);
- link technical solutions to environmental performance requirements;
- evaluate the impact of regulatory changes on the designed configurations;
- support collaboration between industrial and technical partners through shared, navigable models.

CAPELLA Workflow

Figure 3.2 shows a flow diagram summarizing the key steps to follow when modeling a complex system in Capella. The focus given in Figure 3.3 and also Figure 3.4 clarify some relevant aspects. Within the **Operational Analysis** phase, the first step is to create the **Operational Capability Diagram**, a model that identifies the expected operational capabilities of the system in its usage context. This diagram includes four key elements:

- **Operational Capabilities (OC)** – what the system should be able to do in operational terms;
- **Operational Entities (OE)** – entities involved in or influencing the operation (e.g., ships, ports, operators);
- **Operational Actors (OA)** – external actors interacting with the system (e.g., clients, authorities, suppliers);
- **Operational Requirements (OR)** – stakeholder-expressed needs in operational terms.

Once Operational Capabilities have been identified, they are broken down into **Operational Activities**, which are assigned to the relevant actors and entities. The result is the **Operational Architecture Diagram**, detailing the activities carried out by each actor across various operational scenarios.

In the next phase, **System Analysis**, Operational Activities are transformed into **System Functions**, allocated to **System Actors** (elements external to the system) and to the **System (Solution)** itself. In parallel, **System Requirements (SR)** are derived from the Operational Requirements. This transformation often requires specific calculations (e.g., energy performance, regulatory constraints), which are typically performed **outside CAPELLA** using appropriate simulation tools tailored to each requirement.

The integration of System Functions and System Requirements leads to the construction of the **System Architecture Diagram**, in which **System Boundaries** are defined and the essential elements of the Solution to be modeled are established. At this stage, high-level analyses can be carried out using **Functional Chains**, which represent logical sequences of functions related to a scenario or operational mission. These functional chains help assess the system's overall behavior in relation to specific objectives.

Once the **Need Analysis** phase is complete, the process moves to the **Solution Architectural Design** phase, where the Solution is progressively decomposed, transitioning from a "black box" to a "white box" representation.

The first step involves defining the **Logical Architecture**, in which the Solution is broken down into **Logical Components** with their corresponding **Logical Functions**. This results in the **Logical Architecture Diagram**, which provides an organized, abstract, and functional view.

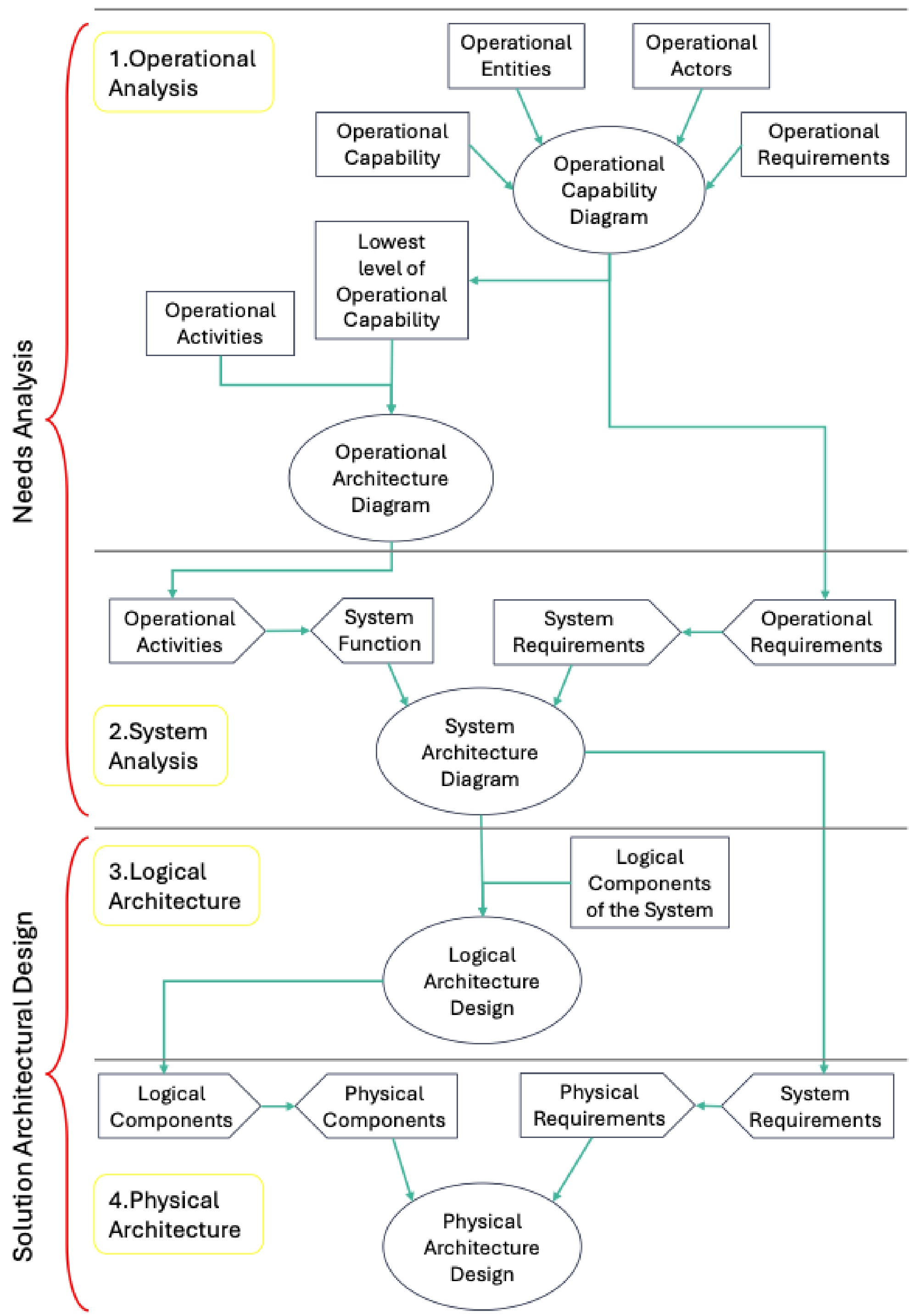


Figure 3. 2 - ARCADIA/CAPELLA Methodology Flowchart

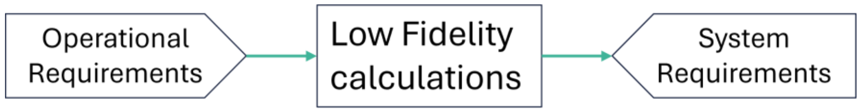


Figure 3. 3 - Focus on the transition between OR and SR.

As a next step, the Logical Components are transformed into **Physical Components**, and System Requirements are translated into **Physical Requirements**, resulting in the **Physical Architecture Diagram**. At this stage, the modeled solution can be evaluated against real-world physical, technological, and performance constraints.

A key strength of the CAPELLA environment is its **flexibility and traceability**: throughout the modeling process, it is always possible to go back, modify downstream or upstream elements, update relationships between requirements, functions, and components, and assess the impact of changes in real time.

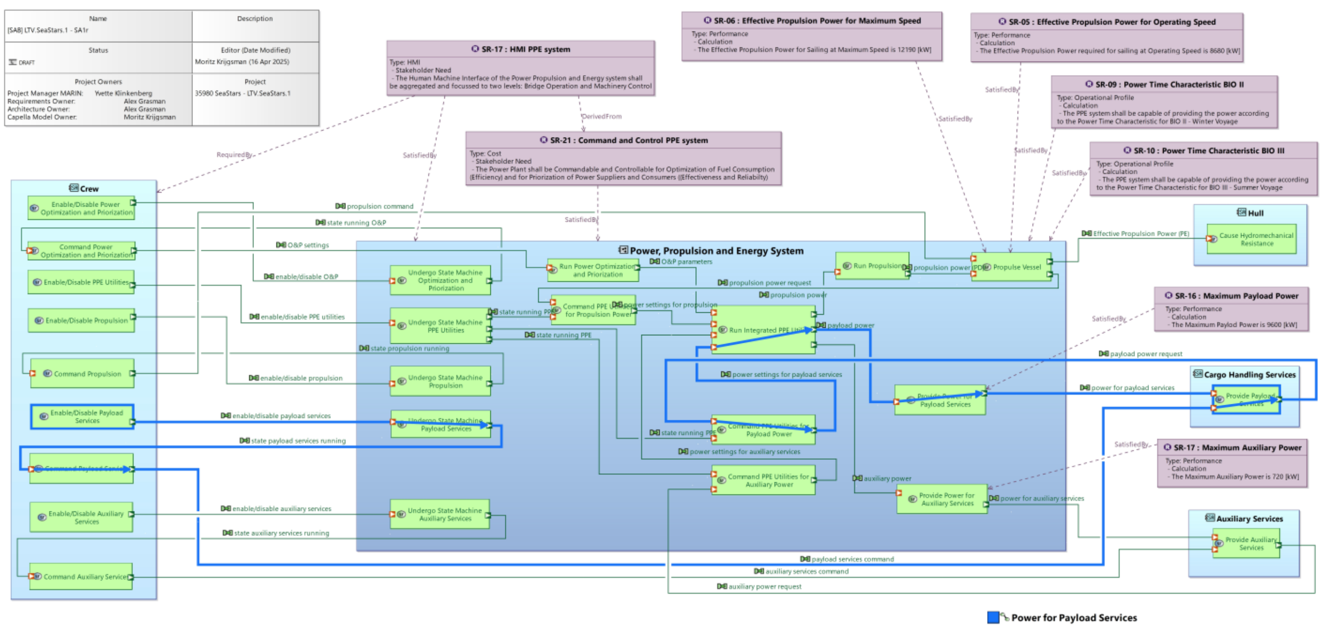


Figure 3. 4 - Example of "functional chain" for a "highest level function analysis"

3.4.1 The SPEC software environment

SPEC (Ships Power and Energy Concepts) is a low-fidelity tool that can be used during the exploration and concept design phases of ship design. It starts out with the ship owner's requirements: endurance, emission levels, technical readiness levels etc. SPEC can propose different energy and power systems that may be suitable given a certain emission target and readiness level. Figure 3. 5 gives an overview of the input (the requirements) and output (the technologies).

The list of technologies considered by SPEC is given in the Sustainable Power database (Sustainable Powe Application Marin, s.d.). Based on the scalable properties contained in this database (energy density, power density, emission factors, efficiency) the tool performs calculations and gives back a list of compliant technologies and their properties. If weighing factors are provided, the technologies will be scored and ranked based on its performance. The decision on which technology to select for further design is up to the user is supported by the tool.

Requirements:
Operational profile:
Average and maximum:
- Payload power
- Propulsion power
- Auxiliary power
- Endurance (duration between refuelling)
- Downtime

Minimum achieved readiness level:
- Technology Readiness level
- Societal Readiness Level
- *Commercial Readiness Level**
- *Regulatory Readiness Level**
- *Port Readiness Level**

Emission constraints
- Greenhouse Gas Emissions
- Harmful emission level (Zero emission, Stage V, Tier III)

Weight and volume constraints
- Max. energy carrier volume
- Max power system volume
- Max. energy carrier weight
- Max power system weight

Economical constraints
- CapEx of total system
- OpEx of energy carrier
- CO_2 price per ton

Weighing factors:
For the above criteria weighing factors can be specified

*Part of SEASTARS developments

Compliant technologies
List of technologies & properties:
- Greenhouse Gas Emissions per year (CO_2eq)
- System efficiency (in nominal condition)

Weight and volume of technology
- Energy carrier volume
- Power system volume
- Energy carrier w eight
- Power system weight

Economical
- CapEx of total system
- OpEx of energy carrier
- CO_2 cost

Readiness level achieved:
- Technology Readiness level
- Societal Readiness Level
- *Commercial Readiness Level**
- *Regulatory Readiness Level**
- *Port Readiness Level**

Ranked list of technologies
Each technology receives a score based on its properties and the set weighing factors.

Figure 3. 5 - Input and output of the SPEC tool.

SPEC fits within the Model-Based Systems Engineering (MBSE) methodology. Based on the functional requirements a matching technology can be proposed. SPEC helps defining the basis of the logical architecture, based on the inputs set in the Operational and System Analysis. The SPEC input defined in Figure 3.5 is typically defined in the Operational Analysis. From the output a suitable technology can be chosen by the user. The elementary SPEC components (see Figure 3.6) are the first logical components to be defined. This is visualised in Figure 3.7 where an example of a liquid hydrogen fuel cell technology is given. In SPEC four main logical components are defined, which can be matched with the major components in the logical architecture as developed in CAPELLA.

A data input sheet for SPEC was set-up in WP1, as also specified later in Chapter 4 (see Figure 3.8) and shared with the project partners. The data input sheet follows the logical components contained in SPEC:

- Energy storage
- Energy carrier pre-treatment
- Spent-fuel
- Energy-conversion
- Power distribution and drives
- Exhaust after-treatment

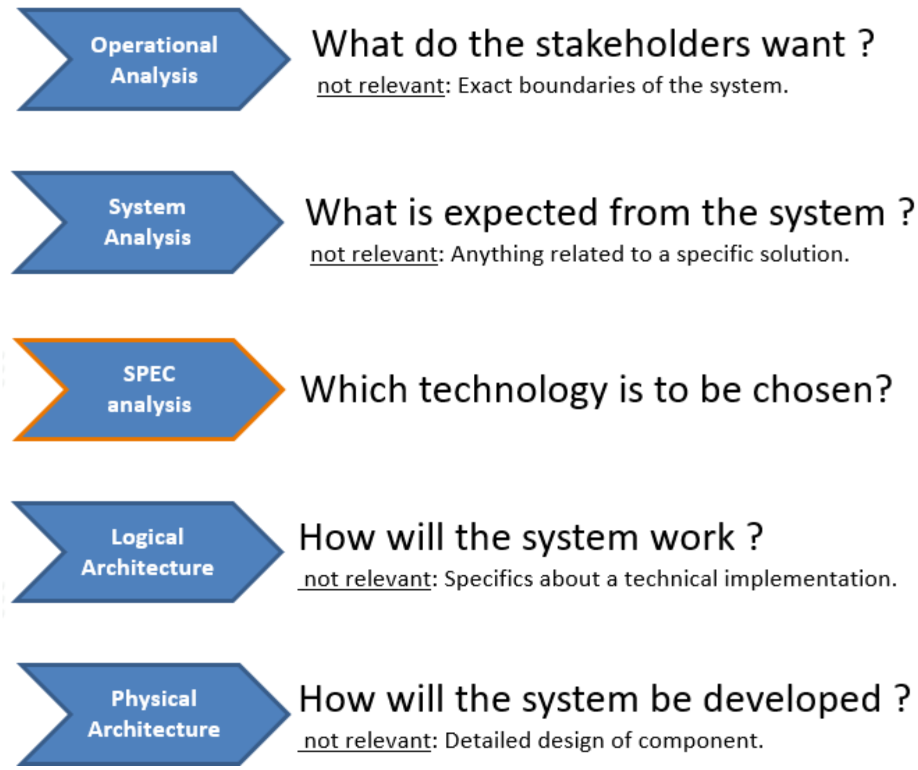
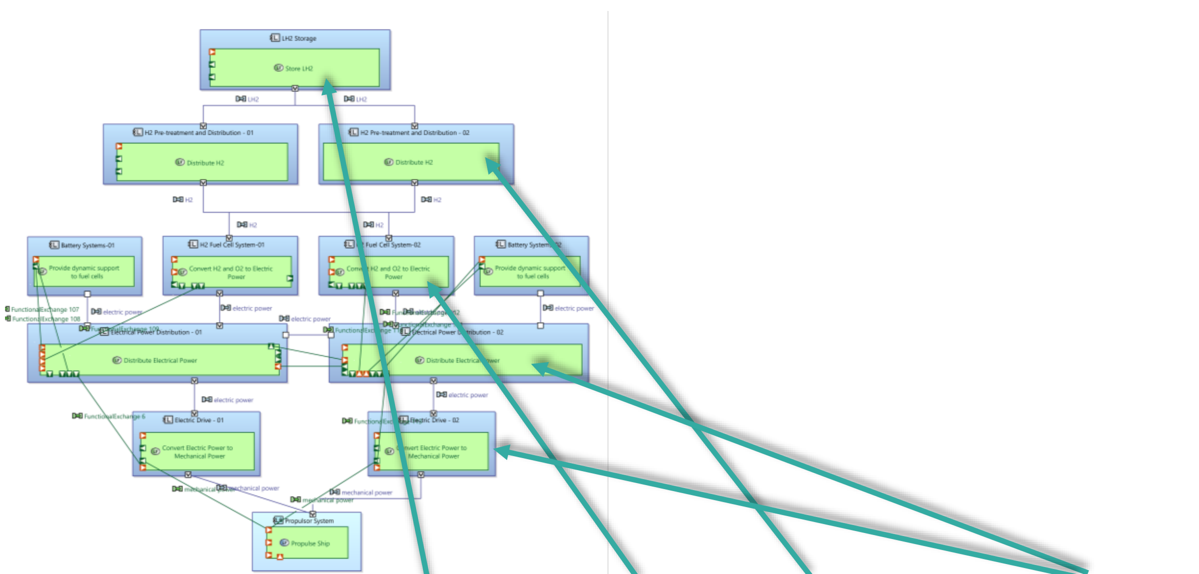


Figure 3. 6 - MBSE steps including SPEC analysis.



Parameter -> #System type:	SystemName$ [Str]	EnergyCarrier$ [Str]	EnergyConversion$ [Str]	PreTreatment$ [Str]	AfterTreatment$ [Str]	PowerConfiguration$ [Str]
#20	e-LH2 LT PEMFC	e-LH2 (renewable)	LT PEMFC	Evaporation	None	FC Electric Propulsion

Figure 3. 7 - SPEC components (bottom) and their match with the logical architecture (top), example of liquid hydrogen fuel cell technology

The components are visually connected in Figure 3.9 though spent-fuel is not yet in this figure: it only applies to a limited number of technologies that need to store remains of the fuel like Liquid Organic Hydrogen Carriers (LOHC), or for instance CO_2 when applying on-board carbon capture. The document is set-up to suit the format of SPEC data input, but will likely not match with all the data to be supplied by technology providers, and it will therefore act as a starting point. At the same time, the SPEC component-model is being updated in Task 4.5, in order to be more flexible and suitable for a wider range of technologies.

Inputsheet New Energy and/or Power System MARIN SPEC			
Project:			
MARIN Project nr:			
Editor:			
Version:			
Date:			
Template version:	V3.5		

Properties for energy storage	Description	Value	Explanation / origin
Volumetric energy density [MJ/l]	Of the pure fuel without storage system		
Gravimetric energy density [MJ/kg]			
Volumetric contained energy density [MJ/l]	Of the product in a stored format. This can be calculated by the energy stored divided by		
Gravimetric contained energy density [MJ/kg]	the mass or volume of the energy itself and the fuel combined		
CO_2 emission [kg/GJ]	Per supplied unit of energy		
N_2O emission [kg/GJ]	Per supplied unit of energy		
CH_4 emission [kg/GJ]	Per geleverde energie-eenheid		
CapEx [€/kWh]	Kosten van tank en leidingsystemen per opgeslagen energiehoeveelheid		
OpEx [€/kWh]	Werkelijke kosten 'aan de pomp' van de energie incl. distributie kosten.		
TRL/CRL	Technology Readiness Level/Commercial Readiness Level (see scale on the right)		
RRL	Regulatory Readiness Level		
PRL	Port Readiness Level (see scale on the right)		

Figure 3. 8 - Data input sheet SPEC (link to SharePoint: InputSheet_SPEC_New_Technology_V3.5.xltx).

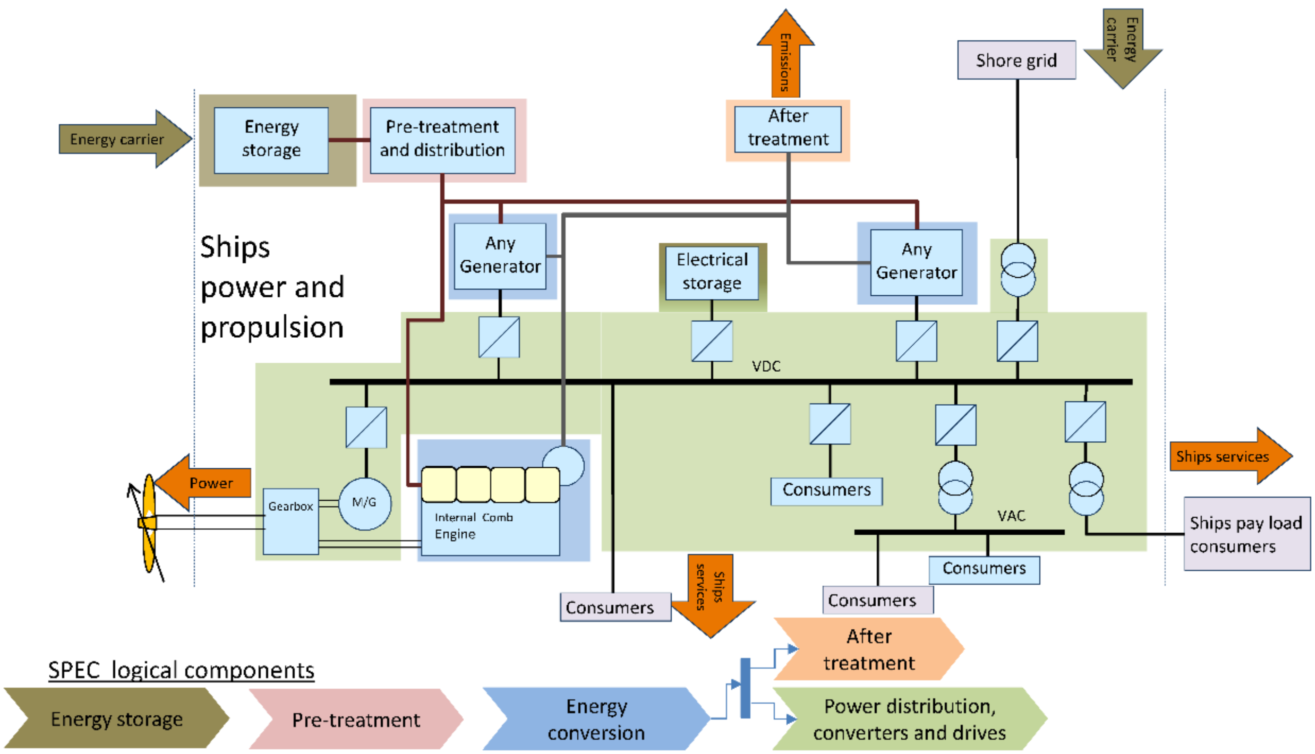


Figure 3. 9 - SPEC logical components visualised.

3.5 Collaborative modelling strategy

A key element of the SEASTARS methodological framework is the adoption of a collaborative modelling strategy, rooted in the principles of MBSE. Given the multidisciplinary nature of the project and the variety of technologies under assessment, the creation of accurate and functional digital models cannot be approached as an isolated or sequential task. Instead, it requires continuous interaction between technology providers, modelling and validation partners teams, throughout the lifecycle of each digital model. The collection of the data is assigned to AMC, while the development of each digital model is assigned to DG Twin and UoB, which are responsible for the simulation and analysis, while the technology providers contribute with: technical documentation, experimental datasets, and model-specific inputs; engineering support to clarify behaviour, control logic, and limitations of the real system; feedback on model outputs and calibration consistency. This co-development process ensures that each model reflects not only the physical characteristics of the system but also the operational logic as understood by the system developer. In many cases, this collaboration extends to iterative refinement cycles where simulation results are reviewed and adjusted. Figure 3.10 illustrates the data collection process for both shipowners and technology providers. The block diagram visually represents the workflow between the various partners in the SEASTARS process. The path followed by the data from shipowners is highlighted in blue, while the data from technology providers is highlighted in green.

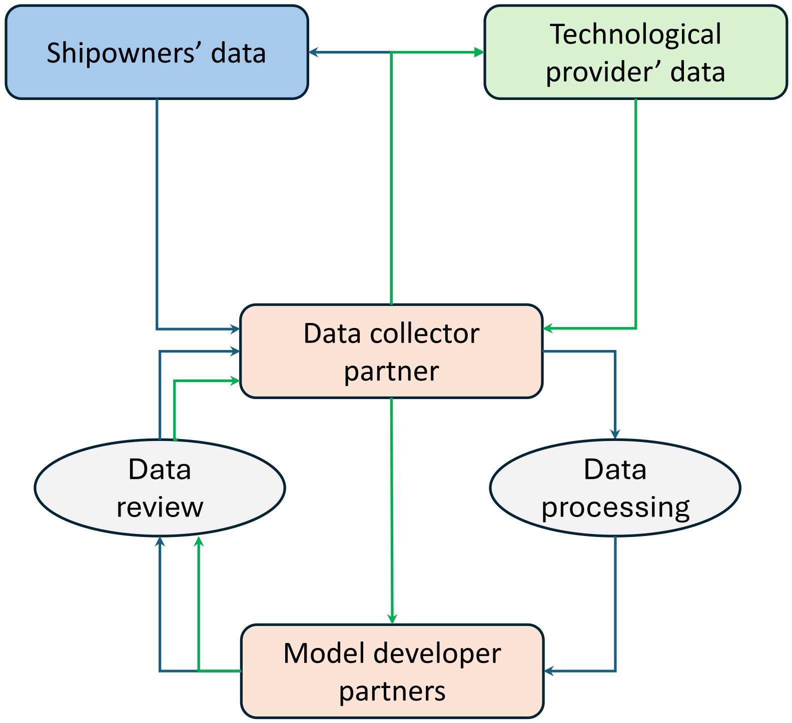


Figure 3. 10 - Workflow of the data collection process.

4 Data requirements

The successful implementation of Model-Based Systems Engineering (MBSE) methodologies fundamentally depends on the availability, quality, and management of comprehensive data sets that support model development, validation, and maintenance throughout the system lifecycle. Unlike traditional document-centric approaches where information exists in disparate formats across multiple tools and repositories, MBSE requires integrated, structured, and semantically consistent data that can be systematically accessed, updated, and traced across all engineering activities.

Data requirements for MBSE encompass multiple dimensions including technical specifications, performance parameters, requirements hierarchies, stakeholder information, regulatory constraints, and operational characteristics. These data elements must be captured in formats that support automated analysis, model synthesis, and cross-domain integration while maintaining traceability and configuration management throughout the system development process.

4.1 Core Data Categories

Generally speaking, the following categories of data are needed within MBSE:

Requirements Data: Comprehensive capture of stakeholder needs, functional requirements, performance specifications, and regulatory constraints in structured formats that enable systematic traceability and impact analysis. This includes requirement attributes such as priority, rationale, verification methods, and approval status.

System Architecture Data: Hierarchical representation of system elements, interfaces, and relationships that support multiple architectural viewpoints and abstraction levels. Architecture data must accommodate both logical and physical system representations while maintaining consistency across different engineering disciplines.

Performance and Behavioral Data: Quantitative parameters that describe system behavior under various operational conditions, including performance metrics, operational constraints, environmental conditions, and failure modes. This data enables model validation.

Configuration and Version Data: Systematic tracking of model evolution, change history, and configuration baselines that ensure model integrity and enable collaborative development across distributed engineering teams. This includes model element versioning, change approval workflows, and baseline management capabilities.

A detailed discussion about data type, format and their management is given in the Data Management Plan (DMP) of the SEASTARS project.

4.2 Data Quality and Consistency Requirements

MBSE robust implementation and portability requires data that meets stringent quality standards including accuracy, completeness, currency, and semantic consistency. Data must be structured using standardized taxonomies and ontologies that enable automated reasoning and cross-model integration. Additionally, data provenance and validation status must be maintained to support engineering decision-making and regulatory compliance requirements.

The transition from traditional engineering practices to MBSE often reveals significant data gaps and inconsistencies that must be systematically addressed through data cleansing, standardization, and enrichment activities. The Consortium is establishing a data governance framework that defines data ownership, quality standards, and maintenance responsibilities while ensuring data accessibility for authorized stakeholders across the engineering organization. Also, these aspects will be broadly discussed in the DMP.

4.3 WP1 Data Collection Focus

Within the SEASTARS project framework, Work Package 1 (WP1) has concentrated on gathering and structuring critical data from two primary stakeholder groups that are essential for the execution of the project and, indeed, for maritime transport decarbonisation decision-making: shipowners and technology providers. This targeted data collection approach recognizes that effective MBSE implementation for maritime decarbonisation requires a comprehensive understanding of both demand-side operational requirements and supply-side technology capabilities.

Shipowner Data Collection: The Consortium has established rules to systematically gather relevant data from representative shipowners across different vessel segments, including detailed vessel operational profiles, route characteristics, cargo handling requirements, fuel consumption patterns, maintenance schedules, and commercial performance metrics, as specified in the following. Data, collected with suitable time steps, provide essential insights into real-world operational constraints, performance expectations, and economic drivers that influence decarbonisation technology adoption decisions. The shipowner data encompasses historical operational performance as well as projected future requirements under various regulatory and market scenarios.

Technology Provider Data Acquisition: Comprehensive technical and commercial data must be collected from technology providers representing the full spectrum of maritime decarbonisation solutions, including alternative fuel systems, propulsion technologies, energy storage solutions, and operational optimization tools. This data includes detailed technical specifications, performance parameters, cost structures, implementation timelines, regulatory approval status, and integration requirements. Technology provider data serves as the foundation for understanding available decarbonisation options and their potential applicability to different vessel types and operational profiles, hence to derive proper models that are the core point of MBSE.

As mentioned above, the integration of shipowner operational requirements with technology provider capabilities forms the essential data foundation for MBSE model development within the SEASTARS project, enabling systematic evaluation of decarbonisation technology options against real-world operational constraints and commercial requirements.

4.4 Data gathering from Shipowners (SOs)

Real-world data provided by shipowners enables project partners to:

- Ground the digital models in actual vessel behaviour;
- Provide verifiable baselines for the evaluation of Key Performance Indicators (KPIs);
- Identify areas for technological improvement and feasibility constraints;
- Validate assumptions made during preliminary design and analysis phases.

Data are needed to evaluate the integration and contribution of each technology within the ship energy system and propulsion architecture. Without the availability of real operational datasets, the modelling effort would be limited to theoretical or generalized scenarios, significantly reducing the reliability and relevance of the outcomes. Hence, the engagement of shipowners in providing detailed, technology-specific datasets is not only beneficial but crucial to the success of the MBSE-driven digital framework adopted in SEASTARS.

In order to ensure consistency, completeness, and technical relevance in the data collection process, **a structured and standardized data request strategy** was defined. A ship is composed by many different parts: between the, the hull, with all the hydrodynamic information; the powertrain, composed by main engine, diesel generators, propellers; the auxiliary system with all the technologies employed to supply different services such as heating ventilation and air conditioning (HVAC system), or oil-fired boiler (OFB) and the steam system supply. A data gathering strategy was therefore designed by Partners to facilitate the acquisition of all necessary information required for the MBSE application. This was collaboratively defined especially by AURELIA, AMC and DG Twin to reflect the diversity and complexity of ships and their onboard systems, as well as the different modelling requirements across technologies. Accounting for the CAPELLA and SPEC expectations in cooperation with MARIN led a structure that ensures a data collection process both technically robust and easily accessible for shipowners.

As for the project objectives, 4 SOs were considered for ships differing for their constructive features and operational profiles.

A survey of the assumed ships is given in the following Table 4.1.

Identification	Ship name	Photo	IMO	Owner	Type	Typical service	Length overall [m]	GT
[redacted]	[redacted]		[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]		[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]		[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]		[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]

Table 4. 1 - Ships considered within SEASTARS.

4.4.1 Bundle of requested data

A proper template, as reported in Figure 4.1, was defined to collect data from SOs, organized into six major categories. This categorization aims at ensuring completeness and technical relevance across the various systems that contribute to ship energy performance, operational efficiency, and environmental impact. Each category encompasses specific types of data and documents essential for the modelling, simulation, and assessment activities carried out by project Partners.

General data: This section includes general information on the vessel, such as the ship name, IMO number, classification, and basic specifications. It also covers high-level layout drawings, general arrangement plans, and documents describing the vessel's purpose, operational range, and mission profile. These data provide the overall context in which specific subsystems operate. In this category there are information about the capacity plan (water, fuel etc…); booklet of stability and load conditions useful to describe the general load of the ship and the related immersion.

Machinery data: This category contains detailed technical documentation of the main and auxiliary engines, including specifications, engine load diagrams, fuel consumption curves, performance certificates, and machinery layout drawings. These data are essential to define propulsion system, estimate the size of the energy system of the ship: main engine; auxiliary boilers; HVAC systems.

Structural data: This group includes structural drawings and scantling plans, particularly focusing on hull geometry and internal compartmentation. These support the evaluation of ship resistance, weight distribution, and the integration feasibility of retrofit solutions such as new tanks, batteries, or air lubrication systems.

Electrical data: Information under this category pertains to the ship's electrical generation and distribution systems, including generators, switchboards, electrical load schedules, and one-line diagrams, electrical analysis of the on-board services. These data are crucial to reconstruct onboard energy flows, assess electrical loads during different operational modes, and model power-sharing or hybrid configurations. An example is provided in Figure 4.2.

Piping data: The piping category involves diagrams and specifications related to fuel lines, ballast systems, exhaust gas pathways, and cooling water circuits. These are important for valuing the technical compatibility and space constraints when introducing new technologies or modifying existing systems.

Operational data: This category includes voyage reports, routes (Figure 4.3) and engine logbooks. Drydocking schedule, useful for understanding maintenance periods and structural intervention possibilities. NOX technical file, and other information about environmental constraints.

The subdivision of data ensures that all relevant aspects of the ship's architecture and operations are systematically covered, which is critical to meeting the project's MBSE-oriented objectives and allows technical partners to easily map the available information to the corresponding digital model inputs.

Ship Name

* "YES" mark indicates received dwgs
**All drawings that are made available in hard copy, will be returned
*** General drawings to be provided for the lead vessel

	Required Documentation	Received	Drawing Number					Remarks
	GENERAL							
1	List of Finished Plans							
2	Lines Plan or Offset Tables							
3	Model test or Sea Trials							
4	Capacity Plan (with dwt scale)							
5	General Arrangement							
6	Fire Control & Safety Plan							
7	Docking Plan							
8	Dangerous Zone Plan							
9	Midship Section							
10	Shell expansion							
11	Profiles and Decks plan							
12	Loading Manual / Trim & Stability Booklet/ Grain Loading Manual							
13	Equipment Number Calculation							
14	Damage Control Booklet							
15	Navigation Bridge Visibility							
	MACHINERY							
1	Engine Room Arrangement							
2	Funnel Arrangement							
3	Main Engine Technical File							
4	Aux. Engines Technical File							
5	Aux. Boiler Technical File							
6	Air compressors specifications							
7	Air compressors specifications							
8	ECR Arrangement							
9	CCR Arrangement							
10	HVAC Arrangement							
11	Propeller Plan							
12	Propeller open water characteristics/efficiency curves kt, 10kq, h0							
13	ESD drawings							
14	Rudder Construction Drawing							
15	Arrangement of Main Pump Room							
	STRUCTURAL							
1	Aft End							
2	Fore End							
3	Pump & Engine Room							
4	Cargo Area							
5	Double Bottom							
6	Funnel							
7	Engine Casing							
8	Accomodation Block/ Deckhouse Construction							
	ELECTRICAL							
1	Arr't of Electric Equipment							
2	Electric Power Balance / Electric load analysis							
3	Wiring Diagram Of Power System							
4	Main Switchboard (Including fault current settings of breakers)							
5	Instrument & Alarm Point List							
6	Wiring Diagram Of Lighting							
7	Short Circuit Calculation							
8	Wiring Diagram of Automation & Control							
9	Wiring Diagram of Communication & Equipment (for GPS signal)							
10	Arrangement of Electric Equipment (Nav.Comp. Deck)							
	PIPING							
1	Piping Diagram in Engine Room							
2	Hull Piping Diagram							
	OPERATION DATA							
3	Drydocking Schedule							
4	General Trade Route of the vessel (voyages and port/topography)							
5	Vessel's IAPP Certificate including supplement							
6	M/E Nox Technical File							

Figure 4. 1 - Template for the collection of data from shipowners.

The data template focuses on gathering technical data — a comprehensive set of structured documentation related to the ship's systems and equipment. These include datasheets, layout drawings, wiring diagrams, machinery certificates, load schedules, and other engineering documents. A future step will be the development of a digital platform with APIs for continuous shipowner data collection, integrating real-time operational data from vessel monitoring systems with projected requirements through structured questionnaires and scenario modeling tools.

SUMMARY OF GENERATOR LOAD S843/844/845/846-1/15

(For details, refer to page 3/15 to 8/15.)

CONDITION OF SHIP	NORMAL NAVIGATION kW		DEPARTURE/ARRIVAL kW		UNLOADING kW		LOADING kW		EMERGENCY kW	
	Pc	Pi	Pc	Pi	Pc	Pi	Pc	Pi	Pc	Pi
ENGINE AUXILIARIES (1/2)	219.3	18.6	313.9	18.6	110.2	18.6	110.2	18.6	0.0	0.0
ENGINE AUXILIARIES (2/2)	96.2	0.0	133.8	0.0	311.3	0.0	109.4	0.0	1.9	0.0
SHIP SERVICE AUXILIARIES (1/2)	13.2	59.3	13.2	100.5	66.4	54.3	66.4	54.3	0.0	0.0
SHIP SERVICE AUXILIARIES (2/2)	94.1	70.2	94.1	70.2	94.1	70.2	94.1	70.2	1.9	0.0
CARGO GEAR & DECK MACHINERY	17.1	0.0	305.7	0.0	804.5	136.2	460.7	70.2	110.2	0.0
LIGHTING, IC & NAUTICAL EQUIPMENT	67.1	0.0	77.4	0.0	77.4	0.0	77.4	0.0	33.6	0.0
REQUIRED POWER — TOTAL LOAD (kW)	507.0	148.1	938.1	189.3	1463.9	279.3	918.2	213.3	147.6	0.0
REQUIRED POWER — Pi — LARGEST LOAD (MAX Pi)		36.7		46.2		70.2		70.2		0.0
REQUIRED POWER — Pi — (Σ Pi − MAX Pi)/3 (kW)		37.1		47.7		69.7		47.7		0.0
REQUIRED POWER — Pi — EQUIVALENT Pc LOAD (kW)	73.8		93.9		139.9		117.9		0.0	
REQUIRED POWER — GRAND TOTAL = Σ Pc + EQUIV Pc (kW)	580.8		1032.0		1603.8		1036.1		147.6	
GENERATOR IN SERVICE — MAIN GENERATOR (kW × SETS)	1020	1	1020	2	1020	2	1020	2		
GENERATOR IN SERVICE — EMERGENCY GENERATOR (kW × SETS)									160	1
DEMAND FACTOR (%)	56.9%		50.6%		78.6%		50.8%		92.3%	

GENERATOR PLANT	NUMBER	OUTPUT kVA	OUTPUT kW		MAIN ENGINE TYPE : B&W 6G60ME-C9.5, 11,730 kW × 88 min-1
MAIN DIESEL GENERATOR	3	1275	1020	450V AC 60Hz PF:0.8	NOTE:
AUX DIESEL GENERATOR					1. Pc: CONTINUOUS LOAD, Pi: INTERMITTENT LOAD
TURBO GENERATOR					2. REQUIRED POWER (GRAND TOTAL)
SHAFT GENERATOR					= Σ Pc + EQUIVALENT Pc
EMERGENCY GENERATOR	1	200	160		

Figure 4. 2 - Electrical load analysis. Here and in related documents the electrical analysis of the on-board services. This type of data is useful to elaborate the electrical load profile and to size new electrical technologies (i.e. batteries).

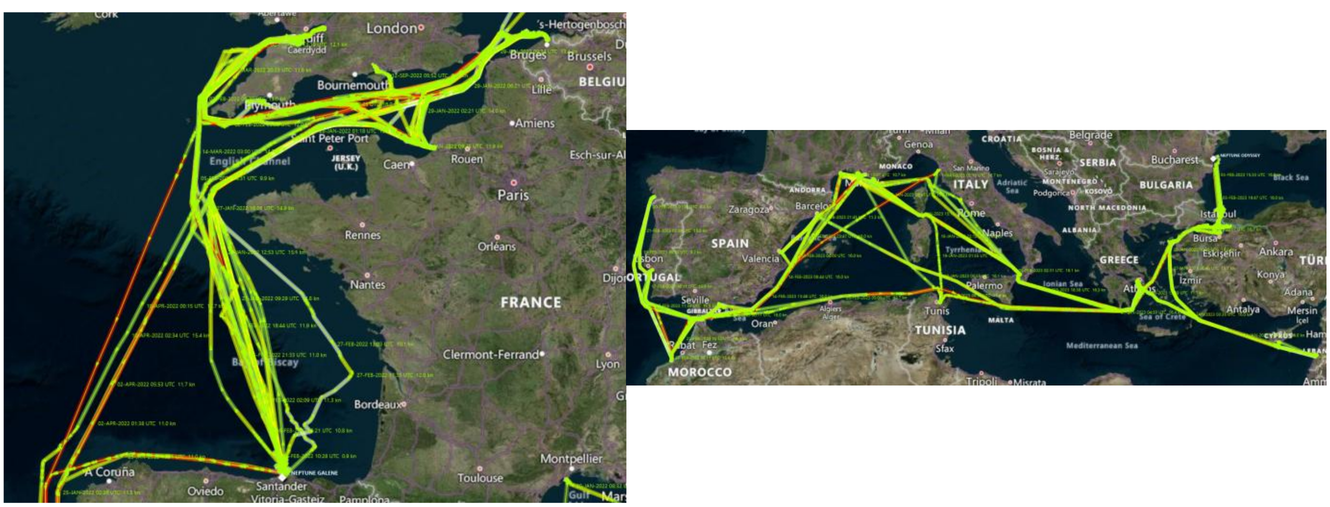


Figure 4. 3 - Example of the ships' routes of Neptune Galene - provided by the ownership.

Up to present, the template was distributed through the dedicated SEASTARS Partner responsible for coordination with shipowners, who also provided technical support to ensure clarity in data interpretation and adherence to the collection framework. Additional assistance and follow-up activities were managed by AMC, who worked closely with shipowners to identify any missing data. The goal of this phase was to obtain all the static and design-related information needed to extract specific parameters, define system architectures, and populate the digital models with real-world characteristics. This type of data is critical during the modelling and simulation setup, ensuring that the virtual systems represent the actual onboard configurations with a high degree of fidelity.

In parallel, a second category of data focused on the collection of operational reports, with a particular emphasis on Noon Reports (Figure 4.4). These daily logs, recorded by the ship's crew typically around 12:00 local time, contain detailed information on the vessel's position, speed, heading, fuel consumption, machinery status, environmental conditions, and voyage progress. Unlike static technical documentation, Noon Reports provide a temporal snapshot of the vessel's real-world behaviour across its operational lifecycle.

Ship Name

* ME = Main Engine / AE = Auxiliary Engine / EE = Emergency Engine
** RH = Running Hours [h] / Avg = Average / EW = Electrical Work
*** [YY-VY N°-ID] = Year - Voyage N° - ID / Voyage State = Port/Sea passage/Maneuvering/Anchoring/drifting
/ The list of pumps, their consumption and working hours will be completed as appropriate.
// The total number of trips indicated is an example, the ID will be extended depending on the measurements made by the crew (make more than one measurement - ID 1=Start of trip / IDX=End of trip).

			Voyage State	Total HFO	Total MDO/MGO	SFOC ME	RH ME	Avg. Power ME	Avg. RPM ME	SFOC AE1	RH AE1	Avg. Power AE1	Avg. RPM AE1	SFOC AE2	RH AE2	Avg. Power AE2	Avg. RPM AE2	SFOC AE3	RH AE3	Avg. Power AE3	Avg. RPM AE3
[YY]	[Voyage N°]	[ID]	[remark]	[m3]	[m3]	[g/kW.h]	[h]	[kW]	[Rpm]	[g/kW.h]	[h]	[kW]	[Rpm]	[g/kW.h]	[h]	[kW]	[Rpm]	[g/kW.h]	[h]	[kW]	[Rpm]
25	1	1	Port	**Initial	**Initial		0				0				0				0		
25	1	2																			
25	1	3																			
25	1	4																			
25	1	5	Port	**Final	**Final																
25	2	1	Port				0				0				0				0		
25	2	2																			
25	2	3																			
25	2	4																			
25	2	5	Port																		

Figure 4. 4 - Template for gathering up the information present in the "noon report".

The value of data from SOs is twofold:

- First, they enable the reconstruction of realistic mission profiles (transit, manoeuvring, port stays, idle periods), which are essential to test the behaviour of the digital models under real-life conditions.
- Second, they serve as baseline operational patterns against which the impact of new technologies can be quantified. This comparison is essential to assess whether and how each solution contributes to the project's overarching goals in terms of energy efficiency, emission reduction, and operational optimization.

By combining technical documentation and operational logs, it is ensured that each digital model is structurally accurate and can be realistically tested.

In future work, the Consortium will establish ongoing data collection protocols with participating SOs, implementing regular requirement updates through digital surveys, performance monitoring systems, and structured feedback sessions to track how projections evolve with changing market conditions and regulatory developments. Further details about the future requirements collection by SOs will be given in the DMP. The Consortium will leverage its shipowner partners and also the advisory board to conduct structured collections, utilizing existing relationships to ensure high-quality data from representative vessel operators across different segments and geographical regions.

4.4.2 Data Review and Validation

A procedure was defined by DG Twin to review and certify the request, receipt, and availability of data. An Excel document was prepared supporting the data validation, an extract of which is provided in Annex II. The document is a comprehensive checklist of the received data, also enabling final use within the MBSE approach. Each step of the data gathering phase is evaluated, and any relevant issue is documented, including data type, format, compliance verification, and any necessary modifications or adjustments needed during the process.

A final certification is built at the initial sheet of the file that serves as a record to ensure that all data handled are appropriately documented, to be processed and made accessible for the project's ongoing research and development activities. The checklist is organized in different sections.

1. Data Request

This section describes the characteristics of the data requested from SOs, with a focus on their type and format.

- Type of data requested (e.g., performance maps, system layout, dynamic consumption profiles, noon reports).
- Required formats (e.g., Excel, .csv, .pdf).

2. Data Reception

This section documents the data received, verifying its compliance with the requested formats. In case of discrepancies, any issues encountered and necessary modifications to ensure the data complies with the requirements are described.

- Data received (compliant or non-compliant format).
- Compliance with requested format (e.g., Excel, .csv, .pdf).
- Issues encountered (if the data is non-compliant).

3. Compliance Verification

At this stage, it is verified that the data is ready for use in digital models and for KPI calculation.

- Preparation for digital models/KPIs.
- Any feedback for improvements or data integration.

4. Data Revision and Adaptation

If the received data is non-compliant, this section outlines the steps taken to modify or process the data. This includes format conversion (e.g., from .pdf to Excel), data cleaning, and any other necessary operations to make the data usable. Operations performed (e.g., conversion, aggregation) and a brief description of modifications are included.

Once the SO's data are correctly reviewed and validated, the successive step of processing for the MBSE application purposes can start.

4.4.3 Data processing

Once received, the datasets undergo a structured post-processing phase coordinated by the technical partners, in particular AMC in WP5, to ensure the usability, consistency and accuracy of the information before their use for the development and testing of digital models. This phase is essential as it guarantees that input data meets the strict quality and format requirements necessary for reliable system simulation and analysis. It especially serves to:

- Verification of completeness and internal consistency of the data, to ensure that all requested parameters have been provided and that values fall within plausible ranges;
- Alignment and synchronization of time-series data from different sources—such as engine logs, GPS coordinates, meteorological records, and fuel consumption reports—to allow integrated analysis of performance over time;
- Data cleaning and interpolation, aimed at handling missing values, correcting anomalies, and ensuring continuity in the datasets

The outcome of this activity is a curated and technically validated dataset, ready for use in model calibration and scenario simulation. By implementing a robust post-processing strategy, SEASTARS ensures that digital models not only reflect the physical and operational characteristics of each vessel but also deliver relevant and actionable insights when used to evaluate technological solutions.

An example of the defined process of data processing is given in the document of Annex II.

4.4.4 Integration into the digital modelling framework

After the post-processing phase, the selected datasets can be integrated into the SEASTARS digital modelling process.

A key reference for this phase is the baseline scenarios that provides the essential technical and operational inputs needed to test the digital models of each ship under realistic conditions.

The classification of the data into technical and operational categories enables project partners to systematically retrieve:

- Diagrams and schematics for the reconstruction of the ship's powertrain, electrical network, and piping systems;
- Equipment specifications and design parameters, including performance maps of engines, oil-fired boilers, and auxiliary components such as HVAC components;
- Time-resolved operational profiles detailing propulsion loads, fuel consumption, hotel energy demand, and voyage patterns.

This structured approach ensures that each digital model developed in Seastars is not based on theoretical assumptions or generic configurations, but rather on ship-specific, validated information that reflects the real characteristics and behaviour of the vessel. The integration of this information into the MBSE modelling environmentsenables the following:

- Model initialisation, using actual design and operational parameters as starting points for simulation;
- Scenario analysis and sensitivity studies, allowing the assessment of alternative technological configurations against real-world operational patterns.

By using the cleaned and structured datasets, SEASTARS ensures that its modelling process is fully linked in operational reality. This guarantees that models can accurately simulate existing ship conditions and provide reliable insight into the expected impact of retrofit or new-build technological solutions.

4.4.5 Use of data in KPI evaluation and system design

The datasets provided by shipowners—once cleaned, classified, and integrated—play a fundamental role in the evaluation of system performance and design optimisation. Data serve as the main reference for quantifying and monitoring Key Performance Indicators (KPIs) linked to the project's decarbonisation and energy efficiency objectives. Specifically, ship-specific datasets are used to:

- evaluate environmental performance, including reductions in greenhouse gas (GHG) emissions such as CO_2 and NO_x, based on fuel consumption and emission factors;
- assess improvements in a reduction of fuel consumption, by comparing the performance of baseline configurations with new and alternative energy systems;
- quantify energy savings, enabled through the development of new energy system configuration with a suitable combination of technologies for each type of ship.

Beyond KPI evaluation, data also informs strategic design decisions by enabling realistic trade-off analyses between competing technical and operational priorities. In particular:

Technology sizing—such as determining appropriate battery storage capacities, auxiliary systems for fuel treatment, or onboard fuel tank volumes—is based on actual energy demand profiles derived from duty cycles, hotel loads, and propulsion power requirements. These are just a few examples of the sizing problems that can be solved with the availability of clean and consistent shipowners' data. Each ship is different and requires appropriate analysis. Retrofit feasibility and integration constraints—such as space availability, weight distribution—are assessed based on detailed technical specifications and layout drawings provided by shipowners. By embedding real-world operational data into both performance assessment and system architecture design, innovative technological solutions become not only theoretically viable, but also practically implementable and aligned with operational constraints. This enables the project to deliver realistic and verifiable results that support informed decision-making for both retrofit and new-build applications.

4.5 Data from Technology Providers

Unlike the data collection process from shipowners, which can be partially standardized around vessel characteristics and operational logs, the nature of the data required from technology providers is inherently heterogeneous. Each technology comes with unique functional principles, physical interfaces, control strategies, and modelling needs. As a result, a universal data template is neither feasible nor appropriate.

Nevertheless, the possibility of adopting a unified approach to collect relevant data for each technology was considered and a proper .xls file was prepared to the scope. The modelling approach is closely linked to the availability of data needed for validation and analysis purposes. Validation is also influenced by the desired analyses to be conducted and the KPIs established in the project. According to the type of software used, different input elements may be necessary, - just as there are different modelling methods, there are various types of software based exactly on these approaches.

The information to be requested to TPs serves, therefore, a dual purpose: first, it provides the physical and functional parameters necessary to build the digital model of the technology; second, and more critically, it allows for model calibration and validation, ensuring that the model can accurately reproduce real-world behaviour across representative operational conditions of the distinctive technology. To guide this process, Table 4.2 preliminarly summarises the key technologies addressed in SEASTARS, the corresponding technology providers, and the modelling partners responsible for developing each digital model. For each case, the specific data types requested have been defined in collaboration between system modellers (DG TWIN, UoB), considering both physical integration and simulation fidelity. Some remarkable examples include:

- for the air lubrication system (SILVERSTREAM), data on air flowrate, system power consumption (e.g. compressor), and hydrodynamic drag reduction performance are essential to replicate its impact on hull resistance;

- for hydrogen reformers (METACON and PEM fuel cells (BALLARD/NEDSTACK), thermodynamic curves, polarisation data, and electrical conversion efficiencies are required for component-level modelling and system integration;
- in the case of CO_2 capture systems (ERMAFIRST), the project requests chemical absorption profiles (e.g. MEA characteristics), sorbent performance data, and thermal working ranges to replicate heat and mass exchange processes;
- for battery systems (EST FLOATECH), voltage vs state-of-charge (SOC) curves, charge/discharge profiles, and module layout data are essential to evaluate energy storage performance and regenerative braking integration;
- for biofuel emulsifiers (QUADRISE), key data such as fuel properties, energy content, and process parameters are needed to simulate combustion impacts and emissions behaviour.

Table 4. 2 - Technology to be developed in SEASTARS project. The layout of the table is organised to describe: technology provider; type of technology; digital model developer. The main type of data requirement is reported below each technology.

- **Control System** DGT+UOB	**BOUND4BLUE** **Rigid Sails/eSAILS** DGT	**BALLARD/NED STACK** **PEM Fuel Cells** UOB	**VERTORO** **Biofuel** UOB	**VOYEX** **Liquid Organic Hydrogen Carrier** UOB	**QUADRISE** **Biofuel emulsifier** UOB
	Size (high, weight, and all the relevant parameters) Wind threshold for activation / deactivation Control system for orientation Energy consumption of auxiliary systems (if present)	Type of cell Geometrical dimension (active area etc..) Operative temperature Polarization curve Cooling system Balance of plant	Type of biofuel used and energy content. Flash and pour point Viscosity and density Emissions factor Storage time	Type of LOCH Storage conditions (pressure) and temperature profiles. Reaction rates and energy efficiency data Hydrogen release rate	Fuel emulsification process parameters. Physical requirements of the emulsification unit (size, power consumption) Biofuel composition Emission factors
The control systems will be developed by DGT and UOB in accordance with the modelling approach of digital models and the availability of data	**ERMAFIRST** **Post-combustion CO2 capture** DGT	**METACON** **Hydrogen generators** UOB	**SILVERSTREAM** **Air Lubrication system** DGT	**EST FLOATECH** **Li-Ion batteries** DGT	**SOLBIAN** **PV flexible panels** DGT
	MEA solution Storage method CO_2 capture efficiency and process data. Temperature levels of working fluids Power (thermal and electrical) consumption	Hydrogen generation rates and efficiency. Pressure and temperature conditions of the generator. Start-up time Type of generator Thermal efficiency	Air flow rate and pressure System power consumption (i.e. electrical consumption of compressors) Working pressure Positioning of injection system Curve of Drag coefficient and flow rate	Type of cell (Li-ion or similar) HPPC test/OCV curve Operational temperature Pack configuration: number cells series and parallels	Type of PV (mono/poly/ etc…) PV efficiency Cell temperature Maximum tension and current I-V curve

This highly targeted data acquisition strategy ensures that each digital model is not only technically robust but also validated against real operating or laboratory data. It forms the basis for credible simulation results that inform the project's broader goals, including scenario evaluation, retrofitting feasibility, and quantifiable progress toward International Maritime Organisation (IMO) - aligned decarbonisation metrics. The collaborative effort between technology developers and system modellers is fundamental to ensuring the integrity of the SEASTARS modelling framework, enabling the project to transition from conceptual feasibility to validated, ship-ready solutions.

4.5.1 Integration into the digital modelling framework

The development of reliable digital models within SEASTARS does not conclude with their construction based on technical specifications and operational parameters. A fundamental step in the MBSE workflow is the validation of these models, which ensures that the simulated behaviour of each technology is consistent with its real-world performance. Validation provides the essential confidence that model outputs—used to support design decisions, scenario evaluations, and KPI assessments—are trustworthy and replicable. In this sense, with the scope to apply the MBSE approach to the ship environment, this step is very important, and the possibility to have access to TPs' data is a key point of the project.

The model validation process is deeply integrated with the broader data management strategy and is tailored to reflect both the nature of the technology and the level of model detail (black box, grey box, white box). Depending on the type of data available from the technology provider, the developed digital model will be validated on the basis of the most common validation tools, such as the Root Mean Square Error (RMSE) - and other model quality indices. Furthermore, the validation process can be conducted on specific quantities, such as the thermal power requirement of the reboiler for the separation of CO2 from the absorption mixture, or on dynamic discharge profiles, such as those typical of a battery for the storage of electrical energy. Once component-level validation is complete, the models are integrated into larger system-level simulations (e.g., full ship energy system), where validation is repeated at the integration level. This includes: comparing full ship fuel consumption simulations against actual voyage logs; assessing the overall energy balance under realistic mission profiles; evaluating multi-technology scenarios (e.g., battery plus sails plus air lubrication) for internal consistency and performance coherence. This kind of process to conduct the analysis about the impact of the single or multiple technologies inside the ship's energy system should be conducted with the SPEC software, developed and provided by MARIN. This system-level validation is critical for ensuring compatibility between models and delivering realistic simulation outputs for design and policy evaluation. The validation process of the digital models of the technologies involved in the SEASTARS Project is more than ever necessary for the MBSE approach that is proposed in the context of naval design, both in retrofit and in new construction

5 Key Performance Indicators for Maritime Decarbonization

The SEASTARS Consortium agreed on defining Key Performance Indicators as the first step towards defining the baseline cases for each specific ship type and monitoring the effect of any considered decarbonization technology or of the integration of some of them.

The Key Performance Indicators (KPIs) that will be utilized as the objective functions for the entirety of the SEASTARS project were preliminary detailed in a proper document prepared by the University of Birmingham and The University of Strathclyde to be then integrated with further considerations about the implementation of the Corporate Sustainability Reporting Directive (CSRD) by DG Twin. The KPIs are first separated into three distinct categories: Powertrain Performance, Emission Quantization, and Economic Analysis. Each category of KPIs includes subsections, adaptable to specific decarbonization technology, provided the baseline case is thoroughly defined. Hence, the establishment of the baseline case for each ship is the vital stepping stone upon which the decarbonization technology modules (standalone or in tandem) will be piled on to create a holistic decarbonization paradigm for each specific ship type, as preliminarily made in the previous experience by DGT (Beatrice, et al., 2022).

In the final part of the Chapter, instead, the reinterpretation of the KPI concept is made in light of the EFRAG indications relevant to the obligations of the CSRD and to the current trend of simultaneous attention to sustainability and resilience objectives while making decisions (Aasa, Phoya, Monko, & Musonda, 2025).

5.1 Powertrain Performance

5.1.1 Fuel consumption

The basis of the baseline case for each specific ship type rests on the fuel consumption calculations. The fuel consumption model employed in this study will utilize real operational data from the ship's main engine and auxiliary engine during a duty cycle (can be adapted to annual fuel consumption). Hence, the specific fuel consumption, engine power, and respective sailing and berth durations remain of paramount importance, particularly when considering alternative fuels such as hydrogen, where carbon intensity varies significantly across production methods (de Kleijne, et al., 2024). Equation 1 is used for the fuel consumption calculation for each case.

$$\begin{aligned} FC_n = \sum SFOC_{ME,n} \cdot P_{ME,n} \cdot t \\ + \sum SFOC_{AE,n} \cdot P_{AE,n} \cdot t \ - FS_n \end{aligned} \quad (1)$$

Here, FC is fuel consumption, $SFOC$ is specific fuel oil consumption, P is power, t is time, and FS is the fuel savings from decarbonization technologies (e.g. WASP). The subscripts n, ME, and AE signify the decarbonization scenario, Main Engine, and Auxiliary Engine, respectively. FS can be calculated using Equation 2.

$$FS_n = FC_{Baseline} - FC_n \tag{2}$$

5.1.2 Pollutant quantization

The emission intensity of each pollutant in the exhaust gas is different and hence requires separate consideration. Given that the fuel consumption and exhaust gas analysis data obtained from shipowners will contain the specific emissions of each pollutant (namely CO2, SOx, and NOx), the emissions can be calculated using Equation 3 (Carbon footprint of methanol).

$$\sum\gamma = \sum(\mathrm{SFE}_{ME,n} \cdot P_{ME,n} \cdot t) + \sum(\mathrm{SFE}_{AE,n} \cdot P_{AE,n} \cdot t) \tag{3}$$

Here, γ represents the emission production rate, expressed in eCO2 emissions, and SFE represents the specific emission rate for CO2, SOx, and NOx. Subsequently, for each case, the emission reduction can be calculated using the equation below:

$$\gamma_n = \sum\gamma - \sum\gamma_n \tag{4}$$

Here, it is pertinent to note that Equation 3 allows for the quantization of each pollutant separately, and the summation of the pollutants for equivalent CO2 emission potential will require consideration of each individual pollutant potency in relation to CO2 based on the 20-year or 100-year potency factors.

5.2 Emission Quantization

5.2.1 Greenhouse Gas (GHG) Emissions

To fully analyze the environmental effects of marine shipping pollutants, it is important to consider both the 20-year and the 100-year effects on the environment. Section 5.1.2 highlighted the calculation of each individual pollutant through the exhaust gas analysis. This section will analyze the equivalent CO2 GHG emissions through total fuel consumption. Both methodologies provide the same conclusions. However, the equations defined in this section provide a more detailed methodology for 20-year and 100-year potency considerations, based on total fuel consumption and engine types, utilizing established emission factors from various literature (Farrukh, et al., 2023), accounting for the Well-to-Wake emissions resulting from fuel production to combustion, with hydrogen production methods showing varying carbon intensities (IEA, 2023). The 20-year and 100-year GHG emission potential can be calculated using Equations 5 and 6, respectively.

$$GHG_{CO2e20,n} = \sum(F_{ME_{CO2e20}} \times FC_{ME_n}) + \sum(F_{AE_{CO2e20}} \times FC_{AE_n}) \quad (5)$$

$$GHG_{CO2e100,n} = \sum(F_{ME_{CO2e100}} \times FC_{ME_n}) + \sum(F_{AE_{CO2e100}} \times FC_{AE_n}) \quad (6)$$

Here, F is the GHG emission factor, which depends on the fuel and engine type and is different for 20-year and 100-year potency.

5.2.2 Energy Efficiency Design Index (EEDI)

The Energy Efficiency Design Index (EEDI) is an IMO approved method to calculate the mass of CO2 emitted per transport work for newly built and existing ships. Equation 7 presents the EEDI calculation, while the detailed description of each parameter and subsequent calculation factors can be found in (Polakis et al. 2019)

$$\frac{(\prod_{j=1}^{n} f_j)(\sum_{i=1}^{nME} P_{\mathrm{ME}(i)} \cdot C_{\mathrm{FME}(i)} \cdot \mathrm{SFC}_{\mathrm{ME}(i)}) + (P_{\mathrm{AE}} \cdot C_{\mathrm{FAE}} \cdot \mathrm{SFC}_{\mathrm{AE}}) + ((\prod_{j=1}^{n} f_j \cdot \sum_{i=1}^{nPTI} P_{\mathrm{PTI}(i)} - \sum_{i=1}^{neff} f_{\mathrm{eff}\,(i)} \cdot P_{\mathrm{AEeff}(i)}) C_{\mathrm{FAE}} \cdot \mathrm{SFC}_{\mathrm{AE}}) - (\sum_{i=1}^{\mathrm{neff}} f_{\mathrm{efff}(i)} \cdot P_{\mathrm{eff}(i)} \cdot C_{\mathrm{FME}} \cdot \mathrm{SFC}_{\mathrm{ME}})}{f_i \cdot f_c \cdot f_l \cdot \mathrm{Capacity} \cdot f_w \cdot V_{\mathrm{ref}}} \quad (7)$$

For the calculation of the EEDI for different decarbonization technologies, there is no regulation from the IMO for adjustments to the EEDI formula. Hence, a factor was developed to calculate the EEDI for each case.

$$F_{EEDI,n} = 1 - \left(\frac{Annual\ CO_2\ Reduction}{Annual\ \mathrm{CO2\ production}}\right) \quad (8)$$

Then, the new EEDI can be calculated as:

$$EEDI_n = EEDI_{Baseline} \times F_{EEDI,n} \quad (9)$$

5.2.3 Carbon Intensity Index (CII)

The carbon Intensity Indicator (CII) is an operational efficiency indicator, which measures the vessel carbon intensity over time, though implementation challenges have been identified (Wang, Psaraftis, & Qi, 2021). Recent studies have demonstrated optimization approaches for CII compliance (Hua & Yin, 2024). CII can be calculated using:

$$\mathrm{CII} = \frac{M}{W} = \frac{\mathrm{FC}_j \times CO_2e_{WTW}}{\mathrm{Capacity} \times D_t} \quad (10)$$

Where, Mis the sum of CO2 emissions, FC_j is the total fuel consumption of fuel type j, W is defined as the product of a ship's capacity, Dt is the distance the ship has traveled Dt (in nautical miles), and CO_2e_{WTW} is the Well-to-Wake (WTW) carbon dioxide equivalent (CO2e) emissions of fuel type j. The Well-to-Wake has two carbon footprints: Well-to-Tank (WTT) and Tank-to-Wake (TTW).

$$CO_2e_{WTW} = CVF \times (CEF_{WTT} + CEF_{TTW}) \tag{11}$$

Where, CVF is the calorific value of fuel, CEF_{WTT} is well-to-tank carbon dioxide equivalent factor for the fuel, and CEF_{TTW} is tank-to-wheel carbon dioxide equivalent factor for the fuel.

The same factor in Equation 8 was used to calculate the CII for each decarbonization case. Hence, the CII would become:

$$CII_n = CII_{Baseline} \times F_{EEDI,n} \tag{12}$$

5.3 Economic Analysis

The examples presented in this section utilize battery and fuel cell technologies but will be adapted for other decarbonization technologies.

5.3.1 Capital Cost

The capital cost (Capital Expenditure, CAPEX) represents the initial powertrain and auxiliary equipment cost together with installation and commissioning costs, and represented by Equation 13:

$$\begin{aligned} Cap = C_{Powertrain} + C_{Auxiliaries} \\ + C_{Commissioning} \\ + C_{Installation} \\ + C_{Decarbonization} \end{aligned} \tag{13}$$

Furthermore, the decarbonization technology costs encapsulate the overall cost of purchase, installation, and commissioning of the technology on-board the vessel, which will be different based on different technologies. For example, the cost of the accompanying auxiliary equipment e.g. electrical components, DC/DC bidirectional converters, wiring, valves for cryogenic systems, air filtration and water purification systems, desalination units, fire suppression systems etc. will be included as and where appropriate. An example is provided below for a pseudo case where fuel cells and batteries are utilized as the decarbonization technology, following optimization approaches for hybrid systems (Liu, et al., 2024).

$$C_{Decarbonization} = C_{FC} + C_{Bat} + C_{BC} + C_{DC} \tag{14}$$

C_{FC}, C_{Bat}, and C_{BC} represent the capital costs of the fuel cell stacks, battery, boost converter, and bidirectional DC/DC converter, respectively.

$$C_{FC} = C_{FC\_unit} \times P_{FC} \times n_{FC} \tag{15}$$

C_{FC_unit} is the unit price of the power of the fuel cell, P_{FC} is the power of a single fuel cell, and n_{FC} is the number of configured fuel cells.

$$C_{Bat} = C_{Bat\_unit} \times U_{Bat\_unit} \times m_{bat} \times Q_{Bat\_unit} \times \frac{n_{bat}}{1000} \tag{16}$$

C_{Bat_Unit} is the unit price of lithium battery, U_{Bat_Unit} is the voltage of a single battery, Q_{Bat_Unit} is the capacity of a single battery, m_{bat} is the number of battery packs in series, and n_{bat} is the number of battery packs in parallel

$$C_{BC} = C_{BC\_unit} \times P_{BC\_max} \tag{17}$$

C_{BC_unit} is the unit price of the Boost converter and P_{BCmax} is the maximum power of the boost converter.

$$C_{DCDC} = C_{DCDC\_unit} \times P_{DCDC\_max} \tag{18}$$

C_{DCDC_unit} is the unit price of the bidirectional DC/DC converter and P_{DCDC_max} is the maximum power of the bidirectional DC/DC converter.

Once the total capital cost, including the decarbonization technology cost, is finalized, the capital investment is converted to the amortized annual investment cost ($C_{inv,a}$), expressed as:

$$C_{inv,a} = \frac{r(Cap)}{1-(1+r)^{-z}} \tag{19}$$

Where r is the annual interest rate, Cap is the capital cost, and z is the system lifetime.

The annual operating and maintenance cost ($C_{O\&M,a}$) need to be considered on a case-by-case basis. The annual operating and maintenance cost can be calculated using the following equation:

$$C_{O\&M,a} = C_{O\&M,Engines} + C_{O\&M,Fuel\ cost} + C_{O\&M,decarbonization} \tag{20}$$

Equation 20 includes the cost of insurance, spare parts, labor costs, and port fees (non-exhaustive list and may include additional costs TBC). Some scenarios may also include the addition of the carbon tax.

Furthermore, fuel cost considerations must account for more general trends, as, for an example, for hydrogen, so to correctly factor this aspect in the economic analysis (European Hydrogen Observatory, s.d.). Similar techno-economic methodologies have been applied to alternative fuel systems in transportation (Zhang, et al., 2023).

5.3.2 Replacement Cost

The usual lifetime of a marine powertrain system is specified as 25 years. However, several decarbonization technologies have lower lifetimes, such as batteries and fuel cells, and require replacement, which adds to the overall cost. An example of the replacement of the previously utilized fuel cell and battery scenario is presented where optimization techniques for fuel cell hybrid systems can inform lifecycle cost calculations (Zhang, et al., 2024). This can be adapted to the specific decarbonization technology.

$$C_{rep} = C_{FC\_rep} + C_{Bat\_rep} \tag{21}$$

Here, C_{rep} is replacement cost for key components and includes the replacement cost of fuel cell stack C_{FC_rep} and battery C_{Bat_rep}.

$$Life_{FC} = \frac{\Delta P}{k_{\mathrm{p}}(k_1 n_1 + k_2 t_1 + k_3 n_2 + k_4 t_2)} \tag{22}$$

Here, $Life_{FC}$ is the available life of the fuel cell, ΔP is the degradation of fuel cell performance from the beginning to the end of the life, and k_{p} is the environmental acceleration coefficient. k_1, k_2, k_3, k_4 are the degradation coefficients of fuel cell performance under start–stop, idling, variable load, and heavy load conditions. n_1, n_2, t_1, t_2 are the number of starts and stops, idling time, number of variable loads, and heavy load time

$$C_{FC\_rep} = C_{FC} \times ceil\left(\frac{T}{Life_{FC}} - 1\right) \tag{23}$$

where, T is the ship operating cycle.

$$Life_{Bat} = min\left[Life_{Bat,rl}, \frac{1}{\sum_{j=1}^{10}\left(\frac{N_{bat,j}}{CF_{bat,j}}\right)}\right] \tag{24}$$

Here, $Life_{Bat}$ is the cycle life of the battery, $Life_{Bat,rl}$ is the calendar life of the battery, $N_{Bat,j}$ is the number of cycles of the battery in one year calculated for different DOD interval, and $CF_{Bat,j}$ is the number of cycle life of the battery corresponding to different DOD intervals.

$$C_{Bat\_rep} = C_{Bat\_unit} \times E_{Bat} \times ceil\left(\frac{T}{Life_{Bat}} - 1\right) \tag{25}$$

Here, E_{Bat} is the total energy of the battery pack(kWh). Once the total replacement cost (C_{rep}) has been calculated, it can be annualized using:

$$C_{rep,a} = \frac{i \cdot (1+i)^n}{(1+i)^n - 1} \cdot \frac{C_{rep}}{(1+i)^t} \tag{26}$$

Here, $C_{rep,a}$ is the annual replacement cost, i is the interesting rate, n is the loan years, and t is the lifespan of the system.

5.3.3 Payback Period

The Discounted Payback Period (DPP) is the period (in years) required to recover the initial investment through the cash inflow (assumed revenue through electricity generation) given by the powertrain systems. The Discounted cash flows (DCF) and DPP are calculated as the year at which the following equation is satisfied:

$$DCF = \sum_{j=1}^{DPP} NAI_j - C_{inv} \tag{27}$$

$$NAI_j = \frac{R_{t_j} - C_{O\&M_j} - C_{rep_j} - C_{fuel_j}}{(1+i)^j} \tag{28}$$

Where, $NAI_{j=1,n}$ (the index j is the year in the range of system lifetime) is the Net Annual Income for each power system. R_{t_j} is the annual revenue (for this purpose, it is assumed that the powertrain acts as an electricity generation powerplant to calculate revenue generation), which is given by:

$$R_{t_j} = p_E \cdot P_{Ej} \tag{29}$$

Where, p_E is the specific price of electricity, while P_{Ej} is the annual electricity production (kWh). The payback period can then be calculated using:

$$\sum_{j=1}^{DPP} NAI_j - C_{inv} = 0 \tag{30}$$

5.3.4 Total Cost of Ownership (TCO)

Having calculated the capital cost, replacement cost, and operational costs, together with the interest rates, the total cost of ownership can be determined by:

$$\begin{aligned} TCO \; = \; & ((C_{inv,a} + \; C_{rep,a} + C_{O\&M,a}) \times n) \\ & + \; early\ loan\ repayment\ penalty \\ & - \; resale\ value \end{aligned} \tag{31}$$

Where, n is the number of years owned. Here, it is important to note that the replacement cost may or may not be applicable, depending on the length of ownership. Additionally, the TCO is also dependent on the initial deposit, if the interest rate is variable or fixed-term, and if there are any penalties for early repayment by way of asset resale. This will require consultation with the ship owners through the appropriate channels to gauge information.

5.3.5 Levelized Cost of Electricity:

The levelized cost of electricity (LCOE) can be defined as the cost of producing one unit of electricity through the vessel's powertrain. It can be calculated using the sum of total annualized costs and the annual electricity production by the powertrain ($E_{electricity}$), and is expressed as:

$$LCOE = \frac{C_{ina,a} + C_{rep,a} + C_{O\&M,a}}{E_{electricity}} \tag{32}$$

5.4 The Corporate Sustainability Reporting Directive in the Maritime Transport

The Corporate Sustainability Reporting Directive (CSRD) (Corporate Sustainability Reporting, s.d.), which entered into force in January 2023, represents a paradigm shift in European sustainability reporting requirements. Building upon the Non-Financial Reporting Directive (NFRD), the CSRD mandates comprehensive sustainability disclosures for approximately 50,000 companies across the European Union, including a significant portion of the maritime transport industry.

For the maritime sector, the CSRD's implications are particularly profound. The directive requires detailed reporting on environmental impacts through the European Sustainability Reporting Standards (ESRS), with special emphasis on climate change mitigation (E1), pollution control (E2), water and marine resources (E3), biodiversity and ecosystems (E4), and resource use and circular economy (E5). The maritime industry, responsible for approximately 3% of global greenhouse gas emissions and facing increasing regulatory pressure through the International Maritime Organization's (IMO) decarbonization strategy, must now demonstrate measurable progress toward sustainability goals.

The European Financial Reporting Advisory Group (EFRAG) (Efrag web site, s.d.) has established that sustainability reporting must be based on robust, science-based methodologies that ensure comparability, reliability, and relevance. This requirement creates an unprecedented opportunity for the maritime industry to leverage advanced analytical tools, particularly Life Cycle Assessment (LCA), to quantify the environmental performance of emerging decarbonization technologies.

The SEASTARS project addresses this critical need by developing a comprehensive framework for evaluating ship decarbonization technologies, including air lubrication systems, fuel cells, rigid wing sails, photovoltaic panels, and other innovative solutions. By aligning Key Performance Indicators (KPIs) with

ESRS requirements and employing LCA methodologies, the project aims to provide the maritime industry with scientifically robust tools for technology assessment and regulatory compliance.

5.5 Life Cycle Assessment: Methodology and Application to Maritime Systems

Life Cycle Assessment is a standardized methodology (ISO 14040/14044) that quantifies the environmental impacts of products, processes, or services throughout their entire life cycle—from raw material extraction through manufacturing, use phase, and end-of-life disposal. LCA provides a holistic view of environmental performance, preventing the shifting of environmental burdens between life cycle stages or impact categories.

In the maritime context, LCA enables comprehensive evaluation of decarbonization technologies by considering not only operational emissions but also the environmental impacts associated with manufacturing, installation, maintenance, and disposal. For instance, while a fuel cell system may produce zero direct emissions during operation, its LCA would account for the environmental impacts of hydrogen production, platinum mining for catalysts, and the energy required for system manufacturing.

The LCA methodology consists of four interconnected phases:

Goal and Scope Definition: Establishes the study's purpose, functional unit (e.g., ton-kilometer of cargo transported), system boundaries, and impact categories to be assessed. For maritime applications, the functional unit typically relates to cargo transport capacity over a specified distance and time period.

Life Cycle Inventory (LCI): Quantifies all inputs (energy, raw materials, water) and outputs (emissions, waste, co-products) associated with the system under study. This phase requires detailed data collection on material compositions, manufacturing processes, operational profiles, and end-of-life scenarios.

Life Cycle Impact Assessment (LCIA): Translates inventory data into potential environmental impacts using characterization factors. Common impact categories include climate change potential, acidification, eutrophication, ozone depletion, human toxicity, and ecotoxicity.

Interpretation: Analyzes results, identifies significant impacts, checks completeness and consistency, and draws conclusions aligned with the study's goals.

5.5.1 Integration with Model-Based Systems Engineering

The application of LCA to maritime decarbonization technologies is significantly enhanced when integrated with Model-Based Systems Engineering (MBSE) approaches. MBSE employs digital modeling tools to support systems engineering activities throughout the development lifecycle, enabling comprehensive system representation, requirement traceability, and design optimization.

In the SEASTARS context, MBSE facilitates the creation of detailed digital twins of vessels and their subsystems, incorporating decarbonization technologies within accurate operational models. These digital representations enable dynamic LCA calculations that account for varying operational conditions, route profiles, and technology performance characteristics. For example, the environmental performance of a hybrid propulsion system combining fuel cells and battery storage can be evaluated across different voyage scenarios, weather conditions, and cargo loads.

The synergy between LCA and MBSE creates a powerful optimization framework with several key advantages: enhanced data quality through automated inventory generation, dynamic impact assessment enabling real-time optimization under varying operational conditions, scenario analysis capabilities that systematically guide technology selection and integration, and integrated uncertainty propagation supporting robust optimization decisions. This combination transforms LCA-derived KPIs into active optimization tools within the MBSE environment, enabling iterative design refinement and systematic guidance toward optimal decarbonization solutions while ensuring compliance with both maritime operational complexity and CSRD scientific standards.

5.6 ESRS-Aligned KPI Framework for Maritime Decarbonization Technologies

Based on the ESRS E1-E5 environmental standards and LCA methodology principles, the following comprehensive KPI framework is proposed for evaluating ship decarbonization technologies:

5.6.1 ESRS E1 - Climate Change KPIs

Carbon Intensity Indicators:

- Life cycle GHG emissions per ton-kilometer (kg CO_2-eq/t-km)
- Well-to-wake GHG emissions per nautical mile (kg CO_2-eq/nm)
- Technology-specific emission reduction potential (% reduction vs. baseline)
- Scope 1, 2, and 3 emissions breakdown (kg CO_2-eq)

Energy Performance Metrics:

- Life cycle energy demand per functional unit (MJ/t-km)
- Renewable energy fraction in total energy consumption (%)
- Energy Return on Energy Invested (EROEI) ratio
- Technology-specific energy efficiency improvement (% improvement vs. baseline)

Decarbonization Pathway Indicators:

- Carbon payback time (years)
- Marginal abatement cost (€/ton CO_2-eq avoided)
- Compatibility with net-zero trajectories (binary indicator)

5.6.2 ESRS E2 - Pollution KPIs

Air Quality Indicators:

- Particulate matter formation potential (PM2.5-eq/t-km)
- Nitrogen oxides emissions intensity (NOx-eq/t-km)
- Sulfur dioxide emissions intensity (SO_2-eq/t-km)
- Photochemical ozone creation potential (POCP/t-km)

Water Pollution Metrics:

- Marine eutrophication potential (N-eq/t-km)
- Freshwater eutrophication potential (P-eq/t-km)
- Marine ecotoxicity potential (CTUe/t-km)
- Discharge water quality indicators (various pollutants)

Toxicity Assessments**:**

- Human toxicity potential - carcinogenic effects (CTUh/t-km)
- Human toxicity potential - non-carcinogenic effects (CTUh/t-km)
- Freshwater ecotoxicity potential (CTUe/t-km)

5.6.3 ESRS E3 - Water and Marine Resources KPIs

Water Consumption Indicators:

- Blue water footprint per functional unit (m^3/t-km)
- Water stress index weighted consumption (m^3 world-eq/t-km)
- Technology-specific water demand (m^3/MW installed capacity)

Marine Impact Metrics:

- Marine acidification potential (molc H^+-eq/t-km)
- Impact on marine biodiversity indicators
- Ballast water treatment efficiency (% invasive species risk reduction)

5.6.4 ESRS E4 - Biodiversity and Ecosystems KPIs

Land Use Impact Indicators:

- Land use change impact (m^2·year/t-km)
- Biodiversity damage potential (PDF·m^2·year/t-km)
- Ecosystem quality impact (species·year/t-km)

Marine Ecosystem Indicators:

- Underwater noise pollution levels (dB re 1 μPa at 1m)
- Ship strike risk assessment for marine mammals
- Habitat fragmentation potential

5.6.5 ESRS E5 - Resource Use and Circular Economy KPIs

Material Consumption Metrics**:**

- Critical raw materials intensity (kg CRM/MW capacity)
- Abiotic depletion potential - ultimate reserves (kg Sb-eq/t-km)
- Material circularity indicators (% recycled content, % recyclability)

Circular Economy Indicators:

- Technology lifespan and durability metrics (years, cycles)
- End-of-life recovery potential (% by mass)
- Waste generation intensity (kg waste/t-km)
- Remanufacturing and refurbishment potential (%)

5.7 Implementation Framework and Methodological Considerations

5.7.1 Data Requirements and Quality Assurance

Implementing this KPI framework requires establishing robust data collection protocols aligned with the project objectives or LCA standards. Primary data should be obtained directly from technology manufacturers and operators, covering material compositions, manufacturing processes, operational performance, and maintenance requirements. Secondary data from established LCA databases (ecoinvent, IDEMAT) should be used for background processes, ensuring data quality through uncertainty assessment and sensitivity analysis.

Data quality requirements must align with CSRD verification standards, necessitating documentation of data sources, collection methods, and uncertainty ranges. The framework should incorporate data quality indicators including technological representativeness, geographical correlation, temporal correlation, completeness, and precision.

5.7.2 Technology Assessment Methodology

Each decarbonization technology should be evaluated using a standardized assessment protocol that ensures comparability across different solutions. The assessment should include baseline definition using conventional marine propulsion systems as reference, functional unit standardization ensuring consistent comparison basis across technologies, system boundary definition covering cradle-to-grave life cycle stages, allocation procedures for multi-functional systems, and impact assessment using scientifically robust characterization methods.

5.7.3 Integration with MBSE and Digital Twins

The KPI framework should be integrated within digital twin environments that enable dynamic assessment under varying operational conditions. This integration facilitates real-time monitoring of environmental performance, scenario analysis for route and operational optimization, predictive assessment of technology combinations, and automated reporting aligned with CSRD requirements.

5.7.4 Verification and Validation Protocols

To ensure compliance with CSRD verification requirements, the framework must incorporate independent verification protocols. These should include third-party LCA review procedures, data validation against industry benchmarks, uncertainty quantification and reporting, and traceability documentation for all calculations and assumptions.

5.7.5 Continuous Improvement and Updates

The framework should incorporate mechanisms for continuous improvement, including regular updates to characterization factors, integration of emerging impact categories, incorporation of technological improvements, and alignment with evolving regulatory requirements.

The proposed KPI framework provides a comprehensive foundation for evaluating maritime decarbonization technologies in alignment with CSRD requirements. By integrating LCA methodology with MBSE approaches, the framework enables scientifically robust, transparent, and comparable assessment of environmental performance across the full range of ship decarbonization solutions.

The framework's alignment with ESRS E1-E5 standards ensures that technology assessments support regulatory compliance while providing valuable insights for technology development and deployment decisions. The integration of multiple environmental impact categories prevents burden shifting and supports holistic optimization of maritime sustainability performance.

Future work should focus on refining characterization methods for marine-specific impacts, developing automated data collection and processing systems, and establishing industry-wide standards for technology assessment and reporting. The successful implementation of this framework will contribute significantly to the maritime industry's transition toward sustainable operations and compliance with evolving environmental regulations.

5.8 Segment-Specific KPI Considerations

The maritime transport industry encompasses diverse operational segments, each with distinct characteristics that influence decarbonization technology adoption and KPI prioritization. While the core environmental and technical performance indicators remain consistent across segments, the economic drivers, operational constraints, and regulatory frameworks vary significantly between deep-sea shipping, inland waterways, and short-sea operations. This section addresses the preliminary considerations made by the Consortium as regards these segment-specific sensitivities to ensure the SEASTARS KPI framework provides relevant guidance across all maritime applications.

5.8.1 Deep-Sea and Long Ocean Operations

Deep-sea shipping operations, characterized by long voyage distances, large vessel sizes, and international regulatory compliance requirements, present unique considerations for decarbonization KPI evaluation.

Voyage-Specific Performance Indicators:

- Well-to-wake emissions per ton-nautical mile over extended voyages (kg CO_2-eq/t-nm)
- Fuel efficiency across varying sea states and weather conditions (g/kWh)
- Technology performance degradation over long operational cycles (% efficiency loss)
- Maintenance interval compatibility with port call schedules (days between service)

International Compliance Metrics:

- IMO EEDI and CII compliance across flag state and port state jurisdictions
- FuelEU Maritime regulation compliance for EU port calls (GHG intensity limits)
- Alignment with Green Shipping Corridor requirements for specific trade routes
- International bunker fuel availability and infrastructure compatibility

Economic Scale Considerations:

- Technology CAPEX amortization over high-value cargo volumes (€/TEU or €/DWT)
- Economies of scale benefits for large-capacity installations (cost reduction per MW)
- Charter rate impact from technology integration ($/day charter differential)
- Fuel cost volatility impact on long-term contracts (risk assessment metrics)

Operational Reliability Requirements:

- Technology availability requirements for critical trade routes (>99% uptime)
- Redundancy and backup system requirements for extended voyages
- Remote monitoring and predictive maintenance capabilities
- Emergency response and safety protocols for mid-ocean operations

5.8.2 Inland Water Transportation

Inland waterway operations face distinct economic and operational challenges that significantly influence technology adoption decisions. Unlike deep-sea shipping, inland operators typically operate with constrained margins and more limited financing options, requiring careful evaluation of business case viability.

Business Case Viability Metrics:

- Breakeven gasoil price for alternative fuel viability (€/liter equivalent)
- OPEX per kWh delivered across different fuel options (€/kWh)
- Lifecycle cost per kWh output comparison (€/kWh over asset lifetime)
- Debt Service Coverage Ratio (DSCR) compatibility with banking requirements (minimum 1.3)

Drop-in Fuel Assessment Framework:

For drop-in fuel technologies, representing the lowest-risk decarbonization pathway:

- Fuel cost differential per unit energy (€/MWh vs. gasoil baseline)
- Additional fuel handling costs including circulation, heating, and filtering (€/year)
- Engine maintenance cost impact and reliability under inland navigation conditions
- Cold weather performance and storage stability indicators
- Navigation safety impact assessment during confined waterway operations

Alternative Fuel Technology Evaluation:

For transformative technologies such as methanol and Liquid Organic Hydrogen Carriers (LOHC):

- Fuel conversion efficiency ratios and dual fuel capability reliability
- Breakeven analysis curves showing gasoil price thresholds for commercial viability
- CAPEX tolerance levels with neutral OPEX impact requirements
- Technology readiness timeline estimates (2030, 2035, 2040 adoption scenarios)

Risk-Adjusted Investment Framework:

- Maximum acceptable OPEX increase before operational viability risk (% above baseline)
- ROI threshold flexibility for environmental compliance benefits
- Financing constraint accommodation within typical inland shipping business models

5.8.3 Short-Sea Shipping Operations

Short-sea shipping, operating primarily within regional markets and often serving as feeders to major ports, combines elements of both deep-sea and inland operations while facing unique regulatory and operational pressures.

Regional Compliance Indicators:

- EU ETS compliance for intra-European voyages (carbon cost per voyage)
- Regional emission control area (ECA) compliance requirements
- Port state control compliance rates across operating regions

- Green shipping incentive eligibility (port fee reductions, priority berthing)

Operational Flexibility Metrics:

- Multi-port voyage efficiency optimization potential (fuel savings per rotation)
- Technology compatibility with frequent port calls and cargo handling
- Ballast water treatment integration with short voyage cycles
- Shore power connectivity and utilization rates in regional ports

Market Competitiveness Factors:

- Technology cost impact on freight rates in competitive regional markets (€/TEU)
- Modal shift competitiveness versus road and rail transport alternatives
- Fleet standardization benefits across multiple vessels and routes
- Customer sustainability requirement compliance (shipper ESG mandates)

Infrastructure Integration Requirements:

- Regional fuel infrastructure availability and development timelines
- Port infrastructure compatibility (shore power, alternative fueling)
- Maintenance network accessibility across operating regions
- Technology support and spare parts availability

5.8.4 Cross-Segment Integration Considerations

Technology Scalability Across Segments:

- Modular technology designs enabling deployment across vessel size ranges
- Standardization benefits and economies of scale across maritime segments
- Technology maturation pathways from niche to mainstream applications

Regulatory Harmonization:

- Consistency in environmental performance measurement across jurisdictions
- Technology certification and approval processes for different operational areas
- International cooperation on alternative fuel standards and safety protocols

Supply Chain Integration:

- Alternative fuel production and distribution network development
- Technology manufacturing capacity scaling across market segments
- Skilled workforce development for installation, operation, and maintenance

This segment-specific approach ensures that the SEASTARS KPI framework addresses the diverse operational realities across maritime transport while maintaining scientific rigor and environmental effectiveness. The framework recognizes that successful decarbonization requires technology solutions and evaluation metrics tailored to the economic, operational, and regulatory context of each maritime segment.

6 Conclusions

The SEASTARS project represents a significant advancement in maritime decarbonization through the systematic application of Model-Based Systems Engineering (MBSE) methodologies to address the complex challenges of reducing shipping emissions while maintaining operational efficiency and economic viability. This deliverable has established the foundational framework for achieving the project's ambitious targets of 30% well-to-wake GHG emissions reduction and 20% energy efficiency improvement by 2030.

Summary of Key Findings: The implementation of MBSE, particularly through the ARCADIA/CAPELLA methodology combined with the SPEC software environment, provides a robust digital framework for evaluating and integrating decarbonization technologies across diverse vessel types and operational profiles. The comprehensive data collection strategy from both shipowners and technology providers ensures that digital models are grounded in real-world operational conditions rather than theoretical assumptions. The establishment of Key Performance Indicators creates a scientifically rigorous assessment framework that supports both regulatory compliance and informed decision-making for technology adoption.

Relevance to Project Objectives: The methodological framework directly supports the SEASTARS core objective of demonstrating practical decarbonization solutions for eight vessel designs. By establishing a standardized approach to data collection, model development, and performance evaluation, the project creates a modularization approach and a replicable methodology that can accelerate technology uptake across the maritime industry. The integration of MBSE with Life Cycle Assessment principles ensures that optimization efforts address the full environmental impact spectrum while maintaining focus on operational and economic constraints.

Lessons Learned & Challenges: The complexity of maritime systems necessitates a collaborative modeling strategy that brings together diverse stakeholders including shipowners, technology providers, and research institutions. The heterogeneous nature of decarbonization technologies requires flexible data collection approaches tailored to specific technology characteristics while maintaining consistency in evaluation criteria. The transition from document-centric to model-driven engineering approaches demands significant upfront investment but delivers substantial benefits in terms of system understanding, change impact analysis, and collaborative decision-making.

Recommendations: Future implementations should prioritize the development of standardized data interfaces between MBSE tools and operational monitoring systems to enable real-time model validation and continuous optimization. In the future, the maritime industry should consider establishing common frameworks for technology assessment based on ESRS-aligned KPI structure to facilitate comparison and accelerate adoption of proven solutions. Investment in digital twin capabilities should be pursued to extend the benefits of MBSE beyond the design phase into operational optimization and predictive maintenance.

Next Steps: The methodology established in this Deliverable will be applied in subsequent work packages to develop and validate digital models for specific decarbonization technologies, conduct comprehensive scenario analyses for the eight target vessel designs, and demonstrate the practical applicability of the MBSE approach through real-world case studies. The data collection protocols will be possibly refined based on initial implementation experiences, and the KPI framework will be validated against operational performance data from participating shipowners. The ultimate goal is to deliver a comprehensive smart design tool that enables shipowners to make informed decisions about decarbonization investments while ensuring compliance with evolving regulatory requirements and maintaining competitive operational performance.

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8 Annexes

Annex I – SO Data review and validation checklist

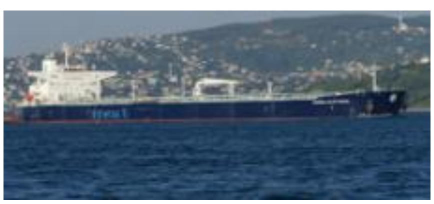
Annex II - SO Data processing example

8.1 Annex I - SO Data review and validation checklist

Examples of included worksheets for the MT MINERVA ELEFTHERIA

Point	Description	Compliant? (Yes/No)	Notes
1. Data Request:	type and format.		
Type of data requested	e.g., performance maps, system layout, dynamic consumption profiles, noon reports.	[ ]	
Required format	e.g., excel, .csv, .pdf.	[ ]	
2. Data Reception:	Documents the received data and checks compliance with requested formats.		
Data received	compliant or non-compliant format.	[ ]	
Compliance with requested format	Compliance with requested format (e.g., excel, .csv, .pdf).	[ ]	
Issues encountered	Any issues if the data is non-compliant.	[ ]	

<table>
<tr><td>MT MINERVA ELEFTHERIA</td><td>Recipient

Alpha Marine Consulting</td></tr>
<tr><td rowspan="2"></td><td>Reviewer

DG Twin S.r.l</td></tr>
<tr><td>Date:</td></tr>
</table>

CK0. CERTIFICATION

MT MINERVA ELEFTHERIA		Noon report	Unit measure	Number of data records	Complete? (y/n)
		Total HFO	[m3]		
		Total MGO	[m3]		
Type of data	Numerical	SFOC ME	[g/kW.h]		
Number of Voyage	10	RH ME	[h]		
Number of records	36	Avg. Power ME	[kW]		
		Avg. RPM ME	[Rpm]		
		SFOC AE1	[g/kW.h]		
		RH AE1	[h]		
		Avg. Power AE1	[kW]		
		Avg. RPM AE1	[Rpm]		
		SFOC AE2	[g/kW.h]		
		RH AE2	[h]		
		Avg. Power AE2	[kW]		
		Avg. RPM AE2	[Rpm]		
		SFOC AE3	[g/kW.h]		
		RH AE3	[h]		
		Avg. Power AE3	[kW]		
		Avg. RPM AE3	[Rpm]		

CK1. NOON REPORT

MT MINERVA ELEFTHERIA	Category	Status[2]	Note*	Accessability[3]	Path	
	General	Partial		Confidential	NAOME_SEASTARS HORIZON-CL5-2024-D5-01 Teams --> Data for MT MINERVA ELEFTHERIA	To fill in the Teams folder
	Machinery	Partial		Confidential	NAOME_SEASTARS HORIZON-CL5-2024-D5-01 Teams --> Data for MT MINERVA ELEFTHERIA	To fill in the Teams folder
	Structural	Partial		Confidential	NAOME_SEASTARS HORIZON-CL5-2024-D5-01 Teams --> Data for MT MINERVA ELEFTHERIA	To fill in the Teams folder
	Electrical	Partial		Confidential	NAOME_SEASTARS HORIZON-CL5-2024-D5-01 Teams --> Data for MT MINERVA ELEFTHERIA	To fill in the Teams folder
	Piping	Complete		Confidential	NAOME_SEASTARS HORIZON-CL5-2024-D5-01 Teams --> Data for MT MINERVA ELEFTHERIA	To fill in the Teams folder
	Operation Data	Partial		Confidential	NAOME_SEASTARS HORIZON-CL5-2024-D5-01 Teams --> Data for MT MINERVA ELEFTHERIA	To fill in the Teams folder

CK2. SUMMARY CHECKLIST

Category	Data	Type of data(1)	Format	Status(2)	Note	Accessability(3)	Path
General	List of Finished Plans	Documental	pdf	Complete		Confidential	To load in the Teams folder
	Lines Plan or Offset Tables			Missing	Received but not available		
	Model test or Sea Trials	Documental	pdf	Complete	Related documents: SK15-03-00F, M37-200-00F	Confidential	To load in the Teams folder
	Capacity Plan (with dwt scale)	Documental	pdf	Complete		Confidential	To load in the Teams folder
	General Arrangement	Documental	pdf	Complete		Confidential	To load in the Teams folder
	Fire Control & Safety Plan	Documental	pdf	Complete		Confidential	To load in the Teams folder
	Docking Plan	Documental	pdf	Complete		Confidential	To load in the Teams folder
	Dangerous Zone Plan	Documental	pdf	Complete		Confidential	To load in the Teams folder
	Midship Section	Documental	pdf	Complete		Confidential	To load in the Teams folder
	Shell expansion	Documental	pdf	Complete		Confidential	To load in the Teams folder
	Profiles and Decks plan	Documental	pdf	Complete		Confidential	To load in the Teams folder
	Loading Manual / Trim & Stability Booklet/ Grain Loading Manual	Documental	pdf	Complete		Confidential	To load in the Teams folder
	Equipment Number Calculation	Documental	pdf	Complete		Confidential	To load in the Teams folder
	Damage Control Booklet	Documental	pdf	Complete		Confidential	To load in the Teams folder
	Navigation Bridge Visibility	Documental	pdf	Complete		Confidential	To load in the Teams folder
Machinery	Engine Room Arrangement			Missing	Received but not available		
	Funnel Arrangement	Documental	pdf	Complete	Available also in Structural folder	Confidential	To load in the Teams folder
	Main Engine Technical File	Documental	pdf	Partial	Related documents in folder: 3_B_Main_Engine	Confidential	To load in the Teams folder
	Aux. Engines Technical File	Documental	pdf	Partial	Related documents in folder: 4_D_Generator_Engine	Confidential	To load in the Teams folder
	Aux. Boiler Technical File	Documental	pdf	Partial	Related documents in folder: 5_E_Steam_Generation_System	Confidential	To load in the Teams folder
	Air compressors specifications	Documental	pdf	Partial	Related documents in folder: 6_F_Compressed_Air_System_And _Fan	Confidential	To load in the Teams folder
	ECR Arrangement			Missing	Received but not available		
	CCR Arrangement			Missing			
	HVAC Arrangement			Missing			
	Propeller Plan	Documental	pdf	Partial		Confidential	To load in the Teams folder
	Propeller open water characteristics/efficiency curves kt,	Documental	png	Partial	Related documents: ETA0; Requested: KT-KQ vs J curves	Confidential	To load in the Teams folder
	ESD drawings			Missing			
	Rudder Construction Drawing	Documental	pdf	Complete		Confidential	To load in the Teams folder
	Arrangement of Main Pump Room	Documental	pdf	Partial		Confidential	To load in the Teams folder
Structural	Aft End	Documental	pdf, txt	Partial	Related documents: H-1-250-00F, H-1-260-00F, Hull lines	Confidential	To load in the Teams folder
	Fore End	Documental	pdf	Partial		Confidential	To load in the Teams folder
	Pump & Engine Room	Documental	pdf	Complete		Confidential	To load in the Teams folder
	Cargo Area	Documental	pdf	Complete	Related documents: H-1-230-00F,H-1-231-00F,H-1-232-00F	Confidential	To load in the Teams folder
	Double Bottom	Documental	pdf	Complete	Related documents: H-1-221-00F, H-1-230-00F,H-1-231-00F, H-1-232-	Confidential	To load in the Teams folder
	Funnel	Documental	pdf	Complete	Available also in Machinery folder	Confidential	To load in the Teams folder
	Engine Casing			Missing			
	Accomodation Block/ Deckhouse Construction			Missing			
Electrical	Arr't of Electric Equipment			Missing	Received but not available		
	Electric Power Balance / Electric load analysis	Documental	pdf	Complete		Confidential	To load in the Teams folder
	Wiring Diagram Of Power System	Documental	pdf	Complete		Confidential	To load in the Teams folder
	Main Switchboard (Including fault current settings of breakers)			Missing			
	Instrument & Alarm Point List			Missing			
	Wiring Diagram Of Lighting	Documental	pdf	Complete	Related documents: E014-00-00F, E014-10-00F	Confidential	To load in the Teams folder
	Short Circuit Calculation			Missing			
	Wiring Diagram of Automation & Control	Documental	pdf	Complete	Related documents: E015-00-00F, E015-10-00F	Confidential	To load in the Teams folder
	Wiring Diagram of Communication & Equipment (for GPS signal)	Documental	pdf	Complete		Confidential	To load in the Teams folder
	Arrangement of Electric Equipment (Nav.Comp. Deck)	Documental	pdf	Partial		Confidential	To load in the Teams folder
Piping	Piping Diagram in Engine Room	Documental	pdf	Complete	Related documents in folder: MA-12_M36-200-00F	Confidential	To load in the Teams folder
	Hull Piping Diagram	Documental	pdf	Complete	Related documents in folder: 5_Hull piping	Confidential	To load in the Teams folder
Operation Data	Drydocking Schedule			Missing			
	General Trade Route of the vessel (voyages and port/topography)			Missing	Received but not available		
	Vessel's IAPP Certificate including supplement	Documental	pdf	Complete	Related documents: EIAPP-ME, EIAPP-GE	Confidential	To load in the Teams folder
	M/E Nox Technical File	Documental	pdf	Complete	Related documents: Nox Technical File ME, Nox Technical file GE	Confidential	To load in the Teams folder

CK3. DETAILED CHECKLIST

8.2 Annex II - SO Data processing example

Objective

To establish a baseline operational profile of the vessel for the year 2022 by analyzing real operational data collected through noon reports. This baseline will serve as a reference for evaluating decarbonization scenarios in future years.

Supporting Documentation

In addition to operational data, appropriate as-built data and technical drawings were gathered from the vessel owners. This included documentation across various technical categories such as: General Arrangements, Machinery, Piping, Structural, Hull, Electrical, Operation, Maintenance Manuals. An informative Excel register was created to maintain a systematic record of the documents received, organized by category and vessel.

Data Collection & Processing

Operational data was gathered from four vessels: Synergy, Neptune Galene, Minerva Eleftheria, and MSC Athens. The dataset includes daily records of fuel consumption (by fuel type), engine output, distance sailed, operational days (laden/ballast), speed, and route characteristics. AMC performed post-processing to clean and structure this data, enabling the creation of operational and dynamic profiles for each vessel.

Benchmark Metrics (2022)

Key performance indicators (KPIs) and emissions metrics were calculated to establish 2022 benchmarks:
Carbon Intensity Indicator (CII)
- Fuel consumption (tons/year)
- CO_2, NO_x, SO_x, PM emissions (tons/year)

These benchmarks are essential for comparison against future decarbonization action plan scenarios.

Outcomes

1. Accurate, vessel-specific benchmarks for emissions and efficiency were derived.
2. Data supports identification of high-emission profiles and optimization opportunities.
3. This baseline is a foundation for assessing the impact of technical and operational improvements under the IMO, EU FIT 55 decarbonization trajectory.

Methodology

1. Data Acquisition

Noon reports and daily logs from four vessels (Synergy, Neptune Galene, Minerva Eleftheria, MSC Athens) were compiled for the full calendar year 2022.

2. Data Processing

AMC performed data cleaning and harmonization, resolving inconsistencies and converting units where necessary. Route-specific data and engine performance were also standardized.

3. Profile Development

Operational profiles were constructed including:
- Fuel consumption by type (HFO, MDO, MGO)
- Vessel activity (ballast/laden days, distance sailed)
- Daily and annualized engine load factors

4. Emission Calculations

Using emission factors from the IMO guidelines, emissions were computed per pollutant (CO_2, NO_x, SO_x, PM) for each vessel.

5. Formulas Used

1. **Carbon Intensity Indicator (CII):**

$$\mathrm{CII} = \frac{\text{Annual CO}_2\text{ emissions [g]}}{\text{Transport Work [ton\cdotpnm]}} = \frac{\sum(\text{Fuel Consumed} \times \mathrm{EF}_{CO_2})}{\text{DWT} \times \text{Distance Travelled}}$$

2. **Emission Estimation (per pollutant):**

For each fuel type f, and each pollutant p, emissions were calculated using:

$$\text{Emissions}_p = \text{Fuel Consumed}_f \times \text{Emission Factor}_{f,p}$$

Where emission factors were obtained from the "Emission Factors & Formulas" sheet:

- CO_2 (g/g fuel): HFO – 3.114, MDO – 3.151, MGO – 3.206
- NO_x: 100 g/g
- SO_x: HFO – 70 g/g, MDO/MGO – 2 g/g
- PM: 2 g/g for all types

6. CII Computation

CII was calculated using fuel-based CO_2 emissions relative to transport work (DWT × Distance).

7. Benchmarking

Annual totals for each vessel were aggregated to establish average benchmarks for:
- Fuel usage
- Emissions
- Carbon intensity