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Mathias Dreier

MBSE in the Maritime Industry
Enabling Digital Transformation for CO_2 Reduction through Wind-assisted Ship Propulsion

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Monographic Series TU Graz

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Enabling Digital Transformation for CO_2 Reduction through
Wind-assisted Ship Propulsion”, presented by Mathias Dreier on April 24,
2025 at Graz University of Technology, Institute of Machine Components
and Methods of Development.

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Systems thinking is a discipline for seeing wholes. It is a framework for seeing interrelationships rather than things, for seeing "patterns of change" rather than static "snapshots."

Peter M. Senge (1947 – present)

Foreword

The maritime industry stands at a pivotal moment in its history, balancing its indispensable role in global trade with an urgent responsibility to address environmental challenges. As one of the largest contributors to international transport emissions, this sector faces the formidable challenge of achieving net-zero greenhouse gas emissions by 2050. This demands systematic and well-planned climate protection measures that are grounded in comprehensive model approaches and underpinned by systems thinking. Incremental changes are no longer sufficient; the industry must embrace comprehensive model-based approaches and a holistic mindset that integrates advanced technologies, smarter operations, and bold innovation.

Model-based systems engineering (MBSE) provides a methodology that enables the maritime industry to navigate this complexity, addressing not only the technical challenges of decarbonization but also fostering the development of more intelligent control systems for logistics. These systems enhance operational efficiency, complementing efforts to develop zero-emission vessels and retrofit the existing fleet. MBSE drives the digital transformation required to modernize processes and systems while ensuring they align with long-term environmental goals. By fostering a holistic understanding of interconnected systems, MBSE supports the systematic planning and implementation of climate protection measures, aligning them with the ambitious 2050 net-zero goal and the broader transformation of the industry. It integrates environmental objectives into the core of ship design and operational strategies, ensuring that sustainability is not an afterthought but a guiding principle. Such comprehensive frameworks allow stakeholders to align technological innovations with regulatory and societal goals, paving the way for practical and impactful solutions.

The reduction of greenhouse gas emissions must be addressed with urgency, precision, and collaboration. MBSE enables these qualities by offering a structured methodology that supports clear communication, traceability, and adaptability. It brings together diverse stakeholders – shipbuilders, operators, policymakers, and researchers – to work toward shared objectives, creating a unified strategy for decarbonization and efficiency.

The author exemplifies how such approaches can be applied to address real-world challenges, showcasing a deep understanding of the potential of rigorous, model-driven strategies to support decarbonization. Looking forward, the maritime industry must seize this unparalleled opportunity to redefine itself. By embracing digital transformation, adopting intelligent logistics systems, and committing to sustainable practices, we can chart a bold course toward a cleaner, more resilient future. It is a call to action for every stakeholder in this vast and vital sector – to think bigger, act faster, and collaborate more deeply. By embedding systematic methodologies like MBSE into the heart of its transformation, the industry can achieve a cleaner, more resilient future. The integration of such frameworks is not merely a technical endeavor; it represents a fundamental shift in how we think about and approach sustainability in one of the world's most vital industries.

Univ.-Prof. Dipl.-Ing. Dr.techn. Hannes Hick

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With all my heart, I dedicate this work to my father Ferdinand Dreier († December 25, 2019), who unfortunately passed away far too early. Thank you for your everlasting support and I am incredibly proud of what you have achieved in your life.

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Abstract

The maritime industry, particularly the international marine shipping sector, consists of a vast network of worldwide stakeholders. This sector is the backbone of our globalized economy as it provides the service of moving goods, resources, and passengers from one place to another by sea using large ocean-going vessels such as container ships, tankers, or bulk carriers. However, the maritime industry faces numerous challenges in a complex environment, including the need for resilient and sustainable supply chains, the *digital transformation* to improve the effectiveness and efficiency of ship design, and the *energy transition* brought on by the impending climate crisis. With the *2023 IMO Strategy on Reduction of GHG Emissions from Ships*, the *International Maritime Organization* (IMO), the most important regulatory authority for the maritime sector, has already outlined pathways to achieve net-zero greenhouse gas emissions by 2050. The strategy is in line with the long-term temperature goal set out in the 2015 *Paris Agreement* to limit the increase in global average temperature to well below 2°C, ideally 1.5°C, above pre-industrial levels. The industry is thus undergoing a major transformation to achieve the reduction of greenhouse gas (GHG) emissions from existing and future vessels. Many new solutions and technologies, including *low- and zero-emission alternative fuels and propulsion technologies*, *energy-saving technologies*, and *operational measures*, need to be integrated and aligned within a complex stakeholder environment. There is a need for new ways of working with and managing the increasing complexity of the maritime industry. To better understand the current situation and develop advanced solutions, *model-based systems engineering* (MBSE) approaches are a promising strategy.

In this context, the *Maritime and Ocean Digital Engineering Laboratory* (MODE Lab) was established as an international project for the decarbonization and automation of the maritime industry, based at the *University of Tokyo* in Japan. This master's thesis aims to complement the existing activities of the MODE Lab by applying MBSE methodologies to the maritime industry, thereby contributing to the industry's *digital transformation* and *decarbonization*.

The objective of this master's thesis is the development of a *descriptive system model* of a bulk carrier ship equipped with a *wind-assistance device* (WAD) for auxiliary propulsion to reduce its GHG emissions by using the *Arcadia* modeling language and method together with the *Capella* modeling tool. A strong focus is placed on a comprehensive *operational analysis* of the system-of-interest and the integration of *wind-assisted ship propulsion* (WASP) into a bulk carrier. As current ship development practices are considered inadequate to meet the challenges of the maritime industry, the integration of this system model into the ship development process and further use cases are also discussed. Implementing MBSE methodologies in ship development can provide numerous benefits, including improved stakeholder communication, better understanding of system complexity, improved knowledge storage and reuse, and traceability of development artifacts, among others. A theoretical framework of *systems engineering* (SE) fundamentals, which includes the underlying modeling languages, methods, and tools of MBSE, is built to support the practical application of this approach in the maritime industry. In addition to examining the fundamentals of SE and MBSE, selected topics related to the maritime industry are also addressed, such as the stakeholders of its transportation sector, the classic ship design process, and ways for successfully achieving decarbonization of international shipping by 2050.

Kurzfassung

Die maritime Industrie und insbesondere die internationale Seeschifffahrt besteht aus einem riesigen Netz weltweiter Akteure. Dieser Sektor ist das Rückgrat unserer globalisierten Wirtschaft. Er ermöglicht den Transport von Gütern, Ressourcen und Passagieren mit großen Hochseeschiffen wie Containerschiffen, Tankern und Massengutfrachtern. Die maritime Industrie steht jedoch vor zahlreichen Herausforderungen in einem komplexen Umfeld, darunter der Bedarf an robusten und nachhaltigen Lieferketten, die *digitale Transformation* zur Verbesserung der Effektivität und Effizienz von Schiffsdesigns und die durch die drohende Klimakrise ausgelöste *Energiewende*. Die *International Maritime Organization* (IMO), die wichtigste Regulierungsbehörde für den maritimen Sektor, hat mit der *2023 IMO Strategy on Reduction of GHG Emissions from Ships* bereits Wege aufgezeigt, um bis 2050 einen Netto-Null-Wert an Treibhausgasemissionen zu erreichen. Die Strategie steht im Einklang mit dem langfristigen Temperaturziel des *Paris Agreements* von 2015, den Anstieg der globalen Durchschnittstemperatur auf deutlich unter 2°C, idealerweise 1,5°C, gegenüber dem vorindustriellen Niveau zu begrenzen. Die Branche befindet sich daher in einem tiefgreifenden Wandel, um die Treibhausgasemissionen bestehender und zukünftiger Schiffe zu reduzieren. Viele neue Lösungen und Technologien, einschließlich *alternativer Kraftstoffe und Antriebstechnologien*, *energiesparender Technologien* und *operativer Maßnahmen*, müssen in einem komplexen Umfeld von Stakeholdern integriert und koordiniert werden. Die zunehmende Komplexität der maritimen Industrie erfordert neue Wege der Zusammenarbeit und des Managements. Um die aktuelle Situation besser zu verstehen und fortschrittliche Lösungen zu entwickeln, sind Ansätze des *Model-based Systems Engineering* (MBSE) eine vielversprechende Strategie.

In diesem Zusammenhang wurde das *Maritime and Ocean Digital Engineering Laboratory* (MODE Lab) als internationales Projekt zur Dekarbonisierung und Automatisierung der maritimen Industrie mit Sitz an der *University of Tokyo* in Japan gegründet. Diese Masterarbeit zielt darauf ab, die bestehenden Aktivitäten des MODE Labs durch die Anwendung von MBSE-Methoden in der maritimen Industrie zu ergänzen und damit einen Beitrag zur *digitalen Transformation* und *Dekarbonisierung* der Branche zu leisten.

Das Ziel dieser Masterarbeit ist die Entwicklung eines *Systemmodells* eines Massengutfrachters mit *windunterstütztem Schiffsantrieb* zur Reduktion von Treibhausgasemissionen. Dazu wird die Modellierungssprache und -methode *Arcadia* in Verbindung mit dem Softwaretool *Capella* verwendet. Der Schwerpunkt liegt auf einer umfassenden Analyse des Systemumfelds und der Integration des windunterstützten Schiffsantriebs in einen Massengutfrachter. Da die aktuelle Praxis der Schiffsentwicklung den Herausforderungen der maritimen Industrie nicht gerecht wird, werden die Integration des Systemmodells in den Schiffsentwicklungsprozess und weitere Anwendungsfälle diskutiert. Die Implementierung von MBSE-Methoden in der Schiffsentwicklung kann zahlreiche Vorteile bieten, wie z.B. eine verbesserte Stakeholder Kommunikation, ein besseres Verständnis der Systemkomplexität, eine verbesserte Wissensspeicherung und -wiederverwendung sowie die Rückverfolgbarkeit von Entwicklungsartefakten, um nur einige zu nennen. Um die praktische Anwendung dieses Ansatzes in der maritimen Industrie zu unterstützen, wird ein theoretischer Rahmen für die Grundlagen des *Systems Engineering* (SE) geschaffen, der die Modellierungssprachen, -methoden und -tools von MBSE umfasst. Neben den Grundlagen von SE und MBSE werden auch Themen wie Stakeholder der internationalen Seeschifffahrt, der klassische Schiffsentwurfsprozess und Wege zur Dekarbonisierung der internationalen Schifffahrt bis 2050 behandelt.

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List of Abbreviations

Arcadia	Architecture analysis and design integrated approach
ASNE	American Society for Naval Engineers
BPMN	Business process model and notation
BAU	Business-as-usual
C	System capability
CAD	Computer-aided design
CAE	Computer-aided engineering
CE	Concurrent engineering
CII	Carbon intensity indicator
CO_2e	Carbon dioxide equivalent
COP 21	21st Conference of the Parties
DNV	Det Norske Veritas
DWT	Deadweight tonnage
ECU	Electronic control unit
EEDI	Energy efficiency design index
ETS	Emissions Trading System
EU	European Union
EEXI	Energy efficiency existing ship index
E/E	Electrics/electronics
f.	Folio (and following page)
ff.	Folia (and following pages)
GHG	Greenhouse gas
Gt	Gigatonne
HDV	Heavy-duty vehicles
HFO	Heavy fuel oil
HOLISHIP	Holistic optimisation of ship design and operation for life cycle
Ibid.	Ibidem (in the same place)
ICE	Internal combustion engine
IEA	International Energy Agency
ILO	International Labour Organization
IMO	International Maritime Organization

ISO	International Organization for Standardization
IT	Information technology
IVV	Integration, verification, and validation
IWSA	International Windship Association
L	Logical component
L	Logical system
LA	Logical actor
LA	Logical architecture
LAB	Logical architecture blank diagram
LCBD	Logical component breakdown diagram
LF	Logical function
LFBD	Logical function breakdown diagram
LFCD	Logical functional chain description
LDFB	Logical data flow blank diagram
LDV	Light-duty vehicles
LNG	Liquefied natural gas
LPG	Liquefied petroleum gas
LR	Lloyd’s Register
JASNAOE	Japan Society of Naval Architects and Ocean Engineers
JIT	Just-in-time
JMU	Japan Marine United Corporation
JSA	Japanese Shipowners’ Association
M	System mission
ME	Main engine
MEPC	Marine Environment Protection Committee
MBD	Model-based development
MBSE	Model-based systems engineering
MCB	Missions capabilities blank diagram
MODE Lab	Maritime and Ocean Digital Engineering Laboratory
Mt	Megatonne
NAF	NATO Architecture Framework
NDC	Nationally determined contributions
OA	Operational activity
OA	Operational analysis

OAB	Operational architecture blank diagram
OABD	Operational activity breakdown diagram
OAIB	Operational activity interaction blank diagram
OBO	Ore/bulk/oil
OCB	Operational capabilities blank diagram
OE	Operational entity
OEBD	Operational entity breakdown diagram
OFE	Owner-furnished equipment
OPM	Object-process methodology
OOSEM	Object-oriented systems engineering method
P	Physical behavior component
PBC	Physical behavior component
P	Physical node component
PNC	Physical node component
PA	Physical actor
PA	Physical architecture
PAB	Physical architecture blank diagram
PCBD	Physical component breakdown diagram
PDFB	Physical data flow blank diagram
PDP	Product development process
PF	Physical function
PFBD	Physical function breakdown diagram
PID	Propulsion improving devices
PLM	Product lifecycle management
PM	Project management
PMBOK	Project Management Body of Knowledge
PTH	Power-Take-Home
PTI	Power-Take-In
PTO	Power-Take-Off
SA	System actor
SA	System analysis
SAB	System architecture blank diagram
SFBD	System function breakdown diagram
SFCD	System functional chain description

SDFB	System data flow blank diagram
SDG	Sustainable Development Goal
SEBoK	Systems Engineering Body of Knowledge
SF	System function
SFI	Skipsteknisk Forskningsinstitutt
SME	Subject matter expert
SNAME	The Society of Naval Architects and Marine Engineers
SoI	System-of-interest
SVN	Stakeholder value network
SysML	Systems modeling language
SYSMOD	Systems modeling process
UML	Unified modeling language
UN	United Nations
UNCTAD	United Nations Conference on Trade and Development
UNEP	United Nations Environment Programme
UNFCCC	United Nations Framework Convention on Climate Change
VDE	Verband der Elektrotechnik, Elektronik und Informationstechnik
VDI	Verein Deutscher Ingenieure
V&V	Verification and validation
WAD	Wind-assistance device
WASP	Wind-assisted ship propulsion
WTW	Well-to-wake
xxBD	Breakdown diagrams
xxB	Blank diagrams
xxS	Scenario diagrams
ZEV	Zero-emission vessel

1 Introduction

The *maritime industry* is the backbone of the modern, globalized economy and represents a vast network of stakeholders engaged in a wide range of operations. From an *economic perspective*, a general overview of those entities and their respective activities within this industry can be given by dividing it into *five high-level segments*: *Vessel operations* include merchant and naval shipping, the cruise industry as well as ports. *Shipbuilding* involves the construction, maintenance, and repair of merchant and naval ships along with the manufacturing of marine equipment. *Marine resources* include the exploitation of offshore oil and gas, renewable energy or other resources like minerals and aggregates. *Marine fisheries* contribute to global food security with commercial fishing or aquaculture, the cultivation of seaweed and seafood processing. *Other marine related activities* are, among others, maritime tourism, marine services or research and development.[1] In addition to this economic classification, other significant stakeholders involved in the maritime industry form the maritime regulatory system and mainly consist of the *International Maritime Organization* (IMO), the *United Nations* (UN), the *International Labour Organization* (ILO), *classification societies* and the *governments* of the maritime states themselves. Maritime regulations, safety standards, environmental protocols as well as the assessment and seaworthiness of vessels are established and enforced by those regulatory entities.[2] Considering all the stakeholders involved it becomes clear that the maritime industry is not only a large but also a complex and strongly interconnected part of the global economy. By focusing solely on the logistics sector of the previously mentioned *vessel operations* segment, its main *mission* can be identified as the transportation of goods, resources, and passengers by sea. This mission is carried out by shipping and trading companies that operate different types of ships on trade routes around the world.

However, the economic and geopolitical context in which those companies are conducting business in 2023 is still highly challenging. The 2022 edition of the *Review of Maritime Transport*, a report which has been published yearly by the United Nations Conference on Trade and Development (UNCTAD) since 1968, states that the disruption caused by the COVID-19 pandemic in 2020 led to a recession of international maritime trade by 3.8% in the same year. Due to a more relaxed pandemic environment in 2021, maritime trade increased by 3.2% to a level that was almost pre-pandemic at 11 billion metric tons.[3] While dealing with the turbulence brought on by the pandemic to this day, the global economy, particularly international trade, was disrupted by another major event in February 2022: The invasion of Ukraine by the Russian Federation. The conflict in Ukraine led to an energy crisis[4] characterized by a significant increase in global oil and gas prices, particularly in Europe, where the region's heavy dependence on Russia as a major supplier worsened the situation.[5] Moreover, this war on Europe’s doorstep reversed the already easing situation of shipping

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[1] Stopford, M. (2009). *Maritime Economics*. Third edition. UK: Routledge., p. 49

[2] Stopford. (2009)., p. 656 f.

[3] United Nations Conference on Trade and Development (UNCTAD). (2022). *Review of Maritime Transport 2022: Navigating stormy waters*. USA: United Nations Publications., p. 3

[4] United Nations Global Crisis Response Group on Food, Energy and Finance. (2022). *Global impact of war in Ukraine: Energy crisis.*, p. 5 f.

[5] Borin, A., Conteduca, F. P., Di Stefano, E., Gunnella, V., Mancini, M., & Panon, L. (2022). *Quantitative assessment of the economic impact of the trade disruptions following the Russian invasion of Ukraine.* In: Occasional Papers - Questioni di Economia e Finanza, No. 700. (June 2022): Bank of Italy., p. 7

costs and grain prices, which have been rising since 2020.[6] In addition to the resulting humanitarian crisis, the war has further added to the already high cost of living and inflation on a global scale. These high levels of inflation are projected to ease by the end of 2023.[7] The geopolitical tensions created by this conflict and its security consequences are far-reaching and have a strong impact on the maritime industry as well, especially on the logistics sector and international trade.[8, 9] The recent escalation of the Gaza conflict in October 2023 continues these tensions.

Globalization has been on the rise since the end of World War II and has been accelerated by events such as China's open-door policy, the end of the Cold War, the Internet revolution, or just-in-time (JIT) manufacturing.[10] In the context of reduced trade barriers and cheaper transportation, globalized supply chains have become the first choice of companies seeking to minimize costs and improve efficiency, leading to the production and sourcing of goods in lower-cost countries to exploit comparative advantage, also known as arbitrage.[11] Disruptions to global supply chains and maritime trade, caused by events such as the pandemic or the humanitarian crisis in Ukraine, have highlighted the fragility of the system, leading companies and even countries or strategic alliances like the European Union (EU)[12] to question their current supply chains and seek greater resilience.[13]

While the beginning of this chapter is intended to serve as a brief introduction to the maritime industry and its current situation from an economic and geopolitical point of view, one major challenge has not been mentioned so far: The need for *decarbonizing* the transportation sector of the maritime industry.[14] According to the International Maritime Organization's *Fourth Greenhouse Gas Study 2020*, total shipping (international, domestic and fishing) in the maritime sector accounts for 1,056 million metric tons or 2.89% of the global 36,573 million metric tons of anthropogenic carbon dioxide equivalent (CO_2e) emissions in 2018, which is an increase of 9.3% between 2012 and 2018.[15]

Within the transportation sector itself, marine shipping accounts for ~11% of global transportation CO_2e emissions in 2020, with the largest contributors in this sector being light-duty vehicles (LDV) at ~40% and heavy-duty vehicles (HDV) at ~30%, as shown in Figure 1-1.[16]

Mitigating the potentially catastrophic consequences of global warming requires a collective effort to reduce anthropogenic greenhouse gas (GHG) emissions, as these emissions are a major driver of climate change. To formally address the emerging climate crisis, a legally binding international treaty on climate change was agreed upon by 196 nations at the 2015 United Nations Climate Change Conference (COP21) in the *Paris Agreement*. Article 2.1 (a):

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[6] United Nations Conference on Trade and Development (UNCTAD). (2022). *Maritime Trade Disrupted. The war in Ukraine and its effects on maritime trade logistics.*, p. 2

[7] McKeown, J. (2023). *From cost of living crisis to banking crisis? Q2 Global Economic Outlook*. UK: Capital Economics.

[8] Ioannis E. Kotoulas, W. P. (2022). *Geopolitics of the War in Ukraine.* In: Report No. 4 (June 2022). Greece: Foreign Affairs Institute (FAINST)., p. 15

[9] UNCTAD. (2022)., p. 4

[10] Ramachandran, R. (2022). *Globalization X.0 and Supply Chain in the New World - A Perspective. Part 1: The Rise of Globalization.* Transport Intelligence. UK., p. 6

[11] Ramachandran. (2022)., p. 5, p. 8

[12] European Parliament Committee on International Trade. (2022). *Draft Report on resilient supply chains in EU trade to address current shortages.* (2022/2040(INI))., p. 3 ff.

[13] McKinsey & Company. (2022). *Taking the pulse of shifting supply chains*., p. 2 ff.

[14] Global Maritime Forum. (2021*). Call to Action for Shipping Decarbonization*., p. 1

[15] International Maritime Organization (IMO). (2021). *Fourth IMO GHG Study 2020*. London: International Maritime Organization., p. 112

[16] International Council on Clean Transportation (ICCT). (2021). *VISION 2050: A strategy to decarbonize the global transport sector by mid-century.*, p. 5

> *“Holding the increase in the global average temperature to well below 2 °C above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5 °C above pre-industrial levels, recognizing that this would significantly reduce the risks and impacts of climate change; […]”* [17]

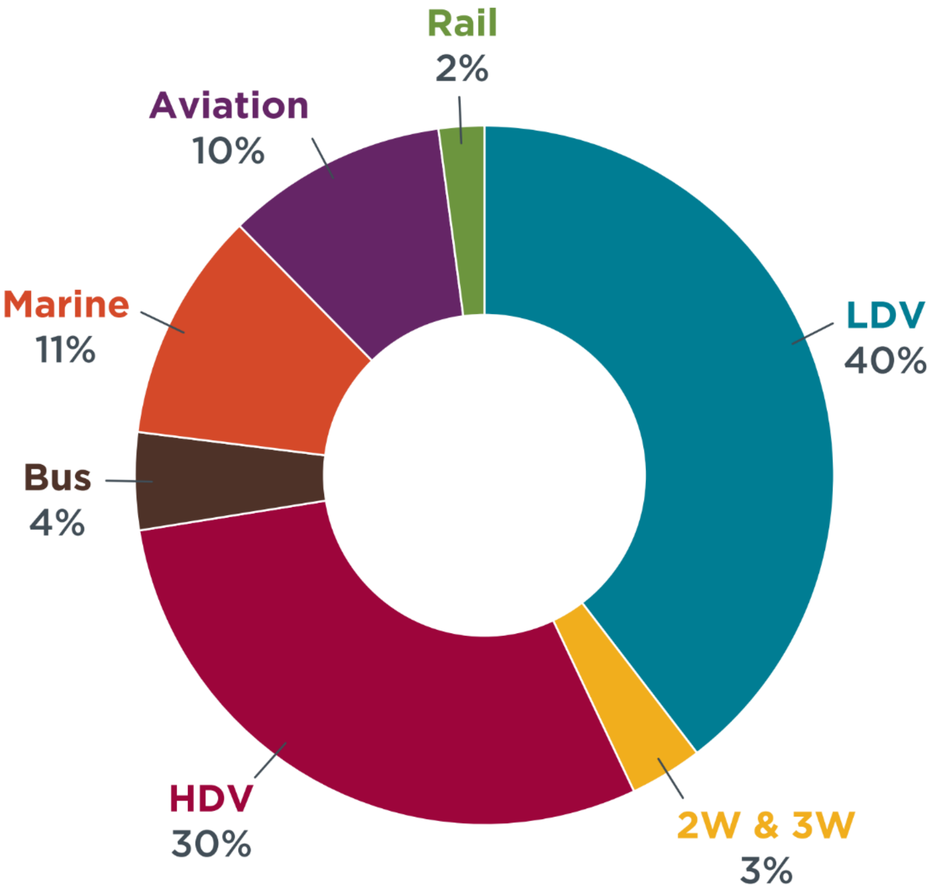

Figure 1-1: Share of transportation sector well-to-wheel CO_2e emissions in 2020, according to *ICCT* [18]

Although GHG emissions from international shipping are not explicitly mentioned in the Paris Agreement, the International Maritime Organization has adopted the *2018 Initial IMO GHG Strategy* to support the reduction of GHG emissions from ships, with the aim of phasing them out as soon as possible by the end of this century. The strategy is consistent with the Paris Agreement's temperature targets as well as the United Nations *Sustainable Development Goal* (SDG) *13*, which commits to fight climate change and its effects by taking quick action.[19] One of the most significant developments in the effort to reduce GHG emissions of shipping and achieve net-zero emissions was the adoption of the *Initial IMO GHG Strategy* in 2018. By providing a policy framework for IMO Member States, the objective has been set to achieve a 70% reduction in carbon emissions by 2050 (compared to 2008 levels), and a reduction of at least 40% by 2030, with a minimum of 50% by 2050.[20] However, the *Emissions Gap Report 2022* of the United Nations Environment Programme (UNEP) warns that we are far from the

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[17] United Nations Framework Convention on Climate Change (UNFCCC). (2015). *Paris Agreement*. At: 21st Conference of the Parties (COP 21)., p. 22

[18] ICCT. (2021)., p. 5

[19] United Nations General Assembly. (2015). *Transforming our World: The 2030 Agenda for Sustainable Development*. Resolution A/RES/70/1. At: United Nations Sustainable Development Summit. New York. (2015)., p. 23

[20] International Maritime Organization (IMO). (2018). *Initial IMO Strategy on Reduction of GHG Emissions from Ships*. London: International Maritime Organization. At: UNFCCC Talanoa Dialogue., p. 6

goals of the Paris Agreement, with current policies alone projected to lead to global warming of 2.8°C by the end of the century, 2.6°C and 2.4°C if unconditional or conditional nationally determined contributions (NDCs) are implemented. It is pointed out that meeting the goal of limiting global warming to 1.5°C will require a significant reduction in global annual GHG emissions of 45% by 2030 compared to emissions projected under current policies.[21] For these reasons, the *Initial IMO GHG Strategy* has been revised in 2023, with the aim of a 40% reduction in GHG emissions from shipping by 2030, promoting 5-10% energy use from zero or near-zero emission technologies by the same year, and achieving *net-zero emissions* by 2050.[22]

All of these considerations show that maritime transport and trade systems are changing in a complex global economic environment. Challenges that will influence this industry include the need for sustainability and resilience, the energy transition brought on by the impending climate crisis as well as digitalization, to name a few. Reducing GHG emissions has become a top priority for international shipping and its stakeholders, alongside its primary *mission* of providing maritime transport services for goods, resources, and passengers.

Initial situation and objectives: The challenging geopolitical and economic situation of the maritime industry as well as its transportation sector has been discussed in the beginning of chapter 1 to provide a general overview and to serve as a broad introduction to the context of this master's thesis. In the following, the *Maritime and Ocean Digital Engineering Laboratory* (MODE Lab) will be introduced and the initial situation that led to this master's thesis project and its objectives will be further explained.

The *International Maritime Organization* introduced the *Initial IMO Strategy on Reduction of GHG Emissions from Ships* in April 2018 and revised its strategy in 2023, with a new target of *net-zero GHG emissions* from international shipping by around 2050. As a global leader in shipping and shipbuilding, Japan has made a commitment to take the lead in reducing greenhouse gas emissions from international shipping. In 2018, Japan established the *Shipping Zero Emission Project* with the goal of reducing emissions from international shipping. The need to reduce GHG emissions in all sectors has become increasingly urgent, leading Japan to announce in October 2021 that it will target net-zero emissions from international shipping by 2050, exceeding the goals originally set by the IMO.[23, 24]

The MODE Lab was established in this context as an international project with the goal of decarbonization and automation in the maritime industry. The lab is located at the Department of Marine Technology and Environment, Graduate School of Frontier Sciences at the University of Tokyo in Japan. It was founded on October 1st, 2022 and planned as a 5-year project by several companies, including leading Japanese shipbuilding companies such as Japan Marine United Corporation (JMU) or Mitsubishi Shipbuilding Co., Ltd. along with ClassNK as one of the world's largest classification societies, among others. The MODE Lab program aims to address key challenges facing the maritime industry in the context of the global decarbonization trend. It focuses on developing and implementing GHG reduction technologies, introducing automated ships for safety and efficiency, and improving ship design

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[21] United Nations Environment Programme (UNEP). (2022). *Emissions Gap Report 2022: The Closing Window - Climate crisis calls for rapid transformation of societies*. Nairobi., p. 32, p. 36

[22] International Maritime Organization (IMO). (2023). *2023 IMO Strategy on Reduction of GHG Emissions from Ships*. London: International Maritime Organization. At: Marine Environment Protection Committee (MEPC 80)., p. 6

[23] Japanese Shipowners' Association (JSA). (2021). *Japanese Shipping Industry Announces "Challenge of 2050 Net Zero GHG"*. JSA., p.1 f.

[24] Japanese Shipowners' Association (JSA). (2022a). *Toward Achieving Net Zero GHG Emissions from International Shipping - Shipping Zero Emission Project*. JSA., p. 2

and manufacturing processes. In addition, the program promotes international collaboration and human resource development. To achieve these goals and create collaborative "*Maritime Digital Engineering*" development process among all stakeholders involved, *model-based development* (MBD) and *model-based systems engineering* (MBSE) methodologies shall be introduced to the maritime industry.[25]

Model-based development is a widely used term without a formal definition. However, it can be understood as the use of digital models, such as simulation or 3D models, for the development of products, thus moving from a document and file-based development approach to a digital model-based approach.

Model-based systems engineering on the other hand is the formal application of models in development and operations for requirements description, specification, system analysis, and verification and validation. MBSE uses *descriptive system models* to store information that has traditionally been captured in informal diagrams, text, and tables. This system model specifies the *structure* and *behavior* of the system in the *system architecture* and holds information about the system's context and its elements.[26] Since the MBSE methodology and its application in the maritime industry is the main focus of this master's thesis, refer to chapter 2.2 for a more detailed investigation of its definition and further information.

While MBSE has been widely accepted in various industries, including *defense*, *aerospace* (aircraft and space systems), and *automotive*, its adoption in the *maritime industry* remains relatively poor. This is shown in Figure 1-2, which presents the results of an MBSE survey conducted in 2018 and presented at the INCOSE 2019 International Workshop. The survey revealed that the defense industry had the highest level of MBSE adoption at ~43%. Conversely, the maritime industry was classified as part of the "Other" category and is not explicitly portrayed in this figure.

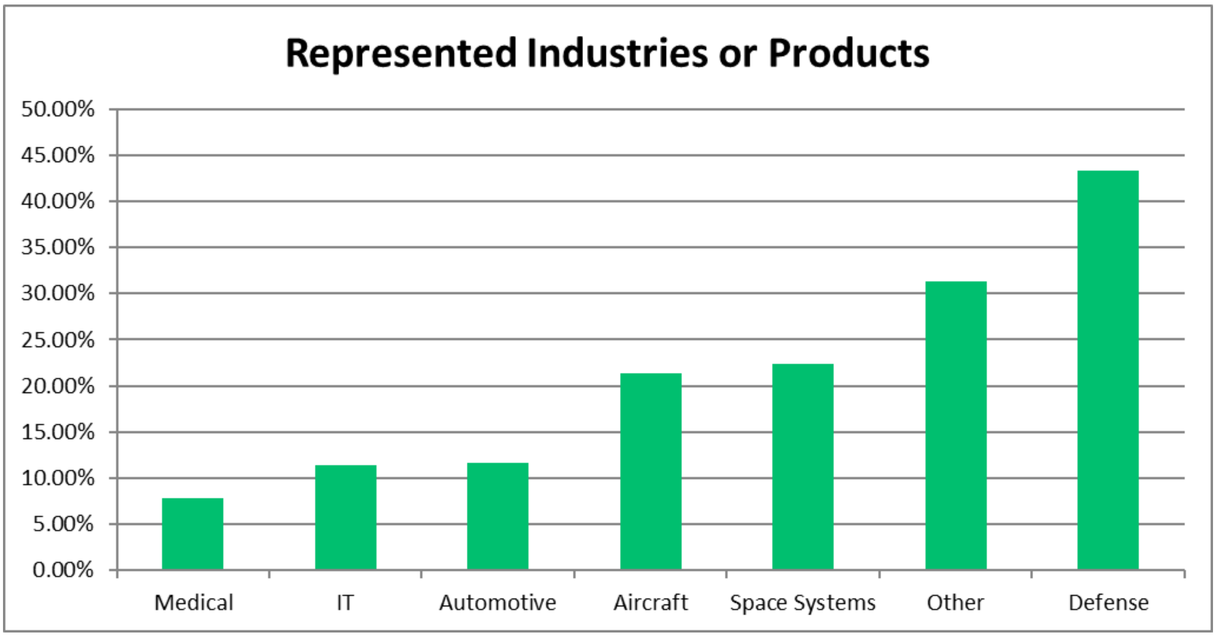

Figure 1-2: MBSE Trends 2018, according to *Cloutier* [27]

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[25] MODE Lab. (2024). *MODE - Maritime and Ocean Digital Engineering Laboratory*. Japan: The University of Tokyo., About MODE (Program Background and Target).

[26] INCOSE. (2023). *Systems Engineering Handbook*. Document Nr.: INCOSE-TP-2003–002-05: International Council on Systems Engineering (INCOSE). John Wiley & Sons Ltd., p. 220

[27] Cloutier, R. (2019a). *2018 MBSE Survey Results.* At: Proceedings of the 2019 INCOSE MBSE Workshop, presented at the INCOSE 2019 International Workshop. Torrance. California. USA. January 26-29 (2019).

This lack of adoption of MBSE in the maritime industry, as well as the general context of the MODE Lab project form the initial situation of this master's thesis. The current activities of the MODE Lab include the investigation of ships equipped with *wind-assisted ship propulsion* (WASP) as well as *autonomous ships* using *simulation models*. As there is currently no *descriptive system model* used in the MODE Lab, which is defined as the center of MBSE, the creation of such a system model in the form of a *bulk carrier* ship equipped with a *wind-assistance device* (WAD) for *auxiliary propulsion* to reduce its GHG emissions is the main objective of this master's thesis. Improved communication between all stakeholders, a better understanding of the system complexity or better knowledge storage and reuse are just some of the many benefits of implementing MBSE methodologies in the overall system development activities.[28] Another objective is to discuss the usage of this *descriptive system model* as a *center of development* and integrate it into the ship development process, along with investigating further *use cases* such as enhanced documentation, artifact traceability, or project management activities. These two objectives can be considered as the *practical part* of this master's thesis. To support the practical application of MBSE in the maritime industry, the *theoretical part* investigates the fundamentals of *systems engineering* (SE), including MBSE and its underlying modeling *languages*, *methods,* and *tools*. Selected topics of the maritime industry, such as the *stakeholders* of its transportation sector, the *classic ship design* process, or how *decarbonizing* international shipping until 2050 can be successfully achieved, are also examined.

In summary, this master's thesis aims to complement the existing activities of the MODE Lab by applying *model-based systems engineering* (MBSE) methodologies to the maritime industry. It focuses on developing a *descriptive system model* of a bulk carrier ship equipped with a *wind-assisted device* (WAD), thereby supporting the goal of *CO_2-neutral* and *automated ships* by 2050 while contributing to the industry's *digital transformation*. In addition, the master's thesis explores the fundamentals of SE and MBSE as well as options for decarbonizing the *transportation sector* within the maritime industry, with a particular focus on *wind-assisted ship propulsion* (WASP).

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[28] INCOSE. (2023)., p. 220

2 Systems Engineering Fundamentals

The creation of a *descriptive system model* (i.e., qualitative system description) requires an understanding of the basic principles and fundamentals of *systems engineering* as well as *model-based systems engineering*. Selected parts of these topics will be discussed in order to prepare the modeling activities in later chapters and to support the understanding of the system model and its usage. In addition, a comprehensive knowledge of SE and MBSE is essential to realize the goal of integrating a descriptive system model into the ship development process. The following chapter 2 serves as an introduction to the qualitative description of a system through the application of SE and MBSE methodologies, and is the theoretical framework used for the creation of a descriptive system model of a bulk carrier ship equipped with a wind-assistance device (WAD).

2.1 Systems Engineering (SE)

When addressing multifaceted problems, such as *decarbonizing international shipping*, finding *solutions* in a complex environment like the maritime industry is a difficult endeavor with no clear path, thus resulting in a high level of uncertainty. Suitable approaches, such as *systems engineering*, are needed to deal with this combination of uncertainty and complexity.[29]

The engineering discipline of SE originated in the early to mid-20th century in industries like aerospace, defense, and telecommunications.[30] Its definition has changed over time, but one of the most recent and widely accepted is provided by the *International Council on Systems Engineering*, which defines SE as follows:

> *"Systems Engineering is a transdisciplinary and integrative approach to enable the successful realization, use, and retirement of engineered systems, using systems principles and concepts, and scientific, technological, and management methods."* [31]

In other words, *Bajzek et. al.* state:

> *Systems engineering is an approach, a philosophy for development, that combines well-proven processes, methods, tools, participating engineers (organization), and stakeholders for the development of complex systems. In the scope of technical development, systems engineering is a structured and connected way of thinking and working. Interdisciplinary collaboration and a holistic perspective are of pivotal importance. A discipline-specific perspective is not sufficient to consider all aspects and influences due to the increasing complexity of the systems […]"* [32]

An approach that combines several components of the SE concept in one single view is the so-called "*systems engineering manakin*", as shown in Figure 2-1. The basic idea is to go from a *problem* (the difference between an *actual state* and a *desired state*) to a *solution* by following

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[29] INCOSE. (2023)., p. 5, p. 15

[30] INCOSE. (2022). *Systems Engineering Vision 2035*. International Council on Systems Engineering (INCOSE)., p. vi

[31] INCOSE. (2019). *Systems Engineering and System Definitions*. San Diego. USA: International Council on Systems Engineering (INCOSE). INCOSE Publications Office., p. 3

[32] Bajzek, M., Fritz, J., & Hick, H. (2021a). *Systems Engineering Principles*. In: Hannes Hick, Klaus Küpper, Helfried Sorger (Eds.). Systems Engineering for Automotive Powertrain Development. First edition (2021): Springer Cham., p. 166

a *problem-solving process* (i.e., the “body” of the manakin) that includes the activities *systems design*, *system architecture* (see chapter 2.1.3), concept development, and *project management* (see chapter 2.1.6). This process is guided by overarching *SE-principles* (i.e., the “head” of the manakin) such as *systems thinking* (see chapter 2.1.1) and the *SE process model* (see chapter 2.1.5). It is supported by *methods & tools* (i.e., the “legs” of the manakin) for systems design (e.g., MBSE, see chapter 2.2) and project management.

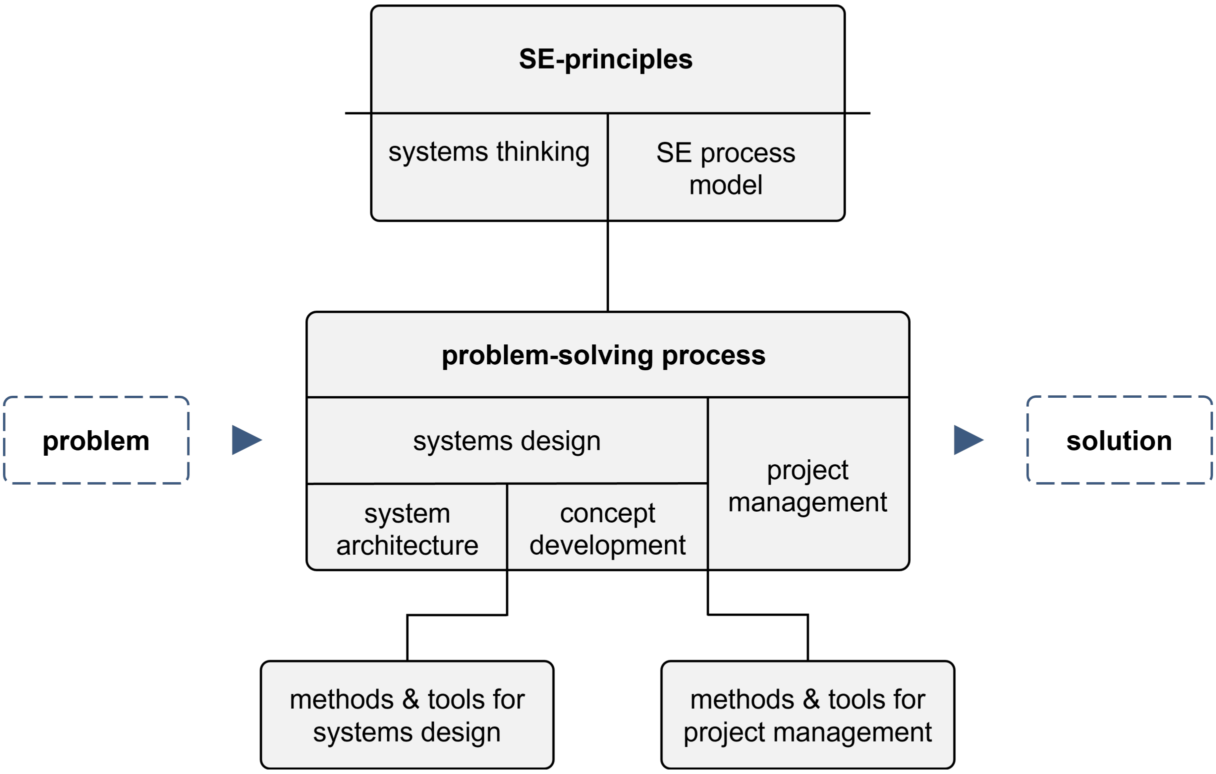

Figure 2-1: Systems engineering concept „*systems engineering manakin*”, inspired by *Haberfellner et al.*[33]

However, activities such as *verification* and *validation* (V&V) or *integration* are missing in this view. Nevertheless, this figure provides a sufficient overview of the SE concept and is therefore suitable to serve as an introduction to SE in general. In the following chapters, selected parts of the *SE-principles*, the *problem-solving process* as well as *methods & tools* are discussed in more detail.

2.1.1 Systems Thinking

An early systems view of the world was formulated by the Greek universal scholar *Aristotle* in the 4th century B.C. with his famous quote “*The whole is greater than the sum of its parts*”. This can be interpreted to mean that the combined effect of a number of parts or things exceeds what any one of them could have achieved on its own.

Today, Aristotle’s early understanding of systems has evolved. In a technical context, a formal definition of the system concept is given by the *International Organization for Standardization* (ISO):

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[33] Haberfellner, R., Weck, O., de Fricke, E., & Vössner, S. (2019). *Systems Engineering Fundamentals and Applications*. Cham: Springer International Publishing., p. vi

> *“A system is sometimes considered as a product or as the services it provides. […] the interpretation of its meaning is frequently clarified by the use of an associative noun, e.g. aircraft system […]. A complete system includes all of the associated equipment, facilities, material, computer programs, firmware, technical documentation, services, and personnel required for operations and support to the degree necessary for self-sufficient use in its intended environment.”* [34]

The term *systems thinking* was first described as such by *Peter M. Senge* in the 1990s. He sees systems thinking as the fifth of five disciplines, the one that integrates the other four – personal mastery, mental models, building shared vision, and team learning – into what he calls a *learning organization*, an evolving system that enables people to work together, learn continuously, and achieve desired results.[35] In the systems engineering concept described above in Figure 2-1, systems thinking is part of the *SE-principles* and is described as a fundamental way of thinking, a key element of SE, enabling the identification of systems patterns within various phenomena, disciplines or problem contexts.[36] It forms the basis for understanding and designing *complex systems*.[37] Some selected principles of systems thinking are described in the following.

Thinking in systems: A necessary first step in systems thinking is to understand *what* a *system* is and *how* it can be described in a practical and understandable way. Three observational methods or views of a system are given by *Ropohl* in the *general systems theory* and are shown in Figure 2-2: The *structural*, *hierarchical* and *functional* view.

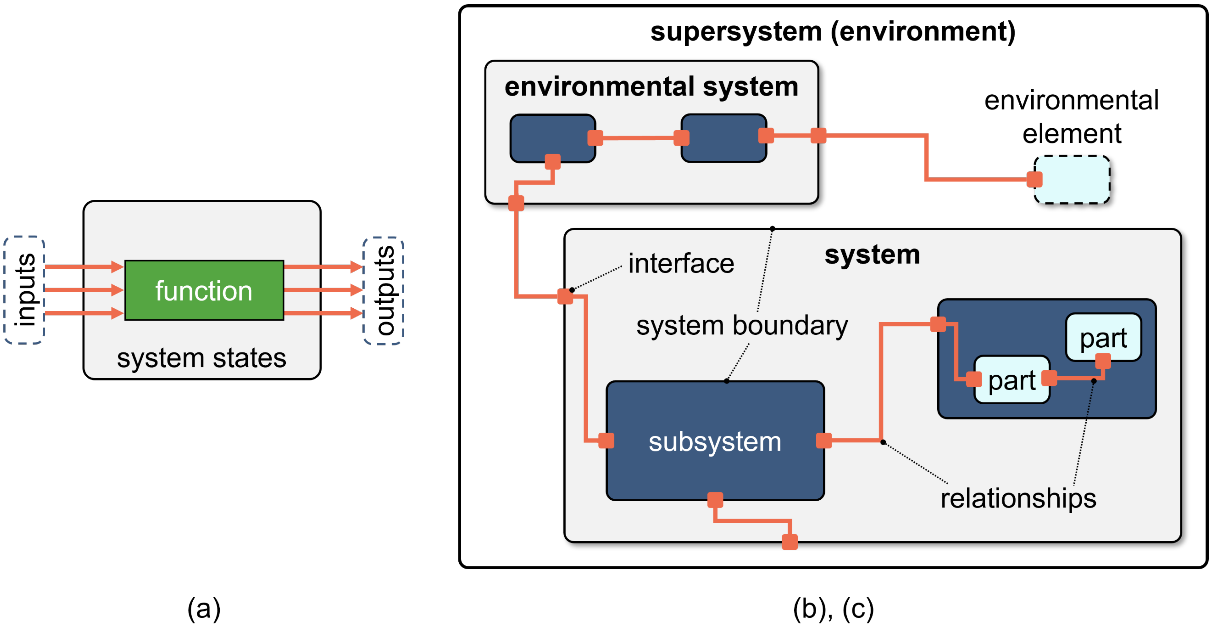

Figure 2-2: *Functional (a)*, *structural (b)* and *hierarchical (c)* view of a system, inspired by *Ropohl* [38], *Haberfellner et al.*[39] and *Bajzek et al.*[40]

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[34] ISO/IEC/IEEE 15288:2023(E). (2023). *Systems and software engineering – System life cycle processes*. ISO/IEC/IEEE., p. 8

[35] Senge, P. M. (1990). *The Fifth Discipline – The Art & Practice of The Learning Organization*. First edition. USA: Bantam Doubleday Dell Publishing Group., p. 8 ff.

[36] INCOSE. (2023)., p. 21, p. 23

[37] Haberfellner et al. (2019)., p. 3

[38] Ropohl, G. (2009). *Allgemeine Technologie – Eine Systemtheorie der Technik.* Third edition. Karlsruhe. Germany.: Universitätsverlag Karlsruhe., p. 76

[39] Haberfellner et al. (2019)., p. 5

[40] Bajzek et al. (2021a)., p. 152

Ropohl emphasizes that the combination of these three views results in a *complete system model*, which he summarizes as follows, translated from German to English:

> *"A system is a model of a whole that (a) has relationships between attributes (inputs, outputs, states, etc.), (b) consists of interlinked parts or subsystems, and (c) is differentiated from its environment or a superordinate system."* [41]

Adding to this summary, part (a) of Figure 2-2 shows the system as a *black box* (refer to Figure 2-11), focusing on *what* it does, rather than its inner structure, which is either unknown or of no interest at this point. Part (b) and (c), on the other hand, explicitly show *how* the system including its subsystems, parts, relationships, interfaces is designed, as well as its integration and relationships with its higher-level superordinate system (i.e., supersystem) or environment.[42]

The *functional view* will be discussed further in chapter 2.1.2, as a thorough understanding of the concept of a function is an essential part of systems thinking.

The *structural view* will be explained in chapter 2.1.3 when discussing the so-called *system architecture*, which combines both the *structure* (i.e., structural/hierarchical view) and the *behavior* (i.e., functional view) of the system. Structure and behavior are two critical aspects of designing and understanding complex systems.

The *hierarchical view* of a system can also be shown using the concept of system levels to break a system down into smaller parts, going from the *supersystem level* to the *system level* – the *system-of-interest* (SoI) – to a certain number of *subsystem levels*, depending on the complexity of the system. At the *part level*, the parts are considered as black boxes. Depending on the selected system-of-interest level, the supersystem changes accordingly. This process of hierarchically structuring a complex system using a *top-down* approach facilitates its development, management, and understanding. Figure 2-3 shows an example of the hierarchical view of a bulk carrier ship system.[43]

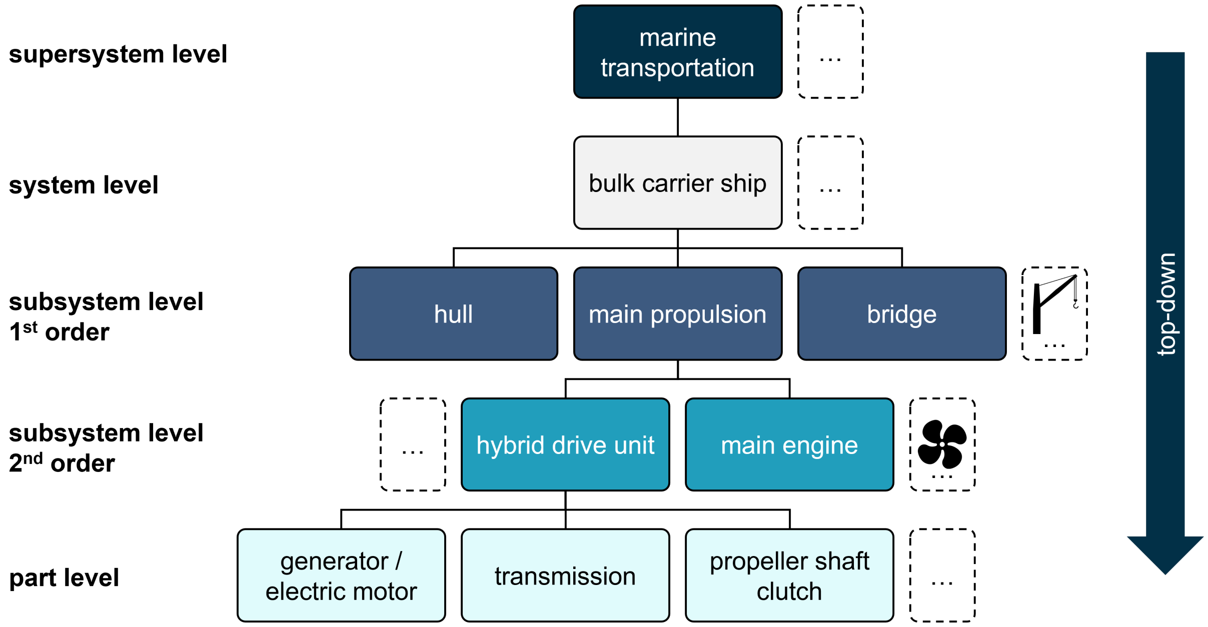

Figure 2-3: Systems hierarchy and top-down approach, inspired by *Haberfellner et al.* [44] and *Bajzek et al.*[45]

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[41] Ropohl. (2009)., p. 77

[42] Bajzek et al. (2021a)., p. 152

[43] Haberfellner et al. (2019)., p. 16 f.

[44] Ibid., p. 8

[45] Bajzek et al. (2021a)., p. 172

A widely used method of obtaining the systems hierarchy of a ship is the *SFI Group System*, developed by the *ship Research Institute of Norway* (SFI = Skipsteknisk Forskningsinstitutt) in 1972. This coding and classification system provides a functional subdivision to break down systems in the maritime and offshore industry. Using *hierarchical groups*, the system of a ship is decomposed, and a specific *detail code* is assigned to every part. This hierarchical structuring facilitates the development and management of systems in the maritime industry from both a technical and financial perspective and is used as a reference in this master's thesis *hierarchical view* on a bulk carrier ship system.[46]

Thinking in functions: Another key aspect of systems thinking is the *thinking in functions* principle. By focusing first on the *problem* rather than the *solution*, it is ensured that all options for fulfilling a particular function are considered.[47] This avoids favoring of specific solutions in terms of concrete realization and implementation options and ensures *solution neutrality*.[48] The concept of a function will be discussed in more detail in chapter 2.1.2.

Reduction of level of detail: The system as a whole is considered and analyzed at an abstract level in early phases of development by using the black box method (see Figure 2-11) and considering only a limited number of subsystems and their relationships.[49] This reduced but at the same time *holistic view* allows a structuring of the system at an early stage and thus manages its complexity, leaving detailed analyses for later phases.[50]

Interconnected thinking: In complex systems, simple cause-and-effect relationships generally exist only in theory. This is also true for a marine transportation system and its transition towards carbon neutrality and green technologies. Decisions made now will have consequences that are not fully understood at the time they are being made. *Vester* points out that it is only when the viewpoint on the SoI (e.g., the marine transportation system) is changed from the usual "inside-out" view to an "outside-in" view that its behavior and interconnections with its environment can be properly understood, leading to meaningful decisions and strategies.[51]

System models: Systems thinking emphasizes the use of model-based representations (i.e., system models) to clarify complex relationships. In general, a model is an abstraction of reality. It simplifies it and includes only partial aspects that are relevant to the problem.[52] The use of system models is a central part of systems engineering, especially *model-based systems engineering*, and is a key focus of this master's thesis. System models in general will be addressed in detail in chapter 2.2.1.

2.1.2 Functions

The *functional view* has been defined as one of three views on a system, along with the *structural* and *hierarchical* views (see Figure 2-2). Building on this fundamental understanding and the *thinking in functions* principle as a key aspect of *systems thinking* (see chapter 2.1.1),

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[46] SFI. (1972). *SFI Group System*. Ship Research Institute of Norway (SFI).

[47] Bajzek et al. (2021a)., p. 171

[48] Feldhusen, J., Becerril, L., Kattner, N., & Schweigert, S. (2016). *Funktionsmodellierung.* In: Udo Lindemann (Eds.). Handbuch Produktentwicklung. First edition (2016): Carl Hanser., p. 698

[49] Haberfellner et al. (2019)., p. 16

[50] Bajzek et al. (2021a)., p. 170

[51] Vester, F. (2007). *The Art of Interconnected Thinking – Tools and concepts for a new approach to tackling complexity*. First edition. München. Germany: MCB Verlag GmbH., p. 17, p. 98 ff.

[52] Haberfellner et al. (2019)., p. 12

it is necessary to discuss the concept of a function in a more extensive way.

From a product or system development perspective, *Feldhusen et al.* define a function as follows, translated from German to English: *"Function is the general and intentional relationship between the input and output of a system with the aim of performing a task."* [53] In this context, a function is seen as a *black box*. Based on its input/output relationship, *what* a system must be able to do is of importance (i.e., its function), but *how* it is implemented is not yet defined or unknown (i.e., a particular solution). Figure 2-4 shows this task-specific description of a technical problem, which is intended to guarantee *solution neutrality* in order to consider the entire *solution space*.[54]

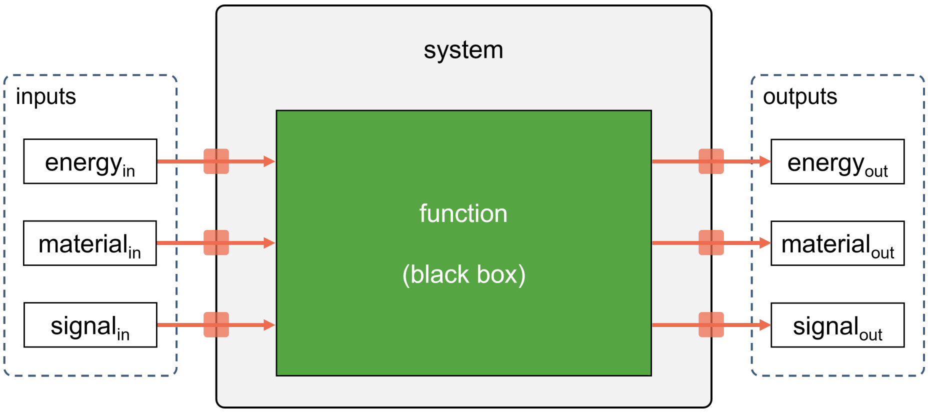

Figure 2-4: General function description with clear input/output relationship, inspired by *Feldhusen et al.*[55] and *Bajzek et al.*[56]

In technical processes, there are three types of inputs/outputs (i.e., object flow) of a function that undergo different kinds of *conversions* while "flowing" through the function, as shown in Figure 2-4:

- *Energy:* mechanical, thermal, electrical, force, heat, etc.
- *Material:* solid, liquid, gas, component, product, etc.
- *Signal:* data, information, control impulse, etc.[57]

The *nomenclature* of a function is usually a combination of a *verb* and a *noun* and is based on the function specific task of converting energy, material, and signals.[58] For example, "generate power", "propel ship" or "handle cargo" can be functions in the context of a ship system, see Figure 2-6.

After clarifying the main task of a system (i.e., *what* a system must be able to do), including its input/output relationship, the *overall function* can be defined, which describes the task in its entirety. Through *functional decomposition*, the overall function can be subdivided and hierarchically structured into *subfunctions*, leading to a *function structure*. A distinction between *main functions* and *auxiliary functions* is another good practice. Main functions are the subfunctions that directly support the overall function. Auxiliary functions, on the other hand, are complementing the main functions but do not directly contribute to the overall function.[59]

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[53] Feldhusen et al. (2016)., p. 691

[54] Pahl, G., Beitz, W., Feldhusen, J., & Grote, K. H. (2007). *Engineering design – A Systematic Approach*. Third edition. London. UK: Springer., p. 31

[55] Feldhusen et. al (2016)., p. 691

[56] Bajzek et al. (2021a)., p. 170

[57] Pahl et al. (2007)., p. 29 f.

[58] Ibid., p. 31

[59] Pahl et al. (2007)., p. 31 f.

Figure 2-5 shows two different views on a function structure. The *hierarchical view* (a) is used to manage the complexity of a function and reflect the hierarchical dependency among functions. The input-output view (b) is based on the general function description of Figure 2-4 and focuses on the flow of all functions, showing the exchanges (i.e., energy, material, signal) between them.

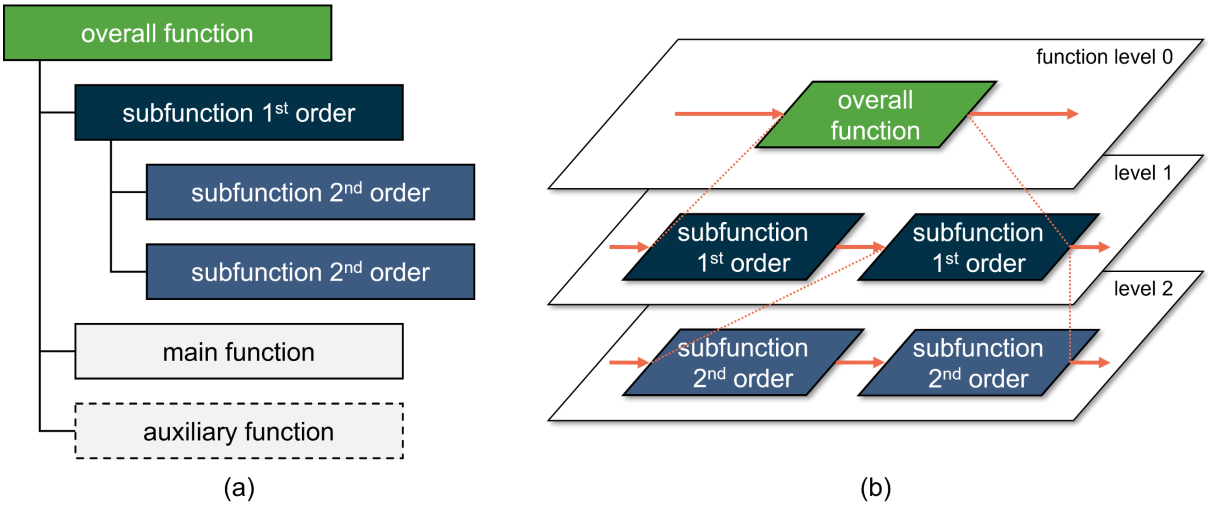

Figure 2-5: Hierarchical (a) and input-output view (b) of a function, inspired by *Feldhusen et al.*[60]

In addition to the classification into overall, sub-, main, and auxiliary functions along with the two views on a function structure, a distinction can be made between *user functions* or *technical functions*. *Bajzek et al.* define user functions as *"[…] to be fulfilled by the system from the point of view of the human (stakeholder, user, etc.) and describe the functionality of the system […]"*, whereas technical functions are defined as *"[…] those that are executed by the system directly but may be hidden to outside observers and users."*[61]

2.1.3 System Architecture

Following the general introduction to systems engineering and the initial discussion of *systems thinking* along with the *function* concept, the *system architecture* can now be introduced. In the *systems engineering concept* shown in Figure 2-1, the system architecture is part of *systems design* in the *problem-solving cycle*, together with *concept development* and *project management*. After the derivation of needs and requirements from the initial *problem*, the process of defining the system architecture is the first step of obtaining an early draft of a *solution*.[62]

Ropohl emphasized three views of a system, as shown in Figure 2-2. The combination of these three views can be done by allocating functions to the elements of a structure, defining interfaces between these elements and with the system environment. This leads to the creation of a *system architecture*, which incorporates a defined value.[63] Two fundamental aspects of a system are now linked in one single view: The *structure* (i.e., structural/hierarchical view) and the *behavior* (i.e., functional view).
Figure 2-6 shows an example of the system architecture of a bulk carrier ship that combines

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[60] Feldhusen et al. (2016)., p. 695
[61] Bajzek et al. (2021a)., p. 161
[62] Haberfellner et al. (2019)., p. 160
[63] Ibid., p. 157

all three views introduced in Figure 2-2. The system *hierarchy* of the bulk carrier is modeled using subsystems (gray and blue blocks) and parts (light blue blocks), creating system levels and thereby structuring the complex system in the process, as previously shown in Figure 2-3. The system *structure* is realized by linking these subsystems and parts through interfaces (small orange squares) and relationships (orange lines). Interfaces that are not linked indicate a high number of relationships in the system but are not explicitly represented here. The system *behavior* is described by functions (green blocks) that are allocated to and fulfilled by subsystems and parts. The exchanges between these functions (i.e., energy, material, signal) are not shown here. The subsystems in this figure are only representative and do not illustrate a complete bulk carrier ship architecture.

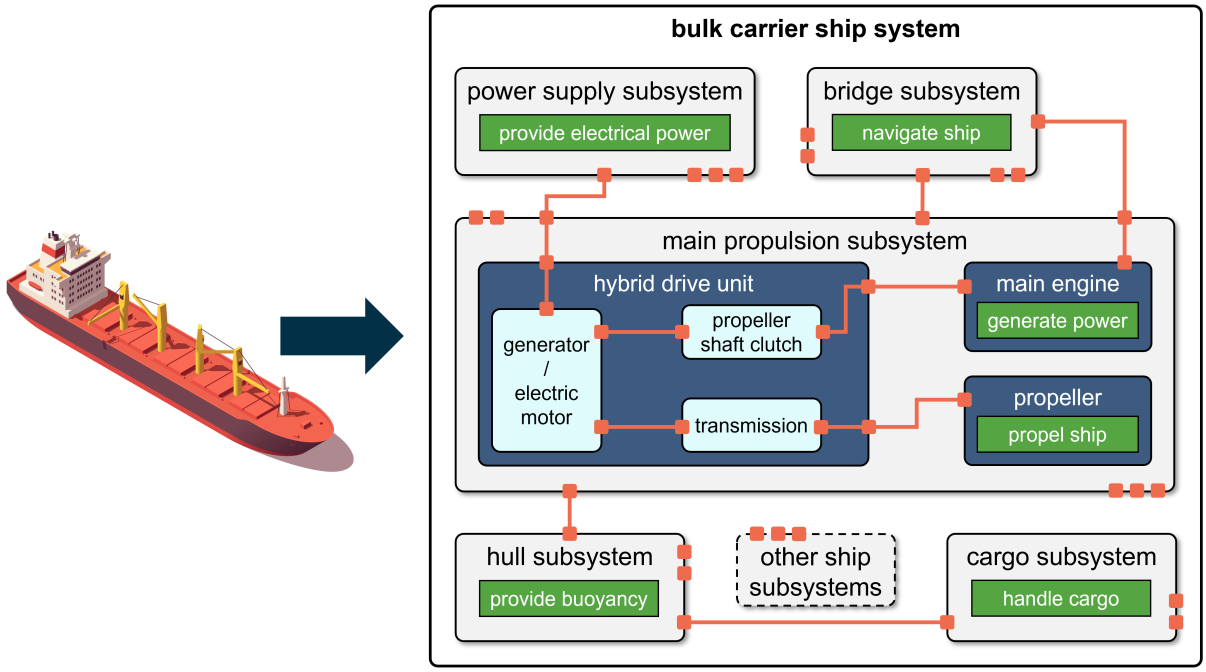

Figure 2-6: Bulk carrier ship system architecture example

In general, a ship consists of a large number of subsystems and interfaces that form a complex system and work together to fulfill the ship's purpose, e.g., in the case of a bulk carrier, to safely transport goods such as ore, coal, or grain around the world's oceans. Considering the role of a ship designer, keeping track of all the components and interfaces is not an easy task if a system architecture model is not used.[64]

Standards for system architecture definition are available, such as *ISO/IEC/IEEE 42020 System Architecture Definition*[65] or *ISO/IEC/IEEE15288 System Architecture Definition Process*[66], which also address the creation of architecture alternatives/variants. *Variant creation* is an important part of the architecting process and helps to find the most appropriate solution. A good way to manage this process is to gradually reduce the number of variants, starting with variants of *solution principles*, then variants of *overall concepts*, and finally variants of *detailed concepts*, as suggested by *Haberfellner et al.*[67]

The adoption of MBSE – which includes system architecture models – is generally low in

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[64] Le Néna, R., Guégan, A., & Rafine, B. (2019). *Systemic Approach to Ship Design*. In: Apostolos Papanikolaou (Eds.). A Holistic Approach to Ship Design - Volume 1: Optimisation of Ship Design and Operation for Life Cycle. First edition (2019): Springer Cham., p. 127 ff.

[65] INCOSE. (2023)., p. 8

[66] ISO/IEC/IEEE 15288:2023(E). (2023)., p. 70 ff.

[67] Haberfellner et al. (2019)., p. 31 ff.

the maritime industry (see chapter 1 and Figure 1-2). This master's thesis in the context of the MODE Lab aims to change this by showing the potential benefits of integrating a *descriptive system model* (i.e., system architecture model) into the overall ship development process.

2.1.4 Stakeholders

The integration of the *system-of-interest* into its superordinate system or *environment* has been shown in Figure 2-2 in the context of *thinking in systems* in chapter 2.1.1. This environment, which surrounds and encompasses the SoI, contains *environmental systems* and elements that stand in some kind of relationship to each other as well as to the SoI. These systems and elements can be *stakeholders* of the SoI and are another essential part of systems engineering.

Some specific stakeholders of the *maritime industry* have already been briefly introduced in the introductory chapter 1. These maritime stakeholders will be further discussed in chapter 3.1. However, a formal definition from a more general point of view will facilitate the understanding of the *stakeholder definition and analysis* carried out later in the practical part of this master's thesis. Such a definition is given by the *International Organization for Standardization*: A stakeholder is an "*individual or organization [..] having a right, share, claim, or interest in a system [..] or in its possession of characteristics that meet their needs and expectations*" [68]. Examples for stakeholders can be *"[..] end users [..], end user organizations, supporters, developers, customers [..], producers, trainers, maintainers, disposers, acquirers [..], suppliers [..], regulatory bodies, and people influenced positively or negatively by a system. […] Some stakeholders can have interests that oppose each other or oppose the system.*" [69]

Haberfellner et al. introduce the *environment-oriented view* as one of the approaches to viewing systems, which focuses on the relations between the system and its surrounding systems or stakeholders. Figure 2-7 shows this view for the exemplary stakeholders specified by *ISO* of a general system.

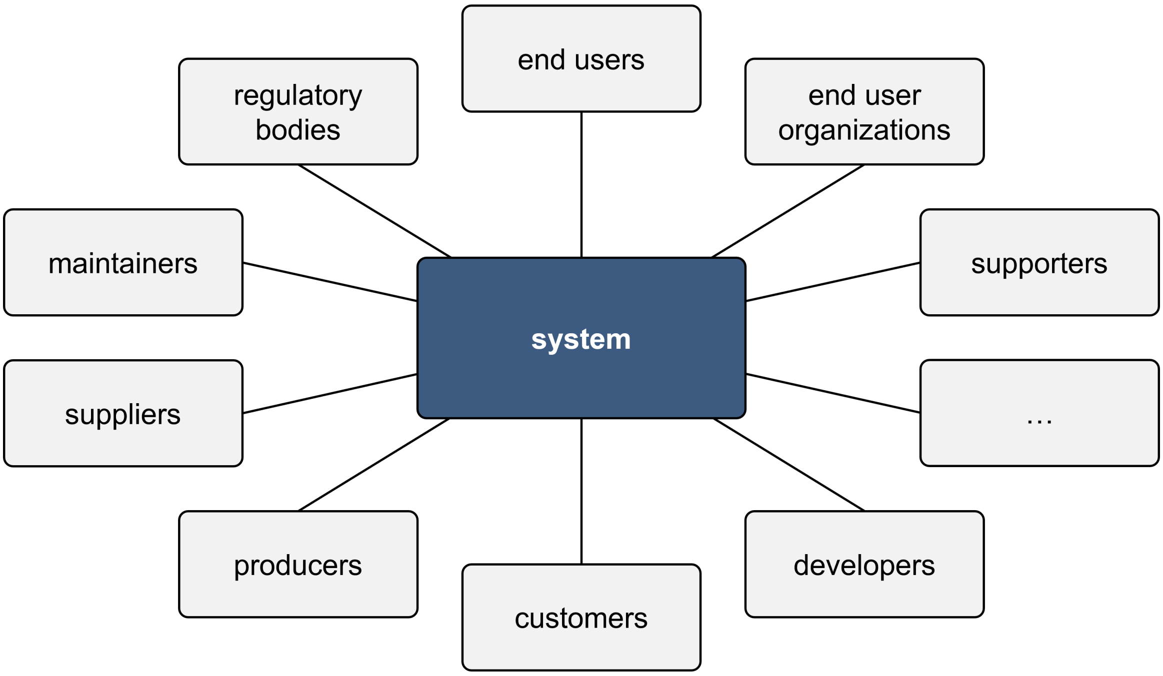

Figure 2-7: Stakeholders in the environment-oriented view, inspired by *Haberfellner et. al.*[70]

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[68] ISO/IEC/IEEE 15288:2023(E). (2023)., p. 7

[69] Ibid., p. 7

[70] Haberfellner et al. (2019)., p. 12

2.1.5 SE Process Models

The *SE process model* introduced by *Haberfellner et al.* and shown in Figure 2-1 is the second SE principle besides systems thinking, which is part of the *systems engineering concept*. This specific process model provides a set of actions and guidelines for systematically moving from a problem to a solution and is based on *four principles*:

- *Top-down approach:* When dealing with complex and non-routine problems, going from the general to the detail avoids early conceptual errors and assists in managing the complexity of the task. This approach has already been shown when discussing the hierarchical view of a system (see Figure 2-2 and Figure 2-3) as well as the reduction of level of detail principle in chapter 2.1.1.
- *Thinking in variants:* Continuously seeking alternatives (e.g., different system architectures), rather than settling for the first available option, ensures that all possible solutions are considered.
- *Structuring the process in phases (macro logic):* Supporting the first two principles, the development of a solution is structured into manageable project phases.
- *Problem-solving cycle (micro logic):* This methodological guideline can assist in solving problems as they arise and should be used at every phase of the project.[71]

Besides this rather universal SE process model, many other discipline-specific process or procedural models have been created for product development, which include disciplines such as mechanical products, electrics/electronic (E/E), and software. Designed to support the entire *product development process* (PDP), these models provide process-oriented guidelines and best practices for each phase of the PDP, which can be run once or iteratively.[72]

According to *Haberfellner et al.*, a rough distinction can be made between *plan-driven* and *agile* models. *Plan-driven models* are characterized by a sequence of steps that provide a logical process structure to projects, enabling efficient development of high-quality solutions. Examples are the waterfall model, the V-model, the VDI Guideline 2221, or simultaneous/concurrent engineering. *Agile models* have been developed because traditional plan-driven models can lead to long development times and do not respond well to specification changes, thus failing to meet the specific needs of software projects. They are also increasingly being used for systems that include both hardware and software components. Examples are the spiral model, feature-driven development, or Scrum. Although the SE process model is primarily plan-driven, it also incorporates agile aspects.[73]

Despite its broad applicability, the SE process model and its superordinate systems engineering concept (see Figure 2-1) do not consider activities such as *integration* or *verification and validation* (V&V). However, the *V-model*, a commonly used plan-driven procedural model, does include these activities, as shown in Figure 2-8. The V-model has first been published by *The Association of German Engineers* (VDI = Verein Deutscher Ingenieure) in 2004 as a systematic approach for developing *cyber-physical mechatronic systems*, responding to the increasing interaction between the domains of mechanics, E/E, and software. It supports a parallel development of all domains and uses both a *top-down* (left side of the "V") and a *bottom-up* (right side of the "V") approach. Starting with the product context, the development approach begins by translating customer needs into requirements. The

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[71] Haberfellner et al. (2019)., p. 27 ff.

[72] Eigner, M. (2014). *Einleitung – Modellbasierte Virtuelle Produktentwicklung.* In: Martin Eigner, Daniil Roubanov, Radoslav Zafirov (Eds.). Modellbasierte virtuelle Produktentwicklung. First edition: Springer-Verlag Berlin Heidelberg., p. 15 ff.

[73] Haberfellner et al. (2019)., p. 56 ff.

design process follows a top-down approach, starting from the system-level architectural design and proceeding to the subsystem and part level design. Domain-specific solutions are designed and implemented at the bottom of the "V" as part of the implementation of system elements. During the bottom-up integration process, these system elements are gradually merged into subsystems and subsequently into the overall system. Throughout this process, the system elements, subsystems, and the overall system are continuously verified against the requirements. Finally, system validation ensures that all customer needs are met, and the product is delivered to the customer.[74]

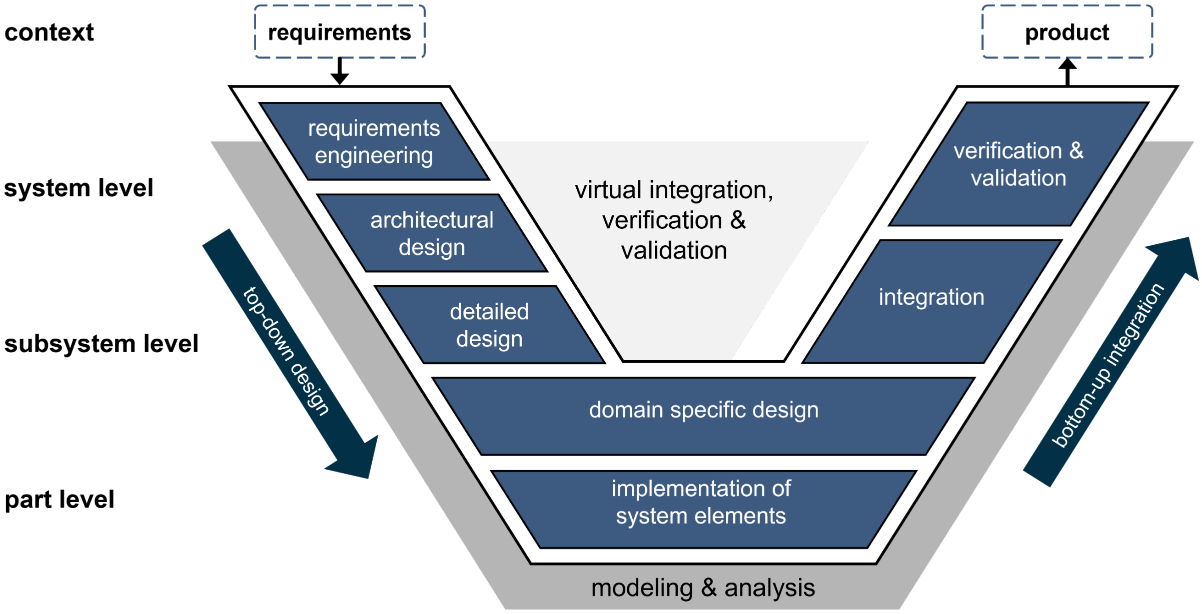

Figure 2-8: V-model, inspired by *VDI 2206* [75] and *Bajzek et al.*[76]

The V-model is a widely used procedure model for system development, with many industry-specific variations. After discussing the classic ship design process in chapter 3.2, the V-model will serve as a starting point to integrate a *descriptive system model* (i.e., system architecture model) into the overall ship development process and to introduce MBSE to the maritime industry in chapter 5.

2.1.6 Project Management

The final part of the systems engineering concept (see Figure 2-1) being discussed is *project management* (PM). In general, systems engineering typically focuses on redesigning or creating new systems, rather than on their routine operation. To achieve this, *projects* are used as the organizational form, making PM an essential part of SE.[77]

The Standard for Project Management defines PM as follows:

> *"The application of knowledge, skills, tools, and techniques to project activities to meet project requirements. Project management refers to*

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[74] VDI/VDE 2206. (2020). *Development of mechatronic and cyber-physical systems*. Verein Deutscher Ingenieure., p. 2 ff.

[75] Ibid., p. 12

Bajzek, M., Fritz, J., & Hick, H. (2021c). *Systems Engineering Processes.* In: Hannes Hick, Klaus Küpper, Helfried Sorger (Eds.). Systems Engineering for Automotive Powertrain Development. First edition (2021): Springer Cham., p. 254

[77] Haberfellner et al. (2019)., p. 137 ff.

> *guiding the project work to deliver the intended outcomes. […]”* [78]

Depending on the environment, organization, or project size, the areas of systems engineering and project management may *overlap* to varying degrees, resulting in shared responsibilities between the systems engineer and the project manager.[79] Figure 2-9 shows an exemplary overlap of activities for both roles:

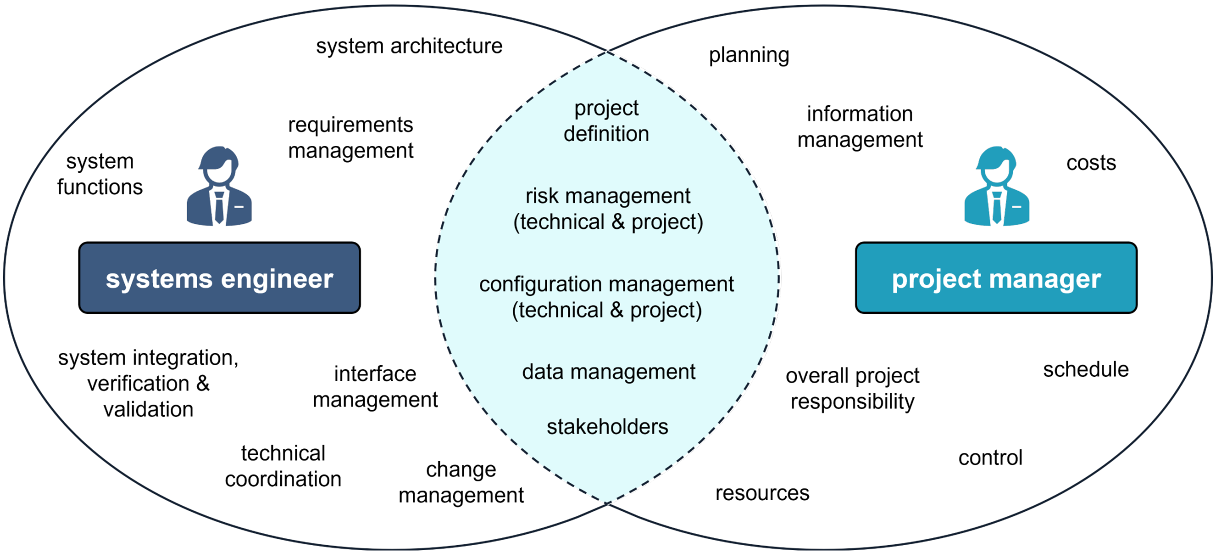

Figure 2-9: Responsibilities of the systems engineer and the project manager, inspired by *Schulze*[80]

This chapter concludes the basic principles and fundamentals of *systems engineering* that have been discussed in chapter 2.1. These principles serve as a theoretical framework for later activities in the practical part of this master’s thesis and are complemented by the following chapters 2.2 and 2.3.

2.2 Model-based Systems Engineering (MBSE)

While traditional systems engineering methods are paper- or document-based, *Model-Based Systems Engineering* (MBSE) takes systems engineering further. It builds on SE fundamentals and principles, but uses *descriptive system models* in development, allowing for a *model-based* and *multidisciplinary* approach.[81] Although the basic idea of MBSE is to describe a complex system using *system models* instead of *text-based documents*, the use of documents is still an important part of development. This is because not all stakeholders can be involved using models alone, or the system lifecycle requires documents for e.g., archiving, legal, warranty, or process compliance reasons. Therefore, MBSE can be seen as an add-on to SE, consistently applying SE principles with a focus on modeling.[82]

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[78] Project Management Institute. (2021). *The standard for project management and a guide to the project management body of knowledge (PMBOK guide)*. Seventh edition. Newtown Square. Pennsylvania. USA: Project Management Institute., p.4

[79] SEBoK. (2023). *Guide to the Systems Engineering Body of Knowledge.*

[80] Schulze, S.-O. (2016). *Systems Engineering.* In: Udo Lindemann (Eds.). Handbuch Produktentwicklung. First edition (2016): Carl Hanser., p. 168

[81] Friedenthal, S., Moore, A., & Steiner, R. (2012). *A Practical Guide to SysML – The Systems Modeling Language.* Second edition. San Francisco: Morgan Kaufmann., p. 15 ff.

[82] Bajzek, M., Fritz, J., Hick, H., Maletz, M., Faustmann, C., & Stieglbauer, G. (2021b). *Model Based Systems Engineering Concepts.* In: Hannes Hick, Klaus Küpper, Helfried Sorger (Eds.). Systems Engineering for Automotive Powertrain Development. First edition (2021): Springer Cham., p. 208

A formal definition of MBSE is given by *INCOSE* in its *Systems Engineering Vision 2020*:

> *"Model-based systems engineering (MBSE) is the formalized application of modeling to support system requirements, design, analysis, verification and validation activities beginning in the conceptual design phase and continuing throughout development and later life cycle phases."* [83]

Put another way, *Noguchi* states:

> *"Model Based Systems Engineering (MBSE) is an emerging new paradigm for improving the efficiency and effectiveness of systems engineering through the pervasive use of integrated descriptive representations of the system to capture knowledge about the system for the benefit of all stakeholders."* [84]

Need for MBSE: The growing interaction of mechanics, electrics/electronics, software, and users has led to a corresponding increase in the complexity of modern systems. The development of *systems designs* often involves collaboration and data exchange across multiple organizations. Traditional systems engineering approaches store the information how the system is designed using documents, forcing the reader of these disconnected and static documents to mentally integrate them. Additionally, such approaches depend on text that is *human-readable*, rather than a language that is designed for specific purposes and with precise semantics (i.e., a *modeling language*, see chapter 2.2.2).[85]

Although systems engineers have always used models to represent technical designs, these *discipline-specific models* (discipline = mechanics, E/E, software; see chapter 2.2.1) are standalone, not integrated, and ultimately share their information using static documents. This leads to difficulties in ensuring consistently documented models as the design evolves and in achieving a common understanding of the system. In addition, today's multidisciplinary teams often face challenges due to their different viewpoints of the system under development, leading to misunderstanding regarding its interpretation.[86]

The need for applying MBSE is also true for the *MODE Lab*, whose objective is to contribute to the *decarbonization* and *automation* of the shipping industry. The MODE Lab's focus lies on GHG reduction technologies (e.g., wind-assisted ship propulsion), automated vessels for safety and efficiency, and the promotion of international collaboration and human resource development in the maritime industry (see chapter 1). Currently, there is no descriptive system model in use within the MODE Lab. Moreover, the adoption of MBSE in the maritime industry is generally relatively low (see Figure 1-2), which this master's thesis aims to address by demonstrating the practical application of MBSE in the form of a *descriptive system model* of a bulk carrier ship equipped with a wind-assisted device.

Adoption of MBSE: *Kossiakoff et al.* points out that the adoption of MBSE into an organization or project might face some challenges. If stakeholders or engineers are used to a document-based approach, presenting model-driven work products (e.g., a system architecture model or functional analysis as part of a descriptive system model) can cause a culture shock and lead to resistance. Distinguishing between the information about a system and the way this

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[83] INCOSE. (2007). *Systems Engineering Vision 2020.* International Council on Systems Engineering (INCOSE)., p. 15

[84] Noguchi, R. A. (2019). *Recommended Best Practices based on MBSE Pilot Projects.* In: INCOSE International Symposium - Volume 29, Issue 1, Pages 753-770. (July 2019): International Council on Systems Engineering (INCOSE)., p. 1

[85] Kossiakoff, A., Seymour, S. J., Flanigan, D. A., & Biemer, S. M. (2020). *Systems Engineering - Principles and Practice.* In: Andrew P. Sage (Eds.). Wiley Series in Systems Engineering and Management. Third edition. Hoboken. USA.: Wiley., p. 254

[86] Dvorak, D. L. (2013). *Model-Centric Engineering, Part 1: An Introduction to Model-Based Systems Engineering*. NASA.

information is presented can be difficult for stakeholders with a document-based mindset. One solution is to present *model-generated* tables or matrices showing system interface and connections in addition to showing large-format *system architecture diagrams*. Although such diagrams are useful for gaining a quick understanding of a system's structure and behavior, they are for example not the optimal tool for error-free analysis of connections when compared to a model-generated table or matrix. Furthermore, the *learning curves* of modeling tools and languages are often considerable. This can be overcome by having so-called *subject matter experts* (SMEs) that are supported by modelers. As the SMEs are not expected to be proficient modelers themselves, but rather to own, contribute to, and consume model-derived work products, a successful modeling approach can be more likely. Early demonstrations of *value*, such as enhanced multidisciplinary team communication, error-checking, or information representation using system model diagrams, further support a modeling effort and contribute to the acceptance of MBSE.[87]

Bajzek et al. list areas of impact and associated difficulties that need to be considered when applying new approaches such as MBSE in development:

- *Processes and methods*: The existing development process landscape and its methods need to be tailored to successfully integrate an MBSE methodology.
- *Tools*: New software tools need to be rolled-out and embedded into the existing IT-tool landscape.
- *Organizational structure*: Roles and responsibilities need to be defined to support the roll-out of MBSE methods and tools.
- *Human factor*: Overcoming concerns of engineers regarding new methodologies can be challenging, which demands a strategy to introduce MBSE.
- *Project execution*: The introduction of MBSE can slow down an experienced team due to uncertainties regarding new methodologies.[88]

Benefits of MBSE: After addressing the need for MBSE and overcoming potential adoption barriers, *INCOSE* has identified several benefits to be gained from using an MBSE approach in development:

- *"Improved communications among the development stakeholders […]*
- *Increased ability to manage system complexity […]*
- *Improved product quality […]*
- *Reduced cycle time […]*
- *Reduced risk by surfacing requirements and design issues early.*
- *Enhanced knowledge capture and reuse of the information […]*
- *Improved ability to teach and learn SE fundamentals […]"* [89]

Given the discussed *need* for MBSE and its prospective *benefits*, it can be argued that MBSE will become the standard approach to applying systems engineering. Although proven SE principles are supported rather than replaced by MBSE, systems engineers will need to develop an understanding for *system models* in general as well as new skills regarding modeling *languages*, *methods*, and *tools*.[90] These topics are introduced in the following chapters to provide a theoretical framework and to prepare for the modeling activities in chapter 4 of this master's thesis.

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[87] Kossiakoff et al. (2020)., p. 258 f.

[88] Bajzek et al. (2021b)., p. 213 f.

[89] INCOSE. (2023)., p. 220

[90] Kossiakoff et al. (2020)., p. 253

2.2.1 System Models

System models have already been shortly introduced in chapter 2.1.1 as one of the selected principles of *systems thinking*, along with *thinking in systems*, *thinking in functions*, *reduction of level of detail*, and *interconnected thinking*. Referring to chapter 1, the practical application of MBSE in the maritime industry through the creation of a *descriptive system model* of a bulk carrier bulk carrier ship equipped with a wind-assisted device and its subsequent integration into the ship development process is defined as the overall objective of this master's thesis. Therefore, a thorough discussion of *system models* is an important part of the theoretical framework that is established in chapter 2.

As the name *model-based systems engineering* already implies, integrated *models* are generally the main product of MBSE, as opposed to the static representations of the system in traditional SE. These models contain information about the system, including system elements, relationships between these elements, attributes, and so on. This information can be viewed, checked for errors, or queried, and is further used in (mostly) automatically generated work products, such as diagrams, tables, or matrices.[91, 92] The question arises as to *what* these models really are, in other words, how they can be used in the development of complex systems. To answer this question, selected parts of general *model theory* as well as a *classification of models* will be discussed in the following, leading to a final distinction between *system models and specific models* and a discussion of their scope and usage.

Model theory: From an MBSE point of view, *Kossiakoff et al.* define a model as *"[…] a simplified representation or abstraction of reality used to mimic the appearance or behavior of a system or system element."* [93] A multitude of alternative definitions of models exist (for example, those proposed by *Zafirov* [94] or *Dori* [95]), which can vary according to the specific field of application. *Stachowiak* identifies three fundamental properties inherent to all models, which he defines in his general model theory:

- *Mapping property:* Models are representations of natural or artificial systems, which themselves can be models.
- *Reduction property:* Models do not replicate all attributes of the original, only those relevant to the model creators or users.
- *Pragmatic property:* Models are not clearly assigned to their original, but rather serve as substitutes.[96]

Stachowiak's definition of models is essentially a conceptual analysis of the term "*model*". While this provides a useful foundation for further investigation, it does not offer a clear distinction between the various existing model types. To determine which models are used in system development and why, a more practical classification of models is necessary.

Classification of models: *Kossiakoff et al.* propose a classification of models into three categories: *schematic* models, *mathematical* models, and *physical* models.[97] *Bajzek et al.* expand on these three categories and present an overview of model types in Figure 2-10.

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[91] Kossiakoff et al. (2020)., p. 256

[92] Friedenthal et al. (2012)., p. 15 ff.

[93] Kossiakoff et al. (2020)., p. 283

[94] Zafirov, R. (2014). *Modellbildung und Spezifikation.* In: Martin Eigner, Daniil Roubanov, Radoslav Zafirov (Eds.). Modellbasierte virtuelle Produktentwicklung. First edition: Springer-Verlag Berlin Heidelberg., p. 80

[95] Dori, D. (2016). *Model-Based Systems Engineering with OPM and SysML.* New York: Springer., p. 92

[96] Stachowiak, H. (1973). *Allgemeine Modelltheorie.* Wien: Springer-Verlag., p.131 ff.

[97] Kossiakoff et al. (2020)., p. 283 ff.

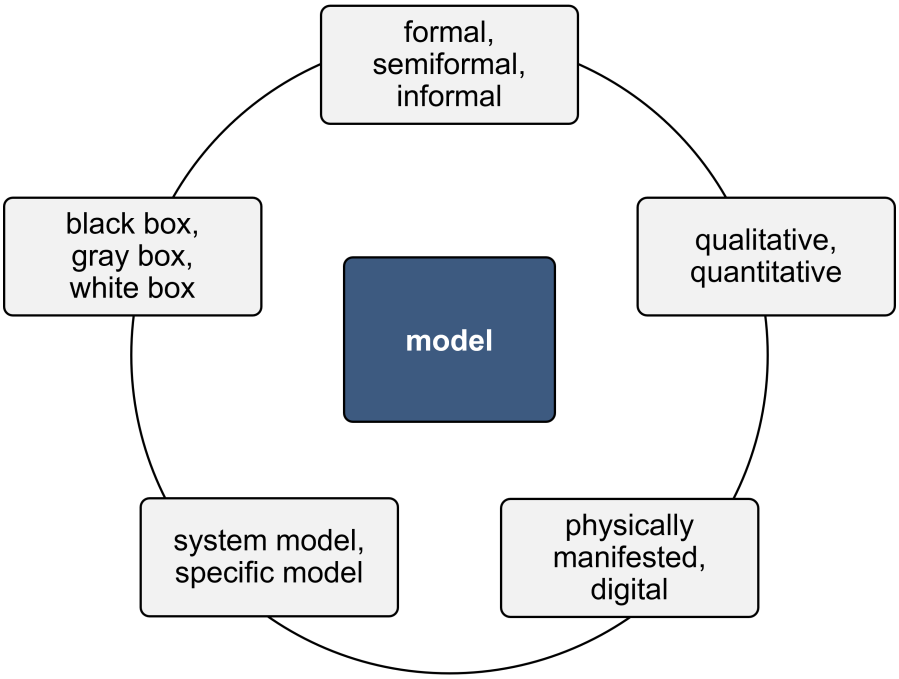

Figure 2-10: Model types, inspired by *Bajzek et al.*[98]

Black box, *gray box*, and *white box models* are a widely used concept when describing complex systems. In chapters 2.1.1 and 2.1.2, the term *black box* has already been used when describing the *hierarchical view* and the *functional view* on a system as introduced by *Ropohl* and shown in Figure 2-2 and Figure 2-4.[99] *Haberfellner et al.* use the black box approach in the *reduction of level of detail* principle of *systems thinking* (see chapter 2.1.1) as well as the *top-down approach* of the *SE process model* (see chapter 2.1.5) as a way to handle system complexity. By gradually moving from a *black box* (i.e., only the function and its inputs/outputs are known) to a *gray box* (i.e., only parts of the internal architecture and links between the inputs/outputs are known) and finally to a *white box* (i.e., the internal architecture and all links between inputs/outputs are known), the system-of-interest is first observed from a high level and then narrowed down. This modeling process also depends on the specific model fidelity and the required internal information level, which is always a *trade-off* between the modeling effort and the benefits to be gained.[100, 101]

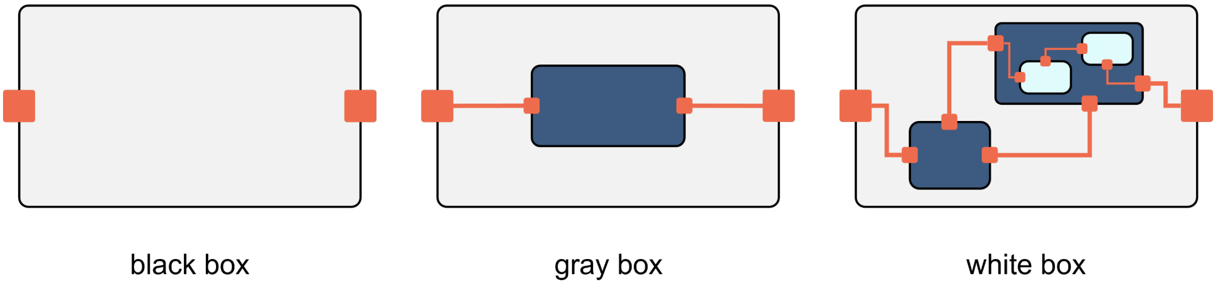

Figure 2-11: Black box, gray box, white box, inspired by *Bajzek et al.*[102]

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[98] Bajzek et al. (2021b)., p. 203
[99] Ropohl. (2009)., p. 76
[100] Haberfellner et al. (2019)., p. 9
[101] Bajzek et al. (2021b)., p. 205
[102] Ibid., p. 206

Formal, *semiformal*, and *informal models* are another way to differentiate models. *Formal models* are characterized by being based on a *formal modeling language* (see chapter 2.2.2) that has a defined *notation* (i.e., the graphical representation/symbols), *syntax* (i.e., the rules/vocabulary for combining the symbols) , and *semantics* (i.e., the meaning of the syntax and associated notation). These elements of formal models are specified in an underlying *metamodel*. *Semiformal models* also have a metamodel that defines the notation and syntax, but their semantics are less strict than formal models. *Informal models*, such as drawings or descriptions by text, are based on *natural language*. They can be created quickly, but because of their informality, they are prone to ambiguity, which can lead to different interpretations of the system. The big advantage of formal and semiformal models over informal models is their ability to be automatically processed by computers.[103, 104]

Qualitative and *quantitative models* are often more difficult to distinguish. *Qualitative models* are schematic models that are commonly used to portray the system in a *logical* and descriptive manner by visualizing its structure or relationships/links between its elements. Examples include system architecture models, block diagrams, or flowcharts. Such a qualitative description of a system is the focus of chapter 4. *Quantitative models* are based on qualitative models. They can be executed (i.e., run) and are characterized by *concrete values*, including their dimensions and units (e.g., weight, speed, torque).[105] A system simulation model is also a quantitative model because it provides quantitative results which are used to verify and validate qualitative models, such as system architecture models.[106]

Physically manifested and *digital models* are an additional way to classify models at a high level. *Physically manifested models* are a representation of the actual system or product, with attributes that are either more or less detailed than the original, depending on the purpose of the model (e.g., a ship hull model to test hydrodynamic properties). *Digital models* are a virtual manifestation of the system or product and can have varying degrees of formalism (i.e., formal, semiformal, informal). Both types of models are used early in development for continuous verification and validation.[107, 108]

System models and specific models: While the previously introduced model types are a useful way to classify models, the classification of system models and specific models, as well as the distinction between these two types, is of great importance in the context of this master's thesis. This is because a clear understanding of system models is necessary in order to understand the purpose of creating such a model in chapter 4 and its subsequent integration into the ship development process in chapter 5.

System models do not have a single definition when examining the *as-is situation*; instead, there are a variety of views and understandings of their scope and usage, which also depend on the discipline and technical domain. Referring back to *Ropohl's* views of a system (structural, hierarchical, and functional view; see Figure 2-2), it also depends on the point of view or the system level, what the system-of-interest is, which can subsequently determine the system model.[109] Currently, *two main views* of a system model exist. The first and most common view considers the system model to be strictly implemented using the *systems modeling language* (SysML) and all its principles. In this SysML-centric view, *"[…] the system*

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[103] Bajzek et al. (2021b)., p. 204

[104] Dori (2016)., p. 91 ff.

[105] Bajzek et al. (2021b)., p. 205

[106] Knaus, O., & Wurzenberger, J. C. (2021). *System Simulation in Automotive Industry.* In: Hannes Hick, Klaus Küpper, Helfried Sorger (Eds.). Systems Engineering for Automotive Powertrain Development. First edition (2021): Springer Cham., p. 500

[107] Bajzek et al. (2021b)., p. 203

[108] INCOSE. (2023)., p. 196

[109] Hick, H., Bajzek, M., & Faustmann, C. (2019). *Definition of a system model for model-based development.* In: SN Applied Sciences - Volume 1, Article 1074. (August 2019): Springer Nature., p. 3

model [is] an interconnected set of model elements that represent key system aspects […], including its structure, behavior, parametrics, and requirements.” [110] The second view positions the system model as a central provider and integrator of relevant information – a *single source of truth*. However, such a system model may not be feasible due to the complexity and volume of specific data or the interdisciplinary nature of projects. Furthermore, when considering the *product lifecycle management* (PLM) approach as a connector of discipline-specific data repositories, the necessity of a system model acting as a central repository may be questioned. To create value for the development activities, the purpose of both PLM and a system model must be aligned.[111] Based on the findings briefly discussed above, *Hick et al.* conclude that, given the different views and domain/discipline specific understandings of system models, there is no common understanding of their purpose. They thus summarize the as-is situation of system models with the following statement:

> *“Due to the huge number of models with different targets and purposes the resulting framework for the definition of these models implies that there can’t exist only one system model in a whole development project. […] The one and only system model in a development project is just a conceptual idea, a way of thinking, an engineering vision.”* [112]

After discussing the as-is situation of system models above, specific models will now be briefly introduced. Also, considering the bigger picture as well as the combined scope and usage of system and specific models will lead to an updated definition of system models.

Specific models are tailored to defined targets and purposes within their respective *technical domains* (e.g., requirements, structure, behavior) and are by various *disciplines* (e.g., mechanics, electrics/electronics, software) in technical development. Discipline-specific experts contribute to the creation of a diverse range of specific models that possess a high level of detail and provide deep insights into the system-of-interest. Examples include mechanical structure or behavior models using CAD/CAE software tools. In summary, a specific model describes the view of one discipline on one technical domain (i.e., system aspect) in detail.[113]

Looking at the *bigger picture*, system models and specific models can be positioned within the *V-model*, which has been introduced in chapter 2.1.5 and shown in Figure 2-8. Here, system models are placed in the upper half of the V-model, while specific models are placed in the lower half. However, if the local point of view (i.e., the system-of-interest) changes, a part at the part level may also be a system. Therefore, it is possible to place system models also at lower levels or to have multiple system models at one level. In addition to their placement in the V-model, the distinction between the two model types can be visualized by using the *model cube* concept to emphasize their different scope and usage as shown in Figure 2-12. Here, the three dimensions are defined as the *discipline* (i.e., the breadth of the cube), the *technical domain* (i.e., the width of the cube), and the *level* (i.e., the depth of the cube). In the example in Figure 2-12, two system models and two specific models are placed in the cube. Each model visualizes a different view of the system, depending on its purpose and target.[114]

Hick at el. summarize their investigations of system and specific models in the context of model-based development as follows:

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[110] Friedenthal et al. (2012)., p. 17

[111] Hick et al. (2019)., p. 4

[112] Ibid., p. 6

[113] Ibid., p. 6 ff.

[114] Ibid., p. 6 ff.

> *"The scope of system models is to provide breadth and width and therefore they incorporate multiple views of at least two technical domains or disciplines. On the contrary, specific models provide depth by detailing the view of a single discipline on a single technical domain."* [115]

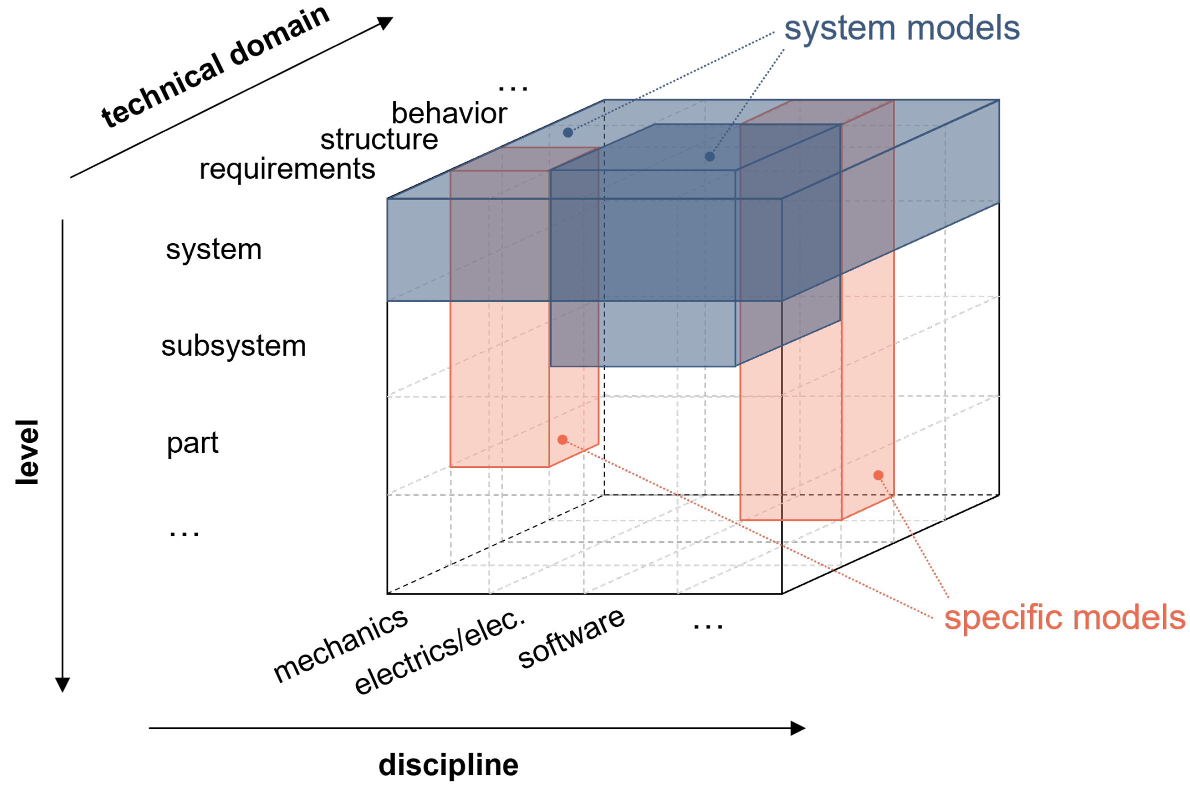

Figure 2-12: System models and specific models in the „model cube", inspired by *Hick et al.*[116]

To conclude this chapter, *Bajzek et al.* provide a list of targets and purposes of system models based on the findings by *Hick et al.*:

- *"Establish the view across disciplines […]*
- *Enable the view across technical domains […]*
- *Provide a platform for stakeholder communication […]*
- *Provide access to key information […]*
- *Compile the system documentation from day 1 […]"* [117]

2.2.2 Modeling Languages

A *system model* must be unambiguous, clear, and interpretable not only by humans, but also by computers, thus making it a *formal* model (see to Figure 2-10 for all model types). To achieve the required explicitness, an artificial language must be used. In the context of MBSE, this is a *system modeling language*.[118] The key aspects of such modeling languages can be summarized as follows:

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[115] Hick et al. (2019)., p. 11
[116] Ibid., p. 8
[117] Bajzek et al. (2021b)., p. 219 ff.
[118] Zafirov (2014)., p. 89

> *"The modeling language is an artificial set of rules consisting of individual elements with a fixed meaning (semantics) and rules for linking them together (syntax). Modeling languages are used to describe models (defined as a model or image of an original) with the main purpose of unambiguous interpretability of the described content."* [119]

Some modeling languages attempt to include all disciplines and technical domain views (see Figure 2-12), while others cover fewer views and are more specific.[120] Modeling languages are specified by an underlying *metamodel*, which defines language concepts, their characteristics, and relationships, serving as the abstract syntax, separate from the concrete syntax that specifies the notation of the language.[121] A first example for a descriptive modeling language (i.e., used to create *qualitative models*) is the *systems modeling lang*uage (SysML).[122] Based on the *unified modeling language* (UML) which is used in software development, SysML (in its 1.x versions) is currently the most widely adopted and supported modeling language, according to many authors.[123, 124] However, SysML is only one possible modeling language. Other modeling languages are for example the *business process model and notation* (BPMN)[125], the *object-process methodology* (OPM)[126], or *Arcadia*[127]. While all of these are descriptive modeling languages that portray the system in a logical way, quantitative and executable models (e.g., simulation models) are created using modeling languages such as *Modelica* or *Simulink*.[128] This master's thesis uses the *Arcadia* modeling language, which will be introduced in detail in chapter 2.3.1 and practically applied in chapter 4.

2.2.3 Modeling Methods

The term *method* refers to a rule-based and planned procedure that outlines the steps to be taken to achieve a specific goal.[129] In the context of MBSE, *Friedenthal et al.* provide a definition of a method, and more specifically, an MBSE method:

> *"A method is a set of related activities, techniques, and conventions that implement one or more processes and is generally supported by a set of tools. A model-based systems engineering method is a method that implements all or part of the systems engineering process, and produces a system model as one of its primary artifacts."* [130]

Methods should not be confused with *methodologies*. Although they are similar terms and are sometimes used interchangeably, a methodology can be thought of as a set of methods, processes, and tools, such as the *MBSE methodology*.[131, 132] Examples for MBSE *modeling*

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[119] Zafirov (2014)., p. 89

[120] Bajzek et al. (2021b)., p. 224 f.

[121] Friedenthal et al. (2012)., p. 90

[122] Object Management Group (OMG). (2019). *OMG Systems Modeling Language (SysML).* Version 1.6.

[123] Kossiakoff et al. (2020)., p. 259 f.

[124] Zafirov (2014)., p. 89 f.

[125] Object Management Group (OMG). (2013). *OMG Business Process Model and Notation (BPMN).* Version 2.0.2.

[126] Dori, D. (2002). *Object-Process Methodology - A Holistic Systems Paradigm.* New York: Springer-Verlag Berlin Heidelberg.

[127] Voirin, J.-L. (2017). *Model-based System and Architecture Engineering with the Arcadia Method.* London / Oxford: ISTE Press Ltd / Elsevier Ltd.

[128] Bajzek et al. (2021b)., p. 225

[129] Lindemann, U. (2009). *Methodische Entwicklung technischer Produkte.* Third edition. Springer-Verlag Berlin Heidelberg., p. 57

[130] Friedenthal et al. (2012)., p. 21

[131] Martin, J. N. (1996). *Systems Engineering Guidebook - A Process for Developing Systems and Products.* Boca Raton. USA: CRC Press., p. 55

[132] INCOSE. (2023)., p. 220

methods (i.e., methods that describe the steps to create a system model) are the *object-oriented systems engineering method* (OOSEM)[133], the *object-process methodology* (OPM)[134], the *systems modeling process* (SYSMOD)[135], or the *architecture analysis and design integrated approach* (Arcadia)[136]. The *Arcadia* modeling method, which is supported by the *Arcadia* modeling language and the *Capella* modeling tool, is used in this master's thesis and will be introduced in detail in chapter 2.3.1 and practically applied in chapter 4.

2.2.4 Modeling Tools

In the broader context of product development, the term *tool* refers to resources that facilitate the application of methods, enhancing their effectiveness and efficiency. A large range of tools exists, including simple forms and checklists, as well as more complex software (e.g., for simulation).[137] *Modeling tools* are an integral part of the MBSE methodology. Benefits of modeling tools include built-in configuration control and automated updates to system model artifacts (e.g., functions or structural blocks) throughout the model, eliminating the need to manually check for changes and updates to diagrams, tables, and matrices.[138] *INCOSE* summarize the typical features of such tools as follows:

> *"[…] a graphical user interface with a hierarchical model structure browser, palettes of model constructs, a graphical and/or textual editor for creation and modification of the model, and multiple views for visualization, reporting, diagnostics, etc."* [139]

There is a large selection of MBSE modeling tools currently available on the market, which can be broadly classified into three categories: *SysML-compliant tools*, *diagramming tools*, and *general MBSE tools*.[140] The *Capella* modeling tool, which supports both the Arcadia modeling language and method, is included in the third category. Capella will be used in this master's thesis for the creation of a descriptive system model in chapter 4, and a brief introduction to the tool will be provided in chapter 2.3.2.

2.3 Introduction to Arcadia & Capella

The *architecture analysis and design integrated approach* (Arcadia) is a *"[…] tooled method devoted to systems & architecture engineering, supported by [the] Capella modelling tool"*.[141] The modeling method has been developed between 2005 and 2010 by *Thales*, a multinational corporation engaged in a number of fields, including defense and security, aerospace and space, digital identity and security, and transport.[142] Thales committed to an MBSE approach in the early 2000s, but after its first experimental operational deployments, they soon realized that the available languages, methods, and tools did not meet the needs of their systems

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[133] INCOSE. (2023)., p. 219 ff.

[134] Dori (2002).

[135] Weilkiens, T. (2008). *Systems Engineering with SysML/UML - Modeling, Analysis, Design.* Burlington. USA.: Morgan Kaufmann OMG Press.

[136] Voirin (2017).

[137] Lindemann (2009)., p. 62

[138] Kossiakoff et al. (2020)., p. 260 ff.

[139] INCOSE. (2023)., p. 198

[140] Fernández, J. L., & Hernandez, C. (2019). *Practical Model-Based Systems Engineering.* Norwood. MA. USA: Artech House., p. 30

[141] Voirin, J.-L. (2023a). *Arcadia User Guide - Arcadia Principles and Contents Overview.* Thales., p. 4

[142] Thales Group. (2024).

engineers as the approach covered too few engineering activities and was outdated in terms of practices and business processes. In particular, the available UML-based modeling languages, originally designed for software development, were perceived as complex, unnatural for systems engineers, and lacking in expressiveness for conveying specific engineering concepts. This did not change significantly after the introduction of *SysML* in 2006-2007, as systems engineers at Thales concluded that SysML inherited too many aspects of UML, making it too difficult for non-computer scientists to understand and use. In addition, SysML itself, as well as its supporting tools, do not initially provide a methodological approach, which further hampers the adoption of MBSE. For these reasons, Thales developed the Arcadia method to meet the needs of its systems engineers and to improve its engineering practices. The method also implicitly defines the Arcadia modeling language. Both the language and the method are integrated into a new modeling tool developed internally at Thales, called Melody Advance. Arcadia has been in use at Thales since 2011, and the associated tool has been available as open-source software under the name *Capella* since 2014/2015.[143, 144, 145] The *Arcadia modeling language* and *method* as well as the *Capella modeling tool* will be further discussed in the following two chapters 2.3.1 and 2.3.2.

2.3.1 Arcadia Modeling Language & Method

As shortly stated in the beginning of chapter 2.3, the Arcadia modeling language and method as well as the associated Capella modeling tool are used for the design of *system architectures*. Arcadia is based on a *functional analysis* and a subsequent allocation of *functions* (i.e., the *behavior* of the system) to architecture *components* (i.e., the *structure* of the system). The goal of Arcadia/Capella is to facilitate the implementation of MBSE by reducing the previously mentioned complexity of SysML, while simultaneously integrating a modeling method directly into the modeling tool, thus providing an intuitive and streamlined approach to learning.[146]

Arcadia modeling language: As previously stated, the Arcadia modeling language is implicitly defined by the Arcadia modeling method. Its intended usage domain is the *functional* and *structural* definition of software and hardware system architectures. The Arcadia modeling language shares similar concepts with other system modeling languages or architecture frameworks, including UML/SysML with about 75% and the NATO Architecture Framework (NAF) with about 5%. However, the language modifies some SysML concepts to be simpler or more specialized in order to facilitate MBSE adoption by systems engineers and other stakeholders. For example, SysML[147] is based on the class and instance principle used in object-oriented programming. This principle is not adopted by the Arcadia modeling language, which reduces its complexity and simplifies the modeling process.[148, 149]

All *artifacts* (i.e., model elements) of the Arcadia modeling language such as functions, components, ports, or exchanges, etc., and their interactions and relationships are formalized in a *metamodel* (refer to formal, semiformal, and informal models in chapter 2.2.1). These artifacts also follow a distinct color code, e.g., the blocks that represent functions are green.[150]

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[143] Voirin (2017)., p. 5 ff.

[144] Roques, P. (2018). *Systems Architecture Modeling with the Arcadia Method - A Practical Guide to Capella*. London / Oxford: ISTE Press / Elsevier., p. 1 f., p. 24 ff.

[145] Eclipse Foundation. (2024a). *Arcadia Method.*

[146] Roques (2018)., p. 24 ff.

[147] OMG (2019).

[148] Voirin (2017)., p. 285 ff.

[149] Eclipse Foundation. (2024b). *Arcadia/Capella and SysML.*

[150] Voirin (2017)., p. 285 ff.

An example of a specification in the Arcadia metamodel would be “*system mission requires system capability*”[151], which describes the relationships between the *system mission* and *system capability* artifacts. All concepts and the complete metamodel of the Arcadia modeling language are provided in a reference document.[152] A simplified version of the Arcadia metamodel and its artifacts traceability is shown in Figure A-1 in the Appendix.

Arcadia modeling method: Arcadia distinguishes two domains, the *need* domain and the *solution* domain. It promotes a *viewpoint-driven* approach, shown in Figure 2-13, which is similar to *Ropohl’s* views of a system (structural, hierarchical, and functional view; see Figure 2-2). Arcadia consists of five perspectives (i.e., phases) that structure the implementation of the method. The fifth phase will not be further considered in this master’s thesis.

- *Operational Analysis (OA): “What system users must achieve.”*
- *System Analysis (SA): “What the system must achieve for users.”*
- *Logical Architecture (LA): “How the system will work to meet expectations.”*
- *Physical Architecture (PA): “How the system will be built.”*
- *End Product Breakdown Structure and Integration Contracts (EPBS): “What is expected of each component, and the conditions of its integration into the system.”* [153]

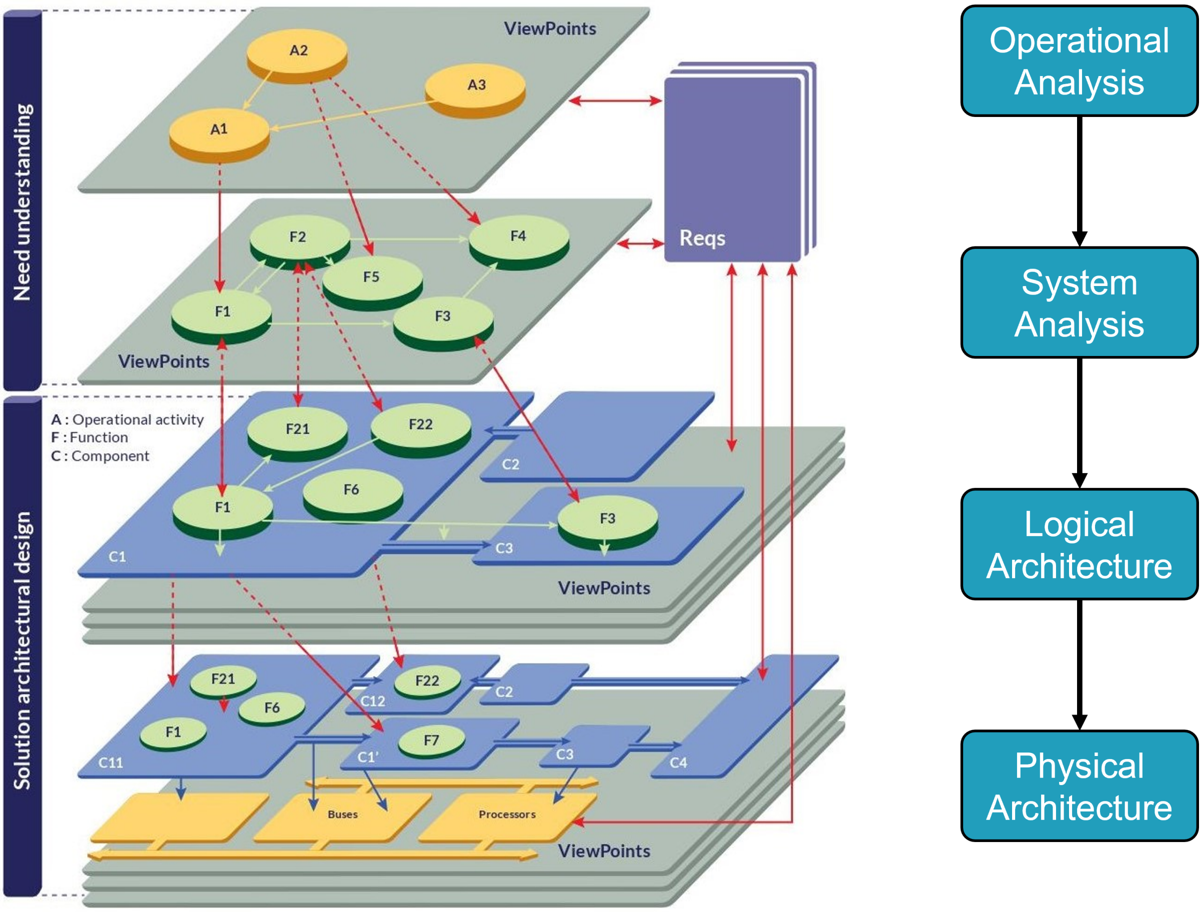

Figure 2-13: Main phases of the Arcadia method, according to *Voirin*[154]

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[151] Voirin (2017)., p. 289

[152] Voirin, J.-L. (2023b). *Arcadia Language Reference: Meta Model - Arcadia Language Concepts in details.* Thales.

[153] Voirin (2017)., p. 15 ff.

[154] Ibid., p. 17

Arcadia formalizes the analysis of needs, operational functionalities, and the definition of the system architecture, thereby ensuring a shared methodological approach and information across all stakeholders. This method facilitates co-engineering between different *system levels* (i.e., supersystem, system, subsystem, part; see Figure 2-3) and *specialties* (security, safety, performance, etc.) through joint model development, enabling comprehensive verification and validation of system architecture properties. By prioritizing *function-driven* modeling, Arcadia places a strong emphasis on the modeling of *functions* and *interfaces*, which enables the seamless integration of *functional requirements* throughout the entire development lifecycle. This approach facilitates the effective design, testing, and validation of systems.[155] *Voirin* summarizes the Arcadia modeling method as follows:

> *“Arcadia is thus a structured engineering method for defining and verifying the architecture of complex systems. It promotes collaborative work among all key players, often in large numbers, from the engineering (or definition) phase of the system and subsystems, until their IVV […].”* [156]

Table 2-1 provides an overview of the specific activities performed in each of the four main Arcadia phases (EPBS is not considered further). Not all activities need to be performed or diagrams created, as the Arcadia method is flexible in nature. The objective and level of detail of the Capella *system model* determine which phases are considered and which diagrams are created to model a particular view.[157] However, when following the Arcadia Method chronologically, the *transition activities* (e.g., from SA to LA) automatically create new model elements/artifacts based on the related elements/artifacts of the previous phase. For example, logical functions are created from system functions and a traceable relationship is automatically established between these elements.[158] This relationship is part of the Arcadia metamodel and is visualized by the “realizes” link between artifacts of different phases in Figure A-1 in the Appendix.

Table 2-1: Arcadia activities, according to *Roques*[159]

Operational analysis (OA)	**System analysis (SA)**	**Logical architecture (LA)**	**Physical architecture (PA)**
Define operational entities and capabilities	Transition from operational activities	Transition from system functions	Transition from logical functions
Define operational activities and describe interactions	Define actors, missions, and capabilities	Refine logical functions, describe functional exchanges	Refine physical functions, describe functional exchanges
Allocate operational activities to operational actors, entities, or roles	Refine system functions, describe functional exchanges	Define logical components and actors	Define physical components and actors, manage deployments
Transverse modeling	Allocate system functions to system and actors	Allocate logical functions to logical components	Allocate physical functions to physical components
	Define interfaces and describe interface scenarios	Delegate system interfaces and create logical interfaces	Delegate logical interfaces and create physical interfaces
	Transverse modeling	Enrich logical scenarios	Enrich physical scenarios
		Transverse modeling	Transverse modeling

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[155] Roques (2018)., p. 2 ff.

[156] Voirin (2017)., p. 12

[157] Ibid., p. 286

[158] Roques (2018)., p. 62, p. 198 f.

[159] Ibid., p. 59 ff., p. 83 ff., p. 196 ff., p. 232 ff.

Moreover, the Arcadia method aligns with many parts of the *ISO/IEC/IEEE 15288* standard, including the *business or mission analysis process*, the *stakeholder needs and requirements definition process*, the *system requirements definition process*, the *architecture definition process*, and the *design definition process*.[160, 161]

Arcadia diagrams and artifacts: The *diagrams* that are created when following the Arcadia method and its language are used to describe the different *viewpoints* of the system. There are several different types of diagrams, most of which are strongly inspired by UML and SysML; see the Capella web site for an extensive comparison of equivalences and differences between SysML and Arcadia/Capella.[162] The seven main Arcadia diagram types are listed below:

- *Data flow diagrams*
- *Architecture diagrams*
- *Scenario diagrams*
- *Mode and States diagrams*
- *Breakdown diagrams*
- *Class diagrams*
- *Capability diagrams*[163]

Figure 2-14 shows a schematic representation of these diagrams.

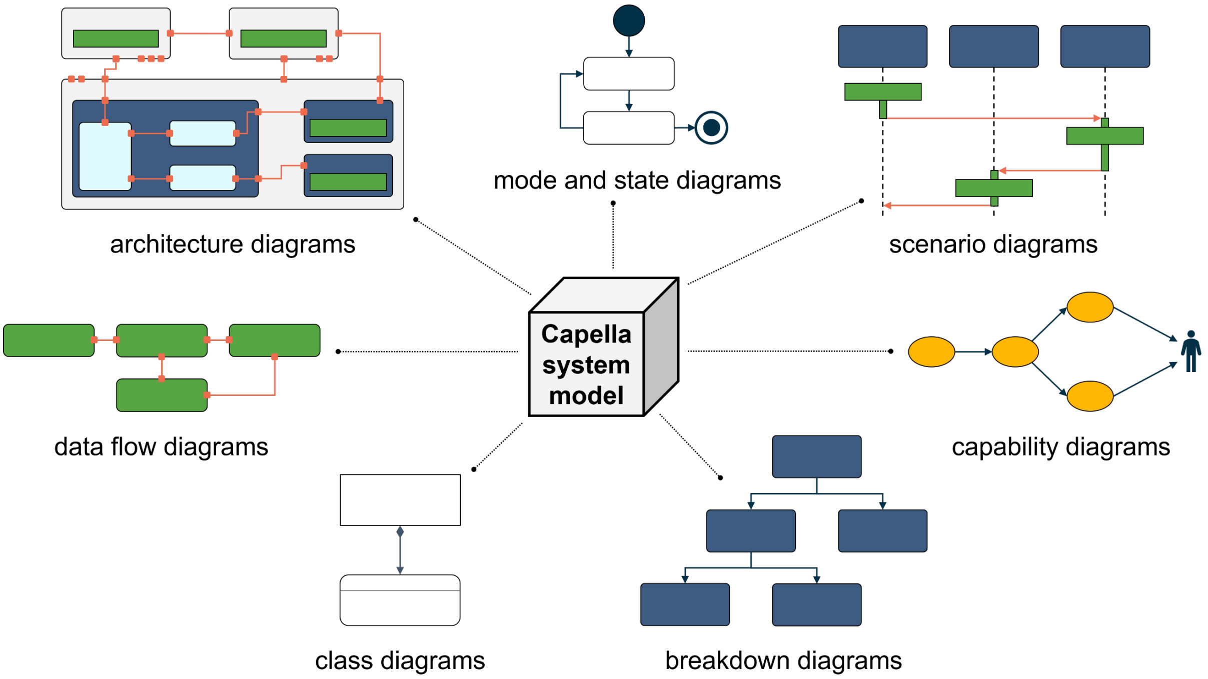

Figure 2-14: Main types of Arcadia diagrams

The seven main diagram types are further divided into three categories: the *breakdown* (xxBD), the *blank* (xxB), and the *scenario* (xxS) categories. The *breakdown* category diagrams (e.g., function or component breakdown diagrams) are automatically updated by default to always be complete. The *blank* category diagrams (e.g., architecture or data flow diagrams) do not update automatically and need to be populated manually, either by creating new model

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[160] ISO/IEC/IEEE 15288:2023(E). (2023).
[161] Eclipse Foundation. (2024b).
[162] Ibid.
[163] Roques (2018)., p. 15 ff.

elements or by inserting existing ones. This diagram category is the most common in a Capella system model and is created specifically for a particular purpose or reader, therefore it does not need to be complete. The *scenario* category diagrams (e.g., functional or exchange scenario diagrams) use references to other model elements such as components and are a special type of diagram. In general, changes to a model element that exists on multiple diagrams are automatically synchronized.[164]

The Arcadia *artifacts* that are used in all diagrams are described by the Arcadia modeling language and specified in its metamodel. Figure A-1 in the Appendix shows the simplified metamodel and many of its artifacts including their traceability (or justification) links. In general, the traces between these artifacts (in the same Arcadia phase or between phases) can be created manually (if authorized) or are sometimes created automatically in the case of using the transition activities (see Table 2-1), which connect model elements/artifacts of the same type and transfer them to the next phase.[165] The usage of these artifacts, such as functions, components, or capabilities, will be explained by showing them in two exemplary Arcadia diagrams, the *missions capabilities blank* (MCB) diagram and the *physical architecture blank* (PAB) diagram.

System missions (M) and *system capabilities* (C) are artifacts of the *system analysis* (SA) Arcadia phase that describe the mission (i.e., high-level goal) and required capabilities (i.e., ability to provide a service) of the system at a high level, addressing the challenges and needs of the stakeholders that have been identified in the previous *operational analysis* Arcadia phase. A system mission can be broken down into submissions, while a system capability can also reference other system capabilities. Functional chains, functional scenarios, or data flow diagrams such as a *system data flow blank* (SDFB) diagram can be used to further describe a system capability by performing a *functional analysis*. This is done by defining *system functions* (SF) and their *hierarchy* (i.e., overall function, subfunctions etc., see Figure 2-5) and by modeling their *interfaces* (i.e., input/output ports) and *functional exchanges*. *System actors* (SA) are human or non-human and may be involved with one or more system capabilities. Figure 2-15 shows the missions capabilities blank diagram that contains these Arcadia artifacts.[166, 167]

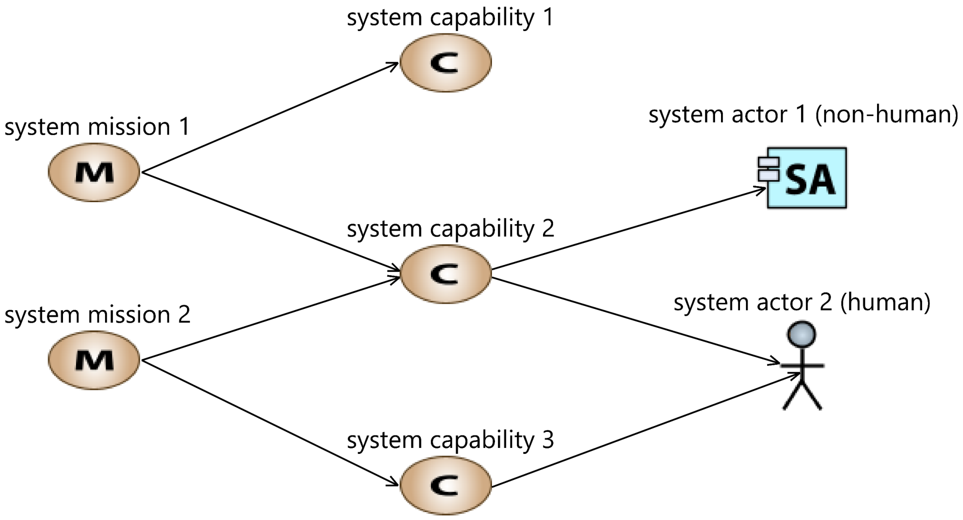

Figure 2-15: Missions capabilities blank diagram example

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[164] Roques (2018)., p. 37 ff.

[165] Voirin (2017)., p. 349

[166] Ibid., p. 296

[167] Roques (2018)., p. 88 ff.

As shortly mentioned in the beginning of chapter 2.3.1, Arcadia is based on a *functional analysis* and a subsequent allocation of *functions* to architecture *components*. Arcadia uses a unique kind of diagram to visualize this allocation: the *architecture diagrams* (refer to chapter 2.1.3 for an extensive discussion of *system architectures*). These diagrams appear in all four main Arcadia phases (OA until PA) and are a powerful way to show the system's structure and behavior in one single view, which allows to gain a quick understanding of the system.[168] Figure 2-16 shows a *physical architecture blank* diagram which is used to explain the main concepts and artifacts of architecture diagrams.

Physical behavior components (P or PBC), *physical node components* (P or PNC), *physical actors* (PA; i.e., entities in the system context), *physical functions* (PF), *physical links*, *component exchanges*, *functional exchanges*, *physical ports*, *component ports*, *function ports*, and *functional chains* (i.e., highlighted function paths) are artifacts that appear in the *physical architecture* (PA) Arcadia phase; some of them also appear in similar form in earlier phases. The PA phase describes the system from a physical point of view, focusing on the physical realization of the system. The structure is comprised of the two types of physical components. While *physical behavior components* contain the physical functions and are therefore part of the behavior of the system, *physical node components* provide the resources that are necessary for one or more behavior components. The physical behavior components can be used to organize additional subsystems based on their specific functional groups. Physical components, actors, and functions are linked through three types of exchanges over three types of ports, as shown in Figure 2-16. Physical links connect physical node components over physical ports, component exchanges connect physical behavior components over component ports, and functional exchanges connect physical functions over function ports. The ports are either input, output, or input/output ports.[169, 170] Examples explaining the concept and correct usage of these artifacts are provided in chapter 4 when applying the Arcadia method on the maritime industry by creating Capella system models of a solar boat and a bulk carrier.

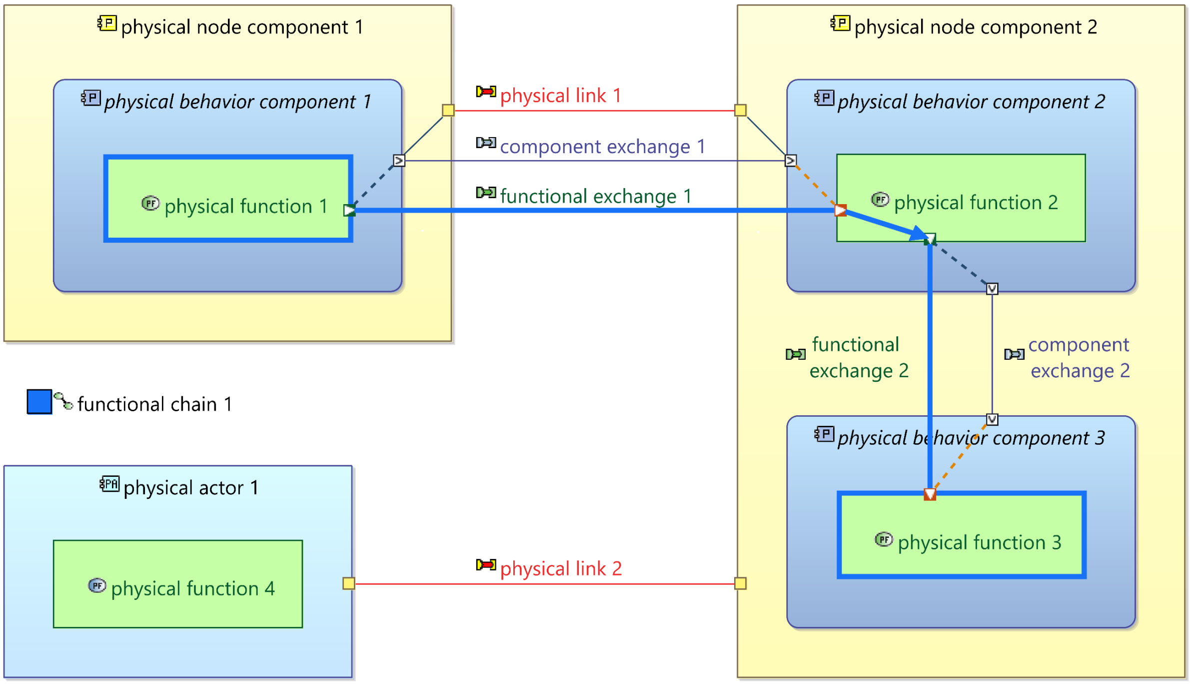

Figure 2-16: Physical architecture blank diagram example

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[168] Roques (2018)., p. 16
[169] Voirin (2017)., p. 131
[170] Roques (2018)., p. 12 ff.

2.3.2 Capella Modeling Tool

The Capella modeling tool (officially *Eclipse Capella*) is an open-source MBSE modeling tool designed for system and architecture engineering. As stated in the beginning of chapter 2.3 when summarizing the development of the Arcadia language and method at Thales, the Capella tool has been developed together with both the language and the method. The close link with the language and the method is one of the most significant aspects of the Capella tool. This integration of a method directly into the tool is unique among other – mostly SysML supporting – tools.[171, 172] The tool can be downloaded directly from the Capella website and can furthermore be extended with a variety of free add-ons and plugins, such as *property values management tools* or *python4capella*.[173]

The integration of the Arcadia method in Capella is realized with an embedded user guide – called the activity explorer – that lists the main activities of the method (see Table 2-1) together with the available diagrams (see Figure 2-14 for the main Arcadia diagram types) grouped at each Arcadia phase. The creation of new diagrams as well as the automated transitions of model elements between the phases (see Table 2-1) is done in the activity explorer. The traceability of all Capella model artifacts (i.e., model elements) is displayed in the semantic browser view of the tool, showing detailed information of all traces or the diagram containment of a specific model element.[174]

In conclusion, several reasons have led to the selection of this combination of modeling language, method, and tool for this master's thesis project. First, the *simplified Arcadia modeling language* (compared to SysML) including the unique *architecture diagram type* has been the most important factor. Furthermore, the *open-source tool Capella* is simple to install, extendable with *free add-ons* and *plug-ins*, and generally effective to work with. The modeling of the various diagrams, based on the Arcadia language, is guided by the *integrated Arcadia method* and is therefore fast and intuitive, enabling a real "*modeling experience*". This means for example that changes to the architecture, such as moving a port from one component to another, can be implemented quickly. In addition, the resulting diagrams are visually appealing. As mentioned at the beginning of chapter 2.3, SysML has inherited too many aspects of UML, which makes it *unnecessarily complicated*; in particular, the class/instance principle is not needed when modeling a hardware system such as a bulk carrier ship. In addition, there is no free tool that supports SysML and works as well as Capella. Finally, the OPM modeling language has not been an alternative either, as its only artifacts are objects and processes, making it too simple for system architecture modeling.

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[171] Voirin (2017)., p. 357 ff.

[172] Roques (2018)., p. 24 ff.

[173] Eclipse Foundation. (2024c). *MBSE Capella.*

[174] Roques (2018)., p. 24 ff.

3 The Maritime Industry

The maritime industry serves as the operational context for the practical part of this master's thesis. As previously discussed in chapter 1, the challenging geopolitical and economic situation of this industry, particularly within its transportation sector, underscores the importance of sustainability, resilience, decarbonization, and digitalization. Understanding this operational context is essential to appreciate the necessity and value of introducing MBSE to this industry through the creation of a descriptive system model of a bulk carrier ship equipped with a wind-assisted device (WAD) and its integration into the ship development process. The following chapter 3 provides an overview of selected parts of the maritime industry, complementing the detailed examination of SE fundamentals in chapter 2. Together, these chapters form the theoretical background and context for the subsequent practical part in chapters 4 and 5 of this master's thesis.

3.1 Stakeholders of the Maritime Industry

Stakeholders in general are an integral part of the systems engineering methodology and have therefore been introduced in chapter 2.1.4 together with a formal definition provided by the ISO/IEC/IEEE 15288 standard.[175] A *stakeholder analysis* of the context of this master's thesis – the maritime industry – is a suitable starting point for further investigations.

From an *economic* perspective, *Stopford* suggests *high-level segments* for the grouping of stakeholders in the maritime industry. These include the segments of *vessel operations* (merchant/naval shipping, the cruise industry, ports), *shipbuilding* (construction/maintenance/repair of merchant/naval ships, marine equipment manufacturing), *marine resources* (offshore oil/gas, renewable energy, other resources), *marine fisheries* (commercial fishing, aquaculture, cultivation of seaweed, seafood processing), and *other marine related activities* (maritime tourism, marine services, research and development, others). Additionally, the maritime industry's *regulatory body* consists of stakeholders such as the *International Maritime Organization* (IMO), *classification societies*, or the *governments* of the maritime states.[176] These stakeholders have already been mentioned in the introductory chapter 1 of this master's thesis to set up the context. It is apparent that the maritime industry altogether is a vast network of stakeholders. Each of the above segments and their sub-segments or regulatory bodies can be further broken down and form a complex network on their own. Therefore, the scope of this stakeholder analysis is limited to the industry's *transportation sector* (i.e., marine shipping) and its directly related entities.

Hiekata et al. provide a *stakeholder value network* (SVN) of the maritime industry's transportation sector, which is shown in Figure 3-1. The SVN is based on interviews with stakeholders that are themselves part of the SVN, including shipping companies, shipbuilding companies, or classification societies. Stakeholders are represented by the gray rectangles, and their relationships are modeled using four types of *value flows*: *policy/regulation/rule* (blue arrows), *knowledge/information* (orange arrows), *money* (green arrows), and *goods/services* (black arrows).[177]

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[175] ISO/IEC/IEEE 15288:2023(E). (2023)., p. 7

[176] Stopford. (2009)., p. 49, p. 656 f.

[177] Hiekata, K., Wanaka, S., Mitsuyuki, T., Ueno, R., Wada, R., & Moser, B. (2020). *Systems analysis for deployment of internet of things (IoT)*. In: Journal of Marine Science and Technology - Volume 26, Pages 459-469. (June 2021): Japan Society of Naval Architects and Ocean Engineers (JASNAOE)., p. 2

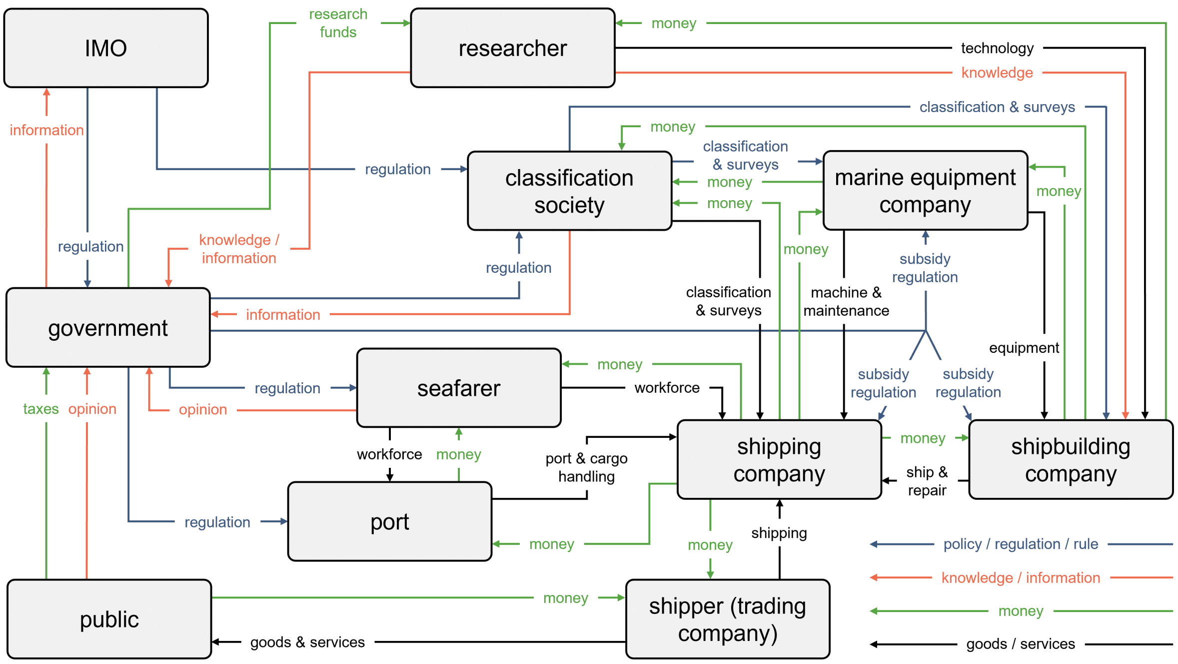

Figure 3-1: Stakeholder value network of the maritime industry's transportation sector, inspired by *Hiekata et al.*[178]

In terms of the economic perspective as provided by *Stopford*, the stakeholders of the SVN in Figure 3-1 are part of all the high-level segments (except marine fisheries) and the regulatory body of the maritime industry. This indicates that the stakeholders of its transportation sector represent a significant share of the entire maritime industry.

The maritime stakeholders introduced by *Stopford* and by *Hiekata et al.* are the starting point for the *operational analysis* Arcadia phase in chapter 4.3.1. Many of these identified stakeholders and their relationships are modeled in the *operational capabilities blank* (OCB) diagram, see Figure 4-4.

3.2 Classic Ship Design

Designing a ship that meets all operational and regulatory requirements is a complex endeavor involving numerous stakeholders and subject to a variety of influencing factors. As outlined in chapter 1, the maritime industry is undergoing a major transformation to introduce GHG reduction technologies such as *wind-assisted ship propulsion* (WASP) or alternative fuels into existing vessels and to develop future carbon-neutral and automated ships (refer to the objectives of the *International Maritime Organization*, *Japan*, or the *MODE lab* in chapter 1). However, the classic ship development process has remained relatively unchanged for a long period of time. It is therefore necessary to discuss the as-is situation of ship design when trying to integrate new approaches such as MBSE into a development process that has yet to catch up with modern methodologies (see MBSE adoption trends in Figure 1-2).

A historical review of ship design shows a change from *traditional craftsmanship* to *systematic engineering methods* that happened particularly in the eighteenth and nineteenth centuries. This period marked a shift toward scientific considerations of ship stability and hydrodynamics, allowing for the development of more efficient and innovative ship designs that

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[178] Hiekata et al. (2020)., p. 2

no longer relied only on handed-down traditions. Advances in materials, particularly the transition from wrought iron to steel, facilitated the construction of larger and more complex ships to meet evolving energy storage needs and operational requirements, such as the shift to steam propulsion. Additionally, the nineteenth century witnessed the specialization of ship types – passenger, naval, and cargo – each with distinct design features and purposes. This period also led to the formalization of ship design processes with the introduction of the design spiral, originally proposed by *Evans*[179] in 1959, which continues to guide modern ship design practices by iteratively addressing all relevant design aspects from concept to production, now heavily reliant on IT-based systems such as CAD and CAE.[180]

Classic ship design process: A definition for the classic ship design process is provided by the *Ni* and *Zeng* in the *Encyclopedia of Ocean Engineering*:

> *"The ship design process is an iterative process that needs to meet various technoeconomic requirements, which are partly contradictory to each other. According to the mission characteristics and the completion, the design process can usually be divided into four steps: concept design, preliminary design, contract design, and detail design, where the first two steps can also be named as basic design."* [181]

This definition is based on the *ship design spiral* and its design phases proposed by *Evans*, which is shown in Figure 3-2.

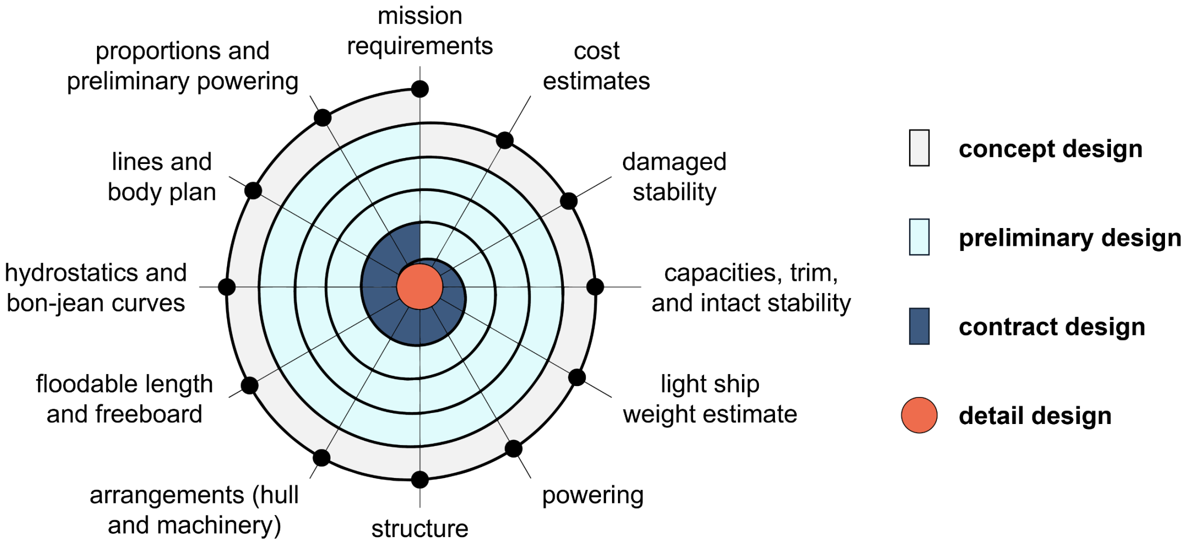

Figure 3-2: Classic ship design spiral, inspired by *Evans*[182]

The ship design spiral is a *sequential process* that reflects a series of *iterative* steps, with each iteration refining and updating the ship structure based on calculations and evolving requirements. The starting point is often a set of *requirements* that defines the *capabilities* a ship must fulfill, for example to carry 50 000 deadweight tonnage (DWT) of bulk cargo at a

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[179] Evans, H. J. (1959). *Basic Design Concepts*. In: Journal of the American Society for Naval Engineers (ASNE) - Volume 71, Issue 4, Pages 671-678. (November 1959).

[180] Marzi, J. (2019). *Introduction to the HOLISHIP Project*. In: Apostolos Papanikolaou (Eds.). A Holistic Approach to Ship Design - Volume 1: Optimisation of Ship Design and Operation for Life Cycle. First edition (2019): Springer Cham., p. 3

[181] Ni, B., & Zeng, L. (2022). *Ship Design Process*. In: Weicheng Cui, Shixiao Fu, Zhiqiang Hu (Eds.). Encyclopedia of Ocean Engineering. First edition (2022). Singapore: Springer., p. 1588

[182] Evans. (1959).

speed of 16 knots in average sea conditions. Based on these requirements, a *type ship* (i.e., an existing ship that performs most of the functions of the new ship) is used in the early stages of the process so that early solutions remain within design constraints. As the design progresses, it converges towards a final optimal solution, refining each baseline with new design considerations. The iterative nature of this process allows for the incorporation of changing requirements and design choices. Changes made to one aspect of the ship's design, such as fuel tank size, can have cascading effects on other subsystems or safety criteria such as stability, weight distribution, and structural integrity. This interconnectedness underscores the complexity of ship design, where various design variables are interdependent and require continuous refinement throughout the iterative process.[183, 184, 185]

However, *Nowacki* underscores the incompleteness and inflexibility of the traditional ship design spiral in his unambiguous note *A Farewell to the Design Spiral*, and calls for its replacement by a *"[…] systems analysis based, concurrent engineering, team work oriented paradigm."*[186]

Concurrent engineering in ship design: A more recent iteration of the classic ship design process model employs a *concurrent engineering* (CE) approach, rather than the traditional sequential process, via multi-objective optimization techniques.[187] CE in the ship design process aims to base design decisions at all levels on immediate or near real-time feedback from all stakeholders, such as ship designers, shipbuilders, maintainers, operators, or the shipowner, who are involved in the design, production, marketing, maintenance, and operation of the final product.[188] New approaches to ship design, such as the *HOLISHIP*[189] project, enable parametric, multi-objective and multi-disciplinary optimization through digital phases and coupled simulations. This is achieved by using advanced parametric modeling tools and integrated software platforms. The HOLISHIP approach follows the traditional ship design spiral, but uses a systematic, parallel processing method for improved efficiency and integration.[190, 191]

3.3 Decarbonization of International Shipping

The urgent need to decarbonize the maritime industry and in particular its transportation sector has been outlined in detail in chapter 1, representing the context and starting point of the theoretical investigations and practical applications in this master's thesis. This major transformation of an industry that relies heavily on fossil fuels such as diesel, LNG, or even heavy fuel oil as a source of energy is a challenging task. The implementation of stricter environmental regulations, the adoption of new technologies, and the development of more

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[183] Ma, X., & Ping, W. (2022). *Design Spiral.* In: Weicheng Cui, Shixiao Fu, Zhiqiang Hu (Eds.). Encyclopedia of Ocean Engineering. First edition (2022). Singapore: Springer., p. 350 ff.

[184] Gale, P. A. (2003). *The Ship Design Process.* In: Thomas Lamb (Eds.). Ship Design and Construction - Volumes 1 and 2. First edition (2003): The Society of Naval Architects and Marine Engineers (SNAME)., p. 5-1 ff.

[185] Tupper, E. C. (2004). *Introduction to Naval Architecture*. Fourth edition. Oxford. UK: Butterworth-Heinemann., p. 8, p. 11

[186] Nowacki, H. (2016). *A Farewell to the Design Spiral.* At: Mini-Symposium on Ship Design, Ship Hydrodynamics & Maritime Safety. Athens. (September 2016)., p. 4

[187] Papanikolaou, A. (2010). *Holistic ship design optimization.* In: Computer-Aided Design - Volume 42, Issue 11, Pages 1028-1044. (November 2010)., p. 1 ff.

[188] Gale. (2003)., p. 5-32 f.

[189] HOLISHIP. (2024).

[190] Papanikolaou, A. (2019). *A Holistic Approach to Ship Design - Volume 1: Optimisation of Ship Design and Operation for Life Cycle.* First edition: Springer Cham., p. vi

[191] Flikkema, M., van Hees, M., Verwoest, T., & Bons, A. (2019). *HOLISPEC/RCE: Virtual Vessel Simulations*. In: Apostolos Papanikolaou (Eds.). A Holistic Approach to Ship Design - Volume 1: Optimisation of Ship Design and Operation for Life Cycle. First edition (2019): Springer Cham., p. 465 f.

efficient and CO_2 neutral ships must happen quickly to address the impending climate crisis. A path to net-zero GHG emissions by 2050 and the GHG reduction technologies that can make it happen are discussed in the following.

3.3.1 Net-zero GHG Emissions in Shipping by 2050

The *Initial IMO Strategy on Reduction of GHG Emissions from Ships* from 2018 was revised in 2023 to better address the changes needed to reduce GHG emissions from international shipping, with the goal of achieving net-zero GHG emissions by around 2050. In the *short term*, a key component of the strategy is the emphasis on immediate action by strengthening energy efficiency requirements for ships, adopting technical and operational measures to reduce carbon intensity, and implementing the *Energy Efficiency Existing Ship Index* (EEXI), the *Energy Efficiency Design Index* (EEDI), and *Carbon Intensity Indicator* (CII) regulations. These measures are designed to ensure that existing ships are retrofitted or operated in a more energy efficient manner. In the *medium term*, the strategy focuses on the development and deployment of low- and zero-carbon fuels. This means supporting research and development of alternative fuels, such as hydrogen and ammonia, and promoting their use through incentives and regulations. The strategy also includes building the necessary infrastructure for these fuels at ports around the world. In the *long term*, strengthening regulatory frameworks, continued technological innovation, and fostering global collaboration among stakeholders shall enable the target of net-zero GHG emissions by 2050. The 2023 IMO strategy is in line with the long-term temperature goal set out in Article 2.1 (a) of the *Paris Agreement* (see chapter 1), and is expected to be reviewed every five years, with the first review due in 2028.[192, 193] The indicative checkpoints of the strategy are summarized below:

- 2030: *“to reduce the total annual GHG emissions from international shipping by at least 20%, striving for 30% […] compared to 2008 […]”*
- 2040: “*to reduce the total annual GHG emissions from international shipping by at least 70%, striving for 80% […] compared to 2008 […]”*
- 2050: *“to reach net-zero GHG emissions […]”* [194]

Various regional measures complement the IMO's strategy to reduce GHG emissions in shipping. For example, the European Union's amended *Regulation 2015/757* integrates shipping emissions into the EU *Emissions Trading System* (ETS), and the *FuelEU Maritime Initiative* mandates lifecycle emissions reductions and onshore electricity use for certain ships from 2030.[195] Japan, as one of the three largest shipbuilding nations (along with China and South Korea), has taken the lead in reducing GHG emissions from international shipping by establishing the *Shipping Zero Emission Project* in 2018 and announcing its goal of net-zero GHG emissions in shipping by 2050 as early as in October 2021, both times exceeding the targets set by the IMO at the time.[196, 197] Industry-led voluntary initiatives, such as the *Poseidon Principles* and the *Sea Cargo Charter*, also promote decarbonization by aligning ship finance and chartering activities with climate objectives.[198]

Comer and *Carvalho* from the *International Council on Clean Transportation* (ICCT) have

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[192] IMO. (2023)., p. 5 ff.

[193] UNFCCC. (2015)., p. 22

[194] IMO. (2023)., p. 6

[195] European Commission. (2024). *Reducing emissions from the shipping sector.*

[196] JSA. (2021)., p.1 f.

[197] JSA. (2022a)., p. 2

[198] United Nations Conference on Trade and Development (UNCTAD). (2023). *Review of Maritime Transport 2023: Towards a green and just transition.* USA: United Nations Publications., p. 64 f.

reviewed the 2023 IMO strategy and concluded that the updated strategy is a significant improvement over the initial 2018 strategy, which only targeted a 50% reduction by 2050 and was not compatible with the *Paris Agreement*. Despite this progress, the new strategy will still exceed the 1.5°C carbon budget by around 2032, but stays within the 2°C budget. Figure 3-3 illustrates the *well-to-wake* (WTW) CO_2e emissions pathways under both the revised 2023 and initial 2018 strategies, alongside 2008 emissions and *business-as-usual* (BAU) projections, highlighting the trajectory towards zero emissions by 2050 under the new targets. While the strategy is not legally binding, its implementation through measures such as the *EEXI*, *EEDI*, and the *CII* (refer to the beginning of chapter 3.3.1), which are incorporated into international treaties, holds the potential for significant emissions reductions if further strengthened.[199]

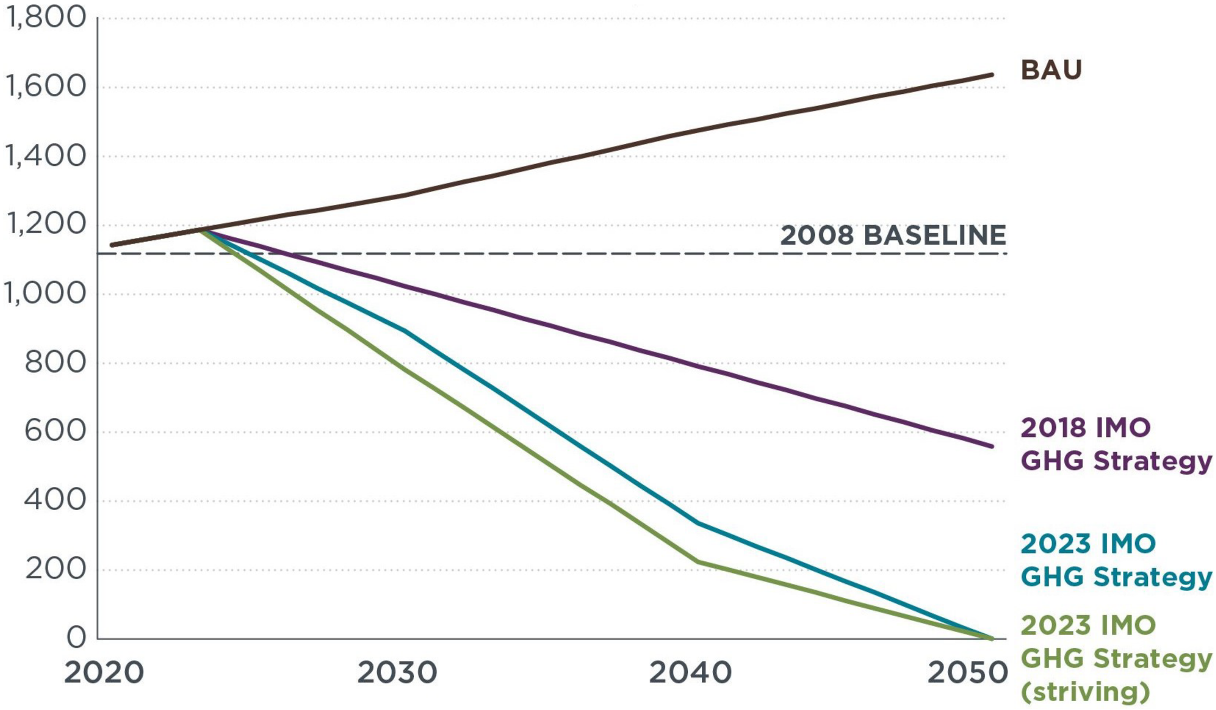

Figure 3-3: Well-to-wake CO_2e (Mt) reductions from international shipping, according to *Comer* and *Carvalho* [200]

Considering the entire global transport sector, *ICCT* has already analyzed how to decarbonize this sector in its *Vision 2050* study published in 2021. The share of well-to-wheel CO_2e emissions from the transportation sector in 2020 (see Figure 1-1) has been presented in chapter 1 and shows that marine shipping accounts for ~11% of global transportation CO_2e emissions in 2020. ICCT confronts two scenarios in Figure 3-4: A *baseline scenario*, which accounts for the policies adopted in 2019, and an *ambitious-yet-feasible scenario*, which includes the necessary adoption of future policies. Considering lifecycle emissions and non-CO_2 GHG emissions, the trajectory for the baseline scenario (i.e., without further mitigation action) indicates a potential 80% increase in GHG emissions from the transportation sector by 2050. However, the ambitious-yet-feasible scenario could lead to sectoral GHG emissions of ~4 Gt in 2050, an 8 Gt reduction from the 2020 baseline. This scenario achieves 85% of the required reduction target, leaving a gap of ~1.4 Gt. Closing this gap will require additional policy measures such as regulatory incentives, carbon pricing and infrastructure investments.[201]

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[199] Comer, B., & Carvalho, F. (2023). *IMO's Newly Revised GHG Strategy: What It Means for Shipping and the Paris Agreement*. At: International Council on Clean Transportation (ICCT). (July 2023).

[200] Comer and Carvalho. (2023).

[201] ICCT. (2021)., p. 16 ff.

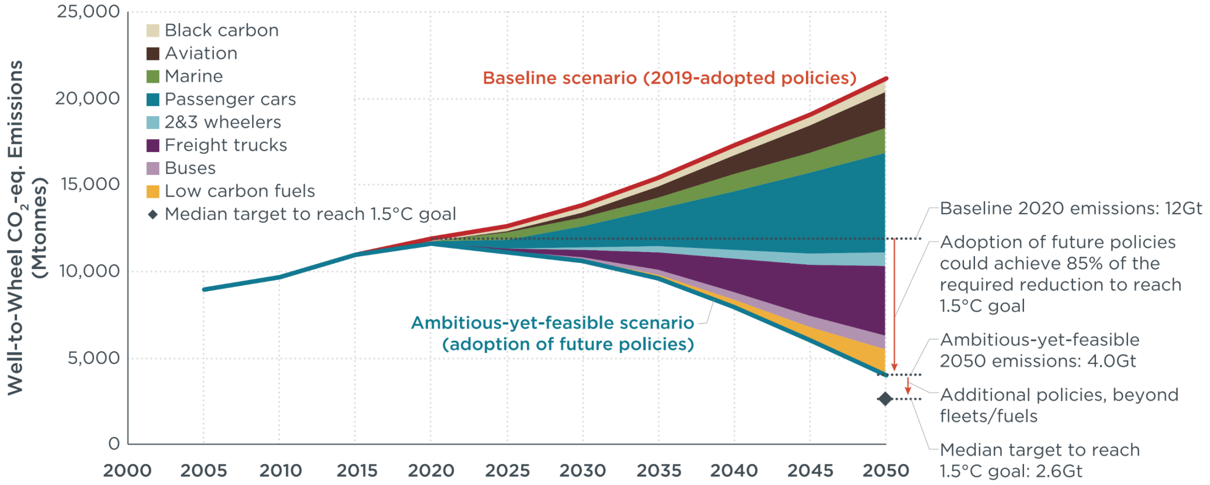

Figure 3-4: Global well-to-wheel CO_2e (Mt) reductions from transportation segments, according to *ICCT* [202]

Although initiatives and regulations have been tightened compared to 2021 (e.g., the 2023 IMO strategy), the study still provides a comprehensive overview and emphasizes the need for a holistic approach and a global effort to achieve decarbonization.

However, in its most recent assessment, the *International Energy Agency* (IEA) has concluded that international shipping is not on track to achieve the net-zero emissions target by 2050. To reach this goal, a reduction of approximately 15% in emissions from 2022 to 2030 is required. The transition to low- and zero-emission alternative fuels and GHG emissions reduction technologies for ocean-going vessels will require technological innovation, supportive policies, and collaboration across the value chain.[203]

3.3.2 Zero-emission Vessel (ZEV)

The shipping industry's transition to *zero-emission vessels* (ZEVs) is in its early stages, and major progress is needed to achieve significant reductions in GHG emissions. While advances in *logistics*, *digitalization*, *hydrodynamics*, *machinery*, and *carbon capture technologies* can reduce GHG emissions by up to 30%, the most effective approach is to switch to *low- and zero-emission alternative fuels*. There is currently no universal solution for this transition. By 2030, zero or near-zero GHG emission technologies, fuels and/or energy sources must represent at least 5% (ideally 10%) of the international shipping fuel mix, according to the IMO 2023 GHG Strategy. Currently, 98.8% of the world's fleet relies on conventional fossil fuels such as diesel or heavy fuel oil (HFO), with only 1.2% using alternatives such as liquefied natural gas (LNG), battery/hybrid systems, liquefied petroleum gas (LPG) and methanol.[204]

Llyod's Register (LR), a leading classification society, identifies *seven technology groups* in its *Zero-Emission Vessels 2030* study based on their capability to feasibly replace the propulsion and operational requirements of a conventional ship. The technology groups and their components that are expected to make ZEVs a reality by 2030 are listed in Table 3-1:

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[202] ICCT. (2021)., p. 17

[203] International Energy Agency (IEA). (2023). *Tracking Clean Energy Progress 2023.* Paris: IEA.

[204] UNCTAD. (2023)., p. 68

Table 3-1: ZEV technology groups and components, according to *Llyod's Register* [205]

Technology Groups	Components	
Electric	▪ Batteries	▪ Electric motor
Hybrid hydrogen	▪ Hydrogen storage ▪ Batteries	▪ Fuel cell ▪ Electric motor
Hydrogen fuel cell	▪ Hydrogen storage ▪ Fuel cell	▪ Electric motor
Hydrogen + ICE	▪ Hydrogen storage ▪ "Emergency" HFO tank	▪ Dual-fuel internal combustion engine
Ammonia fuel cell	▪ Ammonia storage ▪ Reformer	▪ Fuel cell ▪ Electric motor
Ammonia + ICE	▪ Ammonia storage ▪ "Emergency" HFO tank	▪ Dual-fuel internal combustion engine
Biofuel	▪ Biofuel tank	▪ Internal combustion engine

The study concludes that *biofuel*, when considered net-zero over lifetime, stands out as the top zero-emission option in terms of profitability. *Ammonia* and *hydrogen*, used as synthetic fuels in internal combustion engines, are the next most lucrative choices. *Hybrid* and *electric* alternatives, which necessitate significant battery investments and substantial initial costs, are the least economically viable. Other options, such as *nuclear propulsion*, *wind-assisted ship propulsion* (WASP), and other *energy-saving technologies* or *operational measures* (e.g., optimized routing/navigation, slow steaming), are not considered because they have been determined to be unsuitable as the primary power source for a ZEV. However, while biofuels may be the best option from an economic perspective, they also face challenges such as ensuring sustainable production without interfering with food supplies, and the potential for limited availability and rising costs.[206] An up-to-date overview of alternative fuels and the status of their adoption can be found in the *2023 Review of Maritime Transport*.[207]

Since there is currently no single solution for reducing GHG emissions from ships, a holistic approach that includes all options is needed, as pointed out by *ICCT* in a technical workshop on zero-emission vessel technology. This workshop concluded that a mix of technologies and measures will be needed, such as advances in fuel cells, fuel storage, fuel supply, batteries, energy storage, wind-assisted ship propulsion, solar power, and energy-saving technologies, as well as comprehensive research and development, demonstration projects, and retrofitting of existing ships.[208] A comprehensive overview of the energy transition in the maritime industry, including GHG reduction technologies and measures for ZEVs, is available in the latest edition of the *Energy Transition Outlook 2023 - Maritime Forecast to 2050*, published by the classification society *Det Norske Veritas* (DNV).[209]

The fields of technologies and measures to achieve the goal of net-zero GHG emissions in international shipping until 2050 can be summarized in three categories, which are

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[205] Lloyd's Register (LR). (2017). *Zero-Emission Vessels 2030. How do we get there?*. UK: Lloyd's Register / UMAS., p. 10

[206] LR. (2017)., p. 13

[207] UNCTAD. (2023)., p. 68 ff.

[208] International Council on Clean Transportation (ICCT). (2019). *ICCT Technical Workshop on Zero Emission Vessel Technology*. San Francisco. California. USA: ICCT., p. 12 f.

[209] Det Norske Veritas (DNV). (2023). *Energy Transition Outlook 2023 - Maritime Forecast to 2050.* Norway: DNV.

visualized in Figure 3-5:

- *Low- and zero-emission alternative fuels and propulsion technologies* (blue)
- *Energy-saving technologies* (orange)
- *Operational measures* (yellow) [210, 211]

A different categorization of technologies and fuels is possible, such as grouping them into *alternative fuel propulsion*, *non-fuel propulsion*, and *energy efficiency options*.[212] However, the three categories chosen above are considered appropriate for distinguishing the most important technologies and measures from a holistic perspective.

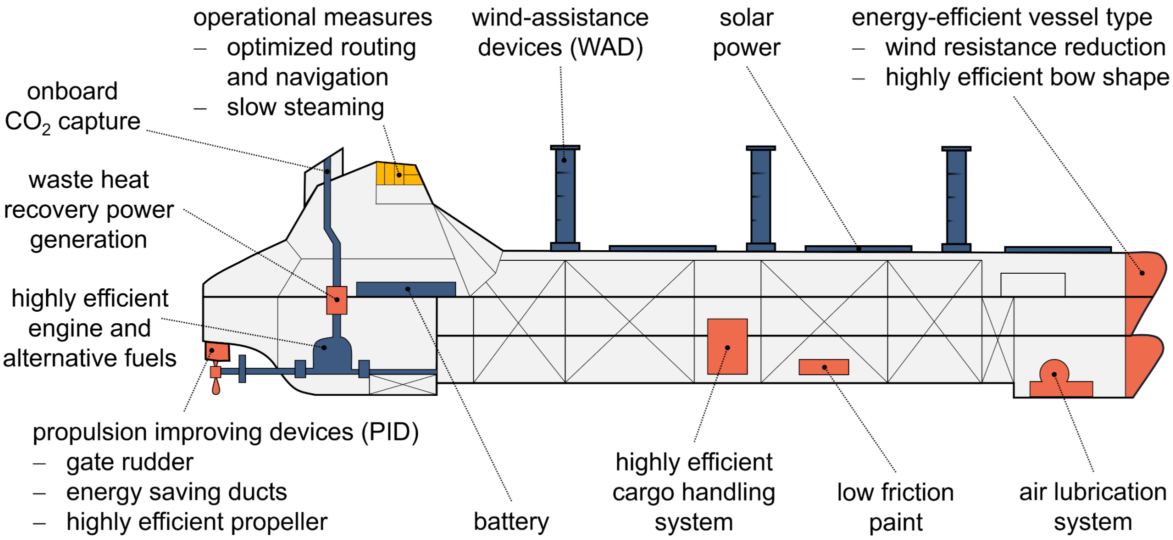

Figure 3-5: Technologies and measures for ZEVs, inspired by *JSA*[213]

Figure 3-5 shows a zero-emission vessel that incorporates a selection of options from the three categories identified above. The GHG emissions reduction technologies shown this figure are particularly important for *short-term* measures as proposed by the IMO (refer to the beginning of chapter 3.3.1). The selection of options is mostly inspired by the *Shipping Zero Emission Project* of the *Japanese Shipowner's Association* (JSA). The technologies listed in this figure provide an overview of options for reducing GHG emissions from ships, and are not an example of a specific type of ZEV, as multiple combinations of these technologies are possible and strongly depend on the economic and operational requirements of the ship type.

3.3.3 Wind-assisted Ship Propulsion (WASP)

Wind-assisted ship propulsion (WASP) technologies are increasingly recognized for their potential to reduce fuel consumption and emissions in the maritime industry. By harnessing wind power to generate aerodynamic forces that assist ship propulsion, WASP can significantly improve the *efficiency* of shipping operations and support the decarbonization of the industry. As a free and zero-emission energy source, wind provides an inexhaustible alternative to conventional fuels, contributing to significant annual fuel savings of 5% to 9% for certain

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[210] JSA. (2022a)., p. 47 f.

[211] ICCT. (2019)., p. 13

[212] Department for Transport. (2019). *Clean Maritime Plan.* London. UK., p. 17

[213] Japanese Shipowners' Association (JSA). (2022b). *Japanese Shipping Industry: The Challenge of 2050 Net Zero GHG.* JSA., p. 48

vessels, with the potential to reach 25% or more for optimized new vessels. WASP technologies, categorized under the *EEXI/EEDI* energy efficiency indices (see chapter 3.3.1), reduce propulsion power requirements rather than serving as an alternative fuel. Modern WASP uses advanced aerodynamics, control and automation systems, computer modeling and advanced materials to create innovative sail systems that operate without additional crew. Integrating WASP with optimized routing/navigation (i.e., weather routing algorithms) and logistics optimization can further enhance these benefits by generating optimal routes for ships. Although transitioning to *low- and zero-emission alternative fuels* typically involves higher costs and reduced energy storage capacity, combining WASP with *energy-saving technologies* (see Figure 3-5) can provide a feasible solution for ZEVs.[214, 215]

Examples of sailing technology concepts are shown in Figure 3-6, including *rotor sails*, *suction wing sails*, *wind turbines*, *towing kite sails*, *soft sails*, and both *soft* and *rigid wing sails*.

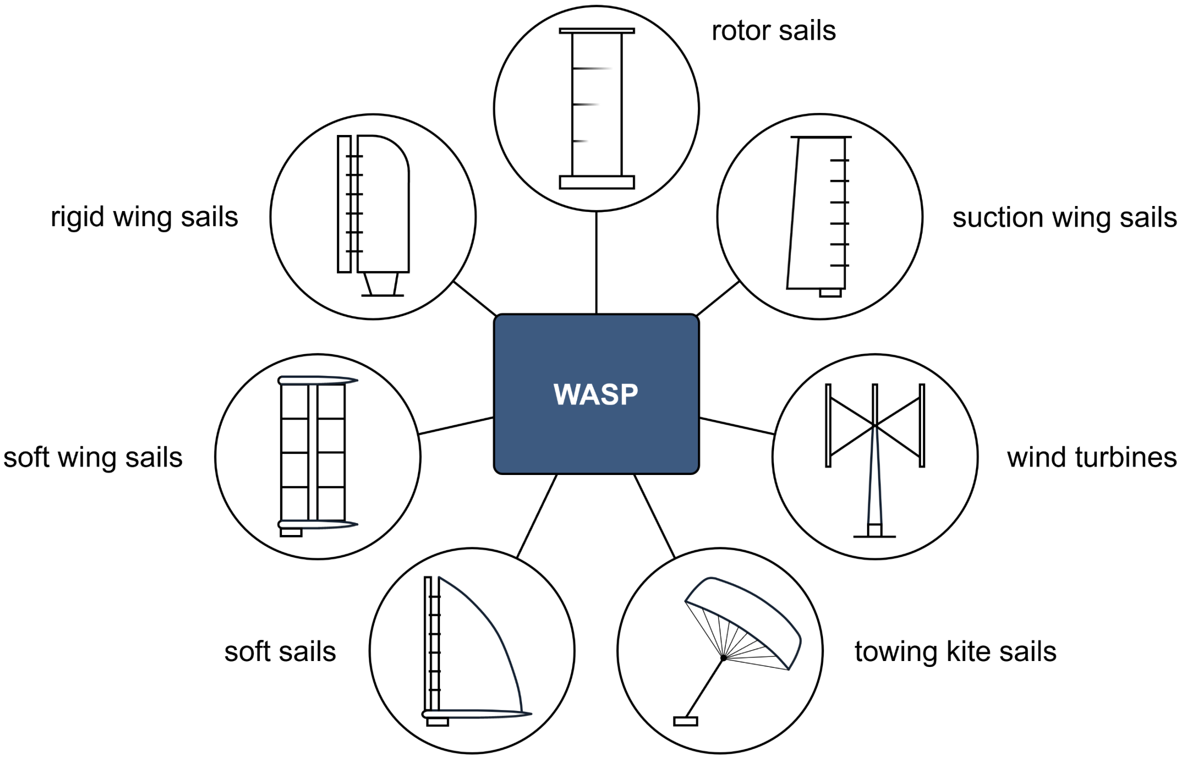

Figure 3-6: Wind-assisted ship propulsion options, inspired by *DNV* [216]

Rotor sails are cylindrical structures with disc end plates that are placed on the deck of a ship. They were developed by Anton Flettner in the 1920s, hence the name Flettner Rotors.[217] The rotor sail is rotated along its longitudinal axis by an electric motor. When air in the form of wind passes over it at right angles, the rotation of the cylinder together with the flowing air creates an air pressure difference on two opposite sides of the cylinder, generating an aerodynamic force (thrust) in the direction perpendicular to both the longitudinal axis and the direction of the air flow (i.e., the *Magnus effect*).[218]

Suction wing sails are non-rotating wing structures with vents and internal fans that use

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[214] Hagen, J. E. (2021). *Sustainable Power, Autonomous Ships, and Cleaner Energy for Shipping.* Norwood. MA. USA: Artech House., p. 95 ff.

[215] DNV. (2023)., p. 31 f.

[216] Ibid., p. 32

[217] Flettner, A. (1926). *Mein Weg zum Rotor.* Koehler & Amelang.

[218] Lu, R., & Ringsberg, J. W. (2020). *Ship energy performance study of three wind-assisted ship propulsion technologies including a parametric study of the Flettner rotor technology.* In: Ships and Offshore Structures - Volume 15, Issue 3, Pages 249-258. (2020)., p. 1 f.

the principle of *boundary layer suction* to produce a high thrust in relation to their small size. The internal fans create suction within the wing, pulling air through the vents to reduce turbulence and drag around the sail, resulting in a smoother and more efficient airflow. The integration of smart suction technology effectively doubles the thrust generated by the suction wing sail and allows for efficient reefing when needed.[219, 220]

Wind turbines convert wind energy into electrical energy, which can be used to power the ship's propulsion systems directly or to support auxiliary systems. Alternatively, the energy is stored in batteries.[221]

Towing kite sails use a large kite that captures wind at higher altitudes, where wind speeds are typically stronger and more consistent, creating lift and pulling the vessel forward.[222]

Soft sails are rooted in centuries of sailing history. They use traditional or modern sail system designs to harness wind power and create lift to propel the vessel.[223]

Soft wing sails differ from traditional soft sails in their fixed or semi-rigid structure, resembling the wings of an airplane rather than flexible fabric. This design provides greater stability and aerodynamic efficiency, creating higher lift forces than soft sails.[224]

Rigid wing sails are solid, non-deformable structures made from lightweight materials such as carbon fiber that provide precise control of aerodynamics and superior performance compared to soft sails and soft wing sails, but with greater complexity and cost.[225]

Further information on WASP technology is provided by the *International Windship Association* (IWSA), a global organization promoting WASP in commercial shipping.[226] The importance of WASP alongside alternative fuels is highlighted by the UK's *Clean Maritime Plan* which forecasts significant growth in the wind propulsion market, from £300 million annually in the 2020s to around £2 billion in the 2050s. However, the widespread adoption of WASP faces challenges, including ensuring the reliability of these technologies in a variety of conditions. Addressing regulatory and non-regulatory barriers will be essential for the successful implementation of WASP, consistent with the IMO’s *Strategy on Reduction of GHG Emissions from Ships* (see chapter 3.3.1) and the UN's *Sustainable Development Goals*.[227, 228]

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[219] Econowind. (2024).

[220] Interreg North Sea Europe. (2024). *WASP: Wind Assisted Ship Propulsion.*

[221] Julià, E., Tillig, F., & Ringsberg, J. W. (2020). ***Concept design and performance evaluation of a fossil-free operated cargo ship with unlimited range.*** In: Sustainability - Volume 12, Issue 3, Pages 1-23. (February 2020)., p. 8 f.

[222] Formosa, W., Sant, T., De Marco Muscat-Fenech, C., & Figari, M. (2023). ***Wind-Assisted Ship Propulsion of a Series 60 Ship Using a Static Kite Sail.*** In: Journal of Marine Science and Engineering - Volume 11, Issue 1, Pages 117. (January 2023)., p. 1 f.

[223] Lu et al. (2020)., p. 2

[224] Ibid., p. 2

[225] Ibid., p. 2

[226] International Windship Association (IWSA). (2024).

[227] Department for Transport. (2019)., p. 17

[228] United Nations General Assembly. (2015)., p. 23

4 Application of Arcadia on the Maritime Industry

The investigations in chapter 3 show that the maritime industry and in particular its transportation section consists of a vast network of stakeholders that need to be aligned to achieve the decarbonization of international shipping until 2050. A variety of *low- and zero-emission alternative fuels and propulsion technologies* (e.g., hydrogen, ammonia, WASP), *energy saving technologies* (e.g., air lubrication systems, PID) or *operational measures* (e.g., optimized routing/navigation, slow steaming) need to be integrated, verified, and validated fast. The real challenge is to implement these technologies and measures while ensuring that the main *mission* of marine transportation is fulfilled: Moving goods, resources, and passengers by sea from one place to another in a timely and cost-effective manner. New approaches such as *systems engineering* (SE), and *model-based systems engineering* (MBSE), which have been explored in detail in chapter 2, are needed to support this challenging task.

4.1 Framework & Methodology

The framework and methodology of the master's thesis, which is used to support the decarbonization and digitalization of the maritime industry through the introduction of MBSE, is shown in Figure 4-1. It follows a *three-step process*, starting with a problem discussion, literature review and the establishment of a theoretical framework in the first step. The application of the Arcadia method and the creation of two Arcadia/Capella system models represent the main part of the process. The final step of the process is to support the digital transformation of the maritime industry by introducing MBSE through the integration of a system model into the ship development process.

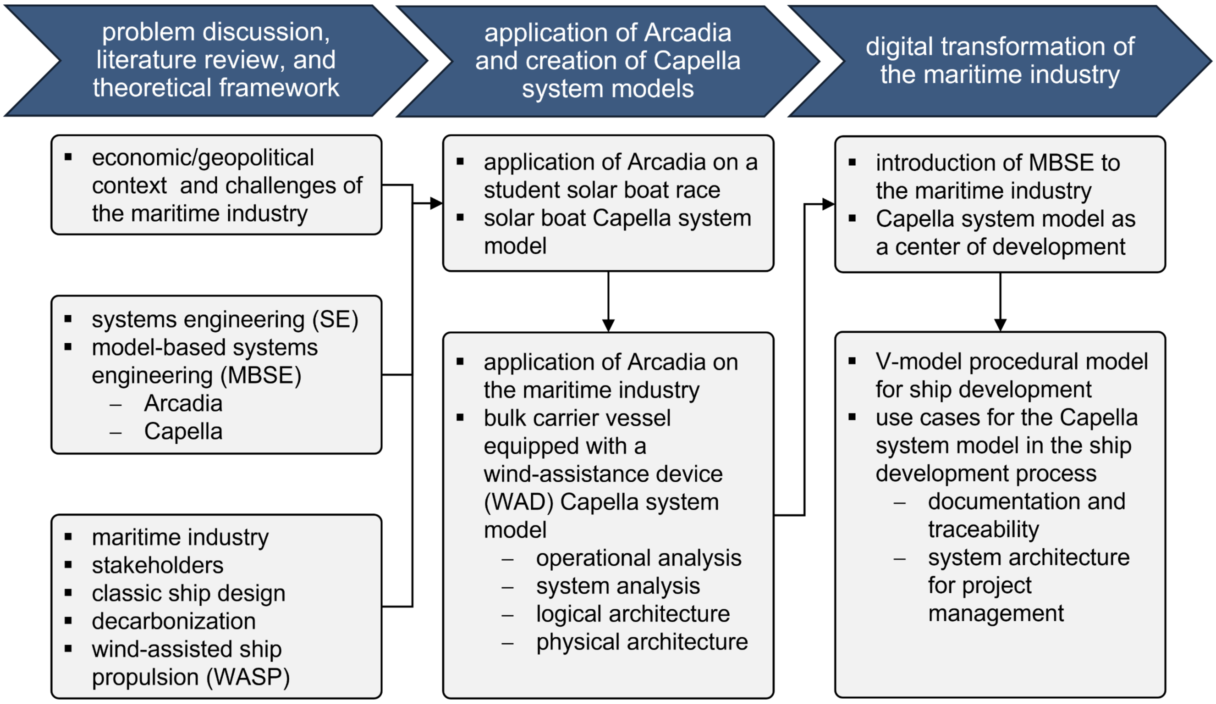

Figure 4-1: Framework and methodology of the master's thesis

Problem discussion, literature review, and theoretical framework: Chapter 1 introduces the maritime industry in general, providing an overview of its *high-level segments* but focusing on its broader *economic* and *geopolitical* context and the resulting *challenges* such as *decarbonization*. The need to adopt MBSE in the maritime industry is identified, leading to an extensive literature review of *systems engineering fundamentals* in chapter 2, with a particular focus on the maritime domain where possible. Chapter 3 addresses the evolving challenges of the *maritime industry*, particularly its decarbonization by 2050. New approaches are needed to integrate *low- and zero-emission alternative fuels and propulsion technologies*, including auxiliary systems such as *wind-assisted ship propulsion*. The limitations of *classic ship design* methods are becoming increasingly apparent, making it essential to implement expansions and innovative solutions such as MBSE to address these new challenges effectively. The chapters 2 and 3 are considered as the *theoretical part* of the master's thesis.

Application of Arcadia and creation of Capella system models: Chapter 4 is the first *practical part* of the master's thesis. It applies the previously introduced *Arcadia method* (see chapter 2.3) in the maritime domain and is the main method that is used to address the challenges and needs identified in the first process step. The reasons why Arcadia and Capella are the modeling language, method, and tool of choice are discussed at the end of chapter 2.3.2. Starting with a *student solar boat race* and a *solar boat system*, the application of Arcadia and the creation of a Capella system model are demonstrated on a small scale. Building on this, the main part now focuses on the *maritime industry*, following the four Arcadia phases *operational analysis* (OA), *system analysis* (SA), *logical architecture* (LA), and *physical architecture* (PA). The *system-of-interest* (SoI) is a conventional bulk carrier ship used to transport bulk cargo from origin to destination. As the maritime industry is under pressure to achieve decarbonization by 2050, the system model focuses on exploring the relationships between the stakeholders in the maritime industry's *transportation sector* and how they work together to implement new *GHG emission reduction solutions* in the SoI, with a strong emphasis on *wind-assisted ship propulsion* (WASP). CO_2 reduction through WASP is shown by integrating a *wind-assistance device* (WAD) into an existing bulk carrier (i.e., the SoI).

Digital transformation of the maritime industry: Chapter 5 is the second *practical part* of the master's thesis. It begins to introduce MBSE to the maritime industry by discussing the operational context of the SoI, including stakeholder interactions. This essential part of system development is not covered by the *classic ship design* process (see chapter 3.2), which does not describe the needs or operational concepts of the system stakeholders, whereas Arcadia's operational analysis does. In addition, the Capella system model of a bulk carrier, based on the Arcadia method and created in chapter 4, can be used as a *center of development*, to link different *disciplines* (i.e., mechanical, electrics/electronics, or software, etc.) with *technical domains* (i.e., requirements, structure, behavior, etc.) across all *system levels*, (see Figure 2-12). The *roles* involved in system development, such as project manager, customer, requirements and test engineer, software developer, system architect, or chief engineer, have varying perspectives and views of the SoI. A *common understanding* of the system can be ensured by combining these different views in a system model (see Figure 2-2 for the views of a system). The integration of the Capella system model into the *ship development process* is further discussed by demonstrating a possible integration of the system model and the Arcadia method into the already introduced *V-model* (see Figure 2-8) to meet the needs of modern ship design. Several *use cases* of the system model are shown, including documentation, traceability of artifacts, or the usage of a system architecture diagram for project management activities.

4.2 Solar Boat System Model

The development of a solar boat system model takes place in the context of a solar boat racing event, which is held annually at the end of August on Lake Biwa, Japan. This inter-university competition invites student teams to design, develop, and autonomously race solar-powered hydrofoil boats over a 20km course. A set of rules and regulations, including technical requirements, are defined by regulating authorities and race committees and determine the technical specifications of the solar boat system.[229]

In general, the solar boat that is to be developed by a student team can be considered as a *mechatronic system*, consisting of a *basic system*, *sensors*, *actuators*, and *information processing* in the form of electronic control units (ECU).[230] Several disciplines are involved in the development, including *mechanical*, *electrics/electronics*, *software*, *controls*, and *naval architecture*. The entire product lifecycle of the system-of-interest (SoI) is covered, which makes the *V-model* a suitable procedural model for the development process (see Figure 2-8). To develop a working system that successfully integrates all subsystems, *system architecture diagrams* can provide an overview of the overall system's *structure* and *behavior*, see Figure 2-2. This overview can support the interdisciplinary development of the system and help to manage and align engineering teams with different system understandings. The Arcadia method (see chapter 2.3) is used to model the operational context and the system architecture of the solar boat, demonstrating the usage of the method together with a Capella system model in ship development on a small scale, as defined in chapter 4.1 and Figure 4-1.

Operational analysis (OA): The first phase of Arcadia focuses on understanding needs from the perspective of operational users by identifying stakeholders, their goals, activities, constraints, and the interactions.

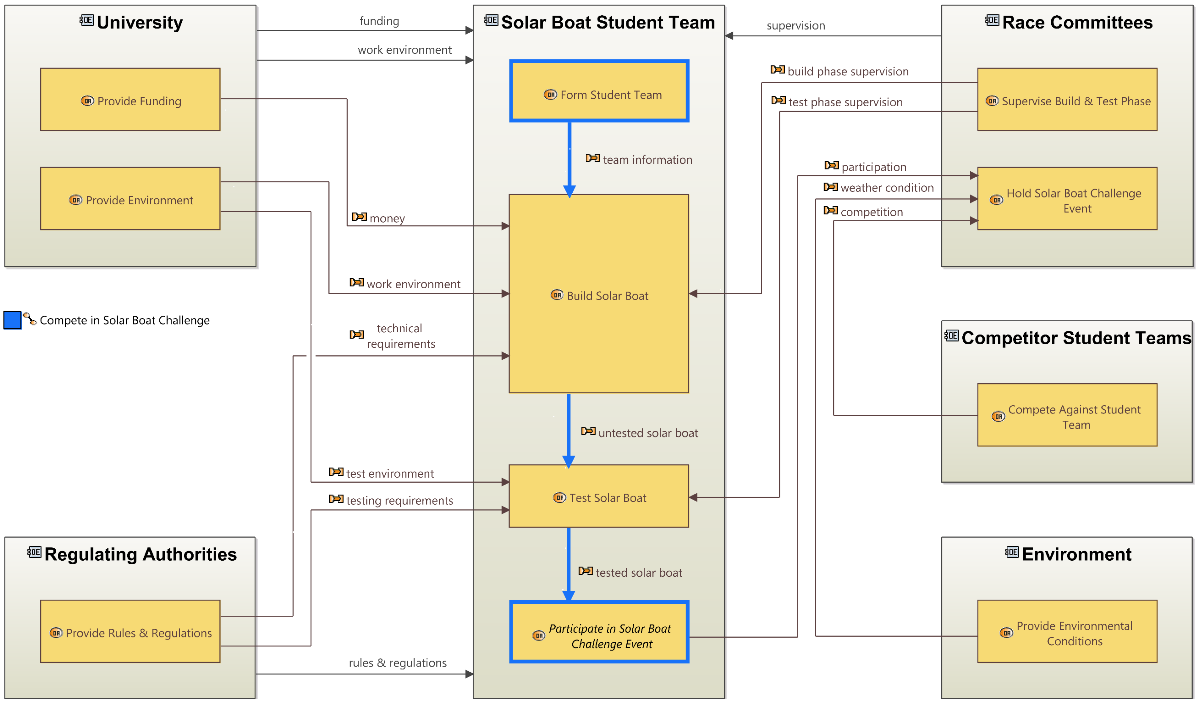

Figure 4-2: Solar boat – Operational architecture solar boat challenge

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[229] Sutherland, J., Kamiyama, H., Aoyama, K., & Oizumi, K. (2015). *Systems Engineering and the V-Model: Lessons from an Autonomous Solar Powered Hydrofoil.* At: 12th International Marine Design Conference (IMDC). Tokyo. (May 2015)., p. 1 ff.

[230] Lindemann, U. (2016). *Von der Mechatronik zu Cyber-Physical-Systems.* In: Udo Lindemann (Eds.). Handbuch Produktentwicklung. First edition (2016): Carl Hanser., p. 870

Figure 4-2 shows an op*erational architecture blank* (OAB) diagram that provides an overview of key *operational entities* (OE; beige blocks) and their *operational activities* (OA; yellow blocks) in the context of the solar boat challenge event. The *operational entities* and their allocated *operational activities* are identified by studying the technical regulations document provided by the regulating authorities.[231] *Operations entities* are the stakeholders in the operational context (i.e., the solar boat challenge event) of the SoI (i.e., the solar boat), such as “University”, “Regulating Authorities”, “Solar Boat Student Team”, “Race Committees”, “Competitor Student Teams”, and “Environment”. *Operational activities* represent the *functions* of the OEs in the operational analysis Arcadia phase. For example, the OAs of the OE “Solar Boat Student Team” are “Form Student Team”, “Build Solar Boat”, “Test Solar Boat”, and “Participate in Solar Boat Challenge Event”. These OAs describe the activities performed by the student team throughout the challenge and are highlighted in the *operational process* “Compete in Solar Boat Challenge”. The beginning and the end of the operational process are marked by the bold blue outline of the first and the last OA. Operational entities and operational activities are linked with two types of *exchanges. Communication means* connect operational entities and *interactions* connect operational activities. *Communication means* are exchanges directly between the OEs, such as “funding” or “work environment” provided by the OE “University” to the OE “Solar Boat Student Team”. *Interactions* are the output or input of an OA, for example, the interaction “untested solar boat” is the output of the OA “Build Solar Boat” and becomes the input of the OA “Test Solar Boat”.

Understanding the *operational context* of an event such as a solar boat race is essential. The rules and regulations determine the technical requirements of the system-of-interest (i.e., the solar boat), so not fully understanding the operational context can, in the worst case, lead to disqualification from the race event. Architecture diagrams, such as the one shown in Figure 4-2, can assist in visualizing the relationships between all stakeholders (i.e., operational entities) as well as their operational activities and interactions. Such a qualitative description is a helpful tool to fully understand the needs of all stakeholders and to create a common understanding of the operational context of the SoI among the interdisciplinary development team.

Several other diagrams of the operational analysis Arcadia phase are created, including an *operational capabilities blank* (OCB) diagram (see chapter 4.3.1 and Figure 4-4 for a detailed description of this diagram type), *operational entity* (OEBD) and *operational activity* (OABD) breakdown diagrams, or an *operational activity interaction blank* (OAIB) diagram. All diagrams of the OA phase are provided in the Appendix.

System analysis (SA): The second phase of Arcadia treats the system-of-interest as a black box. It focuses only on the system’s functions and external interfaces to surrounding *system actors* (SA), building on the domain model of its operational context created in the previous phase. The SA phase is not discussed in the present chapter but will be explained in detail in chapter 4.3.2 using the bulk carrier system model. The solar boat system model diagrams created in this phase, including a *missions capabilities blank* (MCB) diagram (see chapter 2.3.1 and Figure 2-15 for a general description of this diagram type), *system architecture blank* (SAB) diagrams, *system data flow blank* (SDFB) diagrams, and *system function breakdown* (SFBD) diagrams, are provided in the Appendix.

Logical architecture (LA): The third phase of Arcadia focuses on the internal logical structure of the solar boat system, excluding all technological options to remain completely solution neutral. Figure 4-3 shows a *logical architecture blank* (LAB) diagram that includes the *logical*

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[231] Solar Boat Challenge. (2023). *Technical Regulations 2023.* Version 2. (November 2022).

system (L; dark blue block) “Solar Boat System”, its *logical components* (L; dark blue blocks) such as “Control System”, “Hull System”, or “Propulsion System” (i.e., subsystems), and their allocated *logical functions* (LF; green blocks) and interfaces. The logical system is connected with external *logical actors* (LA; light blue blocks) and their logical functions. These logical actors are mostly based on previously defined operational entities and system actors (SA). The Arcadia principle of recovering model elements/artifacts from previous phases is explained by the *transition activities* in Table 2-1 or the “realizes” link between artifacts of different phases in Figure A-1 in the Appendix. Logical components, actors, and functions are linked through two types of *exchanges* over two types of *ports* (i.e., interfaces). *Component exchanges* connect *logical components/actors* over *component ports*, and *functional exchanges* connect *logical functions* over *function ports*. The ports are either input, output, or input/output ports. *Component exchanges* can be based on the *communication means* of the OA phase appear for the first time in the SA phase. They are exchanges directly between the logical components or actors, such as “photon flow”, which is exchanged from the LA “Sun” to the logical component “Power Generation System”. *Functional exchanges* can be based on the *interactions* of the OA phase and also appear for the first time in the SA phase. They are the output or input of a LF, for example, the functional exchange “photons” is the output of the LF “Provide Solar Energy” and becomes the input of the LF “Transform Solar Energy into Electrical Energy”. The allocation of functional exchanges to component exchanges is called *port allocation* and is visualized by a striped line between *component ports* and *function ports*. This allocation symbolizes the *medium* or *way of transfer* of one or multiple functional exchanges, for example, the functional exchange “photons” is made possible by the component exchange “photon flow”. An example of a component exchange that hosts multiple functional exchanges is the component exchange “control data transfer” of the logical component “Control System”, which hosts three functional exchanges, “control data disturbance”, “control data propulsion”, and “control data change direction”.

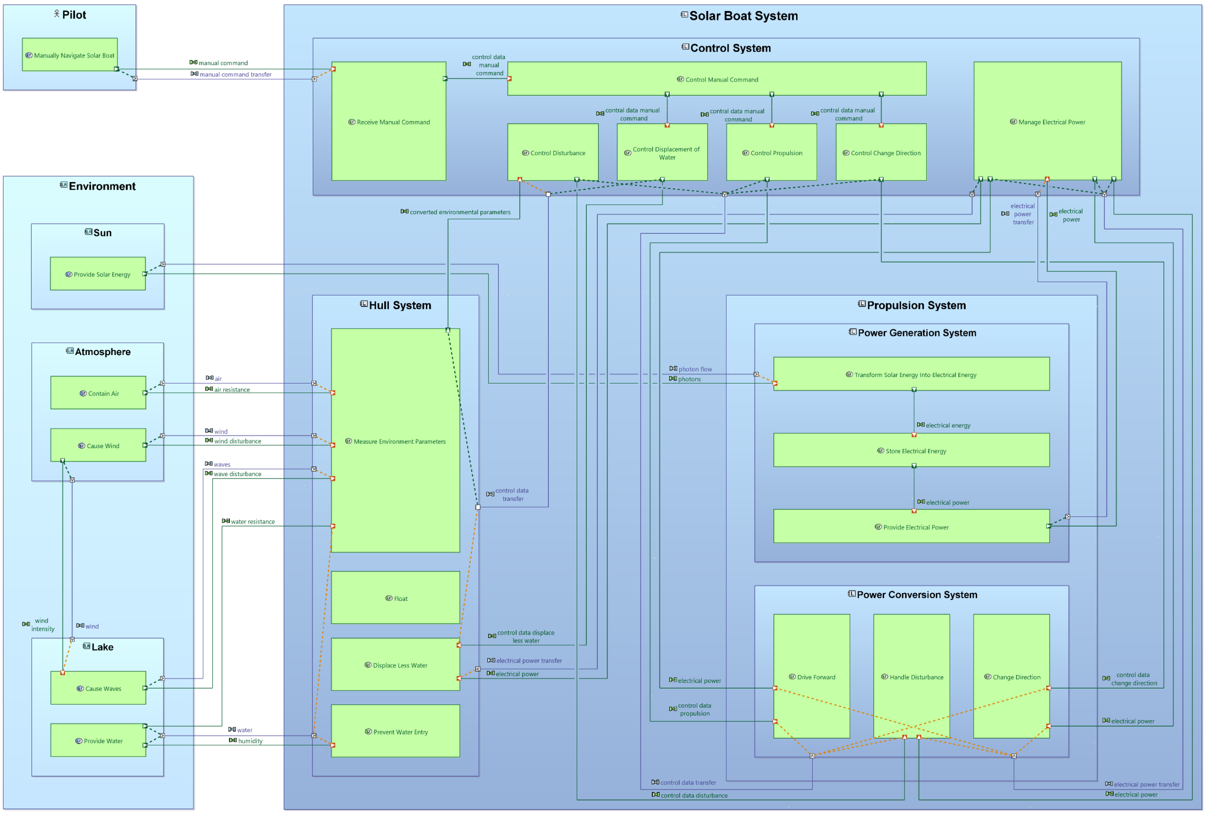

Figure 4-3: Solar boat – Logical architecture

Several other diagrams of the logical architecture Arcadia phase are created, including a *logical data flow blank* (LDFB) diagram and *logical function breakdown* (LFBD) diagrams. All diagrams of the LA phase are provided in the Appendix.

Physical architecture (PA): The fourth phase of Arcadia defines the solar boat system and its subsystems from a physical point of view with, focusing on its realization. The PA phase is not discussed in the present chapter but will be explained in detail in chapter 4.3.4 using the bulk carrier system model. The solar boat system model diagrams created in this phase, including a *physical architecture blank* (PAB) diagram (see chapter 2.3.1 and Figure 2-16 for a general description of this diagram type), a *physical component breakdown* (PCBD) diagram, a *physical data flow blank* (PDFB) diagram, and a *physical function breakdown* (PFBD) diagram, are provided in the Appendix.

4.3 Bulk Carrier System Model

In the previous chapter 4.2, the operational context is a *student solar boat race*, where the system-of-interest is already defined as a *solar boat*. Going from the *need* (i.e., the development of a solar boat capable of participating in the race), to the *solution* (i.e., the developed and built solar boat system) is refined step by step, following the Arcadia method. The stakeholders of this race event are manageable, and the *rules and regulations* provided by the regulating authorities, which result in a set of *technical requirements*, are the most important factor to be considered for the SoI.

The *operational context* is now the *maritime industry*, particularly its *transportation sector* (i.e., marine shipping), which represents a much more complex network of stakeholders and poses bigger challenges. The overall objective within this operational context is *decarbonization* and the path to net-zero GHG emissions in international shipping until 2050, as discussed in detail in chapters 1 and 3.3. At the same time, the main *mission* of marine transportation must be fulfilled, which is the transportation of goods, resources, and passengers from origin to destination. While many technologies and measures to reduce GHG emissions in shipping are identified in chapter 3.3.2 and shown in Figure 3-5, an overall system that is capable of integrating these solutions and meeting the challenges of marine shipping will only be defined on a high level in the second phase of Arcadia (see chapter 4.3.2). However, for the sake of simplicity and clarity, the present chapter 4.3 as well as all diagrams shown here or in the Appendix will be named using the yet to be defined system-of-interest (SoI), which will ultimately be a *bulk carrier* ship. The application of the Arcadia method (see chapter 2.3) is now demonstrated on a much larger scale for ship development. The result is a Capella system model of the maritime industry's transportation sector in the context of its decarbonization, and of a bulk carrier ship that is equipped with a wind-assistance device (WAD), as defined in chapter 4.1 and Figure 4-1.

4.3.1 Operational Analysis (OA)

The first phase of Arcadia, *operational analysis* (OA), examines the operational context of the system-of-interest, focusing on the system users and their needs. Since the operational context is the maritime industry's transportation sector, this phase heavily builds on the research in chapter 3.1 and the *stakeholder value network* shown in Figure 3-1. The goal of this phase is to understand not only the *needs* of the system users, but also their own *activities* and *interactions*. By focusing on the *problem* and the *operational context* rather than the *solution* at the beginning of system development, *solution neutrality* and the exclusion of specific implementation choices are ensured; refer to the *thinking in functions* principle of *systems thinking* in chapter 2.1.1.

This approach differs fundamentally from the *classic ship design* process, which begins with a set of requirements that outline the ship's capabilities, often referencing a so-called *type ship* that performs similar functions of the new ship (see chapter 3.2). This approach quickly progresses to specific technological implementations and largely overlooks the ship's operational context. In the past, this context was stable, and the requirements and functions of the SoI were well understood as the ships being developed were not complex systems.[232] However, the need for decarbonization and the introduction of alternative fuels and new technologies such as WASP now require a collaborative, holistic, operational and functional analysis-based design approach. Analyzing the operational context and stakeholders can reveal previously overlooked areas and interactions, ensuring that the ship aligns with its *mission* and adapts to rapidly changing regulations in the maritime industry.

Operational entities and operational capabilities: The outputs of the operational analysis phase can be several types of diagrams, depending on the scope of the Capella system model. An *operational capabilities blank* (OCB) diagram is shown in Figure 4-4, which provides an overview of the *operational entities* (OE; beige blocks) of the maritime industry's transportation sector, their operational capabilities (OC; brown ellipses), and their exchanges as so-called *communication means* (i.e., exchanges between OEs). This diagram is based on the *stakeholder value network* in Figure 3-1 and extended with additional stakeholders such as "Weather Data & Routing Service Provider" or "International Windship Association (IWSA)". The OEs are divided into two groups:

- "Regulatory Organizations & Public Institutions" (left column)
- "Private Companies" (right column)[233]

Although this diagram type is typically not used to group operational entities or to show their hierarchy, which is usually done in *breakdown* diagrams such as *operational entity breakdown* (OEBD) diagrams (see Figure C-2 in the Appendix), the information of these two groups is still visible in the operational capabilities blank diagram due to the separation into two columns. The classification into these groups also assists in understanding the *functional chain* "GHG Emission Reduction of Shipping" in the *system architecture blank* (SAB) diagram of the next Arcadia phase, see Figure 4-6.

The meaning of *operational capabilities* can be explained using the enlarged part in Figure 4-4. Operational capabilities are capabilities of operational entities in the context of their *operational mission*, which can be defined as the *decarbonization of shipping using wind-assisted ship propulsion (WASP)*, since the focus of this master's thesis is on WASP. For example, the capability of the OE "Shipbuilding Company" is the OC "Build Zero-emission Vessels (ZEV)", while the OE "Marine Equipment Company" has the OC "Retrofit Vessel with WASP" in this context. For the sake of clarity, the operational capabilities selected here do not represent all possible capabilities of a particular stakeholder and focus solely on the context of WASP. *Operational processes* and *operational activities* are used to further describe operational capabilities.

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[232] Gale. (2003)., p. 5-31 f.

[233] Dreier, M., Bajzek, M., Hick, H., Michels, N., Burchardt, C., & Aoyama, K. (2024). ***Application of the ARCADIA Method on a Bulk Carrier Vessel Equipped with a Wind-assistance Device.*** In: INCOSE International Symposium - Volume 34 (July 2024): International Council on Systems Engineering (INCOSE)., p. 4 f.

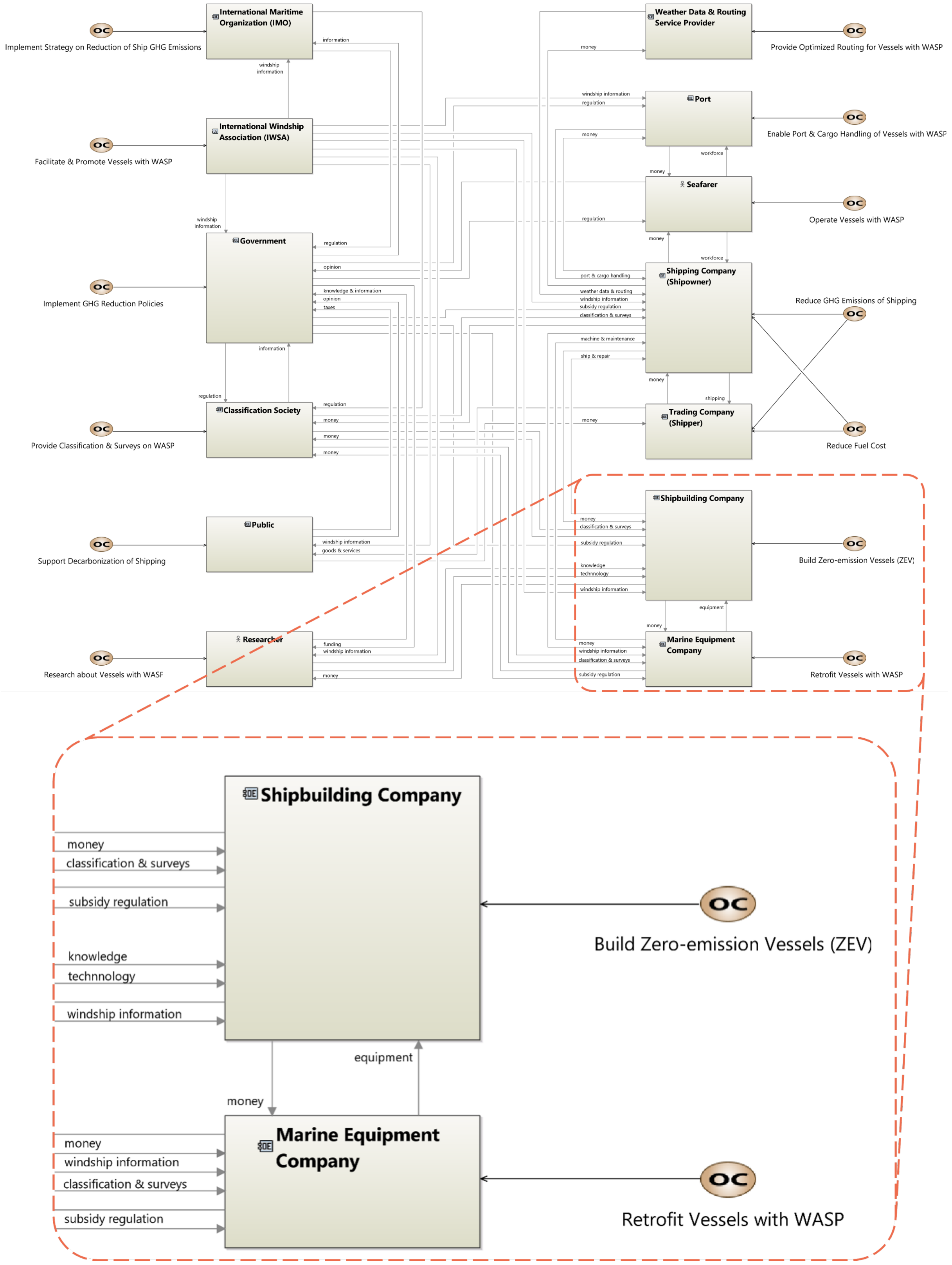

Figure 4-4: Bulk carrier – Operational entities and operational capabilities with highlighted example, inspired by *Dreier et al.*[234]

The enlarged part of Figure 4-4 also shows *communication means* such as “money” and “equipment” between the two OEs. Other incoming communication means come from the

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[234] Dreier et al. (2024)., p. 5

“Regulatory Organizations & Public Institutions” group of the left column, including “classification & surveys” provided by the OE “Classification Society” or “subsidy regulation” provided by the OE “Government”. These exchanges illustrate the connection between the two groups and the interacting network in the operational context of the system-of-interest.

The *operational capabilities blank* diagram (OCB), shown in Figure 4-4, is the main diagram used in the operational analysis phase of this application of the Arcadia method. In addition, two *operational entity breakdown* (OEBD) diagrams are created that present only a hierarchical view of the operational entities, thus reducing the amount of information. All diagrams of the OA phase are provided in the Appendix.

4.3.2 System Analysis (SA)

The second phase of Arcadia, *system analysis* (SA), examines the required capabilities and functions of the system-of-interest (SoI), building on the understanding of operational entities, their interactions, needs and challenges of its operational context explored in the previous phase. The Arcadia/Capella principle of reusing certain model elements and transferring them into the next phase is applied for the first time when moving from the OA phase to the SA phase through automated transitions provided by the Capella tool, which significantly reduces the modeling effort and automatically creates realization links between model elements of different phases (see Table 2-1 and Figure A-1 in the Appendix). The system is now recognized as a model element, but it is treated as a *black box*, containing only allocated *system functions* but no internal structural information. Exchanges with its surrounding *system actors* (SA) are identified and modeled through external interfaces, thus embedding the SoI in its context. The outputs of the system analysis phase can be several types of diagrams, depending on the scope of the Capella system model.

System-of-interest: The focus of this master’s thesis is on *wind-assisted ship propulsion* (WASP) as a GHG emissions reduction solution for vessels in marine shipping, which is investigated in chapter 3.3.3 with all technological options shown in Figure 3-6. *Wind-assistance devices* (WAD), such as *Flettner rotor sails*, can be easily retrofitted to existing or classically designed vessels, thereby contributing to the *short-* and *mid-term measures* of the *2023 IMO’s strategy* (see beginning of chapter 3.3). In general, WASP reduces the propulsion power requirements of conventional fuels and consequently the GHG emissions of the existing and near future shipping fleet. An example of such a vessel is the 63,223 DWT dry bulk carrier “MV Afros”, built in 2018, which is equipped with four rotor sails is claimed to be the *“[…] first-ever bulk carrier to be fitted with the Flettner Rotor System […]”*.[235] A case study of fifteen energy efficiency retrofits on a bulk carrier concludes that WASP, in this case rotor sails and towing kite sails, have a high level of technological maturity and are considered a suitable investment from a techno-economic perspective.[236] For these reasons, the system-of-interest on which the Arcadia method is applied shall be defined as follows:

> *A conventional dry bulk carrier ship equipped with a wind-assistance device (WAD) for auxiliary propulsion.*

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[235] Hagen. (2021)., p. 99

[236] Tsereklas-Zafeirakis, A., Aravossis, K., Gougoulidis, G., & Pavlopoulou, Y. (2014). *Technoeconomic evaluation of energy efficiency retrofits in commercial shipping; a bulk carrier case study.*, p. 7

Bulk carriers: This special type of ship is designed to carry unpackaged *bulk cargo*. They can be divided into *dry bulk carriers* for *dry bulk cargo* such as grain, coal, ore (e.g., iron ore), etc., and *tankers* for *liquid bulk cargo* such as crude oil, products (e.g., refined crude oil), gas (e.g., LNG or LPG), or chemicals. Some are designed as *combination carriers*, such as ore/bulk/oil (OBO) bulk carriers, to carry dry and liquid bulk cargo and improve economic efficiency.[237]

Most bulk carriers are single-deck vessels with longitudinal framing and a double bottom. The cargo space is divided into cargo holds or tanks, with variations in the arrangement to suit different types of cargo. These ships are mostly categorized by *size* in terms of deadweight tonnage (DWT), which is the weight the ship can carry, and the *navigational constraints* they must comply with, which means the specific passage or port they can enter. The following categorization provides an overview of the most popular bulk carrier classes:

- *Panamax:* Ships sized for the Panama Canal, with a beam less than 32.25 meters.
- *Suezmax:* Ships sized for the Suez Canal, with a draught under 19 meters.
- *Capesize:* Ships too large for Panama and Suez Canals.
- *Handysize:* Ships generally under 50,000 DWT.
- *Aframax:* Tankers between 80,000–120,000 DWT.[238]

However, different or more detailed bulk carrier classes including subclasses exists, ranging from small vessels with 10,000 DWT to very large bulk carriers with around 400,000 DWT carrying capacity.[239] The demand for these ships increased significantly in the second half of the 20th century, driven by the need for economies of scale in maritime trade.[240] According to the latest *Review of Maritime Transport* provided by *UNCTAD*, the share of *dry bulk carriers* in the world fleet, measured in thousand DWT, was 42.8% (i.e., 973,743 thousand DWT), which was the highest among the principal ship types such as *bulk carriers*, *oil tankers*, *container ships*, *general cargo ships*, and *other types of ships*.[241] In terms of international maritime trade, the transported dry bulk cargo increased from 2,600 million tons loaded in 2003 to 5,300 million tons loaded in 2022, representing a growth of ~104%.[242] Given their extensive use and critical role in the global trade of dry and liquid bulk cargo, bulk carriers are a cornerstone of the maritime industry's transportation sector.

System mission and system capabilities: One of the first tasks in the system analysis phase is to describe the system's *mission* or missions. This is done using a *missions capabilities blank* (MCB) diagram (see Figure 4-5), which is intended to address the challenges identified during the operational analysis phase; see also chapter 2.3.1 and Figure 2-15 for a general description of this diagram type. As discussed earlier in this chapter, the system-of-interest has already been defined as a *conventional dry bulk carrier ship equipped with a WAD*. The SoI requires several *system capabilities* (C) to fulfill its *system mission* (M).[243]

Since the overall objective within the operational context is *decarbonization*, the system mission and system capabilities in Figure 4-5 correspond to the technologies and measures for *zero-emissions vessels* (ZEV), which are summarized in chapter 3.3.2 and Figure 3-5. The system capabilities are options for the SoI to reduce GHG emissions that can be integrated into existing or newly designed vessels. The system mission of the SoI is defined as follows:

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[237] Molland, A. F. (2008). *The Maritime Engineering Reference Book: A Guide to Ship Design, Construction and Operation.* Oxford. UK.: Butterworth-Heinemann., p. 51 ff.

[238] Tupper, E. C. (2004)., p. 343

[239] MAN Energy Solutions. (2022). *Propulsion trends in bulk carriers.* Copenhagen. Denmark: MAN Energy Solutions., p. 7

[240] Molland, A. F. (2008)., p. 51

[241] UNCTAD. (2023)., p. 30

[242] Ibid., p. 5

[243] Dreier et al. (2024)., p. 6 f.

"Perform Main Mission while Reducing GHG Emissions"

While the main mission is not further modeled in detail, it is recognized in the first system capability "Transport Goods from Origin to Destination". The main part of the system capabilities in this diagram are divided into three groups, which are the above mentioned three fields of technologies and measures for GHG emissions reduction in marine shipping. Examples of system capabilities are "Use Low- or Zero-emission Alternative Fuels", "Use Wind-assistance Devices (WAD)", "Use Waste Heat Recovery", or "Optimize Route". System capabilities are further involved with *system functions* and *system components* and can be described in more detail in *functional chains*. A selection of these system capabilities will be considered in the following phases of Arcadia as part of the system-of-interest.[244]

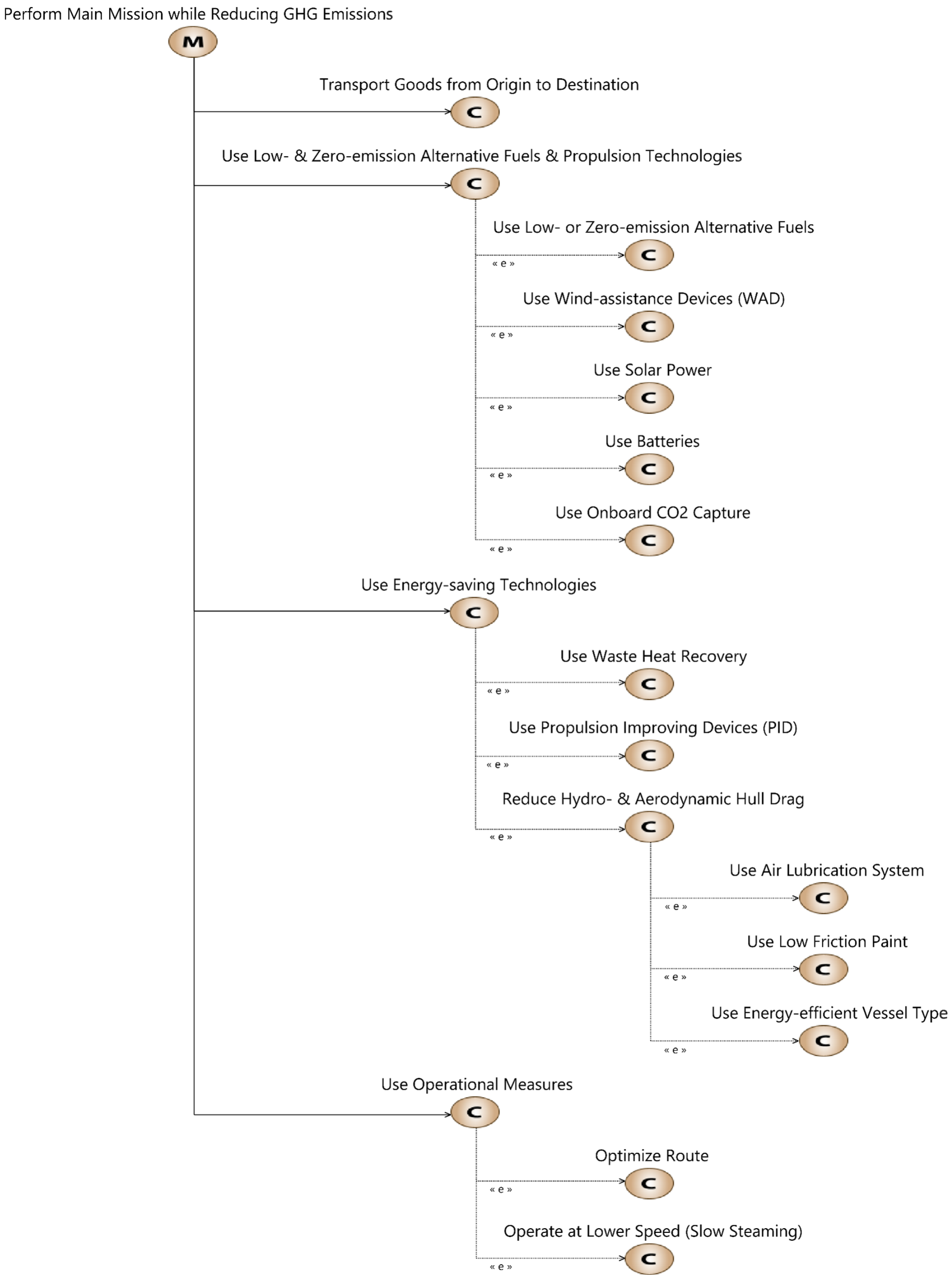

Figure 4-5: Bulk carrier – System mission and system capabilities

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[244] Dreier et al. (2024)., p. 6 f.

Requirements in marine transportation: Regardless of whether the *method* used during system development (e.g., the Arcadia method) explicitly includes *requirements engineering*, defining requirements is an important first step in modern procedural models such as the *V-model*, but also in *classic ship design*. In the classic design process (i.e., the design spiral), this set of requirements defines the capabilities a ship must fulfill and leads to a first basic *specification*.[245] The key perspectives that define a ship's requirements are briefly discussed in the following.

According to *Buetzow* and *Koenig*, a vessel is procured for three main purposes: *National defense*, *marine services*, and *marine transportation*. Each of these categories requires specific considerations when defining requirements because their missions are fundamentally different.[246] In the context of *marine transportation*, four areas of requirements can be distinguished, each addressing a different perspective important to ship development. Table 4-1 lists these four areas and the primary subjects they cover:

Table 4-1: Requirements in marine transportation, according to *Buetzow* and *Koenig* [247]

Top level mission requirements	Other owner's technical requirements	Ownership and operating arrangements	Shipbuilding contract price and total project cost
Outline of a typical new construction specification	Propulsion plant	Tonnage acquisition alternatives	Shipowners costs for acquiring a large commercial trading vessel
Cargo type and capacity	Electrical plant	Operating and other management agreements	List of typical owner-furnished equipment (OFE)
Principal characteristics	Electronic navigational and radio equipment	Vessel financing	
Additional port requirements	Automation		
Rules and regulations	Manning and accommodations		
Service speed	Hull structure		
Endurance	Quality standards		
Design environmental conditions	Maintenance and overhaul strategy		
Vessel design life			

While the first two areas cover the requirements of the *technical perspectives* that are important for the design and construction of the vessel, the last two areas consider the *economic* requirements and deal with commercial aspects of ship ownership and operation, since marine shipping is primarily a *profit-oriented* industry.[248]

Arcadia/Capella supports the definition of requirements directly in the tool, which can be linked to any model element such as functions or components in any Arcadia phase. The Arcadia *capability* artifacts, which appear in all four phases, can be used as a reference when

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[245] Molland, A. F. (2008)., p. 640

[246] Buetzow, M. R., & Koenig, P. C. (2003). *Mission and Owner's Requirements.* In: Thomas Lamb (Eds.). Ship Design and Construction - Volumes 1 and 2. First edition (2003): The Society of Naval Architects and Marine Engineers (SNAME)., p. 7-2

[247] Buetzow and Koenig. (2003)., p. 7-1 ff.

[248] Ibid., p. 7-16

formulating more detailed and specific requirements during the development of the system-of-interest; see the four capability artifacts in Figure A-1 in the Appendix. However, since the Arcadia method does not explicitly include a classic requirements definition step, this activity is not performed during the Capella system model creation.

System architecture: The system-of-interest is now recognized and used as a model element based on the operational entities identified in Figure 4-4, including their operational capabilities and exchanges, and the system mission and system capabilities shown in Figure 4-5. Figure 4-6 now shows the *system architecture blank* (SAB) diagram, which is the main diagram used in the system analysis phase. The *system* (dark blue block; Detail A) “Bulk Carrier System” is treated as a *black box* and is placed in the center of the diagram. This diagram resembles the overall structure of the previous operational capability diagram (see Figure 4-4) in terms of the two stakeholder groups “Regulatory Organizations & Public Institutions” (left column) and “Private Companies” (right column). This is done intentionally to best visualize the transition from the operational analysis phase to the system analysis phase and to improve the readability of this large diagram. The former operational entities are now realized by *system actors* (SA; light blue blocks), which is done by the automated transitions of model elements between the phases provided by the Capella tool (see Table 2-1 and Figure A-1 in the Appendix). *System functions* (SF; green blocks) are allocated to the system and all system actors, and all interactions of these model elements are defined.[249]

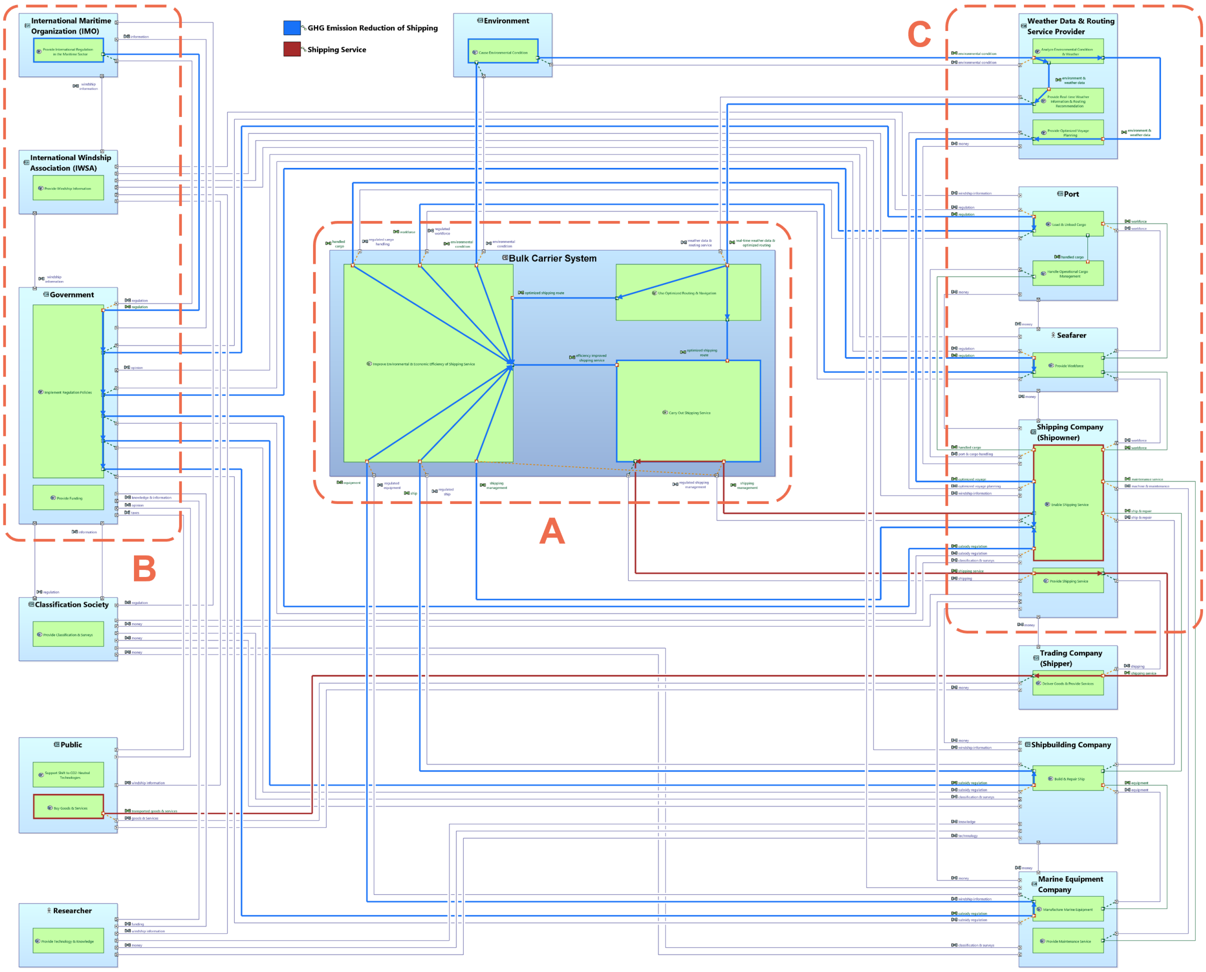

Figure 4-6: Bulk carrier – System architecture, inspired by *Dreier et al.*[250]

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[249] Dreier et al. (2024)., p. 7

[250] Ibid., p. 7

The interactions in the system architecture diagram consist of *component exchanges* and *functional exchanges*. While the component exchanges between the system actors are basically the same as in Figure 4-4, the exchanges of the system actors with the system and the functional exchanges between the system functions are newly modeled. Table 4-2 lists all the *system components* and their allocated *system functions* that are visible in the diagram in Figure 4-6, providing an overview of the *structure* and *behavior* of the system-of-interest and its context as defined in the system analysis phase.

Table 4-2: Bulk carrier – System components and functions, according to *Dreier et al.*[251]

System components		**System functions**
System	Bulk Carrier System	Improve Environmental & Economic Efficiency of Shipping Service
		Use Optimized Routing & Navigation
		Carry Out Shipping Service
SA	International Maritime Organization (IMO)	Provide International Regulation in the Maritime Sector
SA	International Windship Association (IWSA)	Provide Windship Information
SA	Government	Implement Regulation Policies
		Provide Funding
SA	Classification Society	Provide Classification & Surveys
SA	Public	Support Shift to CO2-Neutral Technologies
		Buy Goods & Services
SA	Researcher	Provide Technology & Knowledge
SA	Weather Data & Routing Service Provider	Analyze Environmental Condition & Weather
		Provide Real-time Weather Information & Routing Recommendation
		Provide Optimized Voyage Planning
SA	Port	Load & Unload Cargo
		Handle Operational Cargo Management
SA	Seafarer	Provide Workforce
SA	Shipping Company	Enable Shipping Service
		Provide Shipping Service
SA	Trading Company (Shipper)	Deliver Goods & Provide Services
SA	Shipbuilding Company	Build & Repair Ship
SA	Marine Equipment Company	Manufacture Marine Equipment
		Provide Maintenance Service

Since the system architecture diagram shown in Figure 4-6 is a rather large diagram that may be difficult to read as an exported image outside of the Capella tool, three *detail cutouts* (Detail A, B, and C) of this diagram are used to better understand its contents. *Detail A* of the system architecture diagram, shown in Figure 4-7, focuses on the SoI “Bulk Carrier System”. In the system analysis phase, the target is to integrate the *system* into the operations analyzed in the previous operational analysis phase, along with selected *system capabilities* (i.e., GHG emissions reduction options) of the system, as defined in the *missions capabilities blank*

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[251] Dreier et al. (2024)., p. 7

diagram in Figure 4-5. In this master's thesis, the focus is on integrating the system capability "Use Wind-assistance Devices (WAD)" into a bulk carrier system. However, other system capabilities are also considered, including "Use Low- or Zero-emission Alternative Fuels", "Use Batteries", Use Onboard CO2 Capture", and "Optimize Route". Three system functions are defined and allocated to the system: "Improve Environmental & Economic Efficiency of Shipping Service", "Carry Out Shipping Service", and "Use Optimized Routing & Navigation". Incoming component and functional exchanges to the system show the connection to its surrounding system actors, such as "environmental condition", "real-time weather data & optimized routing", or "shipping management".[252]

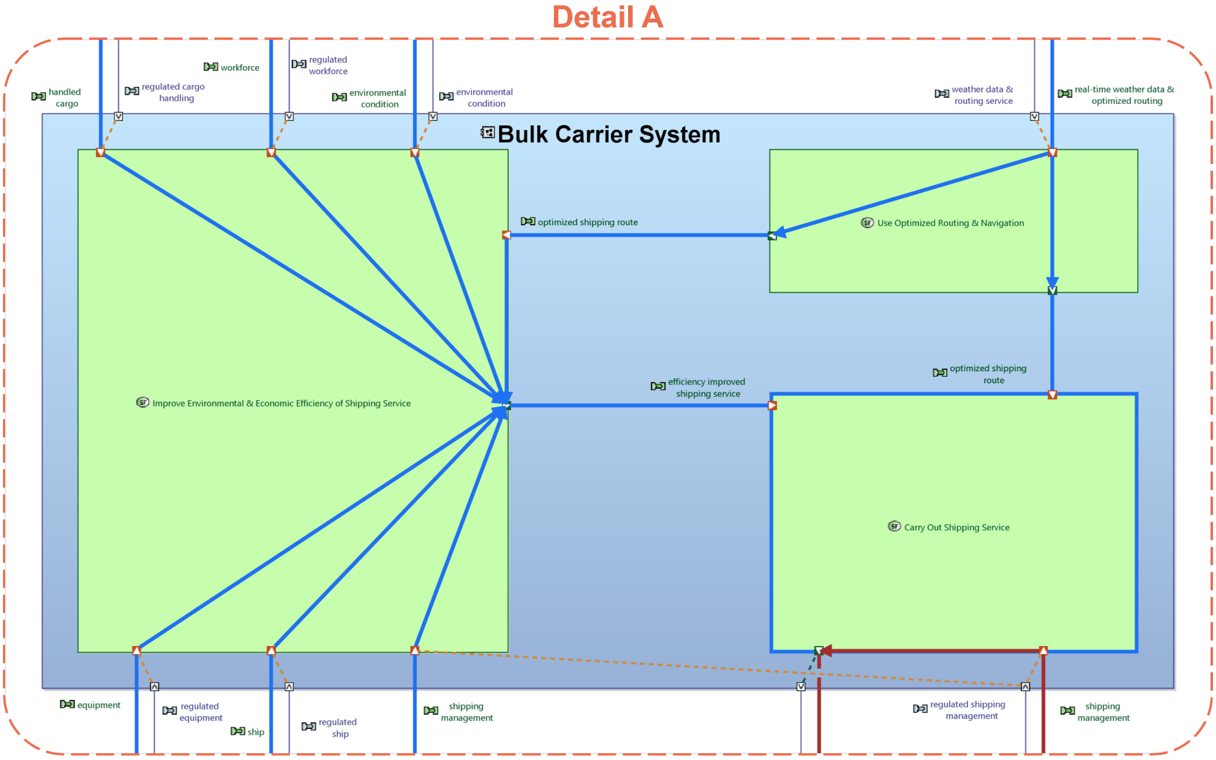

Figure 4-7: Bulk carrier – System architecture; Detail A – "Bulk Carrier System"

Detail B and *Detail C* of the system architecture diagram, shown in Figure 4-8, focus on the *system actors* in the context of the system-of-interest, providing examples of the two stakeholder groups "Regulatory Organizations & Public Institutions" (left column) and "Private Companies" (right column). The allocated system functions describe the behavior of the system actors, such as the SF "Provide International Regulation in the Maritime Sector" of the SA "International Maritime Organization (IMO)", or the SFs "Analyze Environmental Condition & Weather", "Provide Real-time Weather Information & Routing Recommendation", and "Provide Optimized Voyage Planning" of the SA "Weather Data & Routing Service Provider". An example of the connection between the *system actors* and the *system* is the *functional exchange* "real-time weather data & optimized routing", which is the *output* of the SF "Provide Optimized Voyage Planning" of the SA "Weather Data & Routing Service Provider". It then becomes the *input* of the SF "Use Optimized Routing & Navigation" of the system. There are a multitude of incoming and outgoing exchanges on the system architecture diagram, indicating a high number of relationships between the system actors and the system-of-interest.[253]

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[252] Dreier et al. (2024)., p. 7

[253] Ibid., p. 7

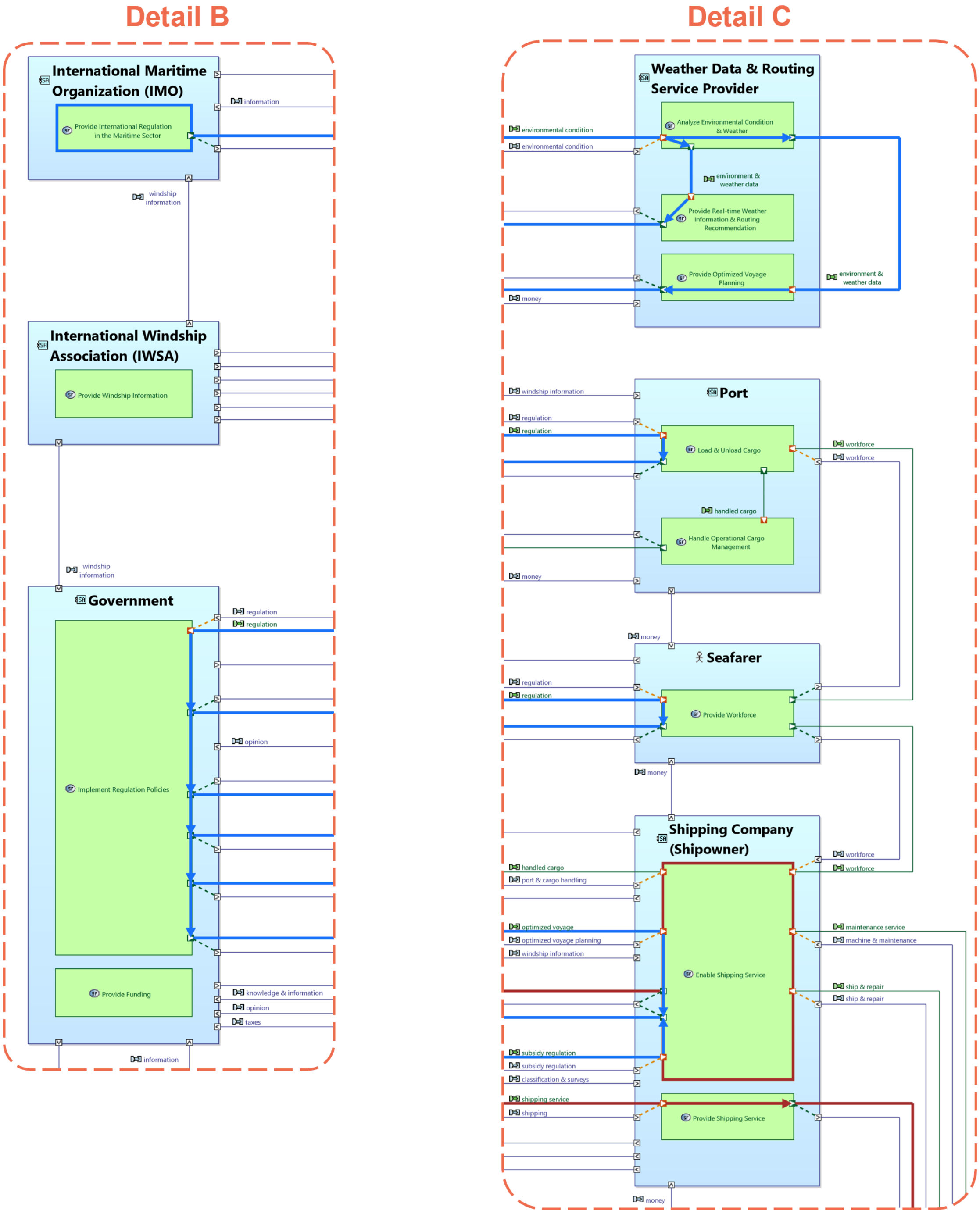

Figure 4-8: Bulk carrier – System architecture; Detail B and C – System actor examples

Functional chains: These model elements are used to visualize and highlight specific paths within functions and functional exchanges. They often describe the behavior of the system, specific relationships it has with its system actors, or contribute to system capabilities by explaining them in more detail. Functional chains can be used in any Arcadia phase (e.g., the *operational process* shown in Figure 4-2) and are a useful way to highlight the key information in architecture or data flow diagrams, thus making large diagrams easier to understand for unfamiliar readers.

In the *system architecture* diagram shown in Figure 4-6, the two *functional chains* “GHG Emission Reduction of Shipping” (bold blue exchanges) and “Shipping Service” (bold red exchanges) represent the *system mission* “Perform Main Mission while Reducing GHG Emissions” defined in Figure 4-5. Here, the main mission is the transportation of goods, resources, and passengers from origin to destination, which is described by the functional chain “Shipping Service” (see Figure C-12 in the Appendix). The functional chain “GHG Emission Reduction of Shipping” is shown in the *system data flow blank* (SDFB) in Figure 4-9. It connects all identified system functions of system actors (blue blocks) with the system functions allocated to the system (green blocks) that contribute to the *decarbonization* of marine transportation. The *beginning* and *end* of the functional chain are highlighted by bold lines around the beginning and ending system functions. In this case, it begins with the SF “Provide International Regulation in the Maritime Sector” of the SA “International Maritime Organization (IMO)” and the SF “Cause Environmental Condition” of the SA “Environment”. The functional chain ends with the SF “Carry Out Shipping Service” of the SoI “Bulk Carrier System”.

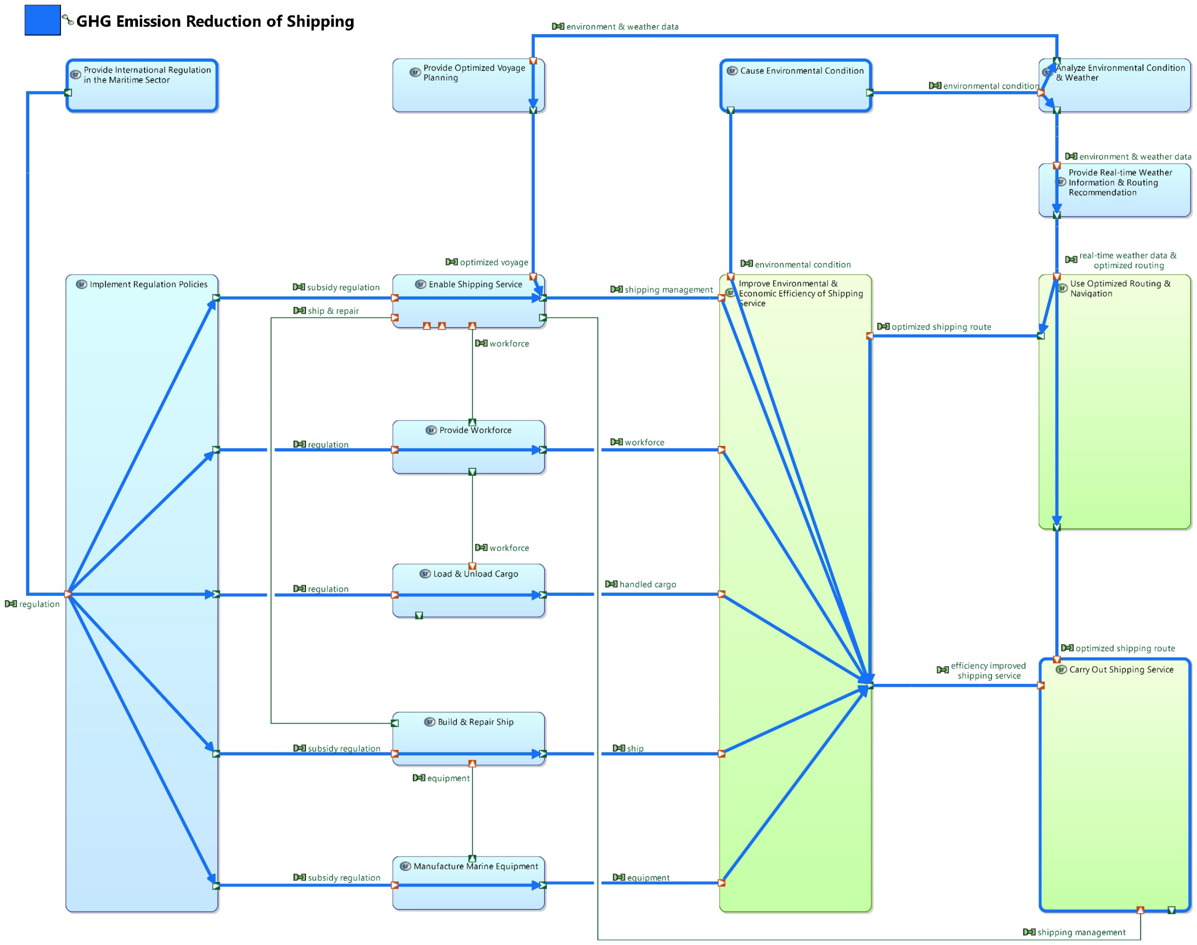

Figure 4-9: Bulk carrier – Functional chain “GHG Emission Reduction of Shipping”

Presenting *large architecture diagrams* such as the one in Figure 4-6 in combination with *functional chains* reveals one of their possible advantages: These diagrams can be used to visualize complex relationships and processes across a vast network of stakeholders or components in a single, large, yet understandable diagram. In traditional *systems engineering* approaches, these complex relationships are often written down and stored in *text-based documents* that may only be understood by a handful of experts and are effectively hidden from the majority of stakeholders; refer to chapter 2.2 for a detailed investigation of *model-based systems engineering*. A large architecture diagram containing all the links and relationships can also be broken down into several smaller diagrams to show multiple views of the system that are relevant to different stakeholders.

The *missions capabilities blank* (MCB) diagram (see Figure 4-5), the *system architecture blank* (SAB) diagram (see Figure 4-6) along with its detail cutouts (see Figure 4-7 and Figure 4-8), and the *system data flow blank* (SDFB) diagram (see Figure 4-9) are the main diagrams used in the system analysis phase of this application of the Arcadia method. In addition, another SDFB diagram is created that shows the functional chain “Shipping Service”. A *system function breakdown* (SFBD) diagram provides an overview of all system functions, and two *system functional chain description* (SFCD) diagrams are used to define both functional chains. All diagrams of the SA phase are provided in the Appendix.

4.3.3 Logical Architecture (LA)

The third phase of Arcadia, *logical architecture* (LA), examines the internal logical structure of the system-of-interest. Logical components (i.e., subsystems) are defined, including their logical functions, exchanges, and interfaces, building on and realizing the system functions, their exchanges and interfaces of the previous system analysis phase. The Arcadia/Capella principle of reusing certain model elements and transferring them into the next phase is also applied when moving from the SA phase to the LA phase through automated transitions provided by the Capella tool. The LA phase explicitly excludes all technological options to remain completely solution neutral. This means, for example, that the theoretical logical component "Main Power Generation System" could be realized by a physical component with the concrete technology option “2-Stroke Low Speed Diesel-Fuel Engine Type XY”. In the specific application of the Arcadia method in the context of this master’s thesis, the LA phase is treated as an *intermediate step* between the system analysis (SA) and the physical architecture (PA) phase. This is done because the focus is on the following PA phase to model the internal structure of the system-of-interest (i.e., its subsystems and components/parts etc.) from a physical point of view. The outputs of the logical architecture phase can be several types of diagrams, depending on the scope of the Capella system model.

Logical architecture: Figure 4-10 now shows the *logical architecture blank* (LAB) diagram that includes the *logical system* (L; dark blue block) “Bulk Carrier System”, its *logical components* (L; dark blue blocks) such as “GHG Emissions Reduction Solutions”, “Propulsion & Power Generation Systems”, “Hull System”, or “Other Ship Systems” (i.e., subsystems), and their allocated *logical functions* (LF; green blocks), exchanges, and interfaces. The logical system is connected with external *logical actors* (LA; light blue blocks) and their logical functions. A detailed description of how to read such a *logical architecture blank* (LAB) diagram is provided in chapter 4.2.

The generic logical component “GHG Emissions Reduction Solutions” is modeled to host selected *logical functions*, each of which describes one of the solutions identified in previous chapters, figures, and diagrams (see chapter 3.3.2, Figure 3-5, and Figure 4-5). These solutions for reducing GHG emissions in ships are logically integrated into actual logical components, such as “Propulsion & Power Generation Systems”. This helps to understand the subsystems that need to be considered when integrating GHG emissions reduction solutions, by showing how each option relates to the bulk carrier system. The large number of *operational entities* and *system actors* identified in the previous two phases is now reduced, leading to a selected choice of *logical actors*, including those that form the “Environment” of the system-of-interest, such as “Wind”, “Current”, “Sun”, or “Maritime Topology”, among others. The LAs are now linked to the logical system, its logical components, and its logical functions.[254]

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[254] Dreier et al. (2024)., p. 8

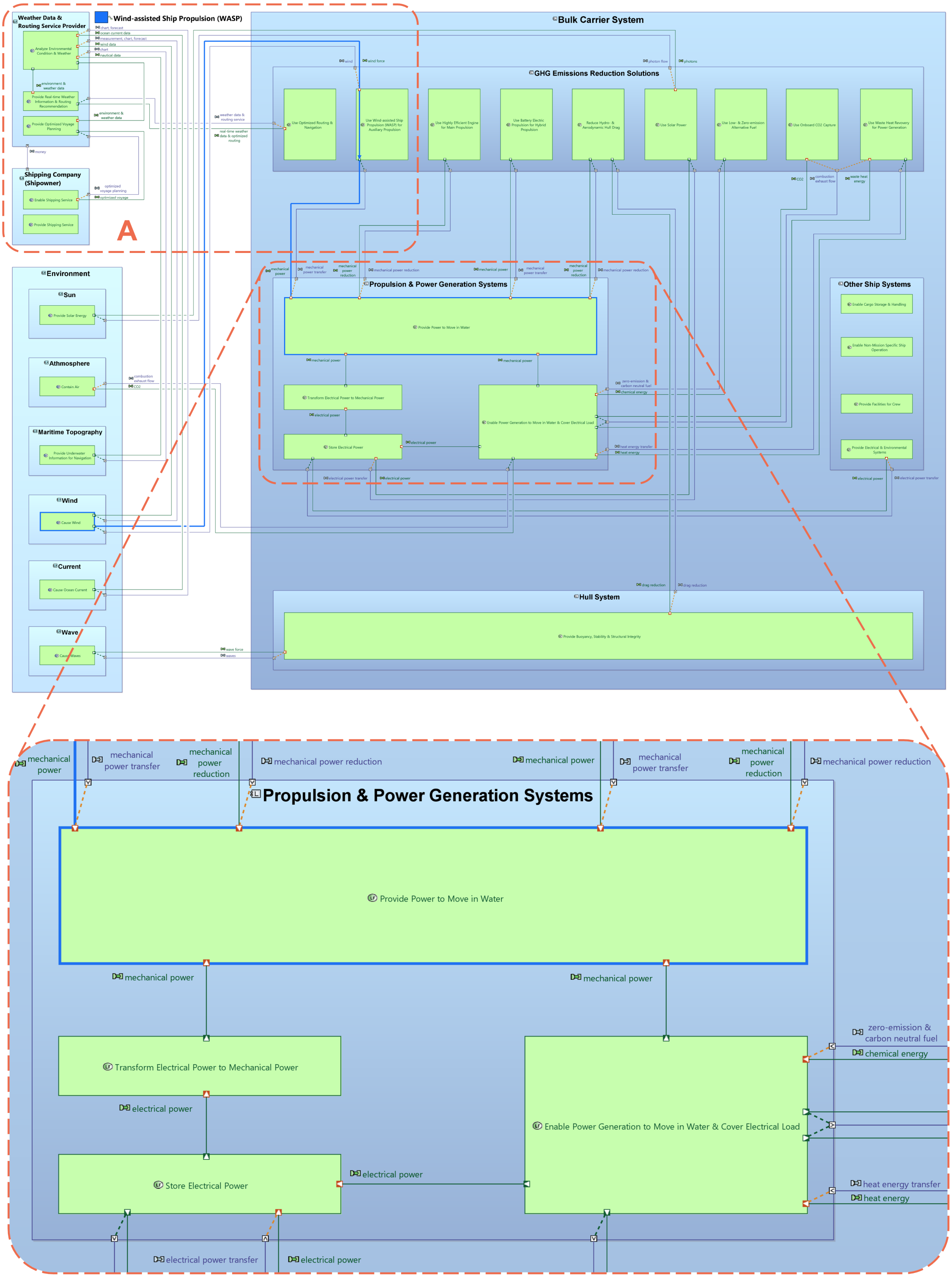

Figure 4-10: Bulk carrier – Logical architecture with highlighted “Propulsion & Power Generation Systems”, inspired by *Dreier et al.*[255]

The enlarged part of Figure 4-10 shows the logical component “Propulsion & Power Generation System” together with its allocated logical functions “Enable Power Generation to

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[255] Dreier et al. (2024)., p. 8

Move in Water & Cover Electrical Load", "Store Electrical Power", "Transform Electrical Power to Mechanical Power", and "Provide Power to Move in Water", as well as incoming component and functional exchanges.

Detail A of the logical architecture diagram, shown in Figure 4-11, focuses on the two logical actors "Weather Data & Routing Service Provider" and "Shipping Company (Shipowner)" and their connections with each other and with the logical system. For example, the SA "Weather Data & Routing Service Provider" receives several exchanges from the SAs that are part of the SA "Environment", such as the functional exchanges "ocean current data", "wind data", and "nautical data". The LF "Analyze Environmental Condition & Weather" converts these inputs into its two outputs "environment & weather data", which then serve as the input of the other two LFs: "Provide Real-time Weather Information & Routing Recommendation" and "Provide Optimized Voyage Planning". The first LF is now linked with the LF "Use Optimized Routing & Navigation" of the logical component "GHG Emissions Reduction Solutions", providing its input as the functional exchange "real-time weather data & optimized routing". The second LF is linked with the LF "Enable Shipping Service" of the SA "Shipping Company (Shipowner)", providing its input as the functional exchange "optimized voyage".

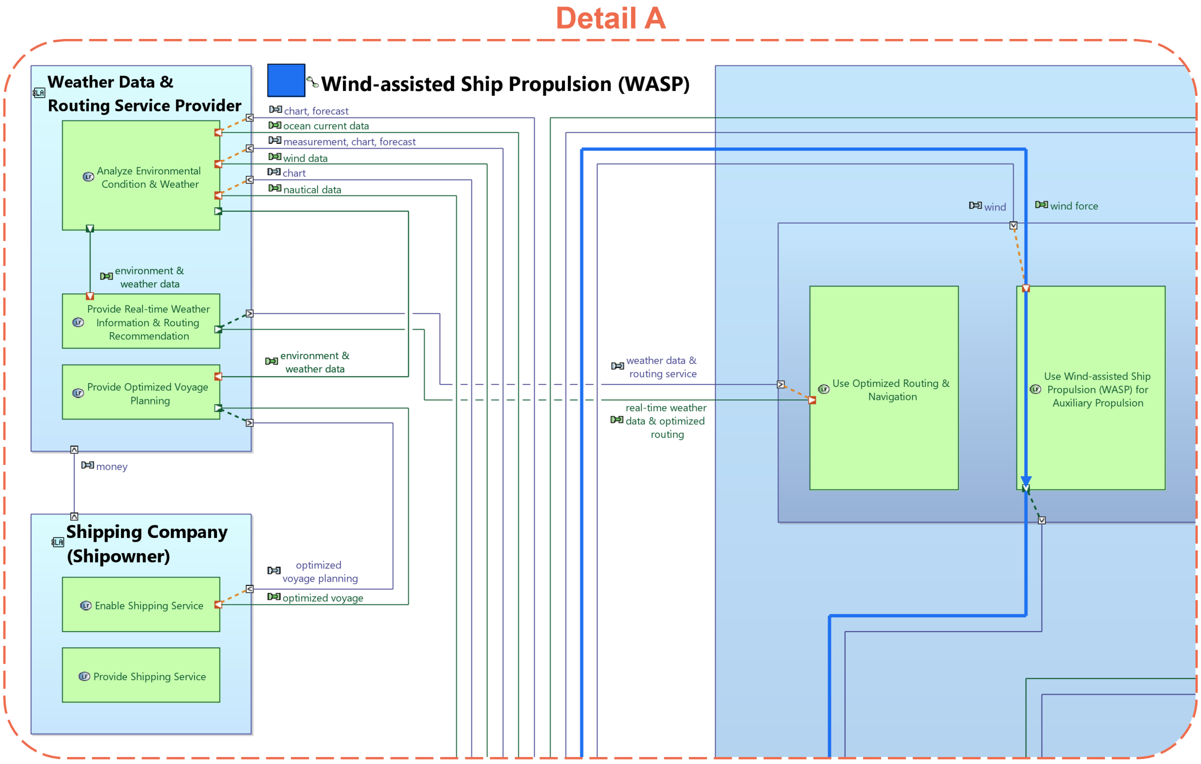

Figure 4-11: Bulk carrier – Logical architecture; Detail A – Exchanges of system actors and logical functions example

Functional chain: An example for the integration of GHG emissions reduction solution into the bulk carrier system is demonstrated by the *functional chain* "Wind-assisted Ship Propulsion (WASP)" (bold blue exchanges) in Figure 4-10; see also Figure C-15 in the Appendix. It begins with the LF "Cause Wind" of the LA "Wind", which has the output (i.e., functional exchange) "wind force" that becomes the input of the LF "Use Wind-assisted Ship Propulsion (WASP) for Auxiliary Propulsion" of the logical component "GHG Emissions Reduction Solutions". This LF now converts its input "wind force" into its output "mechanical power" (in the figurative sense). This output then becomes the input of the last LF "Provide Power to Move in Water", which is part of the logical component “Propulsion & Power Generation Systems”. In summary, this chain of logical functions and functional exchanges illustrates the process of using WASP as auxiliary propulsion on a logical level. In other words, by receiving power from the wind, the LF “Provide Power to Move in Water” reduces the power demand on the vessel's power plant, which is represented by the LF “Enable Power Generation to Move in Water & Cover Electrical Load”.[256]

Logical functions: Figure 4-12 shows a *logical function breakdown* (LFBD) diagram that provides an overview of all logical functions modeled in the logical architecture phase. These logical functions already indicate their physical realization in the next phase. For instance, the LF “Provide Power to Move in Water” will be realized by some kind of power generation system, such as a marine internal combustion engine.

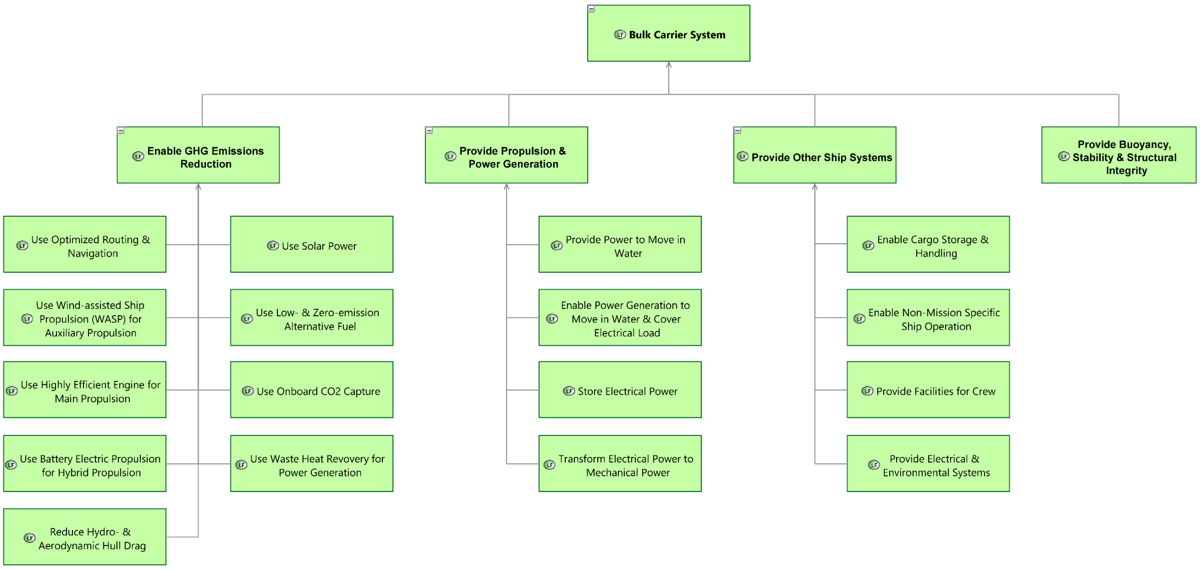

Figure 4-12: Bulk carrier – Logical functions breakdown

The *logical architecture blank* (LAB) diagram (see Figure 4-10) along with its detail cutout (see Figure 4-11), and the *logical function breakdown* (LFBD) diagram (see Figure 4-12) are the main diagrams used in the logical architecture phase of this application of the Arcadia method. In addition, a *logical data flow blank* (LDFB) diagram, and a *logical functional chain description* (LFCD) diagram are created to show and define the functional chain “Wind-assisted Ship Propulsion (WASP)”, as well as three other LFBD diagrams that show only the logical functions of each logical component. All diagrams of the LA phase are provided in the Appendix.

4.3.4 Physical Architecture (PA)

The fourth phase of Arcadia, *physical architecture* (PA), examines the system-of-interest and its subsystems from a physical point of view. The logical components identified in the previous phase, including their logical functions, exchanges, and interfaces, are used as a starting point and are now realized by their physical counterparts in the form of concrete technological options. The Arcadia/Capella principle of reusing certain model elements and transferring them into the next phase is also applied when moving from the LA phase to the PA phase through

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[256] Dreier et al. (2024)., p. 8

automated transitions provided by the Capella tool. In this phase, detailed knowledge of the system-of-interest's internal *structure* and *behavior* is required when modeling its architecture. Besides reasonable assumptions made in the course of modeling, the *SFI Group System* is used as a reference to obtain the *hierarchical view* on a bulk carrier ship system (see chapter 2.1.1).[257] The outputs of the physical architecture phase can be several types of diagrams, depending on the scope of the Capella system model.

Physical architecture: Figure 4-13 now shows the *physical architecture blank* (PAB) diagram that includes the *physical system* (P; yellow block) "Bulk Carrier with WAD", its *physical components* (i.e., subsystems) consisting of *physical behavior components* (P or PBC; dark blue blocks) and *physical node components* (P or PNC; yellow blocks), and their allocated *physical functions* (PF; green blocks), exchanges, and interfaces. The physical system is connected with external *physical actors* (PA; light blue blocks) and their physical functions. A detailed description of how to read such a *physical architecture blank* (LAB) diagram is provided in chapter 2.3.1 and Figure 2-16, where a generic example of this diagram type is described as an introduction to Capella architecture diagrams in general.

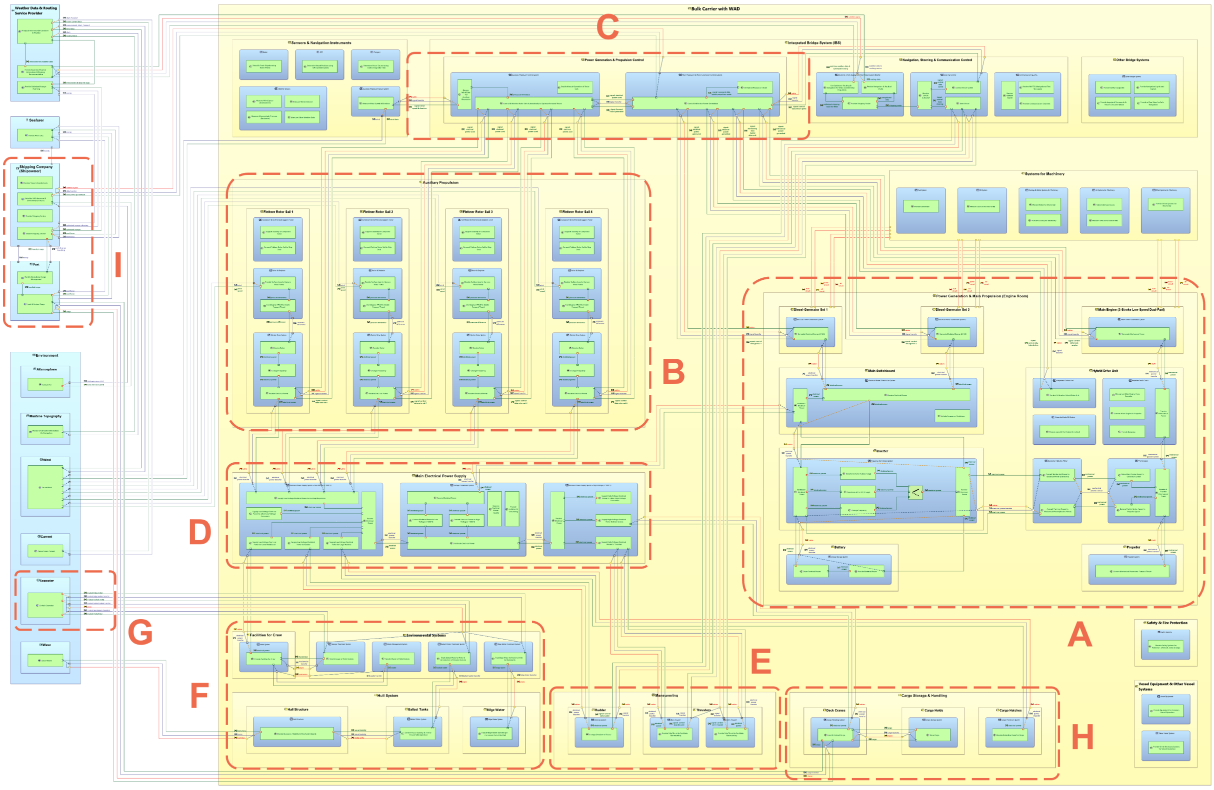

Figure 4-13: Bulk carrier – Physical architecture, inspired by *Dreier et al.*[258]

The system-of-interest is now called "Bulk Carrier with WAD", indicating the actual physical realization of the bulk carrier system that integrates a *wind-assistance device* (WAD). Since the physical architecture diagram shown in Figure 4-13 is a very large diagram that may be difficult to read as an exported image outside of the Capella tool, nine *detail cutouts* of this diagram are used to better understand its contents, which are either explained in this chapter or provided in the Appendix.

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[257] SFI. (1972). *SFI Group System*. Ship Research Institute of Norway (SFI).

[258] Dreier et al. (2024)., p. 9

- *Detail A:* “Power Generation and Main Propulsion” with highlighted “Hybrid Drive Unit” (see Figure 4-14)
- *Detail B:* “Auxiliary Propulsion” including four “Flettner Rotor Sails” (see Figure 4-15)
- *Detail C:* “Power Generation & Propulsion Control” with highlighted “Auxiliary Propulsion Control System” (see Figure 4-16)
- *Detail D:* “Main Electrical Power Supply” with highlighted “Electrical Power Supply System - Low Voltage (< 1000 V)” (see Figure 4-17)
- *Detail E:* “Maneuvering” including “Rudder” and “Thrusters” (see Figure C-26 in the Appendix)
- *Detail F:* “Facilities for Crew”, “Environmental Systems”, and “Hull System” (see Figure C-27 in the Appendix)
- *Detail G:* Exchanges of “Seawater” with “Environmental Systems” example (see Figure C-28 in the Appendix)
- *Detail H:* “Cargo Storage & Handling” including “Deck Cranes”, “Cargo Holds”, and “Cargo Hatches” (see Figure C-29 in the Appendix)
- *Detail I:* Exchanges of “Shipping Company (Shipowner)” and “Port” with “Cargo Storage & Handling” example (see Figure C-30 in the Appendix)

As explained in chapter 2.3.1 and Figure 2-16, *physical behavior components* (PBC) are deployed at *physical node components* (PNC) and host the physical functions. PBC can be used to organize additional subsystems based on their specific functional groups. Therefore, some subsystems of the SoI are modeled using a PNC that deploys multiple PBCs. Table 4-3 lists all the *physical components* (physical node components and physical behavior components) that are visible in the diagram in Figure 4-13 and provides an overview of the hierarchical *structure* of the bulk carrier system in the physical architecture phase. However, for the best understanding of the internal physical structure of the bulk carrier system, it is recommended to use this table along with the diagram directly in the Capella tool.

Table 4-3: Bulk carrier – Physical components, according to *Dreier et al.*[259]

Subsystem level 1st order		**Subsystem level 2nd order**		**Part level**	
PNC	Sensors & Navigation Instruments	*PBC*	Radar		
			GPS		
			Compass		
			Weather Sensors		
			Auxiliary Propulsion Sensor System		
PNC	Integrated Bridge System (IBS)	*PNC*	Power Generation & Propulsion Control	*PBC*	Auxiliary Propulsion Control System
					Main Propulsion & Power Generation Control Systems
			Navigation, Steering & Communication Control	*PBC*	Electronic Chart Display and Information System (ECDIS)
					Steering Control
					Communication Systems
			Other Bridge Systems	*PBC*	Other Bridge Systems

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[259] Dreier et al. (2024)., p. 9 f.

PNC	Auxiliary Propulsion	*PNC*	*4x* Flettner Rotor Sail	*PBC*	Foundation & Internal Steel Support Tower
					Rotor & Endplate
					Electric Drive System
PNC	Systems for Machinery	*PBC*	Fuel System		
			Oil System		
			Cooling & Water Systems for Machinery		
			Air Systems for Machinery		
			Other Systems for Machinery		
PNC	Power Generation & Main Propulsion (Engine Room)	*PNC*	*2x* Diesel-Generator Set	*PBC*	Electrical Power Generation System
			Main Engine (2-Stroke Low Speed Dual-Fuel)	*PBC*	Main Power Generation System
			Main Switchboard	*PBC*	Electrical Power Distribution System
			Hybrid Drive Unit	*PBC*	Integrated Control Unit
					Integrated Lube Oil System
					Propeller Shaft Clutch
					Generator / Electric Motor
					Transmission
			Inverter	*PBC*	Frequency Conversion System
			Battery	*PBC*	Energy Storage System
			Propeller	*PBC*	Propeller System
PNC	Main Electrical Power Supply	*PBC*	Electrical Power Supply System - Low Voltage (<1000 V)		
			Voltage Conversion System		
			Electrical Power Supply System - High Voltage (>1000 V)		
PNC	Facilities for Crew	*PBC*	Hotel System		
PNC	Environmental Systems	*PBC*	Sewage Treatment System		
			Waste Management System		
			Ballast Water Treatment System		
			Bilge Water Treatment System		
PNC	Hull System	*PNC*	Hull Structure	*PBC*	Hull Structure
			Ballast Tanks	*PBC*	Ballast Water System
			Bilge Water	*PBC*	Bilge Water System
PNC	Maneuvering	*PNC*	Rudder	*PBC*	Steering System
			Thrusters	*PBC*	Bow Thruster
					Stern Thruster

PNC	Cargo Storage & Handling	*PNC*	Deck Cranes	*PBC*	Cargo Handling System
			Cargo Holds	*PBC*	Cargo Storage System
			Cargo Hatches	*PBC*	Cargo Protection System
PNC	Safety & Fire Protection	*PBC*	Safety Systems		
PNC	Vessel Equipment & Other Vessel Systems	*PBC*	Vessel Equipment		
			Other Vessel Systems		

The *physical architecture blank* diagram shown in Figure 4-13 is now by far the largest diagram created in the Capella system model of a bulk carrier. This is because a modern bulk carrier consists of a high number of different subsystems, as briefly mentioned when explaining the concept of a *system architecture* using a generic bulk carrier in chapter 2.1.3 and Figure 2-6. The complete visualization of the hierarchical *structure* and *behavior* of all these subsystems in a single architecture diagram subsequently leads to a large diagram size. However, managing the large number of subsystems, including their exchanges and interfaces, that form a complex system to fulfil the main mission of the vessel is a highly challenging task for the ship designer. A large physical architecture diagram, such as the one shown in Figure 4-13, can help the designer keep track of all the subsystems, parts, and their interfaces.[260]

Depending on the scope of the Capella system model, several physical architecture diagrams can be created, each focusing on a different aspect, such as showing only the subsystems at *first order level* or excluding the functional view altogether. However, the interconnectedness of all subsystems is best shown in a single diagram. The Capella tool always provides the possibility of using *filters* to hide specific model elements, such as specific exchanges or all physical functions, thus reducing the amount of information in such a large diagram and improving its readability. This feature can also be used to hide unnecessary information that may not be of value to certain diagram readers.

The exchanges in a *physical architecture blank* diagram belong to the three types of *physical link*, *component exchange*, and *functional exchange*, as shown in Figure 2-16. In technical processes, functional exchanges represent three types of inputs/outputs (i.e., object flow) of a function: *Energy*, *material*, and *signal*; see chapter 2.1.2 and Figure 2-4.[261] An analysis of all these exchanges, including their interfaces at the physical components, can be performed using *model-generated tables* or *matrices* that are based on a highly detailed physical architecture diagram.[262] The Capella tool also provides several model validation options that ensure the correct application of the Arcadia method and language.

Main propulsion and power generation system: *Detail A* of the physical architecture diagram, shown in Figure 4-14, focuses on the physical node component (PNC) “Power Generation & Main Propulsion (Engine Room)”, which is a subsystem at *first order level* of the bulk carrier system. It provides an overview of its own subsystems at *second order level*, such as the PNCs “Diesel-Generator Set 1”, “Diesel-Generator Set 2”, “Main Engine (2-Stroke Low Speed Dual-Fuel)”, “Main Switchboard”, “Hybrid Drive Unit”, “Inverter”, “Battery”, and “Propeller”, see also Table 4-3. The physical functions of the physical behavior components (PBC) deployed at the PNCs and all exchanges (i.e., physical links, component exchanges, functional exchanges) are also shown to provide a complete picture of this subsystem’s *structure* and *behavior*.[263]

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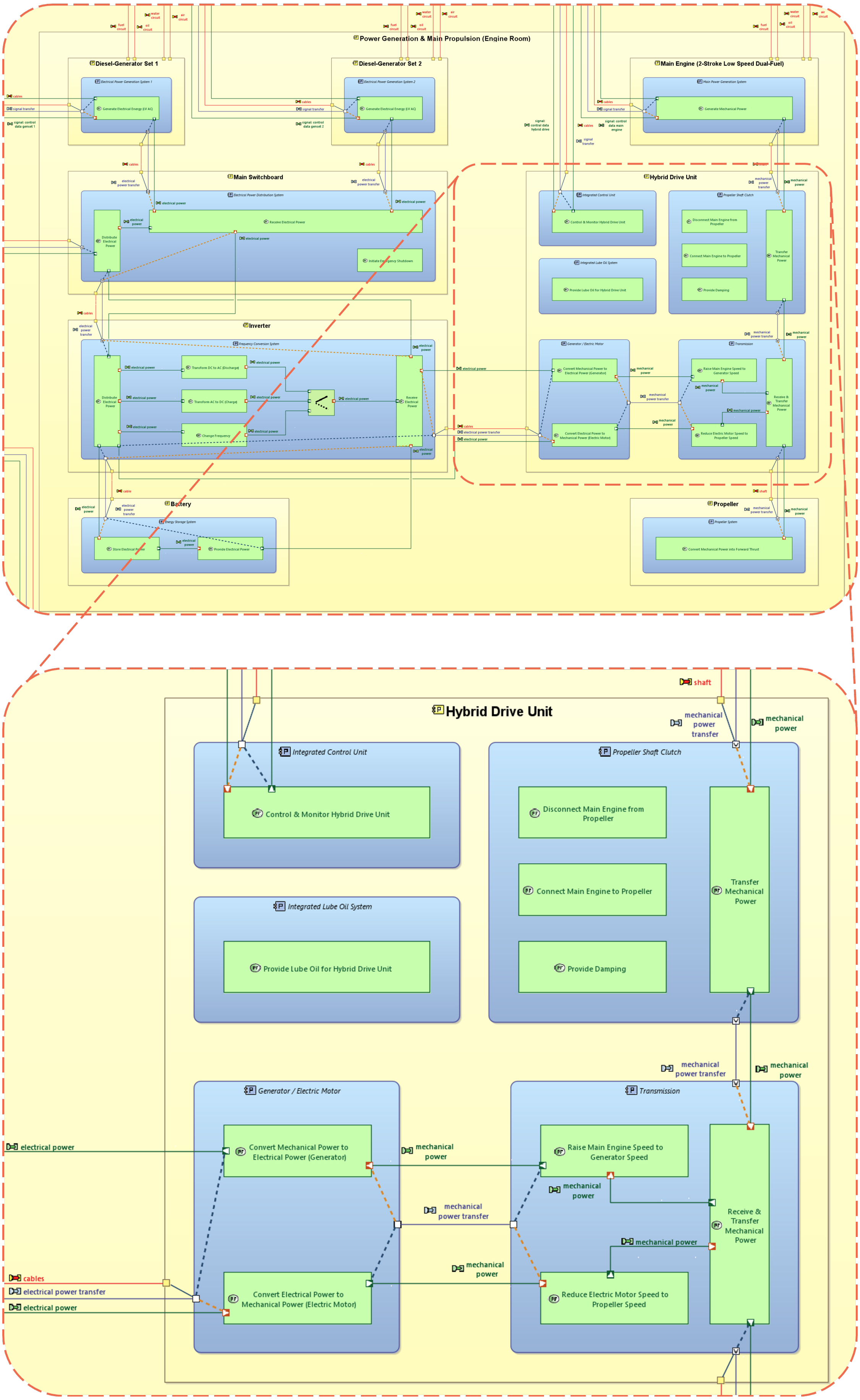
[260] Le Néna et al. (2019)., p. 127

[261] Feldhusen et. al (2016)., p. 691

[262] Kossiakoff et al. (2020)., p. 258

[263] Dreier et al. (2024)., p. 9 f.



Detail A

Figure 4-14: Bulk carrier – Physical architecture; Detail A – “Power Generation and Main Propulsion” with highlighted “Hybrid Drive Unit”

The technology used for main propulsion can be defined as a *dual-fuel diesel/methanol-electric hybrid propulsion system*. *Diesel-electric marine propulsion* systems use diesel engines and generators (diesel-generator sets or gensets) to produce electricity, which power electric motors for propulsion and cover the ship's hotel load or other onboard power needs.[264] *Hybrid marine propulsion* systems combine conventional internal combustion engines and gensets with energy storage systems such as batteries.[265] This hybrid form of propulsion and power generation may not be the best option for a conventional dry bulk carrier (defined as the system-of-interest in chapter 4.3.2) from today's economic perspective, as the initial cost are higher and the added weight of components such as a battery effectively reduces the possible cargo payload. As already mentioned in the system analysis phase when discussing the *requirements* in marine transportation, marine shipping is primarily a *profit-oriented* industry. However, the choice of hybrid propulsion in combination with a high-efficiency, low-speed, dual-fuel, 2-stroke main engine and two diesel-generator sets is made for *two reasons*: On the one hand, this propulsion system is retrofittable to existing conventional fuel vessels and can be operated with net-zero GHG emissions when using green methanol fuel for the more efficient main engine, with the less efficient diesel-generators sets at standstill.[266, 267] On the other hand, a hybrid propulsion system integrates several different components (i.e., electric motors/generators, transmissions, internal combustion engines, etc.).[268] The development of such a complex system and the integration into its supersystem (i.e., the ship) is a showcase that can be supported by MBSE and system models, including architecture diagrams such as the one shown in Figure 4-14. The topic to use MBSE in the maritime industry is discussed further in chapter 5.

The architecture of the PNC "Power Generation and Main Propulsion" is largely inspired by a *maritime hybrid drive* developed by the German company *RENK*. The PNC "Hybrid Drive Unit" shown in the enlarged part of Figure 4-14 consists of several subsystems at *part level*, such as "Propeller Shaft Clutch", "Transmission", or "Generator / Electric Motor", among others. The hybrid drive has *three operating modes*:

- *Power-Take-Home (PTH) mode:* The main engine (ME) is at standstill (i.e., declutched from the propeller shaft), while the gensets alone cover the main propulsion and hotel load via the inverter and the electric motor. This mode is mainly used when the ME fails to safely reach a port.
- *Power-Take-In (PTI) mode:* The ME is running, while the gensets supply booster power via the inverter and the electric motor. This mode is used to increase ship speed or maneuverability.
- *Power-Take-Off (PTO) mode:* The ME is running at its 70 – 100% speed range (with fixed pitch propeller), while the gensets are at standstill. The electric motor operates as a generator, and the ME covers the main propulsion and hotel load alone via the generator and the inverter. This mode takes advantage of the ME's superior fuel efficiency.[269]

Mode and state diagrams (see Figure 2-14) can be used to graphically represent *state machines* that show which physical functions are available in which states of the PNC "Hybrid Drive Unit".

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[264] Molland, A. F. (2008)., p. 375 ff.

[265] MAN Energy Solutions. (2023). *Hybrid marine propulsion systems.* Augsburg. Germany: MAN Energy Solutions., p. 1 f.

[266] JSA. (2022a)., p. 10

[267] MAN Energy Solutions. (2024). *The world's first two-stroke methanol engine.*

[268] MAN Energy Solutions. (2021). *Shaft generators for low speed main engines.* Copenhagen. Denmark: MAN Energy Solutions., p. 6

[269] RENK. (2023). *MARHY – Maritime hybrid drive. An efficient propulsion system for ships.* Rheine. Germany: RENK., p. 5

Auxiliary propulsion system: *Detail B* of the physical architecture diagram, shown in Figure 4-15, focuses on the physical node component (PNC) “Auxiliary Propulsion”, which is a subsystem at *first order level* of the bulk carrier system. This PNC consists of four identical PNCs “Flettner Rotor Sail” at *second order level*, each of which hosts the three physical behavior components (PBC) “Foundation & Internal Steel Support Tower”, “Rotor & Endplate”, and “Electric Drive System” at *part level*.[270]

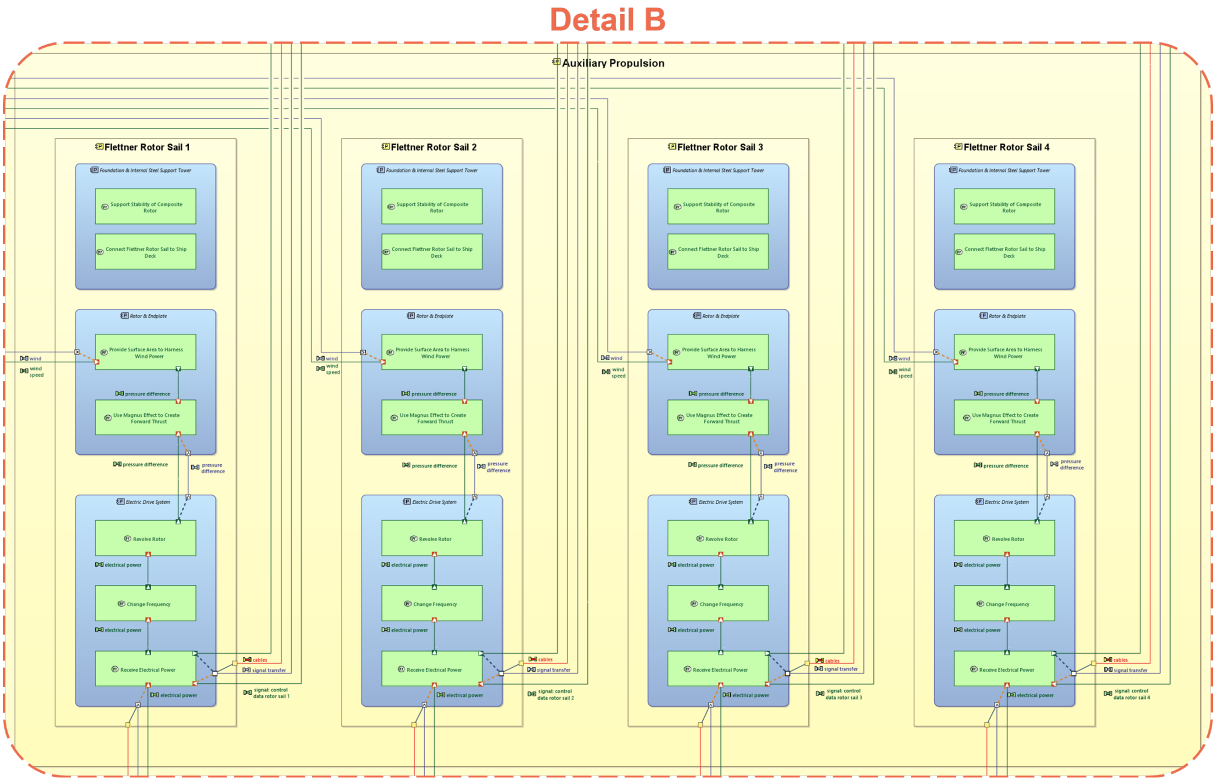

Figure 4-15: Bulk carrier – Physical architecture; Detail B – “Auxiliary Propulsion” including four “Flettner Rotor Sails”

Table 4-4 lists those three PBC subsystems and their allocated physical functions to provide an overview of the *structure* and *behavior* of a *Flettner rotor sail system* as defined in the physical architecture phase.

Table 4-4: Bulk carrier – Physical components and functions of a Flettner rotor sail, according to *Dreier et al.*[271]

Physical components		**Physical functions**
PBC	Foundation & Internal Steel Support Tower	Connect Flettner Rotor Sail to Ship Deck
		Support Stability of Composite Rotor
PBC	Rotor & Endplate	Use Magnus Effect to Create Forward Thrust
		Provide Surface Area to Harness Wind Power
PBC	Electric Drive System	Receive Electrical Power
		Change Frequency
		Revolve Rotor

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[270] Interreg North Sea Europe. (2024). *WASP: Wind Assisted Ship Propulsion.*

[271] Dreier et al. (2024)., p. 9

An introduction to *wind-assisted ship propulsion* (WASP) and examples for other sailing technology concepts besides rotor sails are provided in chapter 3.3.3 and are shown in Figure 3-6.

Control system: *Detail C* of the physical architecture diagram, shown in Figure 4-16, focuses on the physical node component (PNC) “Power Generation & Propulsion Control”, which is a subsystem at *second order level* of the PNC “Integrated Bridge System (IBS)” at *first order level*, see also Table 4-3. This PNC consists of the two physical behavior components (PBC) “Main Propulsion & Power Generation Control Systems” and “Auxiliary Propulsion Control System” at *part level*. These two subsystems are closely linked with the subsystems shown in *Detail A* (see Figure 4-14) and *Detail B* (see Figure 4-15) and provide the control data in the form of functional exchanges such as “signal: control data rotor sail 1” or “signal: control data main engine”.[272]

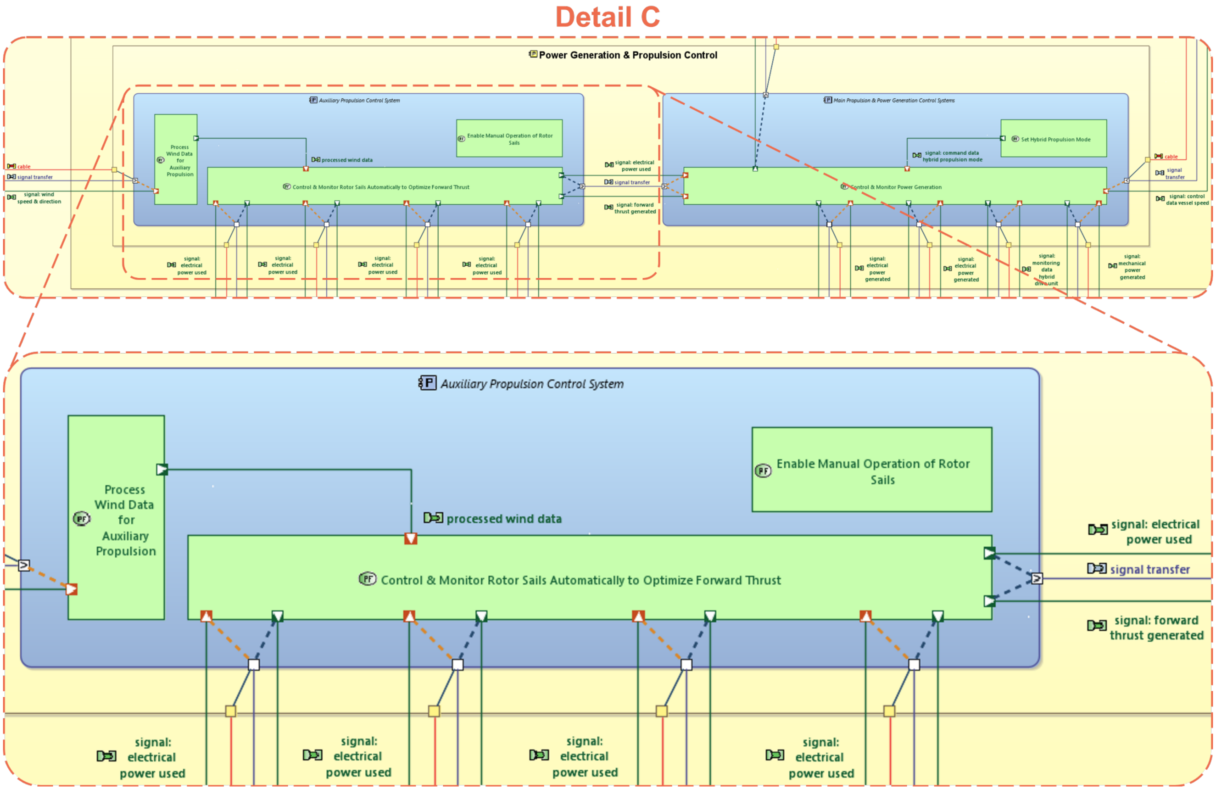

Figure 4-16: Bulk carrier – Physical architecture; Detail C – “Power Generation & Propulsion Control” with highlighted “Auxiliary Propulsion Control System”

Wind-assistance devices (WAD), such as *Flettner rotor sails*, use advanced control and automation systems that allow the WAD to be operated without additional crew. These systems automatically activate the electric motor that turns the rotor sail only when sufficient wind is detected. The rotation of the rotor is necessary to create the Magnus effect and generate forward thrust, as explained in chapter 3.3.3. This intelligent control is indicated by the two physical functions “Process Wind Data for Auxiliary Propulsion” and “Control & Monitor Rotor Sails Automatically to Optimize Forward Thrust” that are allocated to the PBC “Auxiliary Propulsion Control System” shown in the enlarged part of Figure 4-16.[273]

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[272] Dreier et al. (2024)., p. 9 f.

[273] DNV. (2023)., p. 31 f.

Electrical power supply system: *Detail D* of the physical architecture diagram, shown in Figure 4-17, focuses on the physical node component (PNC) “Main Electrical Power Supply”, which is a subsystem at *first order level* of the bulk carrier system. This PNC consists of the three physical behavior components (PBC) “Electrical Power Supply System - Low Voltage (<1000 V)”, “Voltage Conversion System”, and “Electrical Power Supply System - High Voltage (>1000 V)” at *second order level*. The PBC “Voltage Conversion System” and its allocated physical functions receive the functional exchange “electrical power” from the PBC “Electrical Power Distribution System” of the PNC “Main Switchboard” shown in *Detail A* (see Figure 4-14). In other words, the *electrical power* generated by the main engine (via a generator and inverter) and by the two diesel-generator sets is transferred to the PNC “Main Electrical Power Supply”, where it is distributed to all the *low voltage* (e.g., auxiliary propulsion, hotel load, rudder, cargo hatches, etc.) and *high voltage* (e.g., deck cranes, thrusters, etc.) consumers.[274]

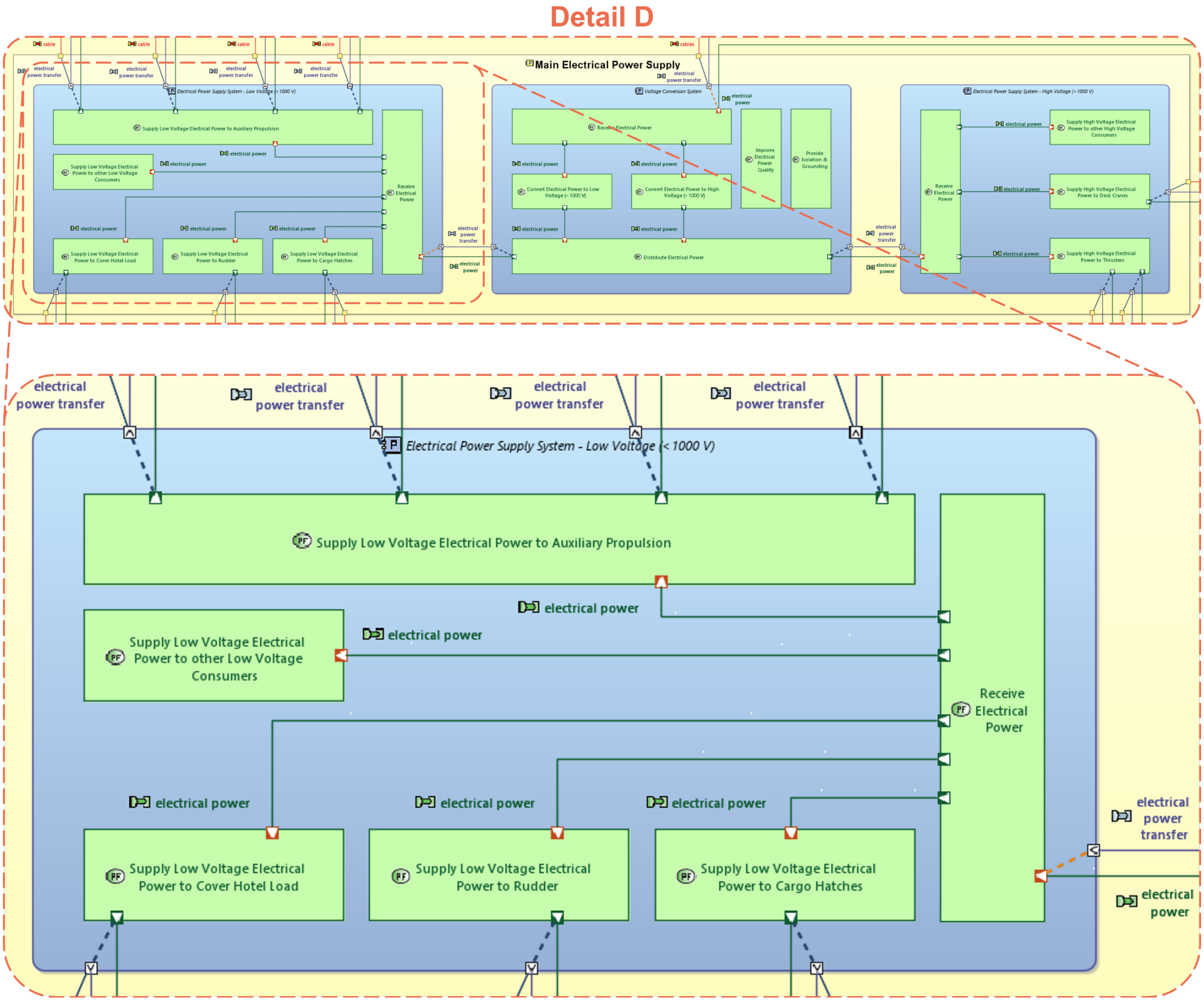

Figure 4-17: Bulk carrier – Physical architecture; Detail D – “Main Electrical Power Supply” with highlighted “Electrical Power Supply System - Low Voltage (< 1000 V)”

The *physical architecture blank* (PAB) diagram (see Figure 4-13) along with four of its detail cutouts (*Details A*, *B*, *C*, and *D*) is the only diagram used in the physical architecture phase of this application of the Arcadia method. In addition, the detail cutouts *Details E*, *F*, *G*, *H*, and *I* show other selected subsystems of the bulk carrier. The PAB diagram with all its detail cutouts is provided in the Appendix.

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[274] Dreier et al. (2024)., p. 9 f.

5 Digital Transformation of the Maritime Industry

The creation of two Capella system models through the application of the Arcadia method on a student solar boat race and on the maritime industry's transportation sector in chapter 4 is a showcase for the application and introduction of the MBSE methodology to a rapidly changing industry. On the one hand, the economic and geopolitical fragility of this industry is revealed by the disruptions to global supply chains and maritime trade caused by events such as the COVID-19 pandemic or the still ongoing humanitarian crises in Ukraine and Gaza, as discussed in the introductory chapter 1. On the other hand, another major challenge for the maritime industry is the need to *decarbonize* its transportation sector. Marine shipping accounts for ~11% of global transportation CO_2e emissions in 2020 (see Figure 1-1), and the GHG emissions reduction solutions, together with pathways to net-zero GHG emissions in this sector until 2050 (e.g., the *2023 IMO's strategy*), are explored in chapter 3.3. These new solutions include *low- and zero-emission alternative fuels and propulsion technologies* (e.g., hydrogen, ammonia, WASP), *energy saving technologies* (e.g., air lubrication systems, PID) or *operational measures* (e.g., optimized routing/navigation, slow steaming) that need to be integrated and aligned within a wide network of different stakeholders. As the *classic ship design* process (see chapter 3.2 and Figure 3-2) lacks in describing the operational context, stakeholder interactions, or alternative design options, new ways are needed to manage the increasing complexity in ship development. The introduction if MBSE into the maritime industry through the integration of a *descriptive system model* into the ship development process is a promising strategy that directly contributes to the *digital transformation* of this industry.

5.1 MBSE in the Maritime Industry

Model-based systems engineering (MBSE) is a methodology in systems development that promotes a model-based (rather than a document-based) and multidisciplinary approach. The general *need* to introduce MBSE, its potential *adoption barriers*, and expected *benefits* are explored in chapter 2.2. A review of the as-is situation of MBSE adoption in the maritime industry indicates that this industry has not yet fully embraced modern methodologies in comparison to other industries such as defense, aerospace, or automotive, as discussed in chapter 1 and shown in the *MBSE adoption trends* in Figure 1-2.

However, initiatives such as the *Maritime and Ocean Digital Engineering Laboratory* (MODE Lab), an international project for the decarbonization and automation of the shipping industry based at the University of Tokyo in Japan, show that there is some momentum for MBSE to be recognized in the maritime industry. The MODE Lab aims to realize its goals by creating a "*Maritime Digital Engineering*" collaborative development process among all involved stakeholders, which is made possible by introducing MBSE together with *model-based development* (MBD) methodologies to the maritime industry.[275] This is a direct response to the challenges of the industry and a clear indication that the current methodologies used in ship development are not up to the task.

Another example for the recognition of the value that MBSE can bring to ship development is demonstrated by a case study conducted by the *Naval Group*, a French shipbuilding

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[275] MODE Lab. (2024).

industrial group. Naval Group adopted a *model-driven engineering* approach using the Capella MBSE tool to more efficiently manage its complex and evolving systems, significantly improving *collaboration*, *traceability* and *early validation* of system designs. Capella's open architecture and technology enabled digital continuity between specialists in different engineering *disciplines* and supported a common understanding of system specifications. The Capella tool is at the core of a *simulation-driven engineering platform*, using standards to interoperate with different types of simulation tools. This integration allowed for extensive early simulation, which reduced late-stage problems and improved interoperability.[276] Further case studies of MBSE adoption using the Capella tool are available.[277]

The latest *Review of Maritime Transport* provided by *UNCTAD* emphasizes that the ongoing *digitalization* of marine shipping is a key enabler for its *decarbonization*. It concludes that improved *stakeholder collaboration*, *energy-saving technologies*, and the transition to *low- and zero-emission alternative fuels* can be unlocked by the combination of digitalization and technology through the use of digital tools.[278] The Capella modeling tool is such a digital tool that can contribute to the digitalization of the maritime industry (e.g., ship development), but also support a collaborative, operations- and stakeholder-oriented approach. These topics, including the usage of the Capella system model as a center of development, its integration into the ship development process, and further use cases will be discussed in the following chapters, as defined in chapter 4.1 and Figure 4-1.

5.1.1 Operational Context & Stakeholder Interaction

In the *classic ship design* process, the development usually starts with a set of requirements that define the capabilities a ship must fulfill. Based on this, a so-called *type ship* (i.e., an existing ship that performs most of the functions of the new ship) is also used as a reference (see chapter 3.2). This procedure often leads directly to specific technological implementation choices at an early stage of development, largely overlooking the broader *operational context* together with its *stakeholder interactions*. In the past, the operational context of ship development remained the same for long periods of time, with only slow and incremental changes in the requirements and functions of the ships to be developed compared to today's rapid transitions. As the ships being developed were well understood, there was no need to consider their context and their functions in much detail before directly advancing to the design phase of the ship.[279] However, the challenge of decarbonization is leading to the introduction of innovative *low- and zero-emission alternative fuels and propulsion technologies*, *energy-saving technologies*, or *operational measures* (see chapter 3.3.2). These new GHG emissions reduction solutions, together with the rapidly changing regulations in the maritime industry (see chapter 3.3.1), require a collaborative, holistic, operational and functional analysis-based design approach. A thorough analysis of the system's operational context and stakeholders, as performed in the *operational analysis* phase of the Arcadia method, can reveal overlooked areas, stakeholders, or interactions that may not have been considered yet in previous solutions that followed the classic ship design spiral (see Figure 3-2). Such an analysis can help align the system with its *mission* and actual operational use, thereby following the *thinking in systems* principle (see chapter 2.1.1).

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[276] Naval Group. (2023). *From Document-Driven to Digital-Native Engineering.* In: Capella Case Studies., p. 1 f.

[277] Eclipse Foundation. (2024c).

[278] UNCTAD. (2023)., p. 74

[279] Gale. (2003)., p. 5-31 f.

Examples for such an analysis of the SoI's operational context conducted in this master's thesis are, on the one hand, the *operational architecture blank* (OCB) diagram created for the context of a student solar boat race (see Figure 4-2), and, on the other hand, the *operational capabilities blank* (OCB) diagram of the maritime industry's transportation sector (see Figure 4-4). These Arcadia diagram types, along with simple *operational entity breakdown* (OEBD) diagrams, are an easy yet powerful way to model the context and environment of the SoI.

Referring back to the theoretical investigations in chapter 2, in particular *Ropohl's* views of a system (structural, hierarchical, and functional view), Figure 2-2 shows the system in its environment (i.e., supersystem). A practical example is provided in Figure 4-6 which shows the bulk carrier system embedded in its operational context. However, depending on the chosen *system level* for the system-of-interest, the respective *supersystem* changes accordingly. For example, when applying the Arcadia method not on the bulk carrier system itself, but on one of its subsystems, e.g., the main propulsion and power generation system, the bulk carrier system becomes the supersystem and thus, the operational context. This particular change of the system level can happen if the point of view is the stakeholder "Marine Equipment Company", and not "Shipbuilding Company", as shown in the enlarged part of Figure 4-4. The integration of the SoI into a more technical supersystem, consisting of environmental systems and elements, can also be supported by the Arcadia method as part of a comprehensive MBSE approach in system development.

Considering the operational context and the interaction of its stakeholder in a more comprehensive way can break down *stakeholder silos* and promote a *shared view* on the system-of-interest. Building more efficient and zero-emission vessels requires optimizing *entire systems*, not just individual components, as illustrated by the different technologies for ZEVs in Figure 3-5. Understanding the ship's *mission* and how its stakeholders interact is crucial to finding effective solutions. Therefore, collaboration and a holistic perspective are essential in the rapidly changing maritime industry.

5.1.2 Capella System Model as a Center of Development

The research conducted in this master's thesis leads to the conclusion that a Capella system model can be used to implement a comprehensive MBSE approach and act as a *center of development*. *Kossiakoff et al.* emphasize the potential of using system models at any stage of a system's lifecycle.[280] Although the MBSE methodology is becoming more widely accepted in many industries, it has not yet been adopted in the maritime industry. However, some initiatives and case studies in ship development are beginning to recognize the value of MBSE and descriptive system models, such as the *MODE Lab* or the *Naval Group*.

Building on the theoretical investigations and practical applications of previous chapters – primarily the stakeholders in the environment-oriented view (see chapter 2.1.4) and the „model cube" (see chapter 2.2.1) – the three categories of *stakeholder*, *discipline*, and *technical domain* are identified in the context of a Capella system model. These categories are shown in Figure 5-1, along with examples of each category that can benefit from or make use of a shared and centralized Capella system model. Referring back to the targets and purposes of system models as defined by *Bajzek et al.* in chapter 2.2.1, such a central system model can be used to *"establish the view across disciplines […]", "enable the view across technical domains […]", "provide a platform for stakeholder communication […]", "provide access to key information […]",* and *"compile the system documentation from day 1 […]"*.[281]

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[280] Kossiakoff et al. (2020)., p. 262

[281] Bajzek et al. (2021b)., p. 219 ff.

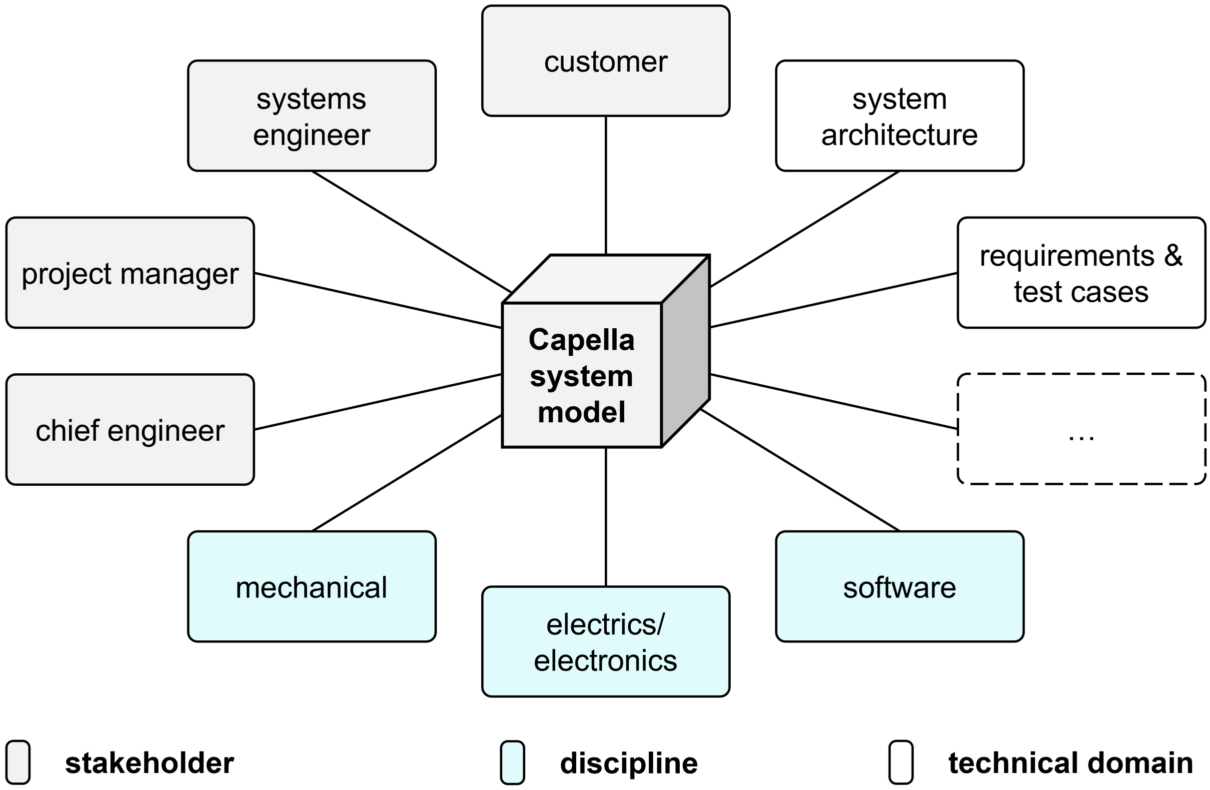

Figure 5-1: Capella system model as a center of development

Stakeholders such as the customer, systems engineers, project managers, or chief engineers, etc., often have different educational backgrounds and varying levels of technical expertise, also depending on the disciplines or technical domains in which they typically work. Using a central Capella system model as a collaboration platform can support a shared understanding of the system-of-interest among these stakeholders. This is even more relevant today, as systems that were once primarily mechanical now include more electrics/electronics and software components, resulting in greater system complexity. The development of zero-emission or automated ships is an example of this trend in the maritime industry.

Disciplines such as mechanical, electrics/electronics, and software, etc., each have a different view on the system-of-interest. Multiple different views can be combined in a central Capella system model, enabling more efficient cross-discipline collaboration and system development by breaking down discipline-specific silos.

Technical domains such as the system architecture, requirements, test cases, etc., and their respective artifacts (e.g., a physical architecture component or a requirement) can be linked through a central Capella system model in combination with a comprehensive product lifecycle management (PLM) system. Linking artifacts in development such as requirements and test cases (V&V) allows for improved traceability and documentation through all phases of the development process.

5.2 Integration of a Capella System Model into the Ship Development Process

After creating two Capella system models through the application of the Arcadia method in chapter 4, the next step in introducing MBSE to the maritime industry is to integrate a Capella system model into the ship development process. This also builds on the findings of the previous chapter 5.1 and its proposal to use a Capella system model as a center of development. There is also a strong motivation to push the theoretical findings of *systems engineering fundamentals* including MBSE in chapter 2 to practical applications in a rapidly changing industry. The thorough operational analysis together with the multiple viewpoint-driven architectural design promoted by the Arcadia method can support stakeholder alignment and the subsequent development of next-generation zero-emission vessels (ZEVs), thereby contributing to the digitalization and decarbonization of marine shipping.

5.2.1 Ship Development with the V-Model & the Arcadia Method

The *V-model* is a plan-driven procedural model for the development of cyber-physical mechatronic systems, which has been introduced in chapter 2.1.5. Since the *classic ship design process* with its *design spiral* (see chapter 3.2) is considered unsuitable to respond to the identified new challenges of the maritime industry, the V-model is the procedural model of choice to integrate a *descriptive system model* such as a Capella system model together with the underlying Arcadia method. The selection of the V-model in the context of modern ship development is also demonstrated by *Nakashima et al.* as part of a study that presents a *model-based design* and *safety evaluation* method for future autonomous vessels.[282]

Figure 5-2 shows a variation of the V-model linked to a Capella system model and the four Arcadia phases of *operational analysis* (OA), *system analysis* (SA), *logical architecture* (LA), and *physical architecture* (PA). The V-model is further extended with *product lifecycle management* (PLM), which is necessary to manage all product data and artifacts created throughout the entire lifecycle of the system. *Processes*, *methods*, *organization*, and *tools* – the so-called "*four interlocking pillars*" – are another extension and form the pillars that are needed to support the industrial application of systems engineering.[283]

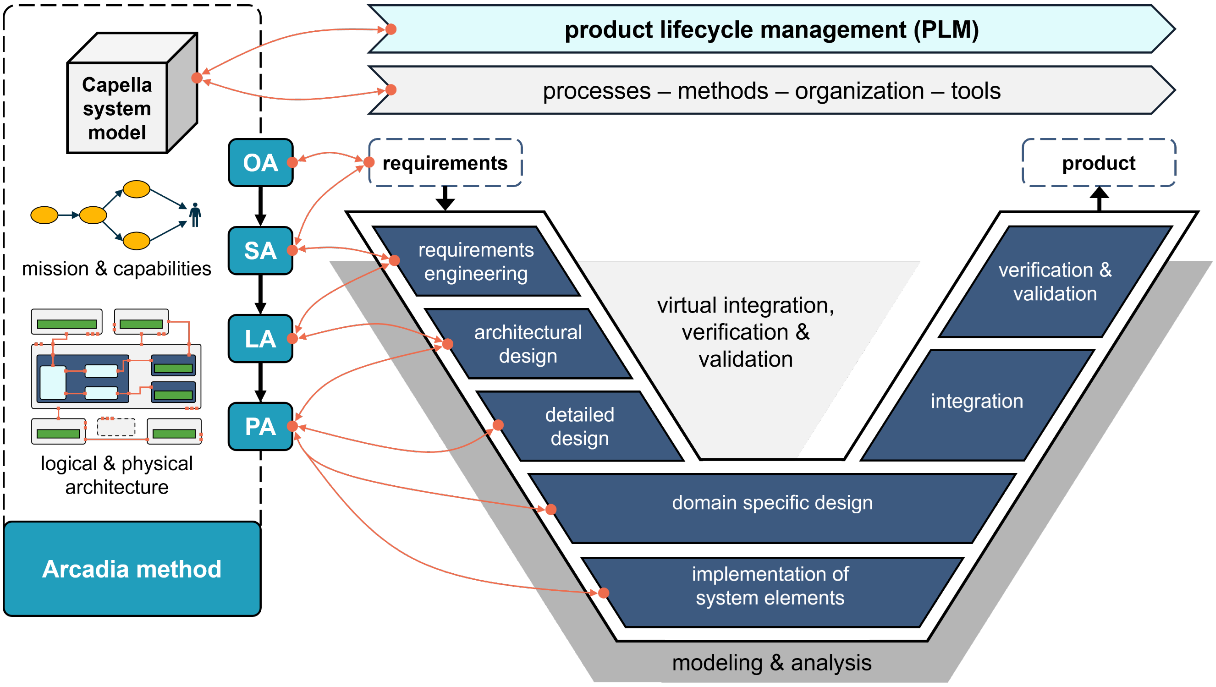

Figure 5-2: Ship development with the V-model and the Arcadia method, inspired by *Bajzek et al.*[284]

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[282] Nakashima, T., Kutsuna, K., Kureta, R., Nishiyama, H., Yanagihara, T., Nakamura, J., . . . Kuwahara, S. (2022). *Model-Based Design and Safety Assessment for Crewless Autonomous Vessel.* In: Journal of Physics: Conference Series - Volume 2311 (J. Phys.: Conf. Ser. 2311 012024)., p. 4

[283] Bajzek et al. (2021a)., p. 186 f.

[284] Bajzek et al. (2021c)., p. 254

Both PLM and the four interlocking pillars stretch over the length of the V-model from beginning to end and are linked to the Capella system model to symbolize their connection. For example, the Capella system model is created by the Capella modeling *tool* and integrates the Arcadia *method*. However, linking artifacts created in different software tools (e.g., simulation or CAD/CAE tools) to Capella system model artifacts such as physical components requires a sophisticated PLM solution. The links of the Arcadia method with steps in the V-model such as *requirements engineering*, *architectural design*, or *detailed design*, symbolize the use of Arcadia phase outputs for further development activities as determined by the V-model. For example, the thorough analysis of the operational context and stakeholder interactions performed in the OA phase serves as an input for the formulation of requirements in the V-model.

According to *Gale*, naval architects and marine engineers are also systems engineers, but the increased complexity of modern ship design requires more sophisticated functional and systems analysis than traditional methods. Marine engineers as part of a multi-disciplinary team must now actively participate in these systems engineering activities to effectively design modern vessels.[285] The V-model, expanded and linked with the Arcadia method, PLM, and the four interlocking pillars of processes, methods, organization, and tools, can provide a basis for deriving an optimized ship development process that better meets the needs of current and future ship development.

5.2.2 System Architecture for Documentation & Traceability

The integration of a Capella system model into the ship development process allows for multiple *use cases*, including a high-quality digital documentation of the ship system, the use of specific diagrams (e.g., architecture diagrams), single model elements (e.g., logical/physical components and functions), or built-in Capella functionality (e.g., the semantic browser).

For example, the *digital documentation* of the system architecture (logical and physical phase) in a system model makes it both *reusable* and *retrievable*. Not only can the system architecture itself be documented, but it can also be used to store information such as technical specifications, simulation parameters, or even simple links to documents. This type of information is usually only available indirectly, for example as part of a *text-based* document. In general, all information stored in the Capella system model can be exported using automated reports created with the *python4capella* add-on.[286]

The architecture diagrams (and other diagrams) created with the Capella modeling tool can be used not only as a communication and validation tool with the customer for a mutual understanding of the system, but also as a *deliverable* for the customer itself, which further enhances the value of the modeling activities. In addition, the system architecture can be used for *traceability* of various development artifacts created over the course of the V-model, such as *requirements*, *use cases*, and *test cases*, providing a continuous *digital thread*. The operational analysis phase can be the basis for eliciting *requirements* and *use cases* (i.e., system capabilities), while the logical/physical components and functions modeled in an architecture diagram can be used for modeling *malfunctions*. These identified malfunctions can lead to *system errors*, which can then be used to derive specific *test cases* to check for these errors. The linking of single model elements – e.g., linking logical/physical components and functions modeled in an architecture diagram with requirements and system capabilities – can be done directly in the Capella tool. However, a continuous management of these artifacts,

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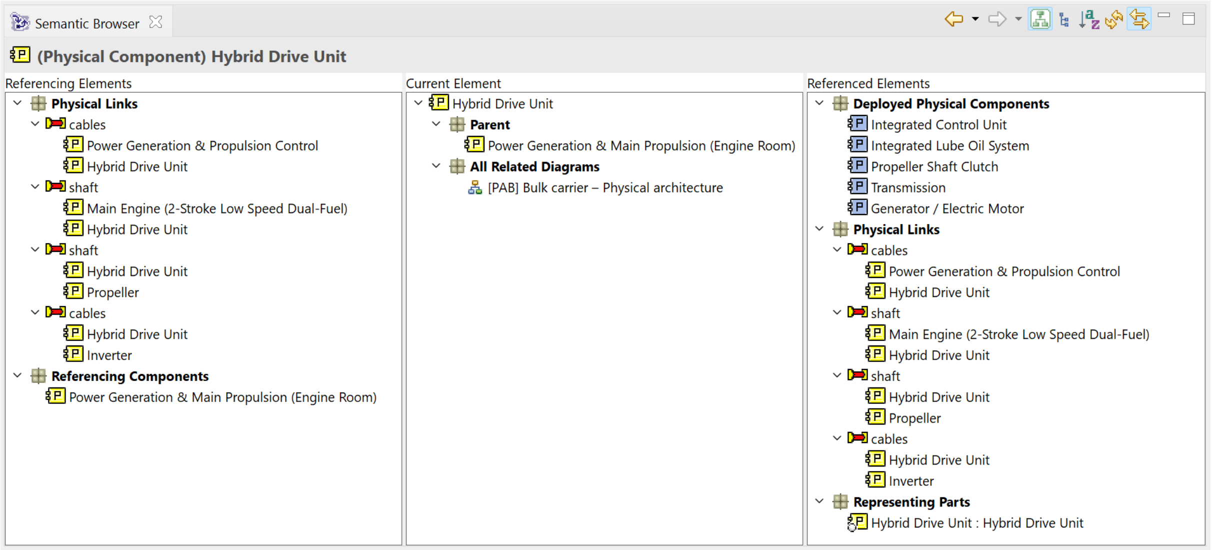
[285] Gale. (2003)., p. 5-31 f.

[286] Eclipse Foundation. (2024c). *MBSE Capella.*

especially across different software tools, requires a sophisticated product lifecycle management (PLM) solution that integrates all tools.

Figure 5-3 shows the *semantic browser* that is part of the Capella user interface. The semantic browser supports easy browsing of the system model and provides full *traceability*. When a model element (such as a physical component) is selected, the semantic browser displays all references associated with that element, including its containment or reference relationships and any diagrams in which the element is contained. The example model element shown in the semantic browser in Figure 5-3 is the physical node component (PNC) "Hybrid Drive Unit"; see Figure 4-14 for the usage of this PNC in the *physical architecture blank* (PAB) diagram of the bulk carrier. All referencing or referenced elements of this PNC are displayed, including physical links, parent components, related diagrams, or deployed *physical behavior components* (PBC).



Semantic Browser

(Physical Component) Hybrid Drive Unit

Referencing Elements

- **Physical Links**
  - cables
    - Power Generation & Propulsion Control
    - Hybrid Drive Unit
  - shaft
    - Main Engine (2-Stroke Low Speed Dual-Fuel)
    - Hybrid Drive Unit
  - shaft
    - Hybrid Drive Unit
    - Propeller
  - cables
    - Hybrid Drive Unit
    - Inverter
- **Referencing Components**
  - Power Generation & Main Propulsion (Engine Room)

Current Element

- Hybrid Drive Unit
  - **Parent**
    - Power Generation & Main Propulsion (Engine Room)
  - **All Related Diagrams**
    - [PAB] Bulk carrier – Physical architecture

Referenced Elements

- **Deployed Physical Components**
  - Integrated Control Unit
  - Integrated Lube Oil System
  - Propeller Shaft Clutch
  - Transmission
  - Generator / Electric Motor
- **Physical Links**
  - cables
    - Power Generation & Propulsion Control
    - Hybrid Drive Unit
  - shaft
    - Main Engine (2-Stroke Low Speed Dual-Fuel)
    - Hybrid Drive Unit
  - shaft
    - Hybrid Drive Unit
    - Propeller
  - cables
    - Hybrid Drive Unit
    - Inverter
- **Representing Parts**
  - Hybrid Drive Unit : Hybrid Drive Unit

Figure 5-3: Bulk carrier – Semantic browser of "Hybrid Drive Unit"

The detailed and up-to-date information stored in a comprehensive system architecture of a ship can be displayed, for example, in the semantic browser and used for further analysis through automated reports. This supports the marine engineer in keeping track of all the subsystems, parts, and their interfaces, which is often a challenging part of ship design.[287]

5.2.3 System Architecture for Project Management

As shown in chapter 2.1.6 the areas of systems engineering and project management can overlap, resulting in shared responsibilities between the systems engineer and the project manager. A consistent and integrated Capella system model can therefore also serve as a comprehensive project management tool by integrating system architecture diagrams with project management processes. For example, it can facilitate the review of development and simulation status of individual subsystems. The model can provide a link to simulation tools, allowing the project manager to document simulation updates and track the approval and release status after simulation and testing. The system architecture diagram can thereby operate as a control and monitoring tool for virtual integration, verification, and validation.

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[287] Le Néna et al. (2019)., p. 127

6 Conclusion & Outlook

As the backbone of our globalized economy, the maritime industry and its transportation sector operate in a complex environment and are at the beginning of a period of fundamental change. The need for *sustainability* and *resilience* is demonstrated by the economic and geopolitical fragility of this industry, as revealed by the disruptions to global supply chains and maritime trade caused by events such as the COVID-19 pandemic or the still ongoing humanitarian crises in Ukraine and Gaza. Nevertheless, the unavoidable shift towards a low-carbon economy in the maritime industry, driven by the imminent climate crisis, represents the sector's most significant challenge in the 21st century. As of 2020, marine shipping accounted for ~11% of global transportation CO_2e emissions. Pathways to achieve net-zero GHG emissions in this sector until 2050 – primarily the *2023 IMO's strategy* – are already in place. However, their realization from a 2024 perspective is uncertain. The strategy aims for a 40% reduction in GHG emissions from shipping by 2030 and promotes 5-10% energy use from zero or near-zero emission technologies by the same year in order to achieve net-zero emissions by 2050. The goal of the IMO can only be realized if the vast network of maritime stakeholders is aligned, and strong regulations are set into place by the regulating authorities. New technologies and GHG emissions reduction solutions and measures are introduced into the industry, including *low- and zero-emission alternative fuels and propulsion technologies* (e.g., hydrogen, ammonia, wind-assisted ship propulsion), *energy saving technologies* (e.g., air lubrication systems, propulsion improving devices) or *operational measures* (e.g., optimized routing/navigation, slow steaming). The *decarbonization* of the maritime industry demands a holistic approach and the implementation of innovative strategies to effectively reduce the GHG emissions of existing vessels and to support the introduction of zero-emission vessels as soon as possible. One of these approaches is *model-based systems engineering* (MBSE), which is needed to implement the above-mentioned technologies and measures while ensuring that the main *mission* of marine transportation is fulfilled: Moving goods, resources, and passengers by sea from one place to another in a timely and cost-effective manner. MBSE is a new approach to the maritime industry and its level of adoption is low. Nonetheless, its benefits include improved communication between a variety of stakeholders, a deeper understanding of the complex system, in addition to supporting the integration of new technologies. Current approaches in ship development are considered unsuitable to respond to the identified new challenges of the maritime industry, as they do not consider the operational context and the interaction of stakeholders in a comprehensive way.

This master's thesis has demonstrated the application of MBSE in the maritime industry through the creation of two *descriptive system models* by using the Arcadia modeling language and method together with the Capella modeling tool. The method has been applied first on a small scale through a system model of a *solar boat* for a student race challenge, and then on a big scale through a system model of a *bulk carrier equipped with a wind-assistance device (WAD) for auxiliary propulsion*. Following the four phases of the Arcadia method, namely the phases of *operational analysis* (OA), *system analysis* (SA), *logical architecture* (LA), and *physical architecture* (PA), the creation of the bulk carrier system model has focused on a thorough analysis of the *operational context* (i.e., marine shipping), the integration of *wind-assisted ship propulsion* (WASP) into a conventional vessel, and the definition of the *physical architecture* of the ship. This application supports the ongoing efforts of the MODE Lab and contributes to the digital transformation of the maritime industry by introducing new methodologies such as MBSE to the ship development process. The usage of a *descriptive* *system model* as a *center of development* and its integration into the ship development process has also been discussed, along with the investigation of other *use cases* such as improved documentation, artifact traceability, or project management activities. The Arcadia method has proven to be an effective approach for providing a more comprehensive description of the *structure* and *behavior* of a bulk carrier system, as well as its environment, operations, and functions. In addition, a thorough *theoretical framework* of *systems engineering fundamentals*, including MBSE and its underlying modeling *languages*, *methods*, and *tools* has been built to support the practical parts of the master's thesis. Selected topics of the maritime industry, such as the stakeholders of its transportation sector, the classic ship design process, or how decarbonizing international shipping until 2050 can be successfully achieved, have also been examined.

Ongoing efforts aim to fully integrate the created Capella system model into the ship development process. A comprehensive system model that includes the ship's system architecture can support and improve the detailed design of subsystems and their verification through better-managed simulations. By providing access to the system architecture and functions of the system-of-interest, MBSE enables parallel optimization across disciplines and promotes collaboration as well as new organizational structures that are essential for change management. The system model can be an effective tool for evaluating the impact of design changes and for integrating new technologies, such as GHG emissions reduction solutions. It supports the linking of development artifacts and the creation of an engineering platform for interdisciplinary teamwork. This platform can be an advanced *product lifecycle management* (PLM) solution that links the integrated system model to *requirements*, *test cases*, and *parameters*. Additionally, *co-simulation* with other modeling tools and *digital thread* realization by linking *system models* with *specific models* can improve *consistency* and *traceability* over the entire product lifecycle. The introduction of MBSE in the maritime industry supports the integration of innovative propulsion technologies, such as wind-assisted ship propulsion, and contributes to the digital transformation of the industry, thereby reducing GHG emissions and the carbon footprint on the world's oceans.

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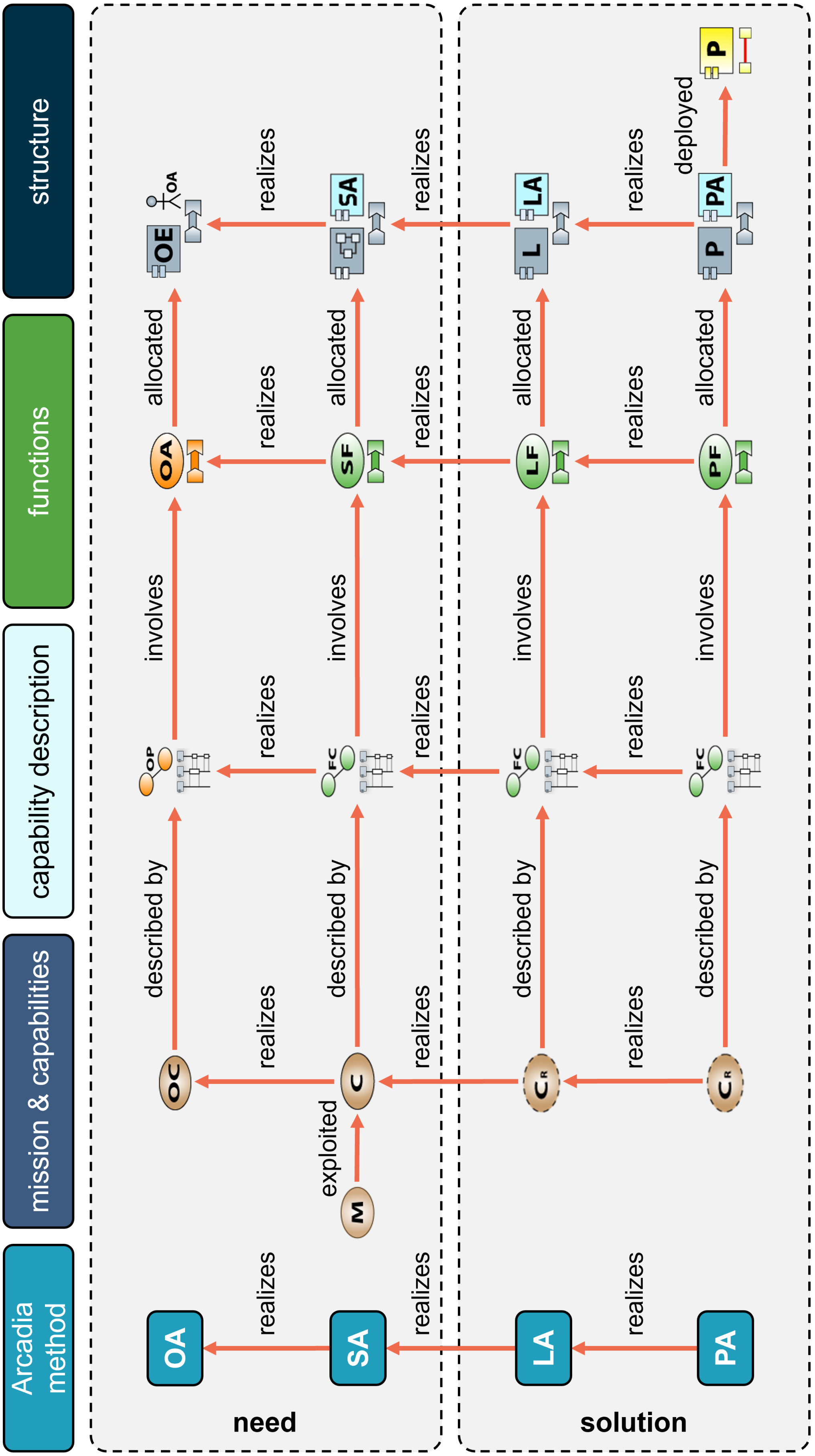

Figure A-1: Arcadia artifacts traceability/simplified Arcadia metamodel, inspired by *Voirin*[288]

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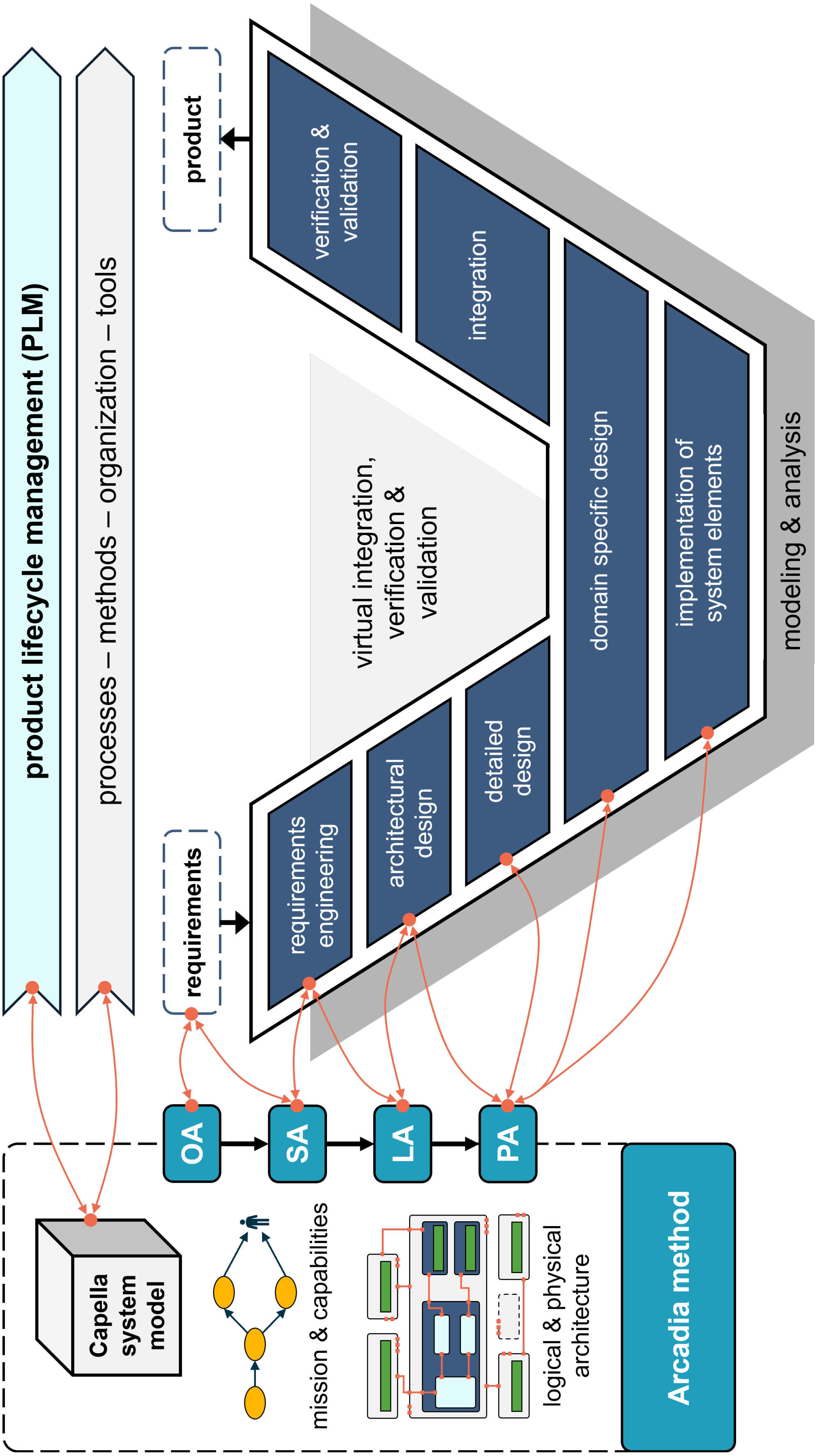
[288] Voirin (2017)., p. 349



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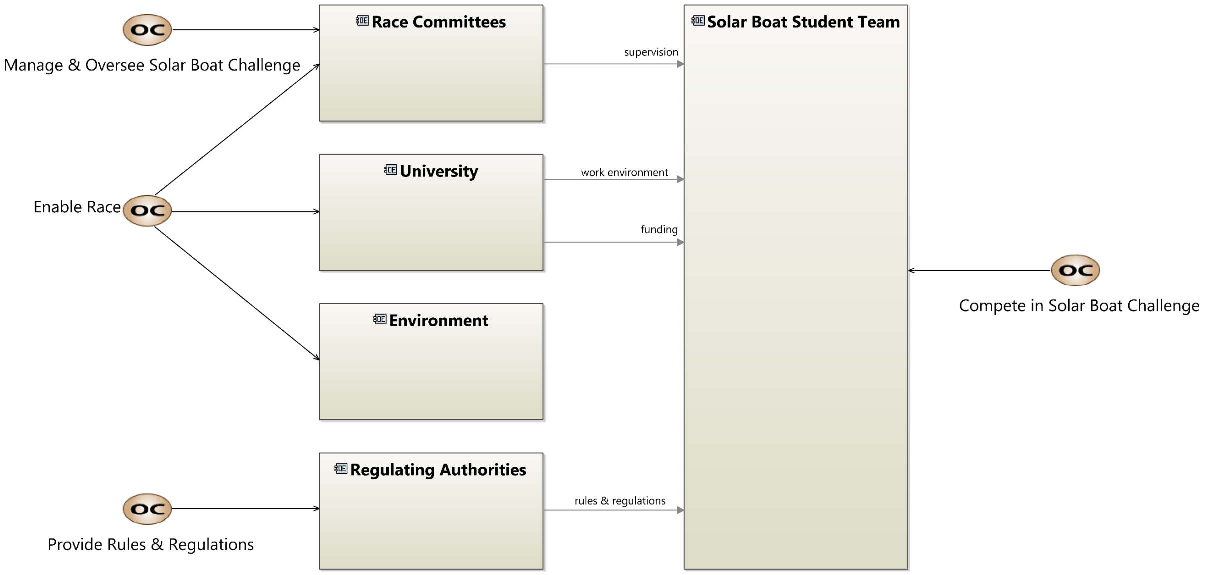

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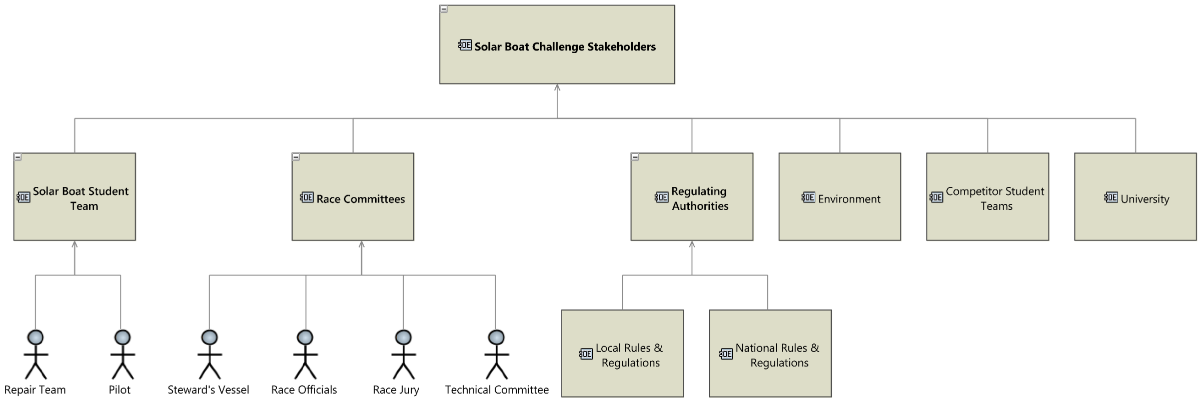

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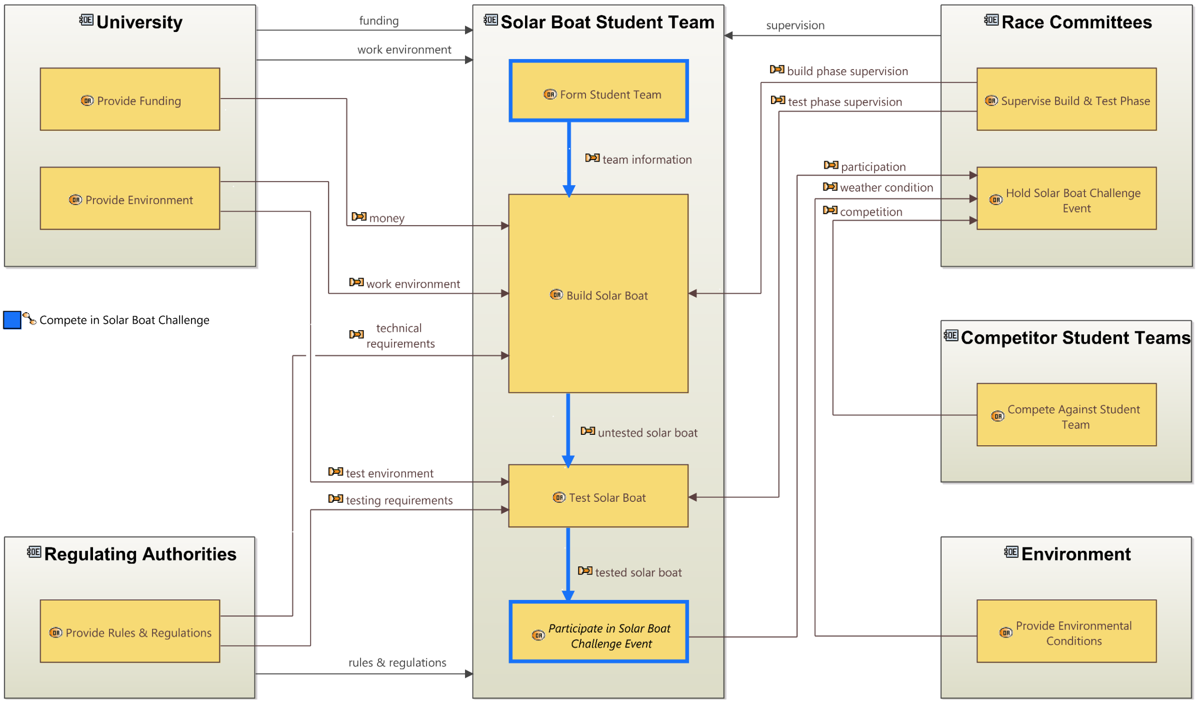

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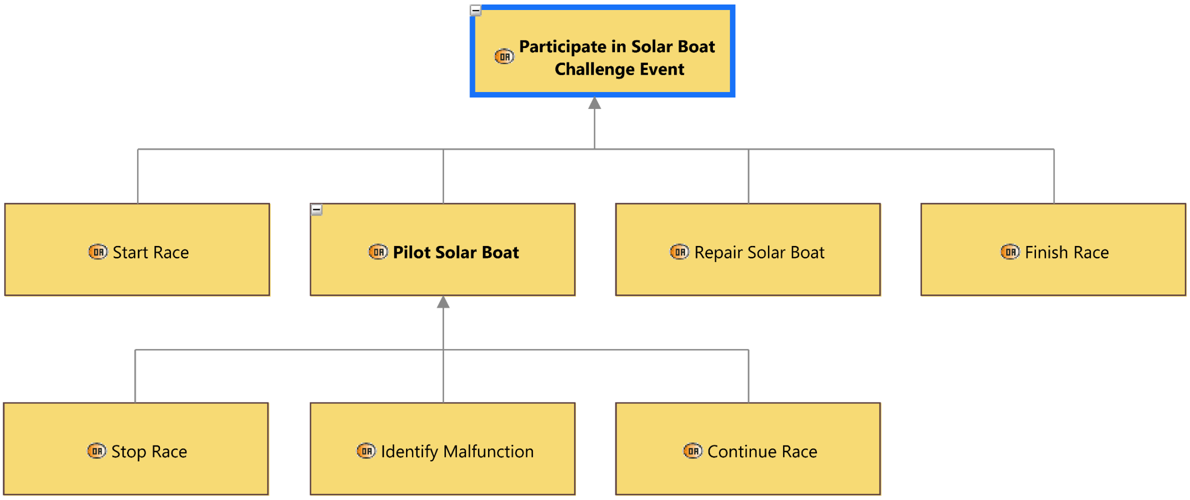

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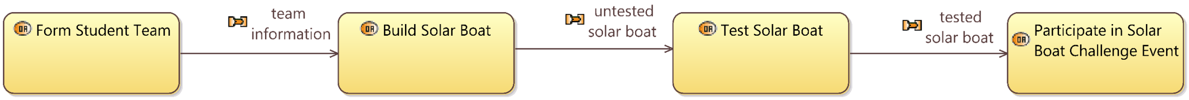

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System Analysis (SA)

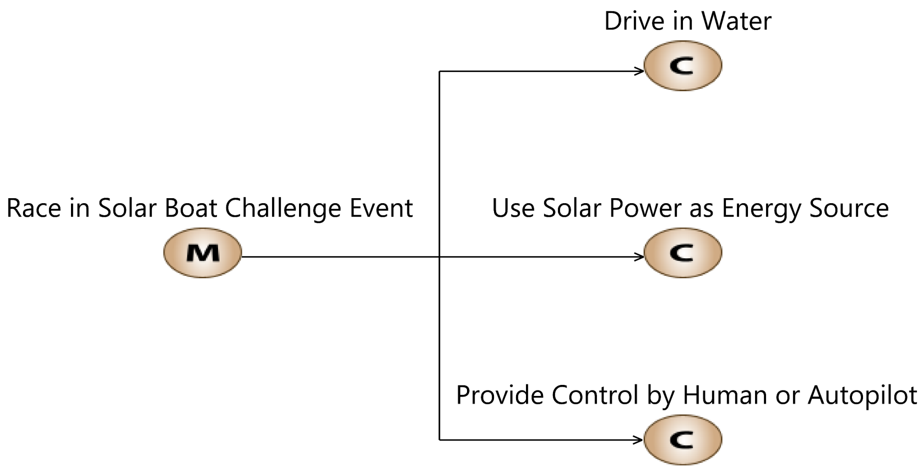
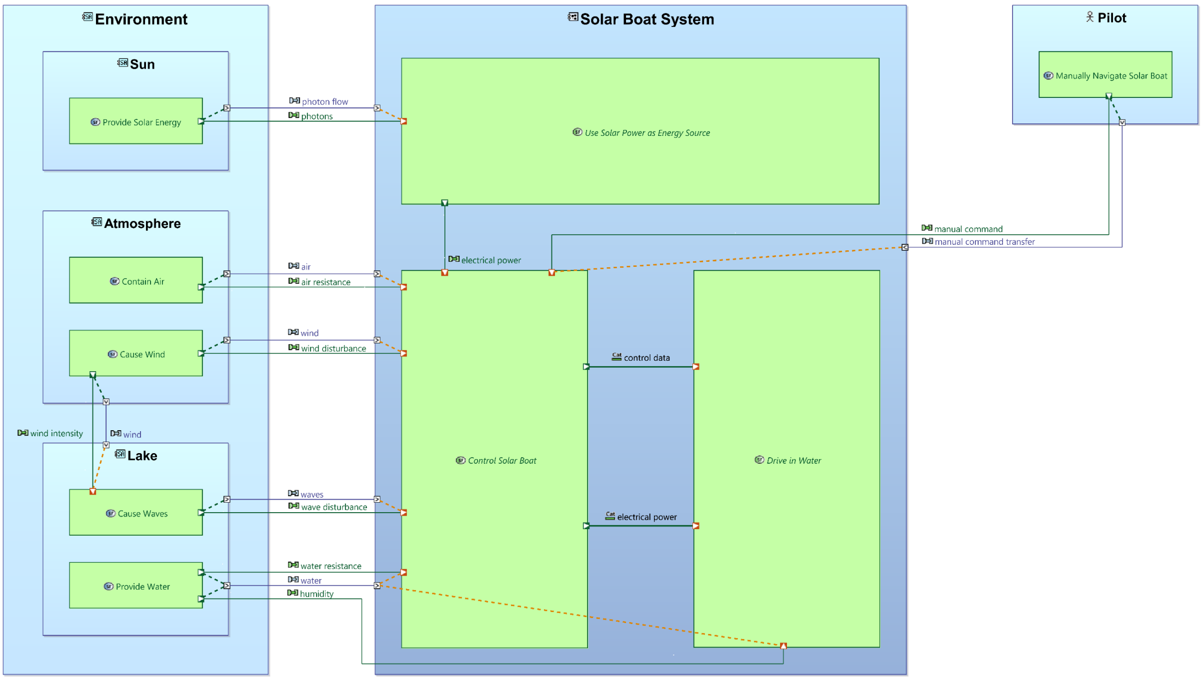


Figure B-6: [MCB] Solar boat – System mission and system capabilities



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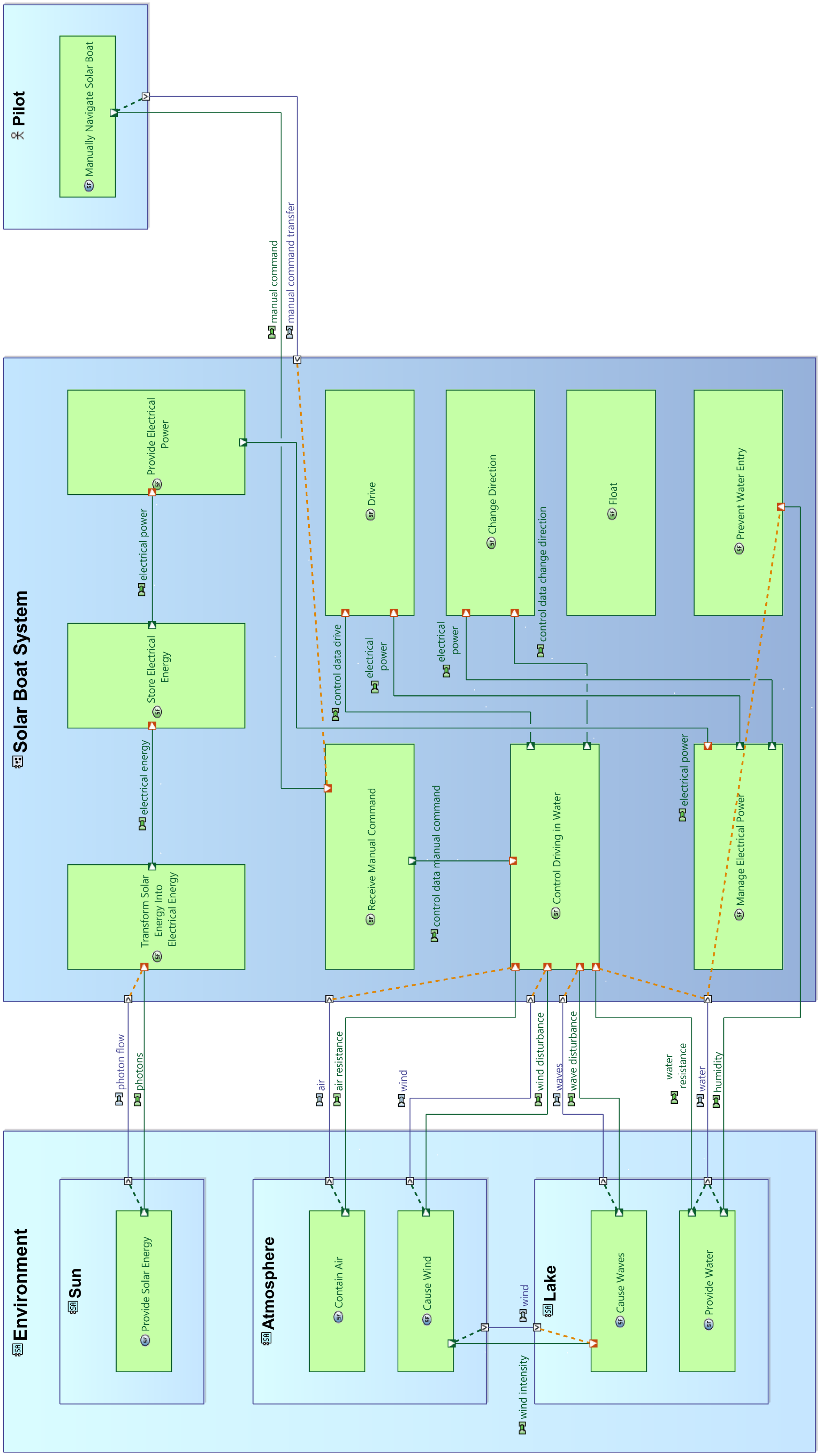

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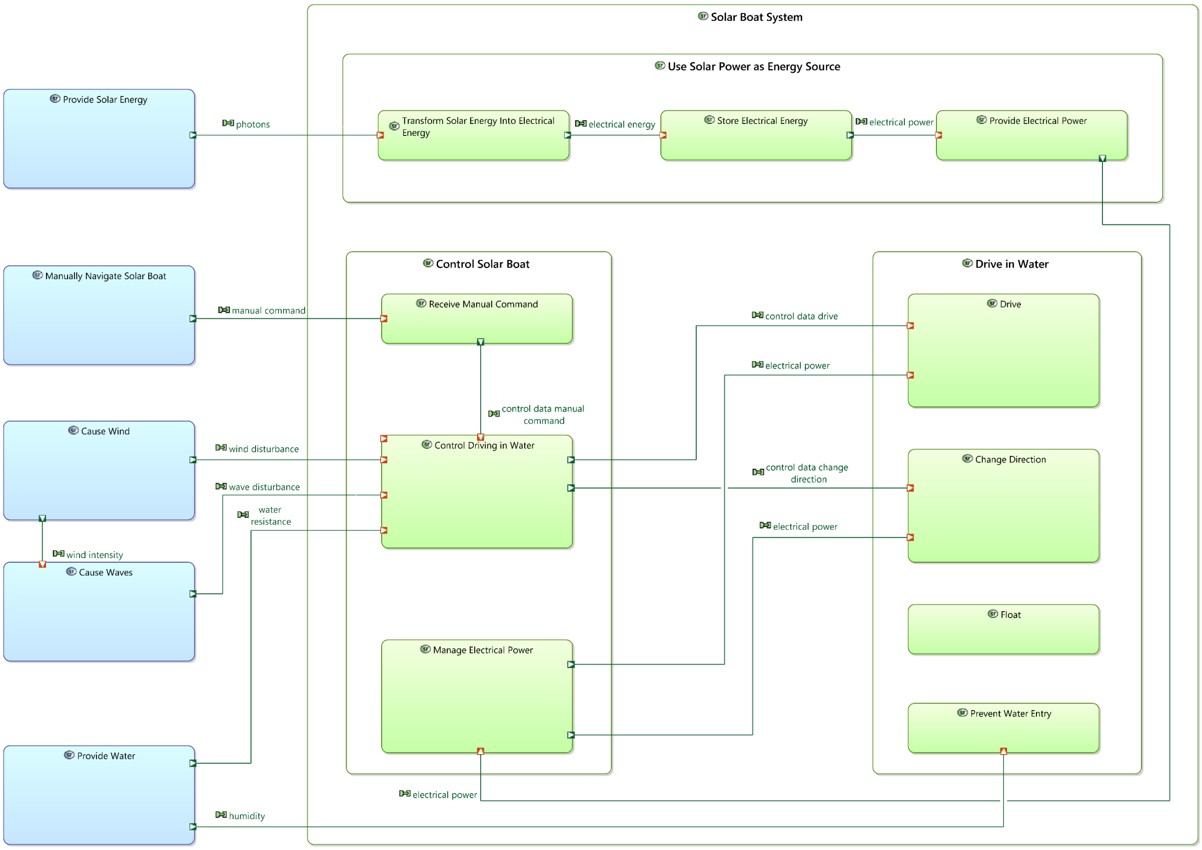

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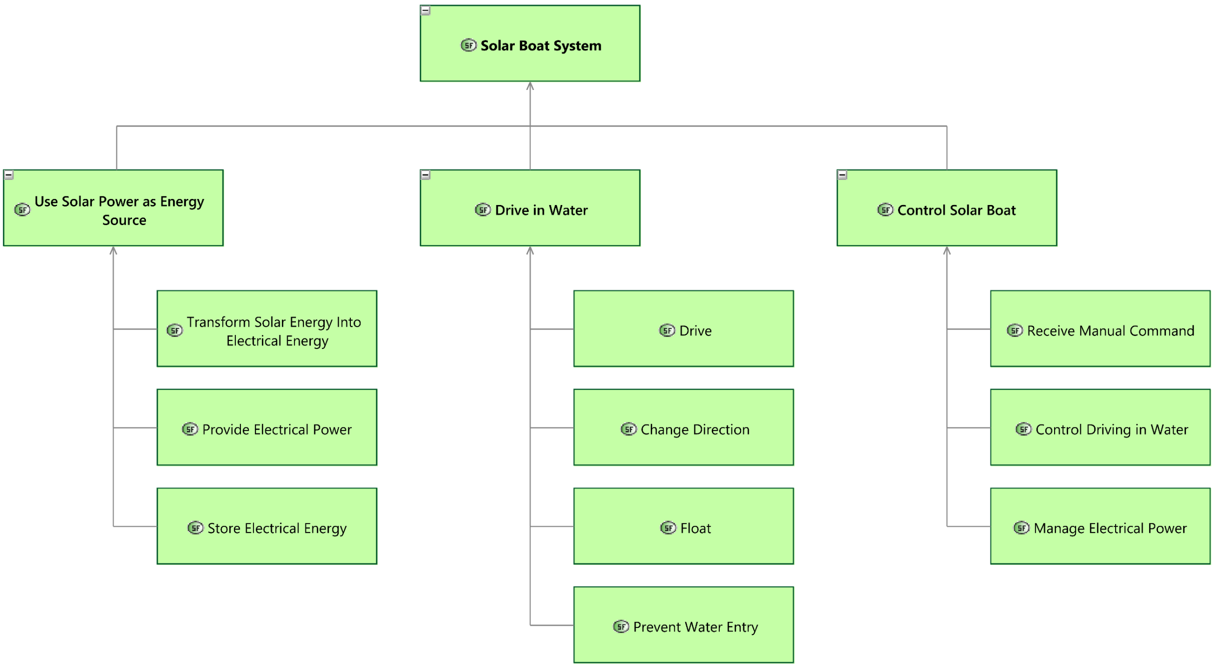

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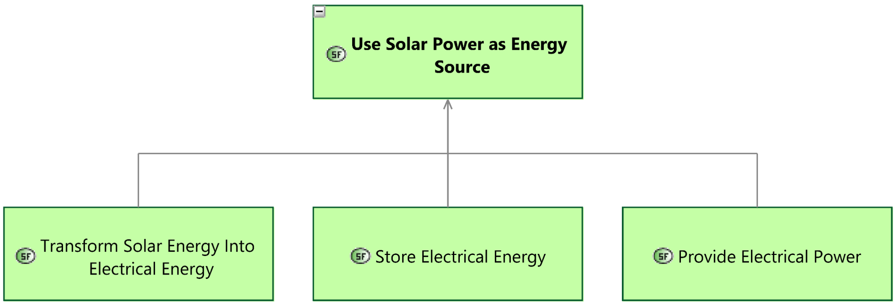

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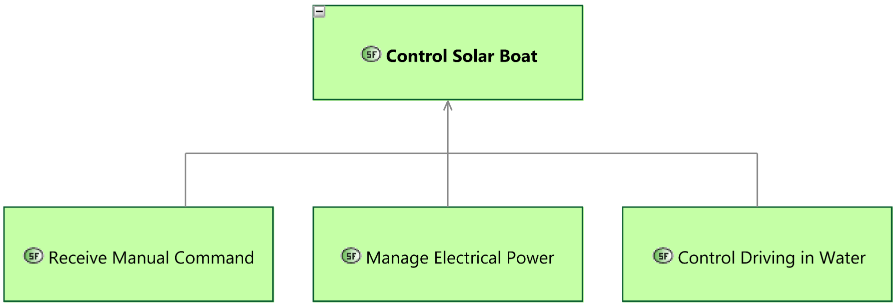

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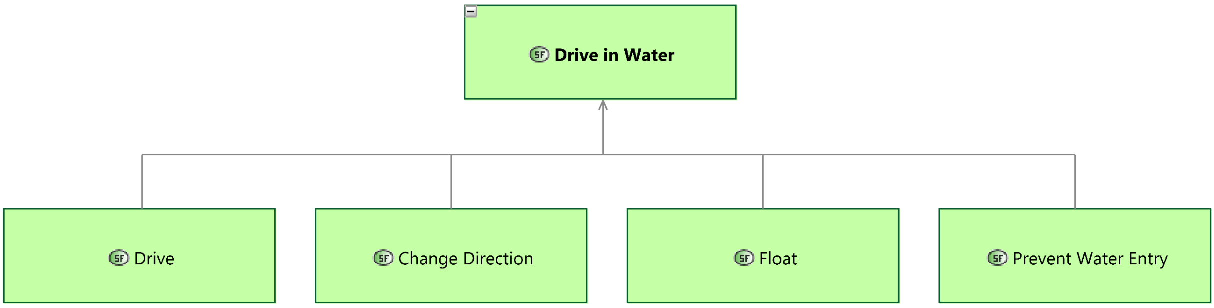

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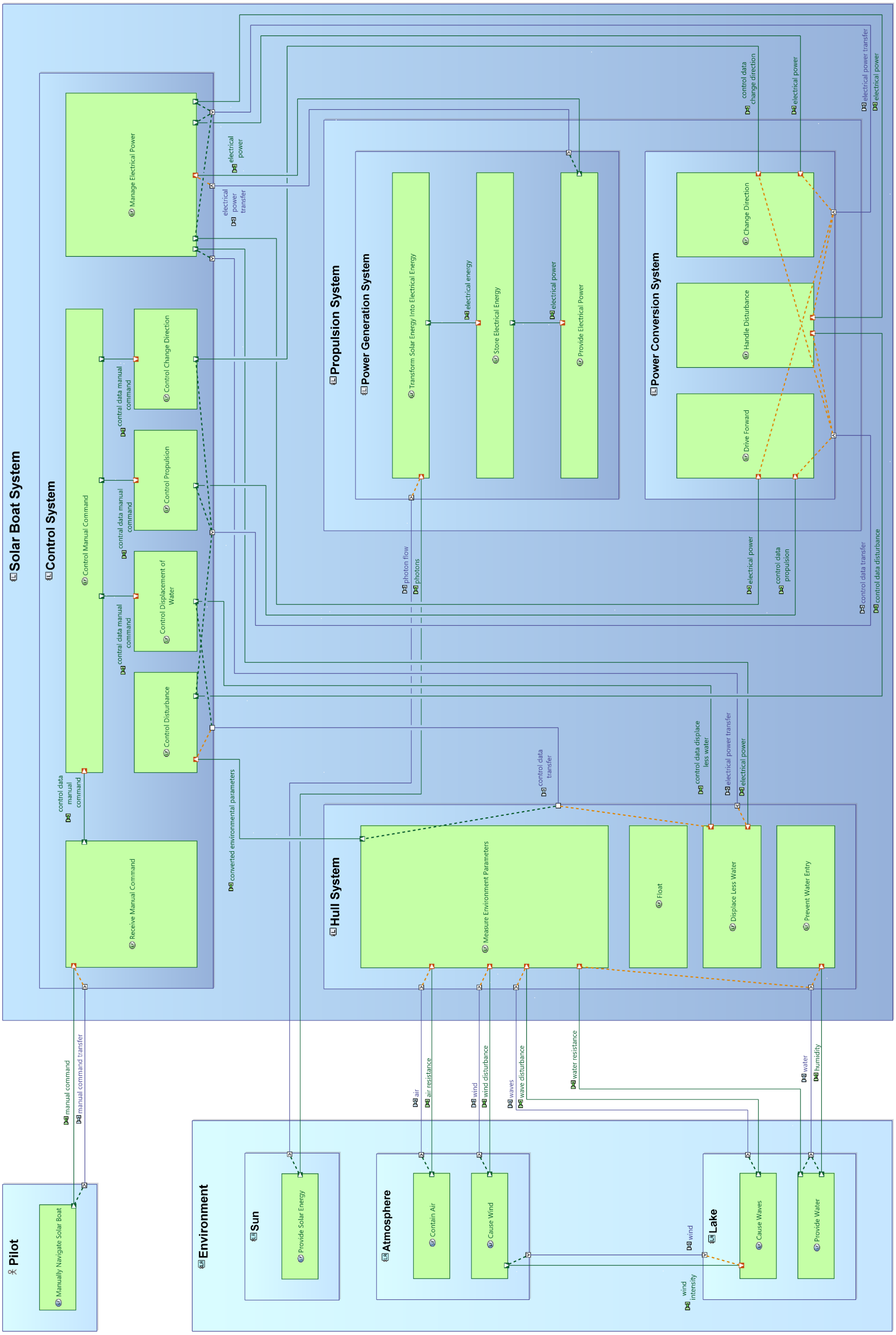
Logical Architecture (LA)



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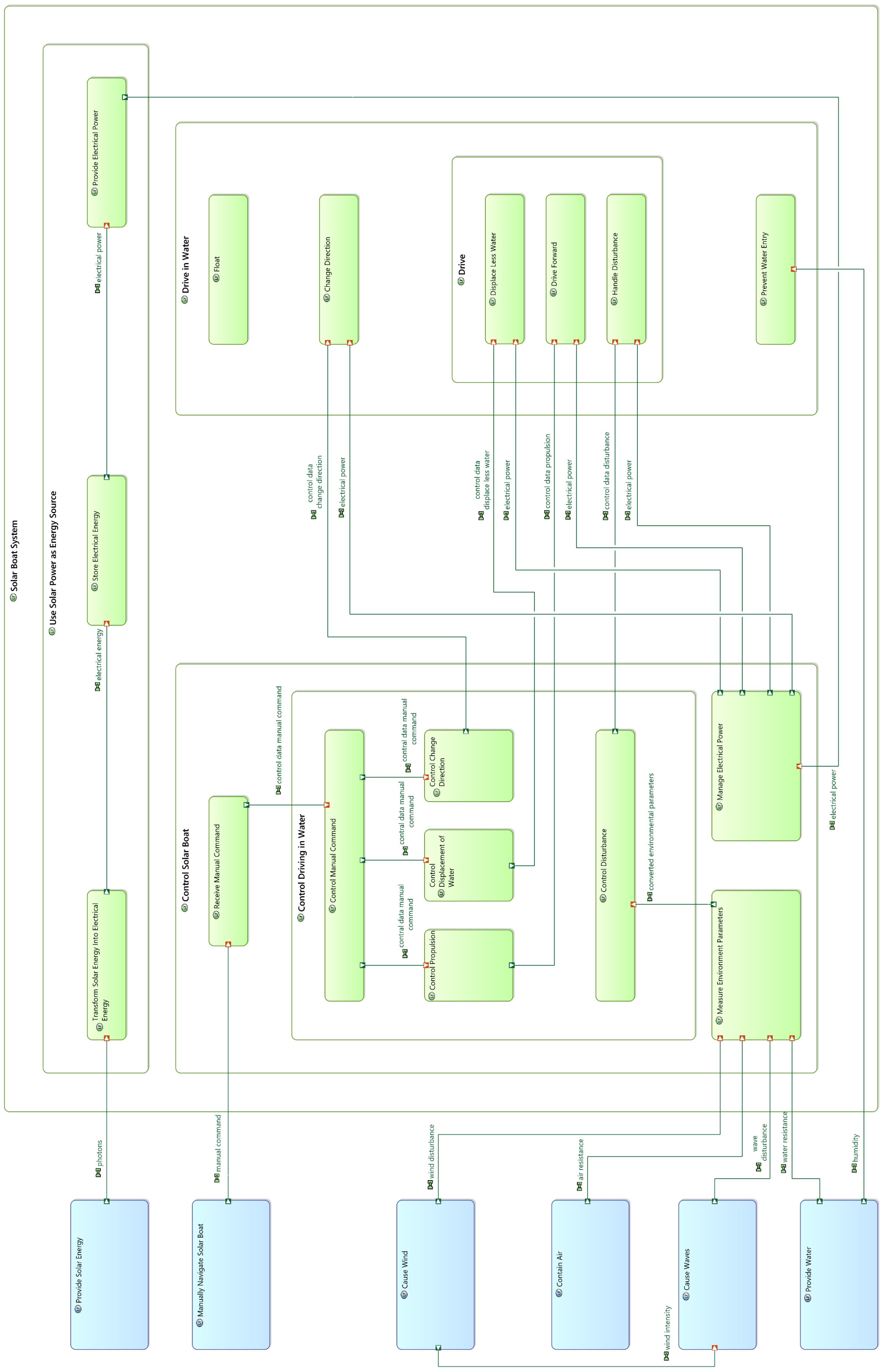

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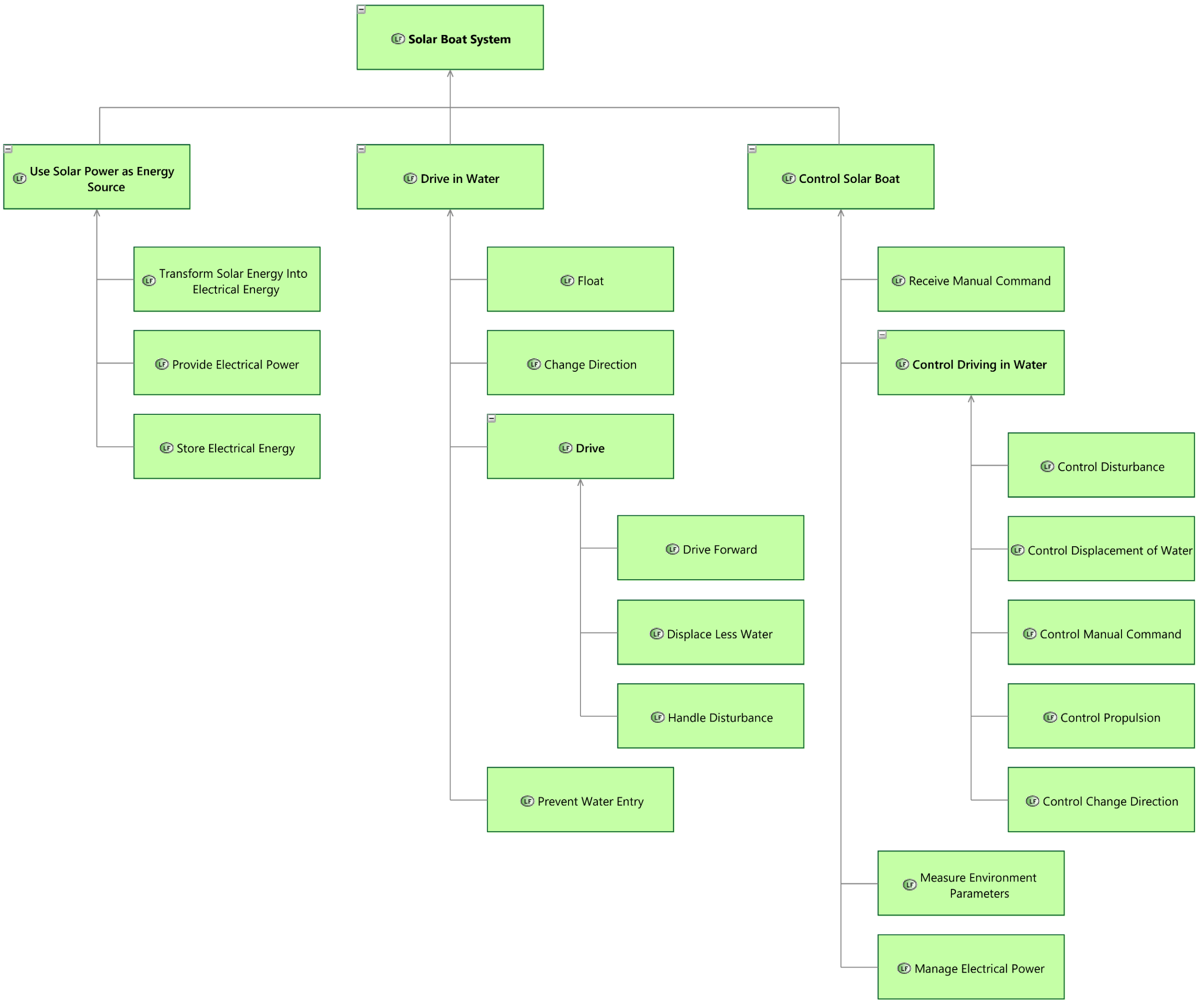

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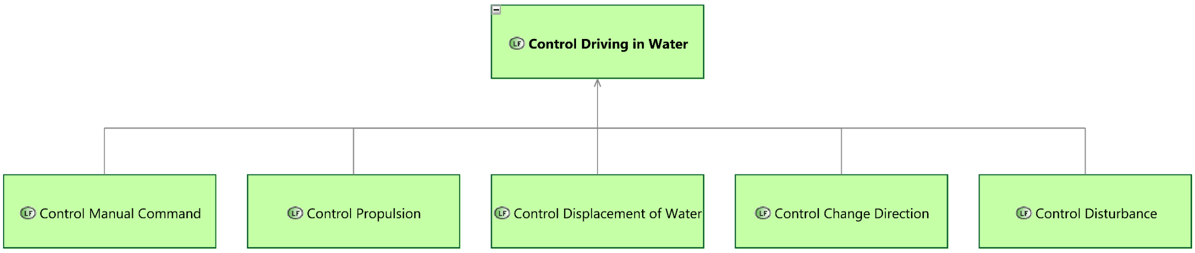

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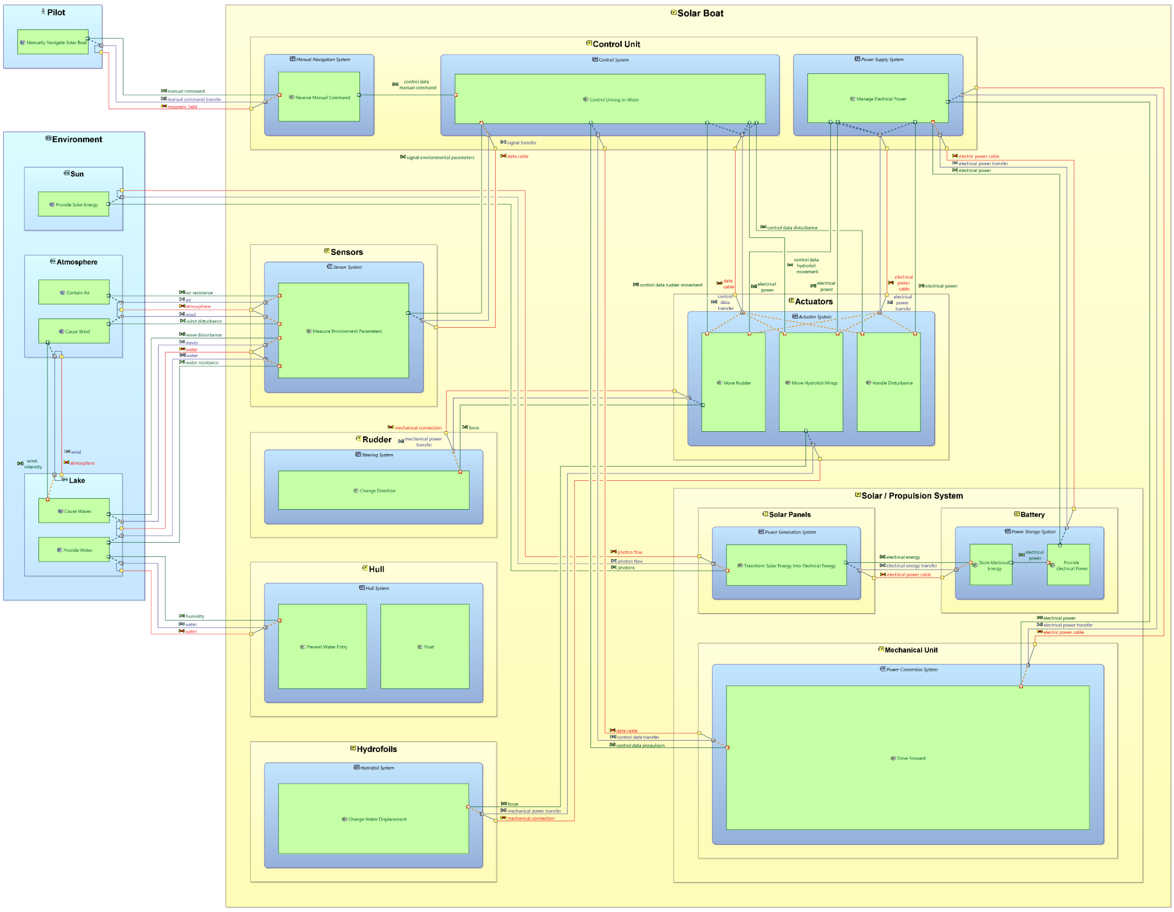
Physical Architecture (PA)



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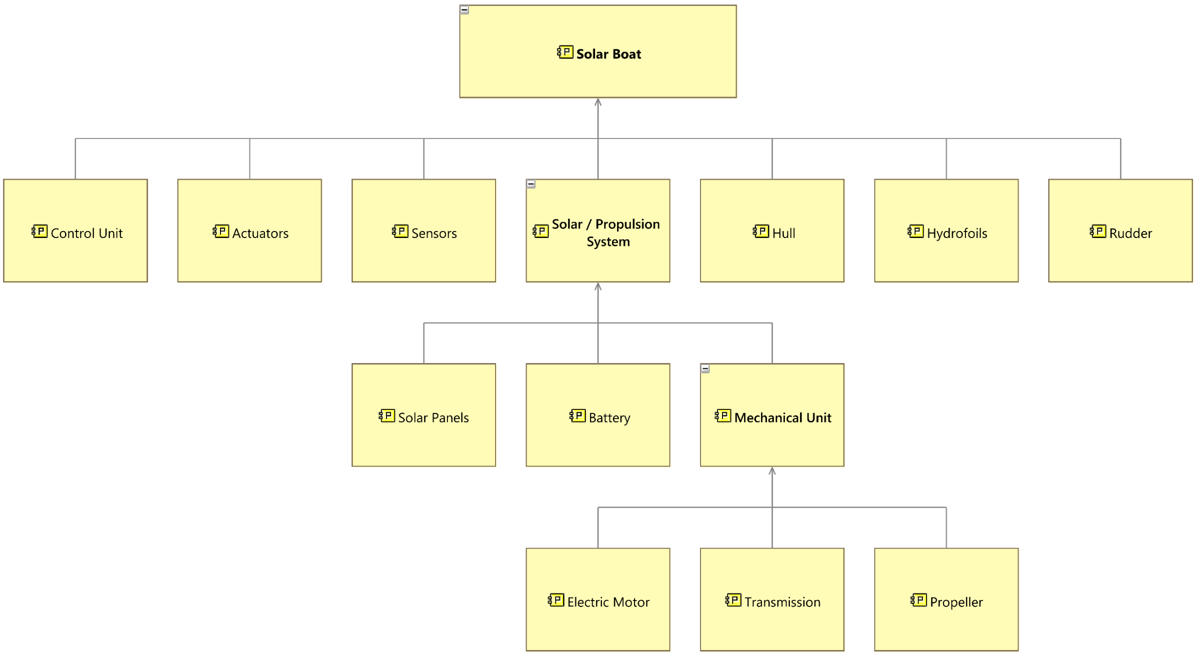

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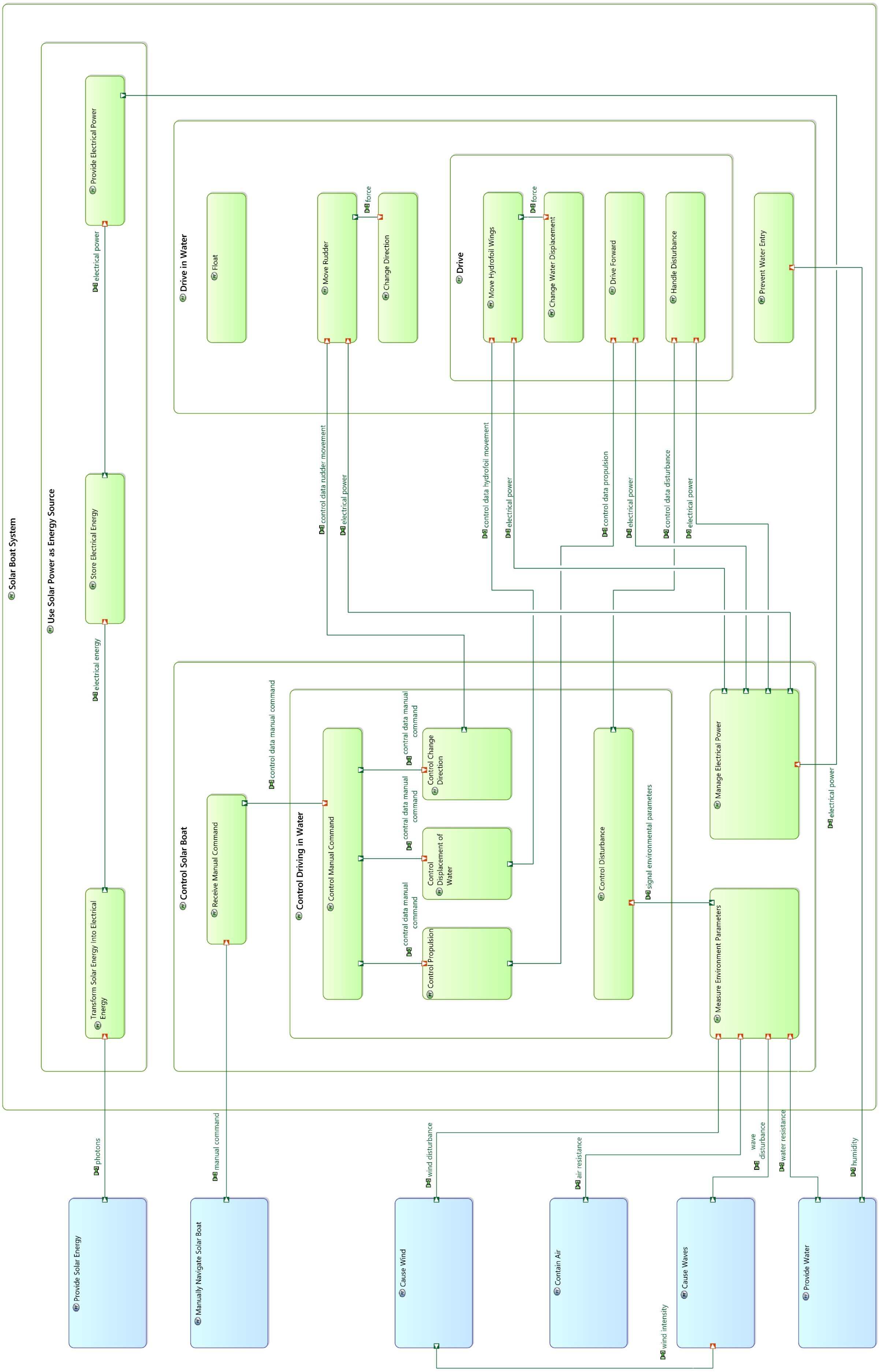
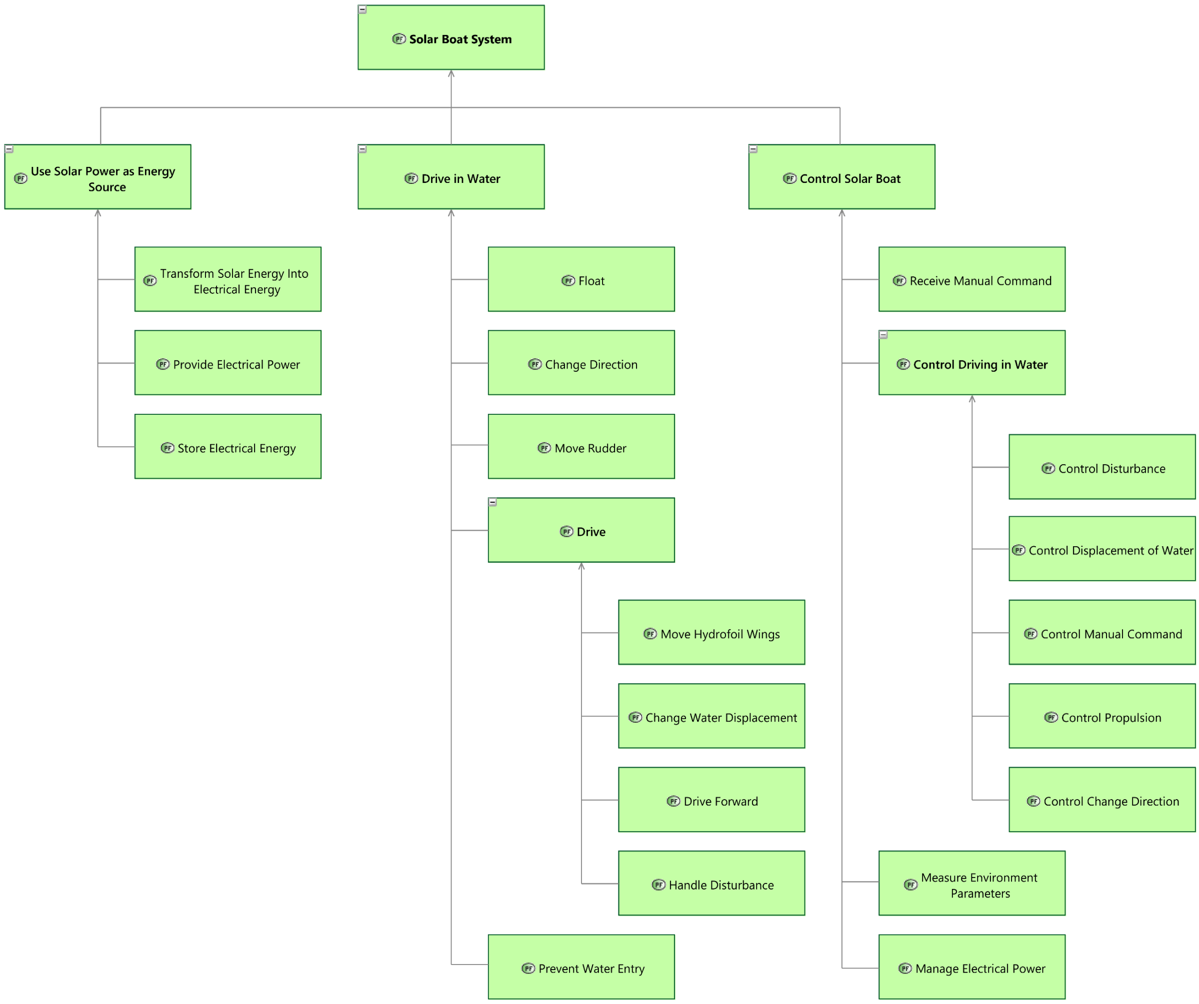


Figure B-20: [PDFB] Solar boat – Physical functions data flow



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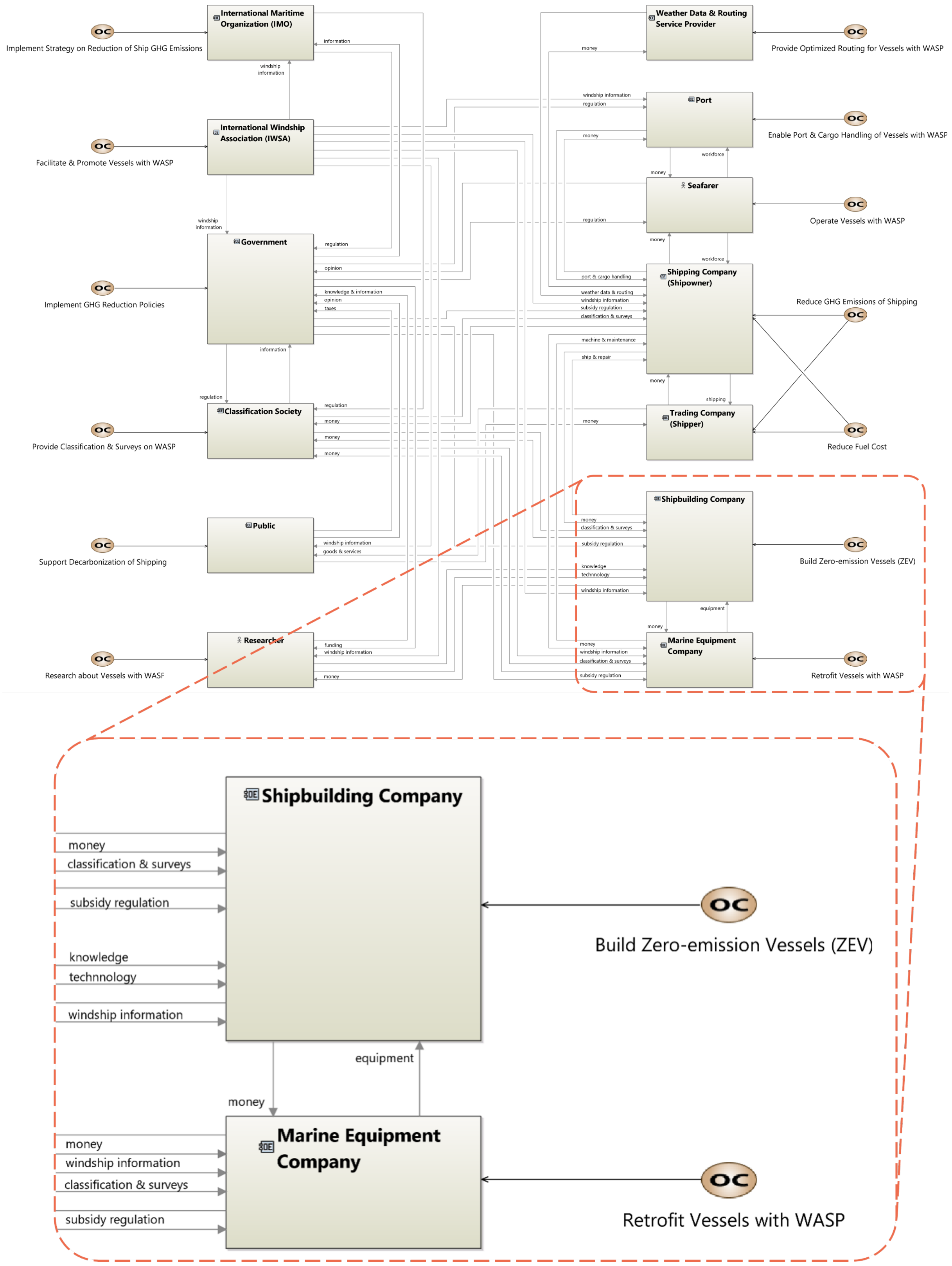

Figure C-1: [OCB] Bulk carrier – Operational entities and operational capabilities with highlighted example, inspired by *Dreier et al.*[290]

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[290] Dreier et al. (2024)., p. 5

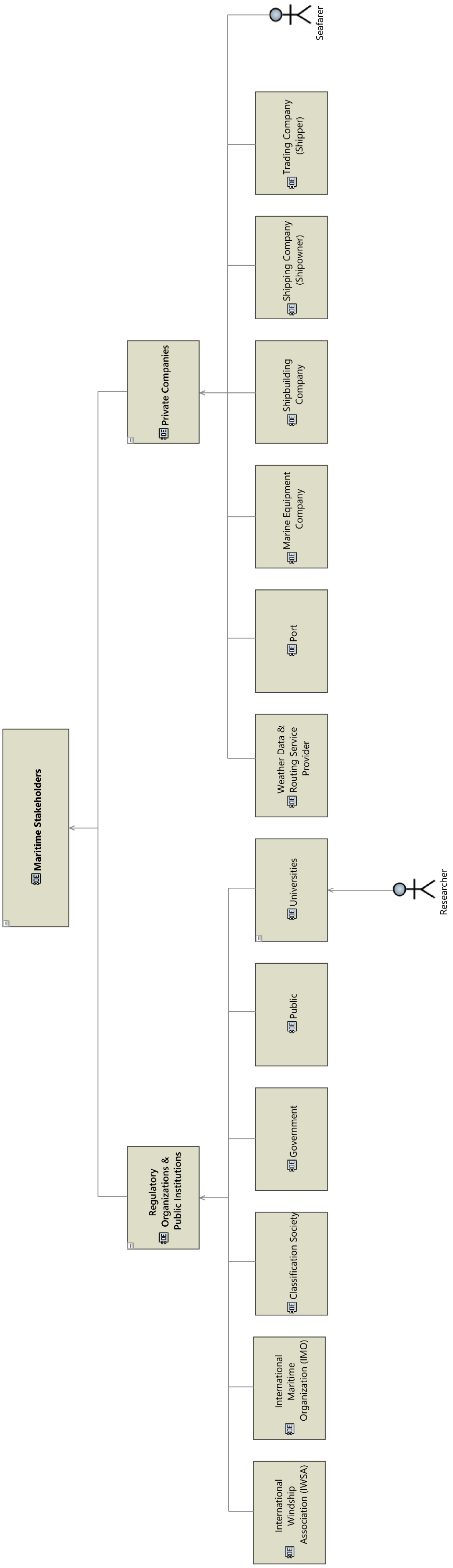

Figure C-2: [OEBD] Bulk carrier – Operational entities breakdown "Maritime Stakeholders"

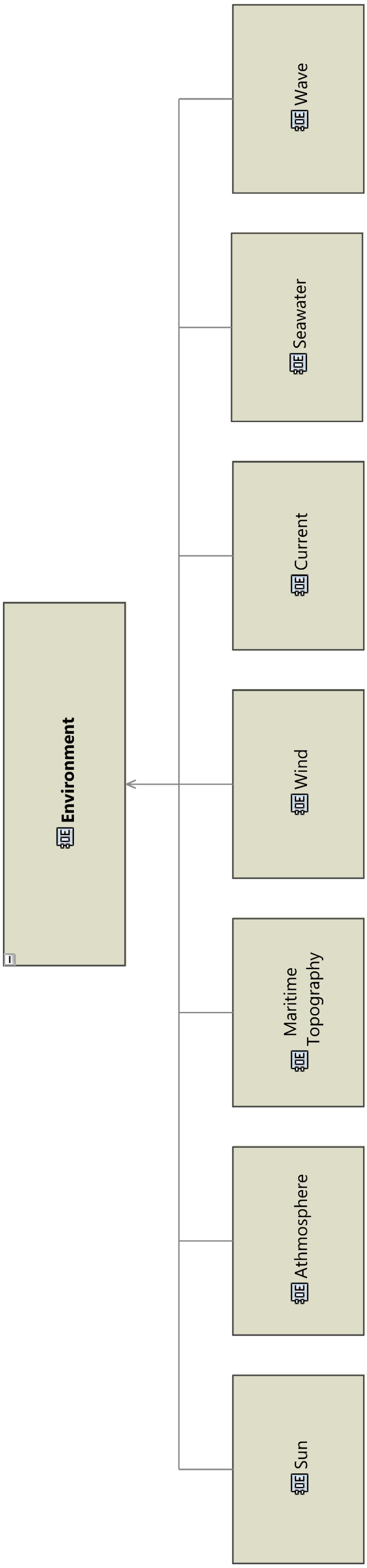

Figure C-3: [OEBD] Bulk carrier – Operational entities breakdown “Environment”

System Analysis (SA)

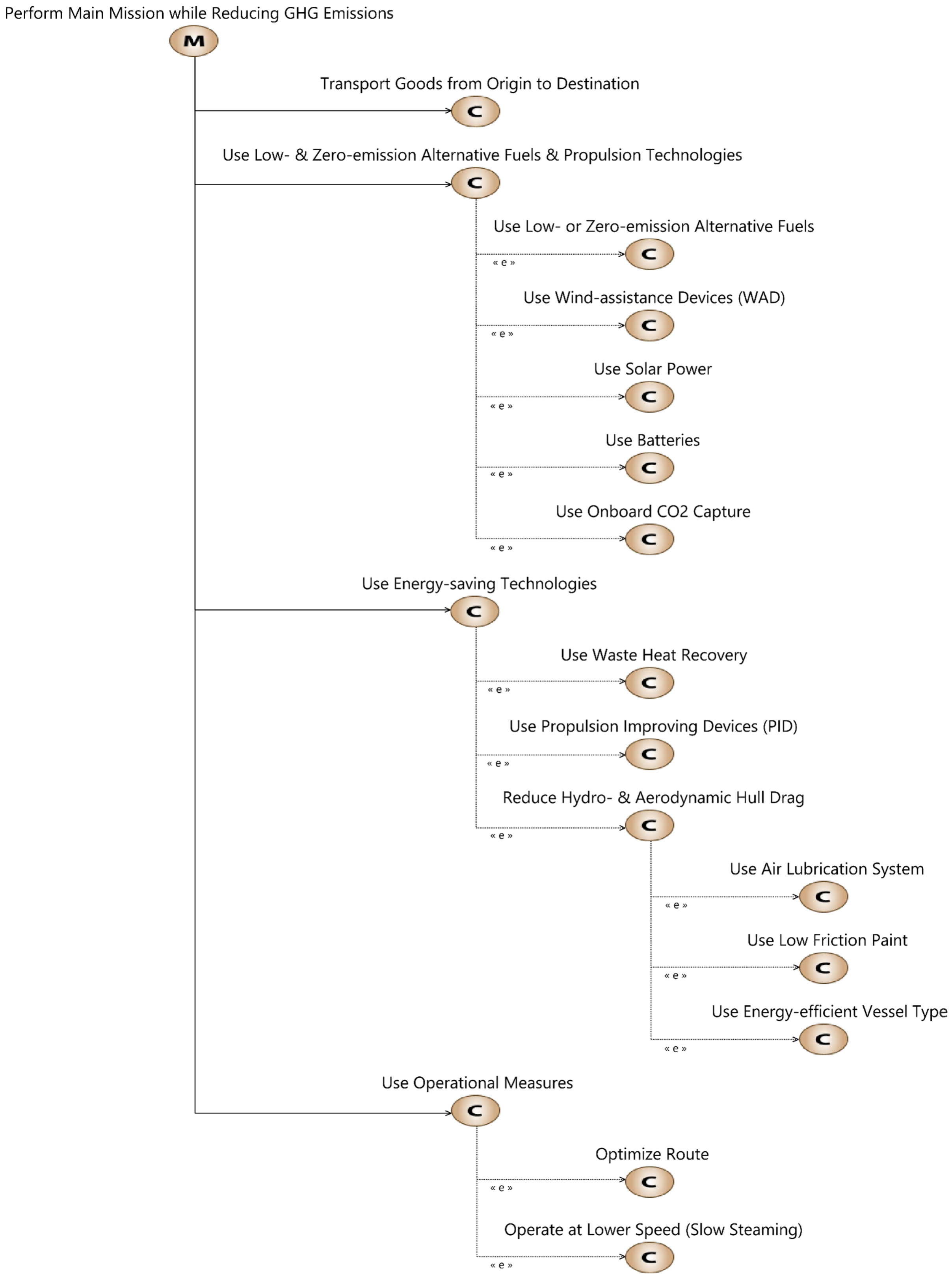

Figure C-4: [MCB] Bulk carrier – System mission and system capabilities

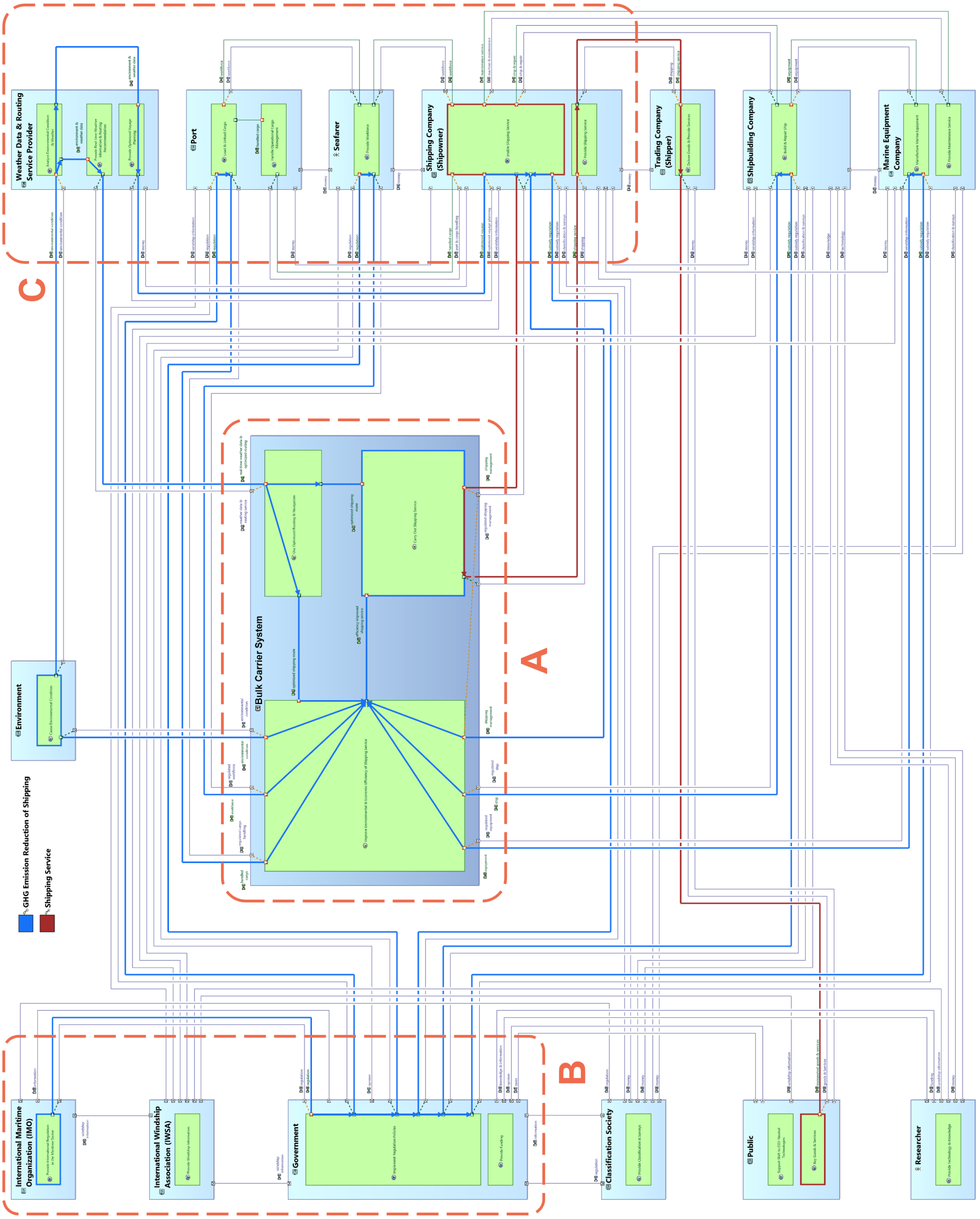

Figure C-5: [SAB] Bulk carrier – System architecture, inspired by *Dreier et al.*[291]

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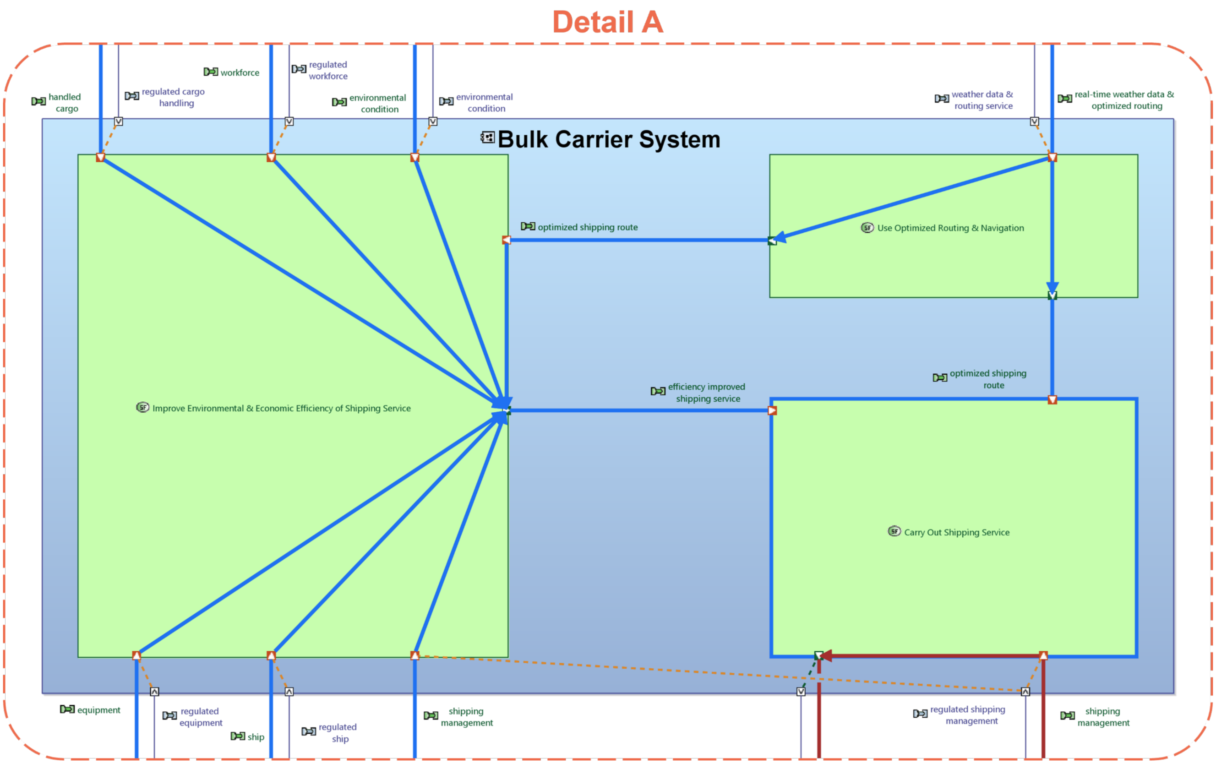
[291] Dreier et al. (2024)., p. 7



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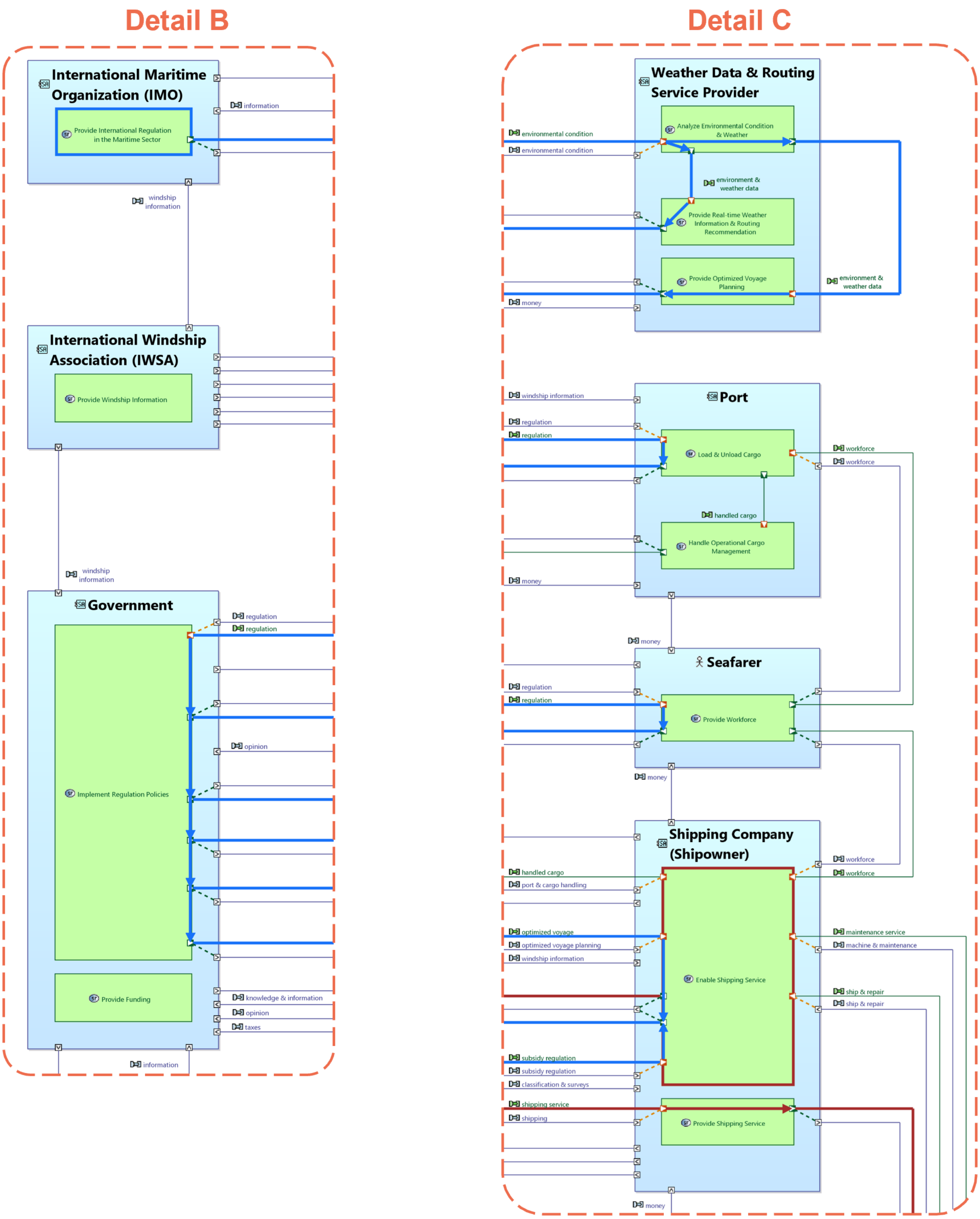

Figure C-7: [SAB] Bulk carrier – System architecture; Detail B and C – System actor examples

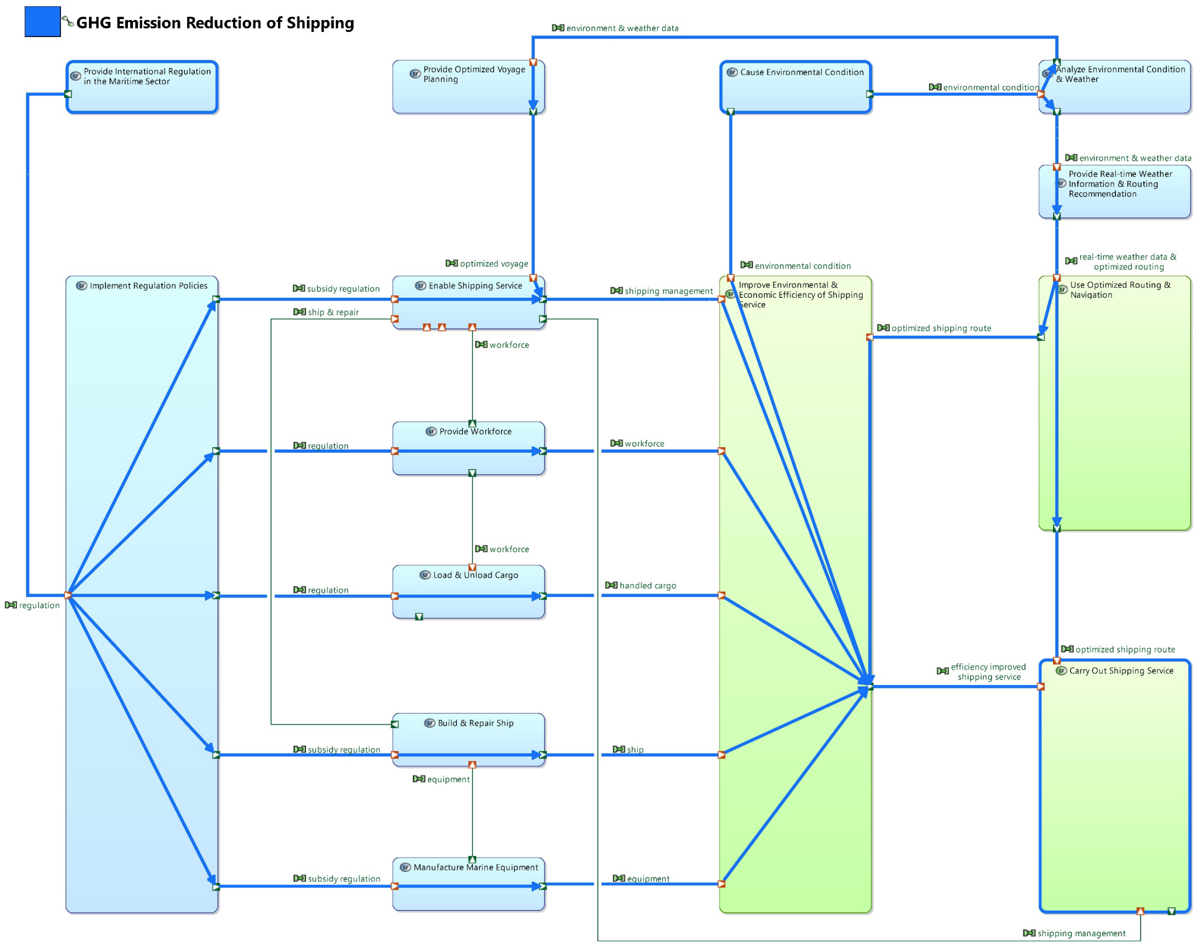

Figure C-8: [SDFB] Bulk carrier – Functional chain “GHG Emission Reduction of Shipping”

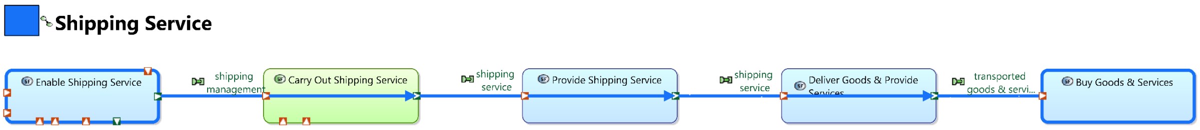

Figure C-9: [SDFB] Bulk carrier – Functional chain “Shipping Service”

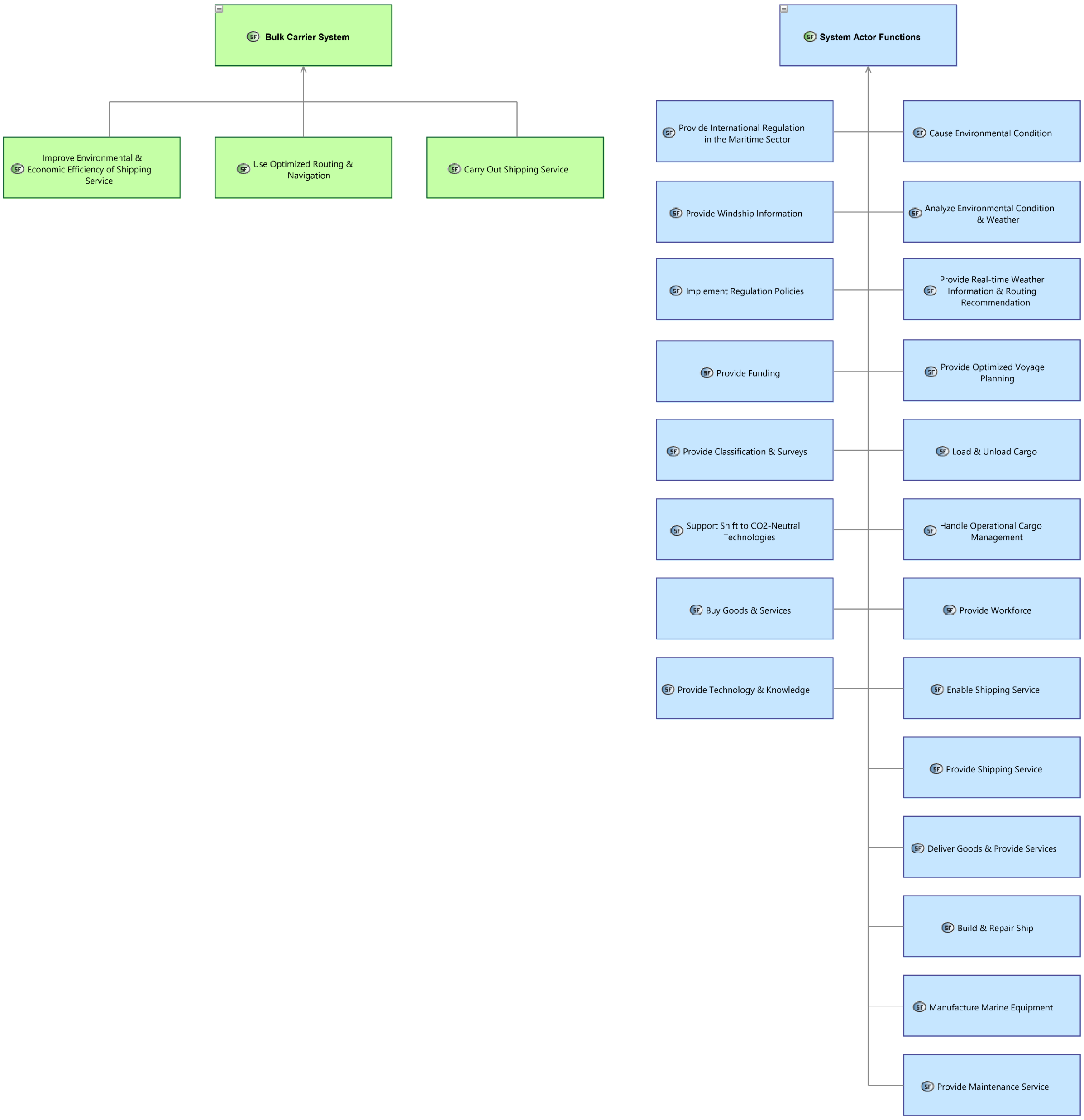

Figure C-10: [SFBD] Bulk carrier – System functions breakdown system and system actors

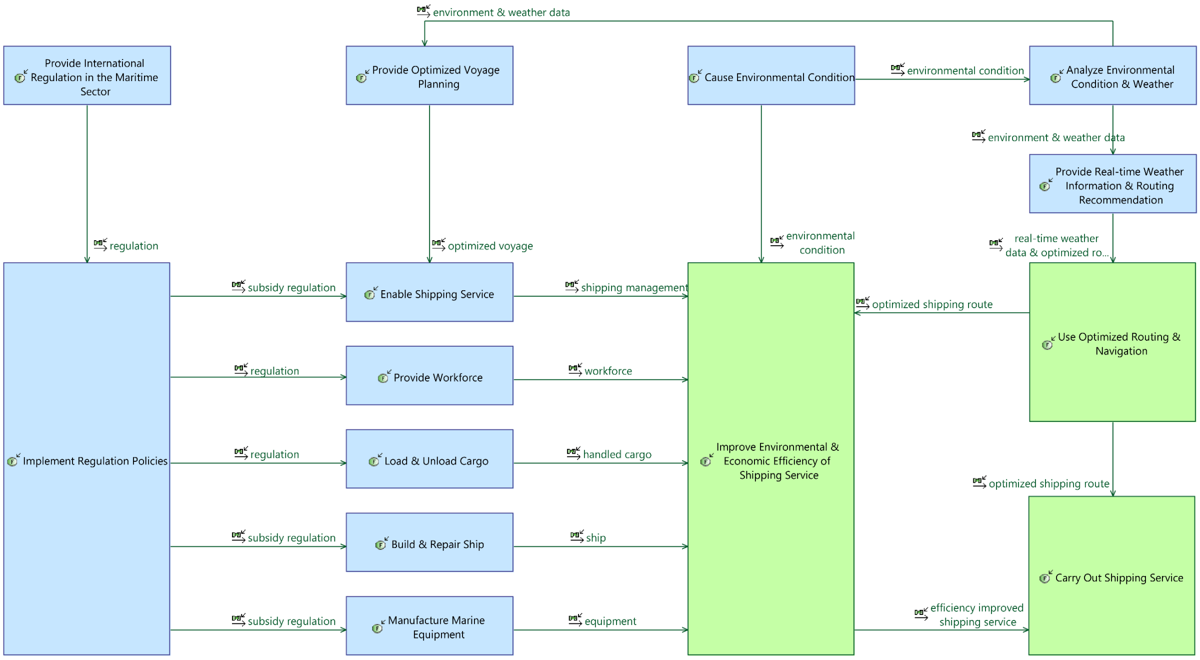

Figure C-11: [SFCD] Bulk carrier – Functional chain description “GHG Emission Reduction of Shipping”

Figure C-12: [SFCD] Bulk carrier – Functional chain description “Shipping Service”

Logical Architecture (LA)

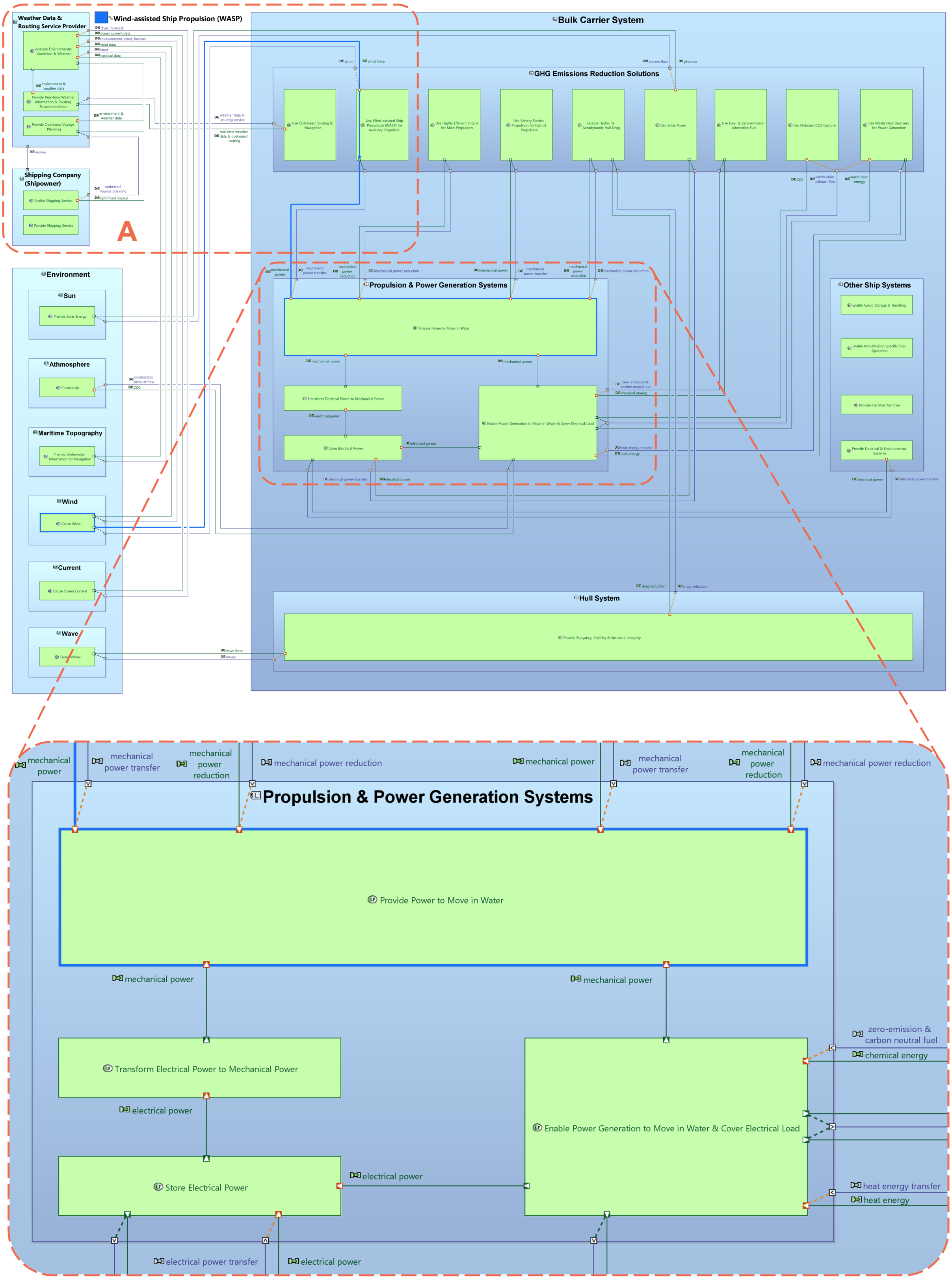

Figure C-13: [LAB] Bulk carrier – Logical architecture with highlighted "Propulsion & Power Generation Systems", inspired by *Dreier et al.*[292]

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[292] Dreier et al. (2024)., p. 8

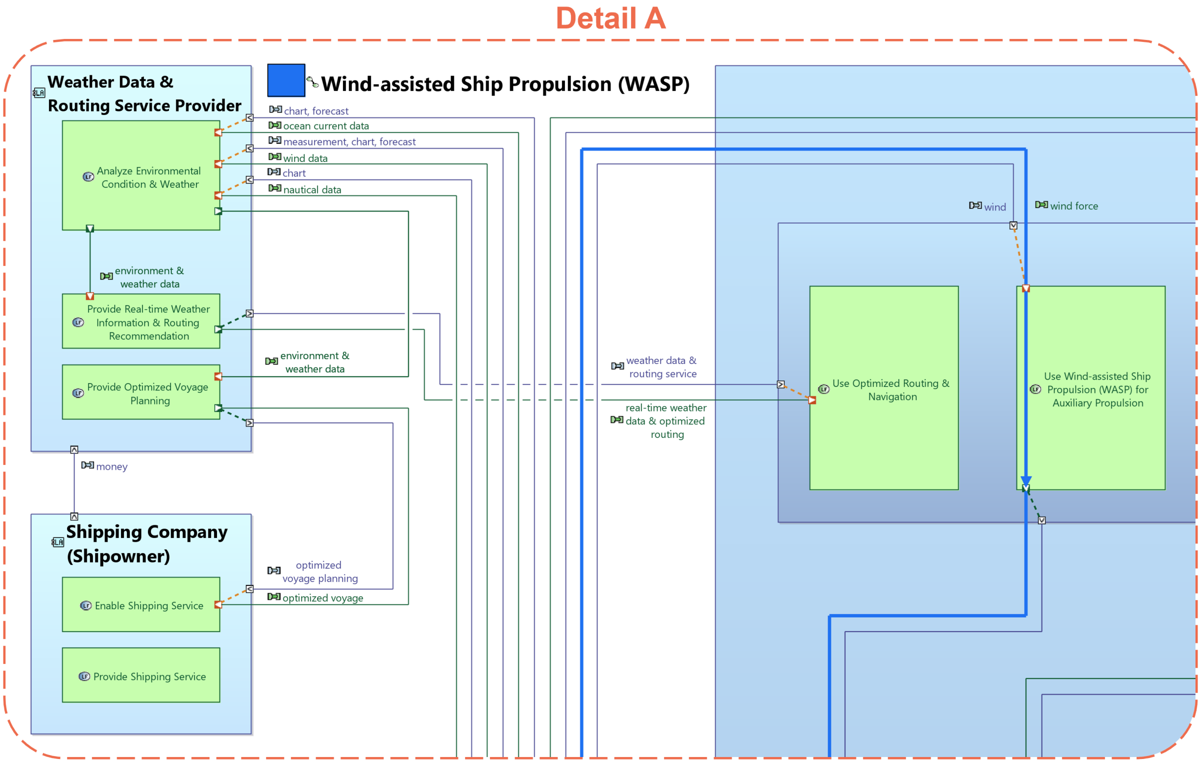

Figure C-14: [LAB] Bulk carrier – Logical architecture; Detail A – Exchanges of system actors and logical functions example

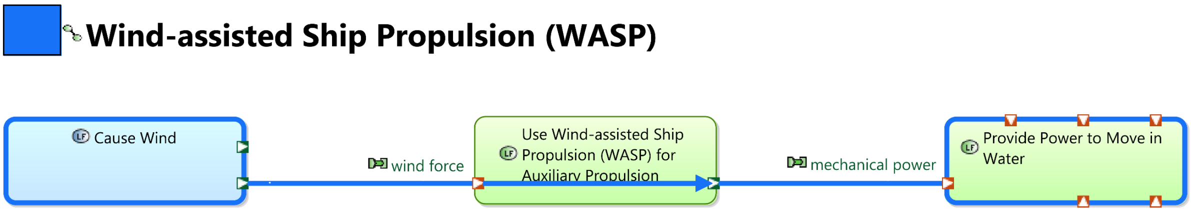

Figure C-15: [LDFB] Bulk carrier – Functional chain “Wind-assisted Ship Propulsion (WASP)”

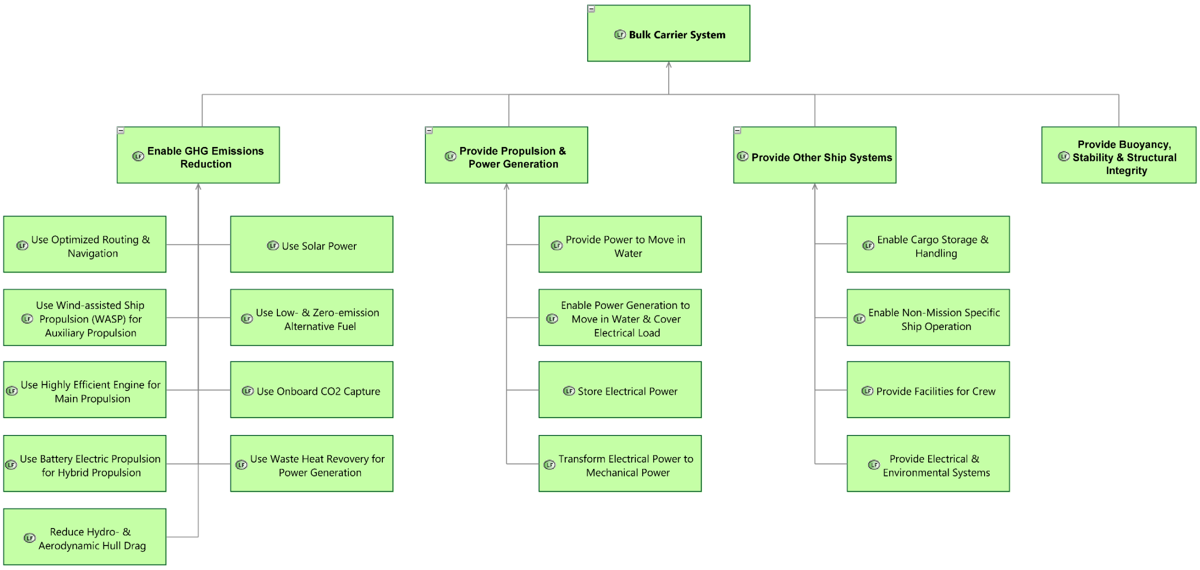

Figure C-16: [LFBD] Bulk carrier – Logical functions breakdown

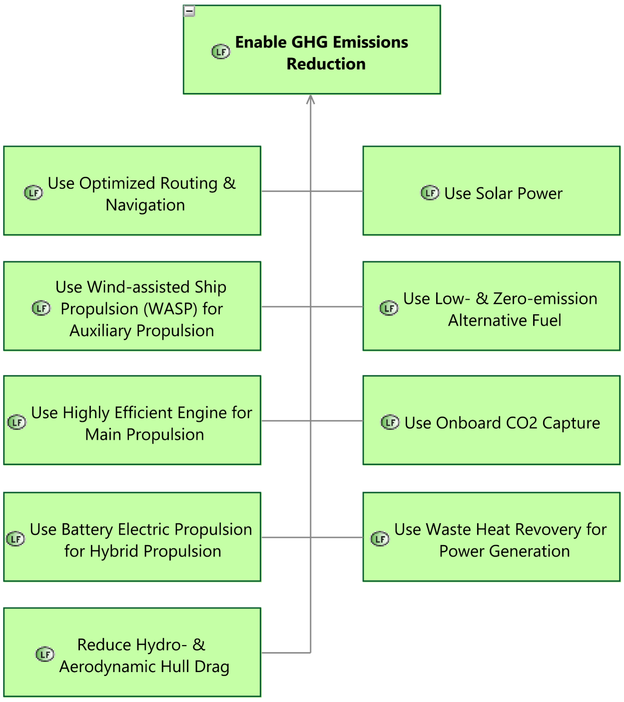

Figure C-17: [LFBD] Bulk carrier – Logical functions breakdown "Enable GHG Emissions Reduction"

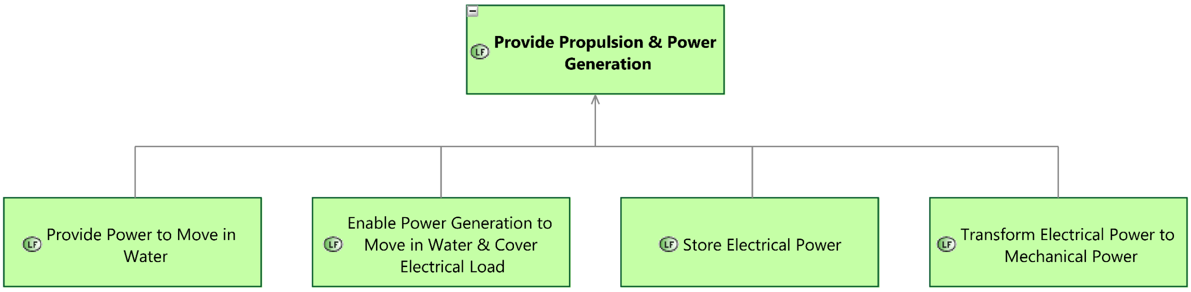

Figure C-18: [LFBD] Bulk carrier – Logical functions breakdown "Provide Propulsion & Power Generation"

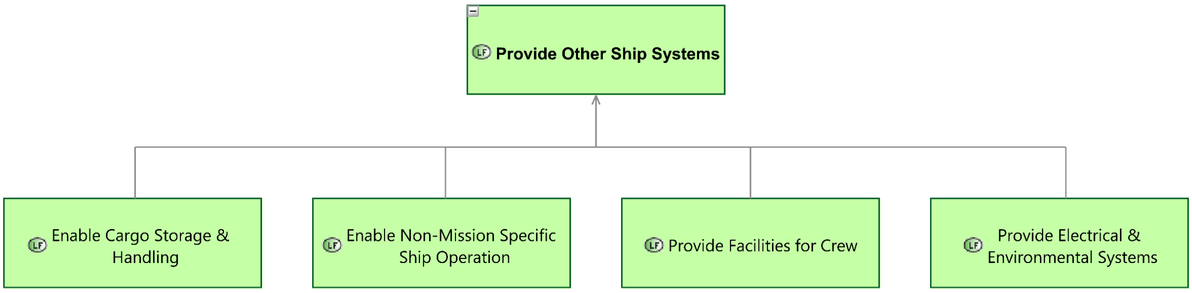

Figure C-19: [LFBD] Bulk carrier – Logical functions breakdown "Provide Other Ship Systems"

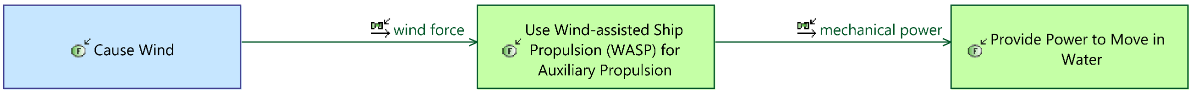

Figure C-20: [LFCD] Bulk carrier – Functional chain description "Wind-assisted Ship Propulsion (WASP)"

Physical Architecture (PA)

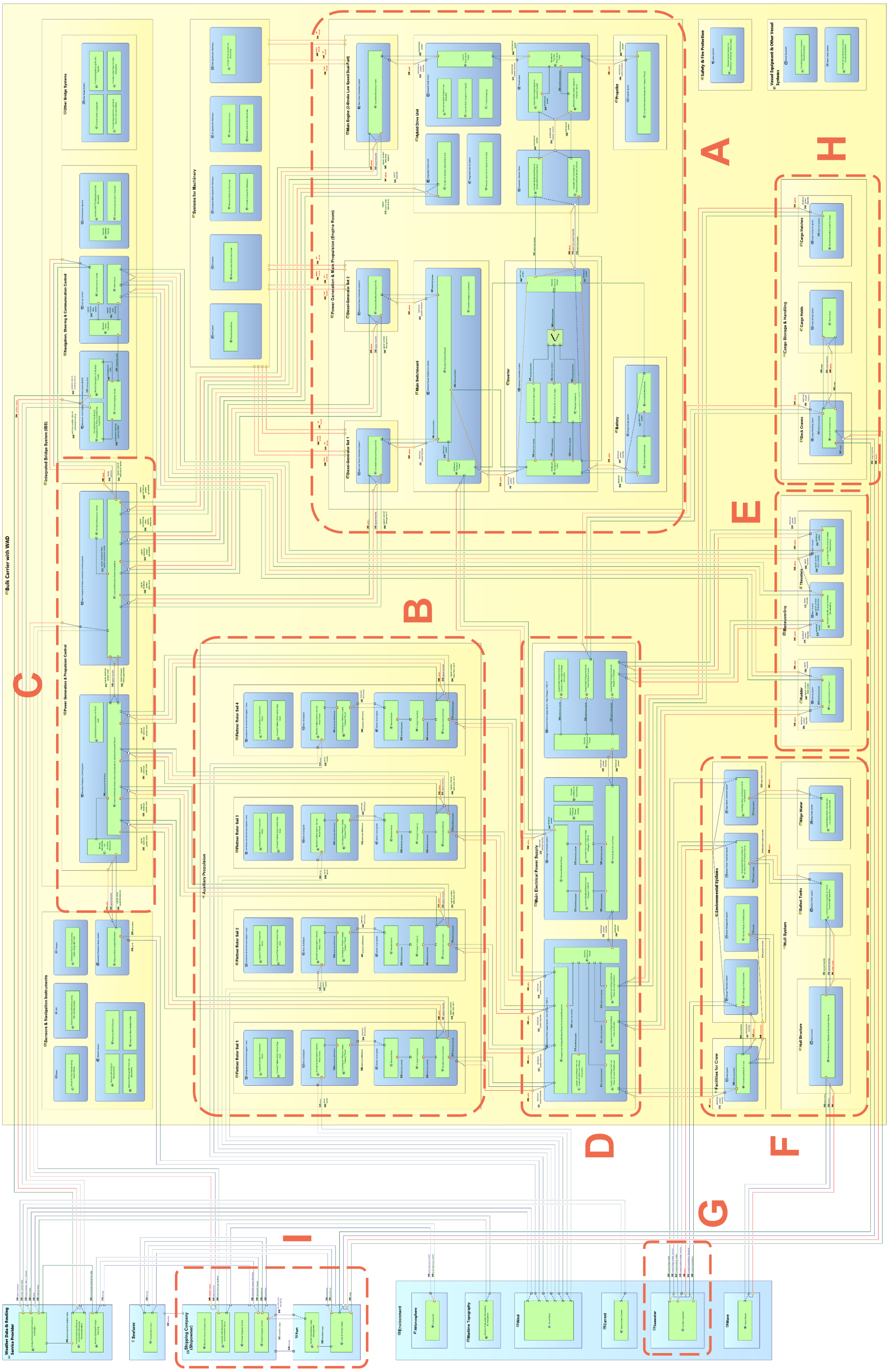

Figure C-21: [PAB] Bulk carrier – Physical architecture, inspired by *Dreier et al.*[293]

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[293] Dreier et al. (2024)., p. 9

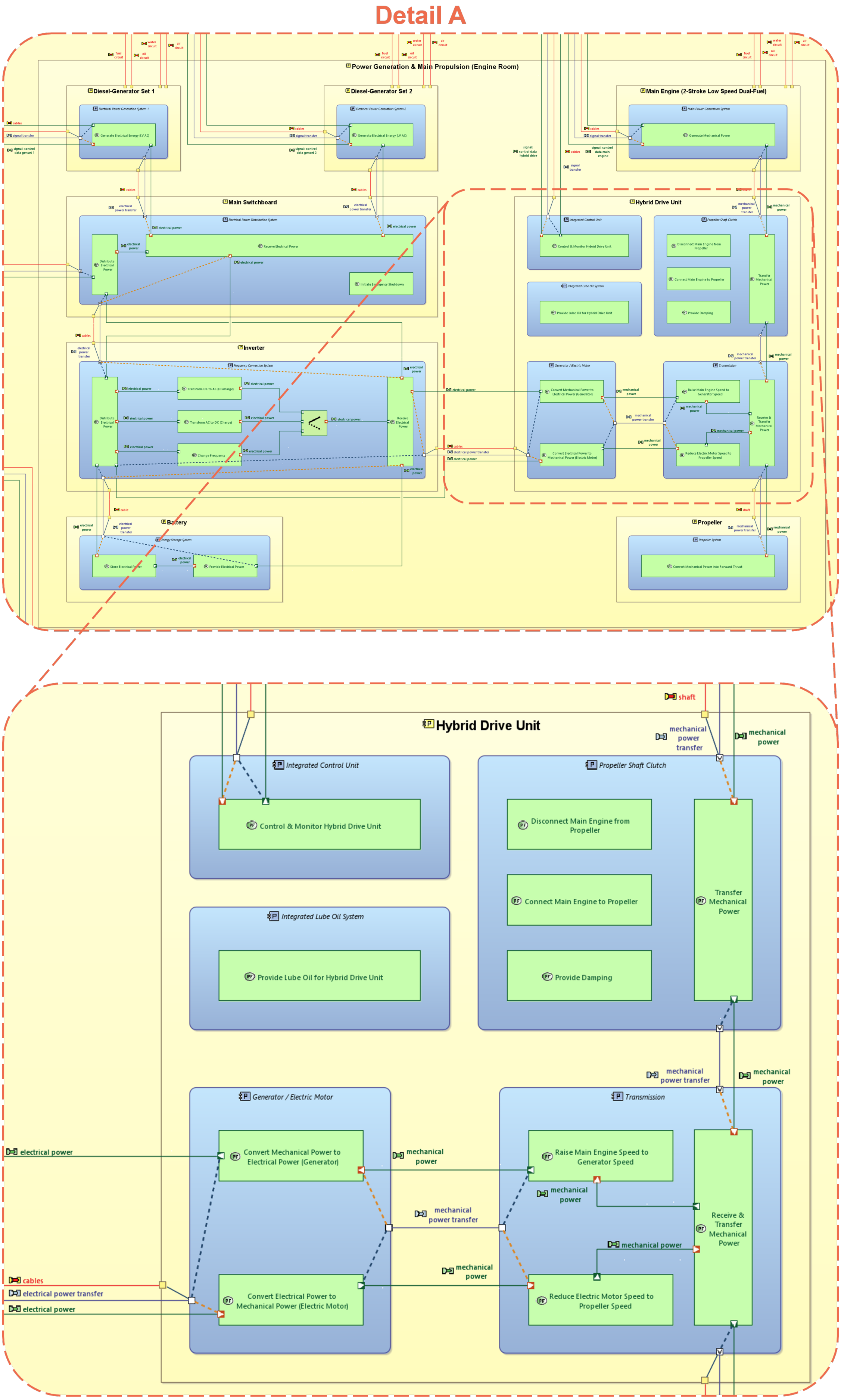

Figure C-22: [PAB] Bulk carrier – Physical architecture; Detail A – “Power Generation and Main Propulsion” with highlighted “Hybrid Drive Unit”

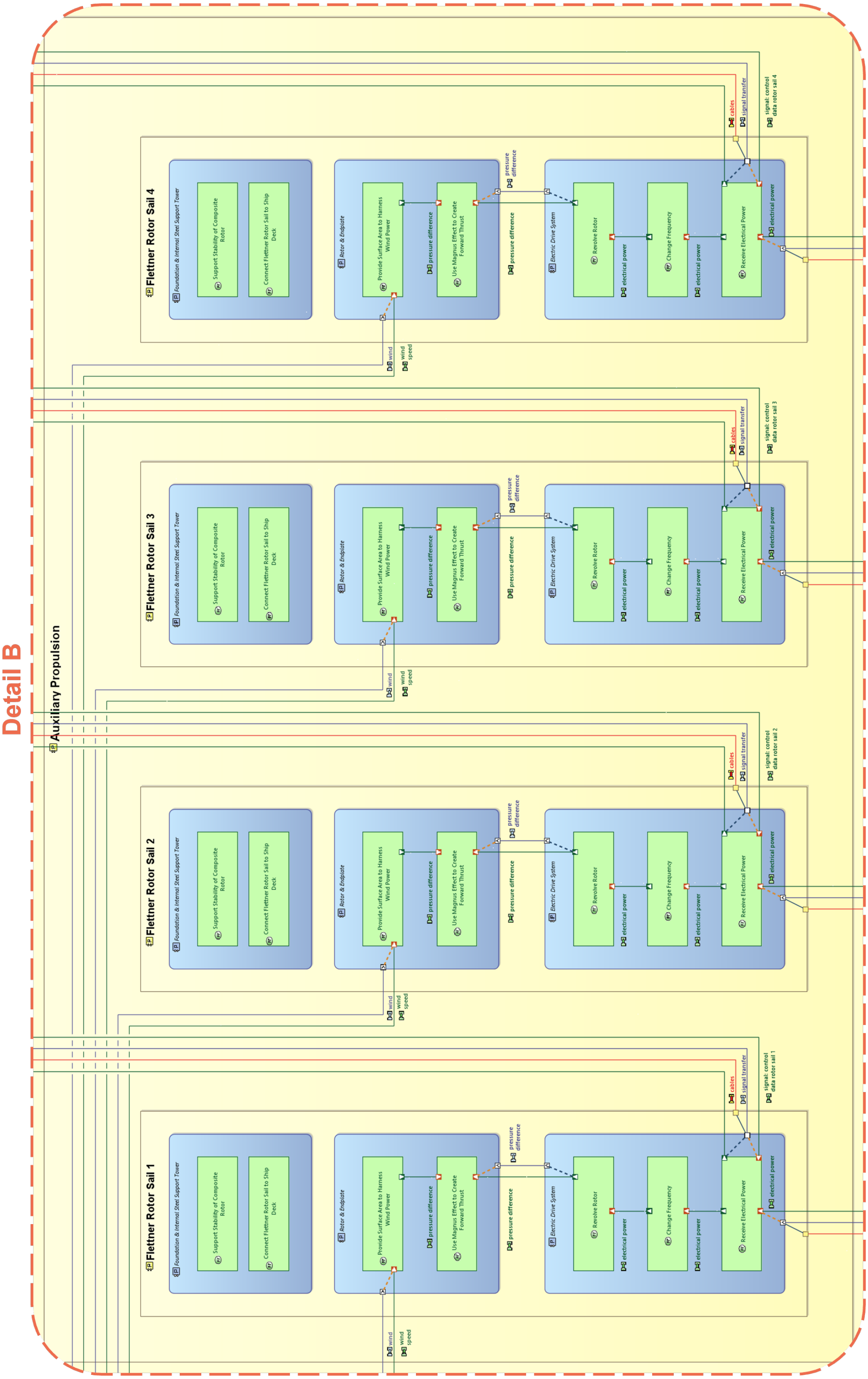

Figure C-23: [PAB] Bulk carrier – Physical architecture; Detail B – “Auxiliary Propulsion” including four “Flettner Rotor Sails”

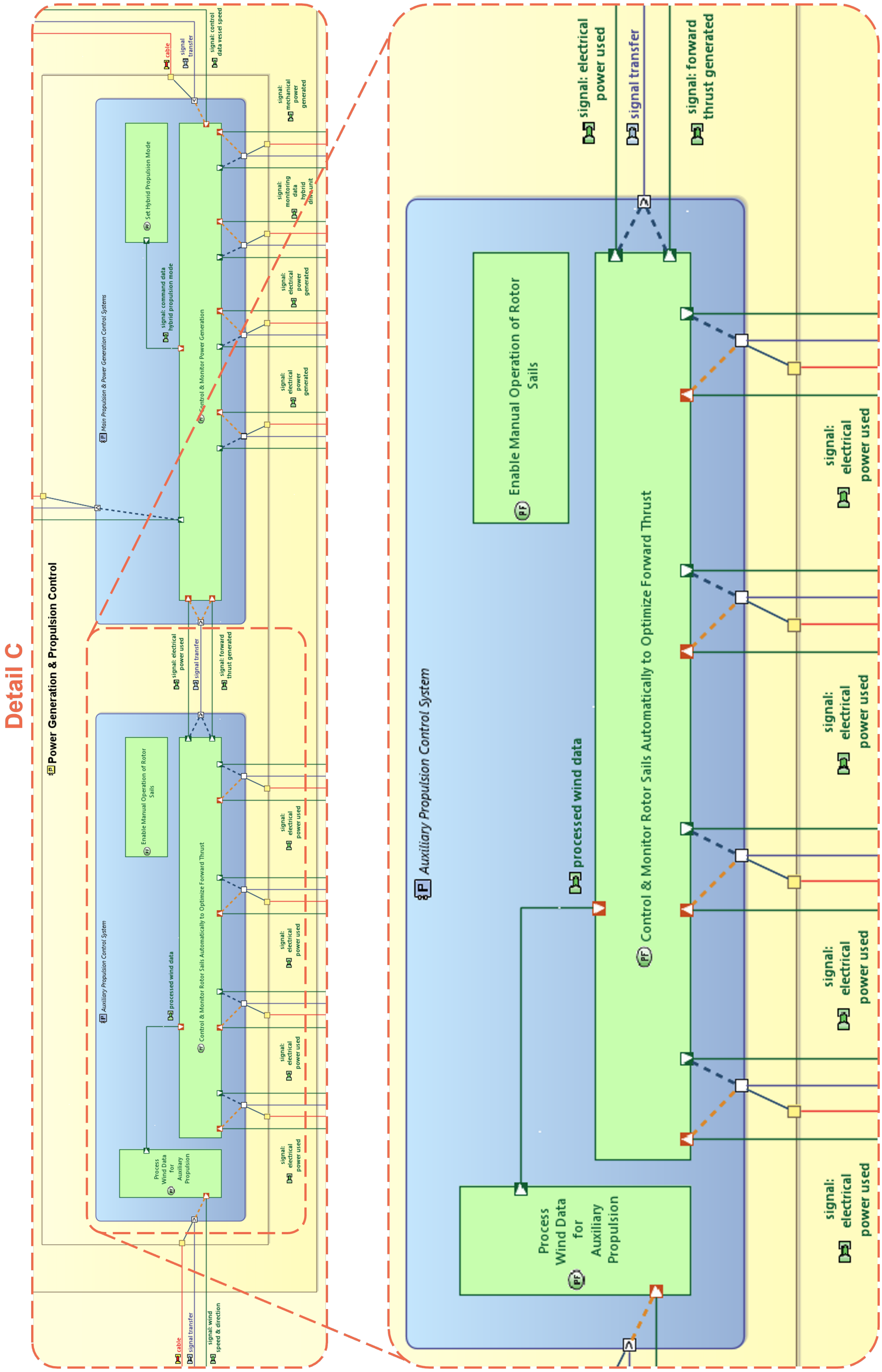

Figure C-24: [PAB] Bulk carrier – Physical architecture; Detail C – “Power Generation & Propulsion Control” with highlighted “Auxiliary Propulsion Control System”

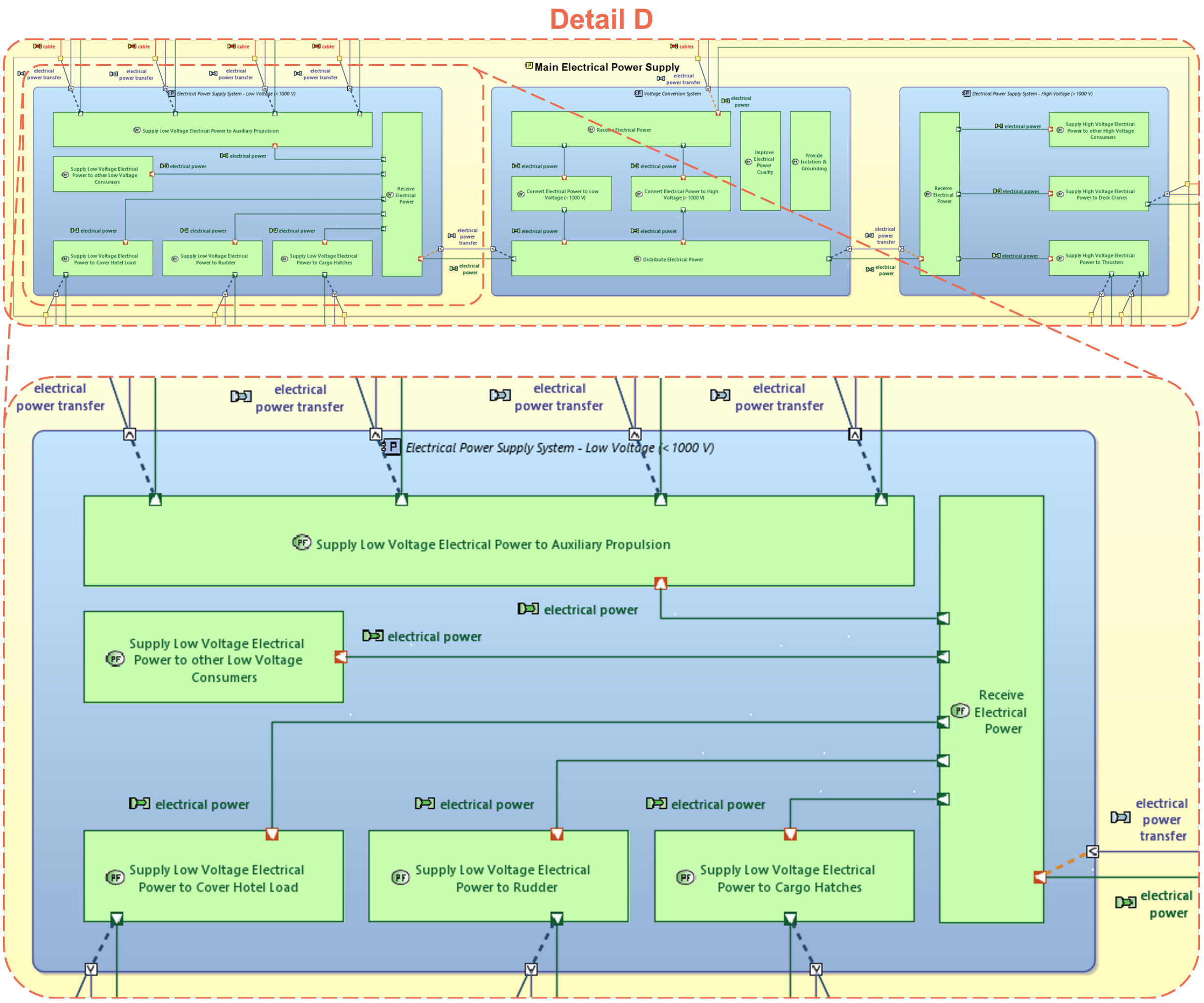

Figure C-25: [PAB] Bulk carrier – Physical architecture; Detail D – “Main Electrical Power Supply” with highlighted “Electrical Power Supply System - Low Voltage (< 1000 V)”

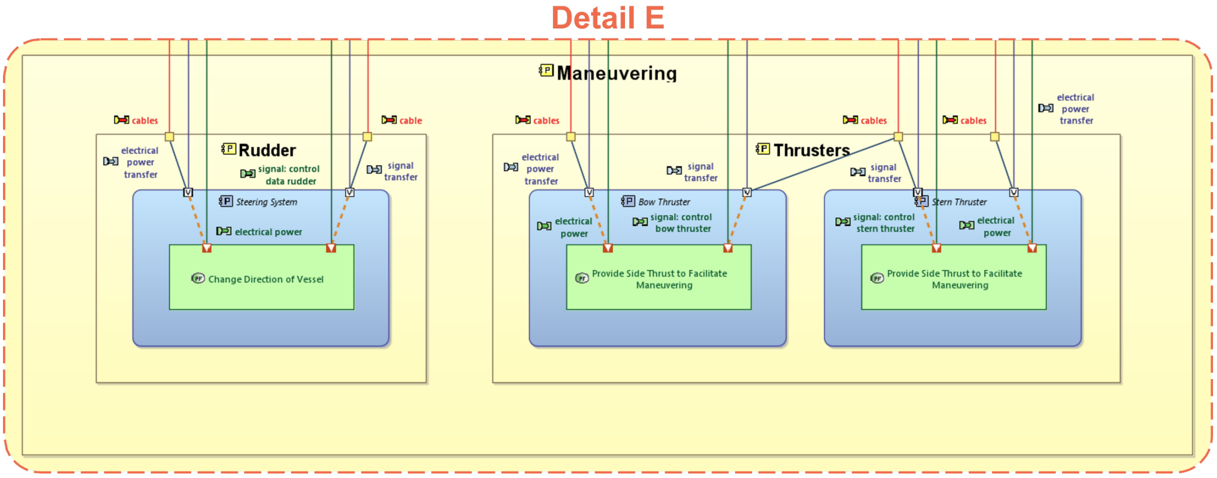

Figure C-26: [PAB] Bulk carrier – Physical architecture; Detail E – “Maneuvering” including “Rudder” and “Thrusters”

Detail F

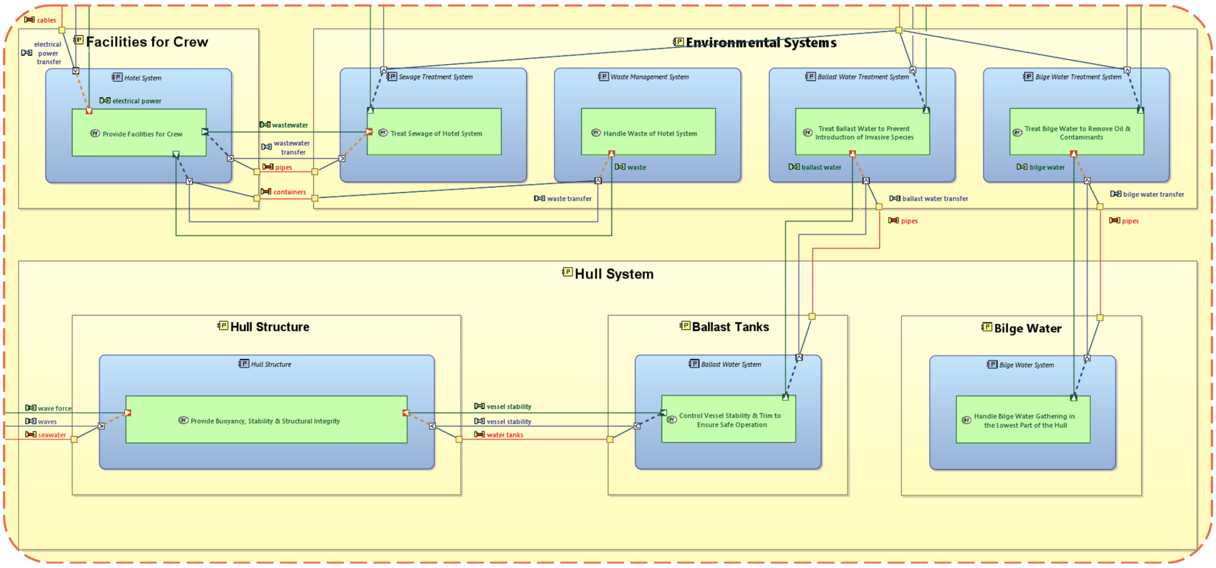

Figure C-27: [PAB] Bulk carrier – Physical architecture; Detail F – “Facilities for Crew”, “Environmental Systems”, and “Hull System”

Detail G

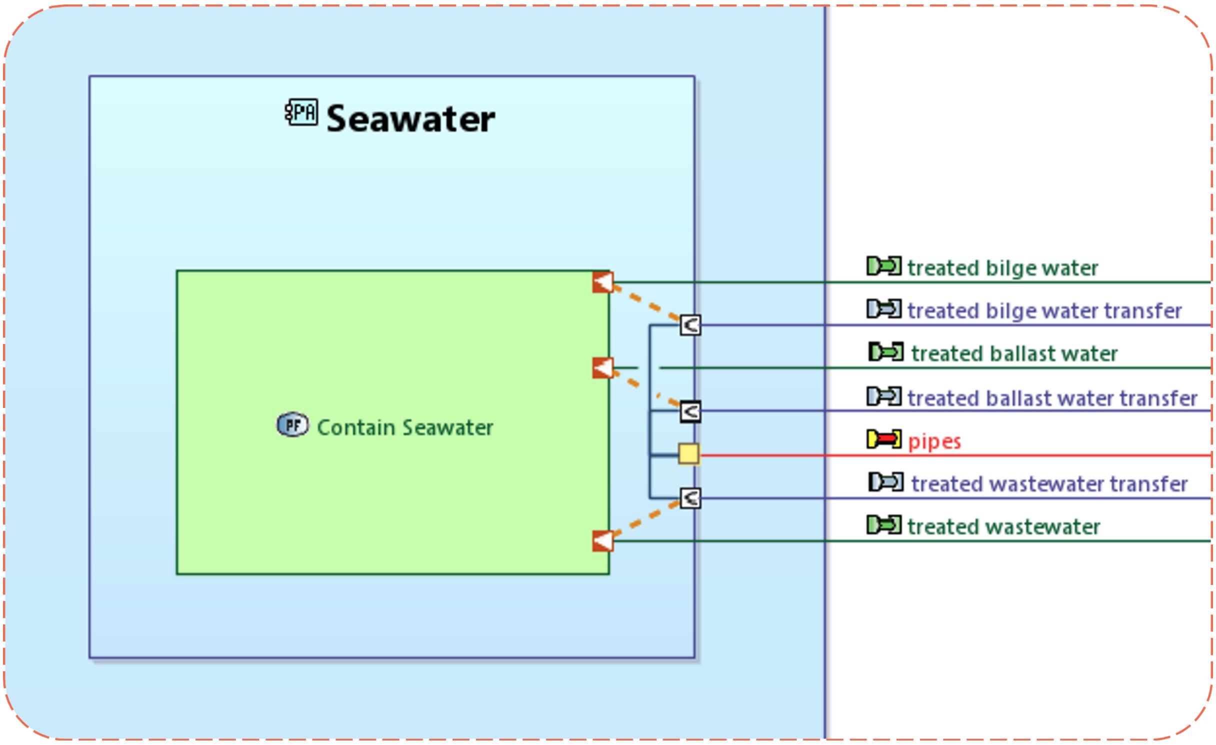

Figure C-28: [PAB] Bulk carrier – Physical architecture; Detail G – Exchanges of “Seawater” with “Environmental Systems” example

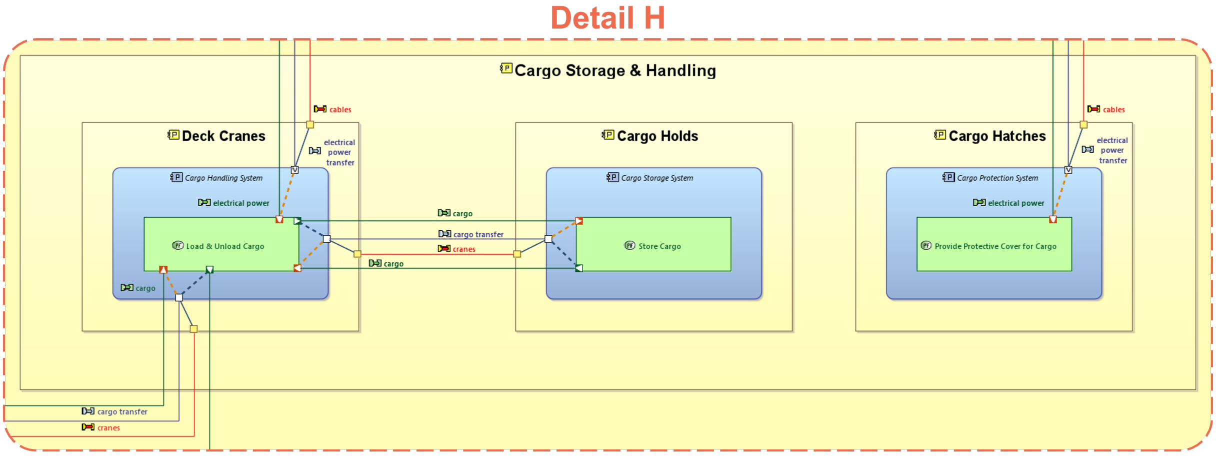

Figure C-29: [PAB] Bulk carrier – Physical architecture; Detail H – “Cargo Storage & Handling” including “Deck Cranes”, “Cargo Holds”, and “Cargo Hatches”

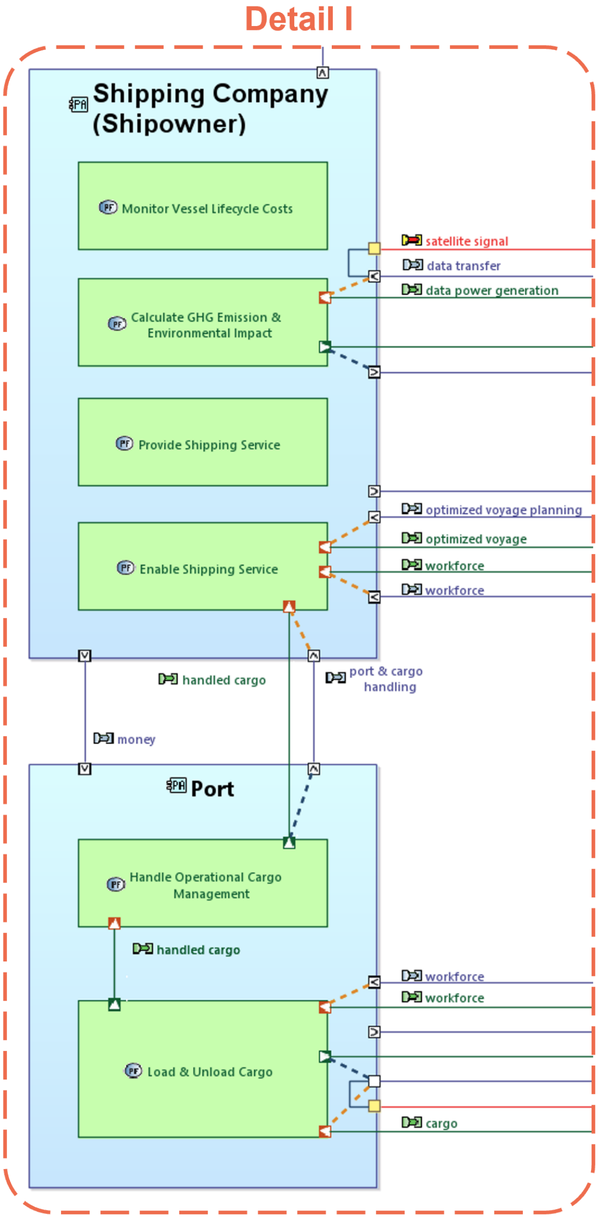

Figure C-30: [PAB] Bulk carrier – Physical architecture; Detail I – Exchanges of “Shipping Company (Shipowner)” and “Port” with “Cargo Storage & Handling” example

MBSE in the Maritime Industry
Enabling Digital Transformation for CO_2 Reduction through Wind-assisted Ship Propulsion

This master’s thesis applies model-based systems engineering (MBSE) methodologies in the maritime industry to support its digital transformation and decarbonization. As a key global economic sector, international marine shipping faces urgent challenges related to resilient supply chains, digitalization, and energy transition in response to the climate crisis. The goal of net-zero emissions in the maritime sector by 2050 has been outlined in the 2023 IMO Strategy on Reduction of GHG Emissions from Ships and is in line with the Paris Agreement.

The thesis presents a detailed system model of a bulk carrier ship that uses a wind-assistance device (WAD) for auxiliary propulsion, developed with the Arcadia modeling language/method and the Capella tool. This work emphasizes the integration of wind-assisted ship propulsion (WASP) into existing and future ships as a strategy to reduce GHG emissions. It highlights the potential of MBSE to enhance ship design practices, improve stakeholder communication, and manage the complexity of marine systems effectively. The thesis also provides a theoretical framework of systems engineering (SE) and MBSE fundamentals, and explores how these methodologies can contribute to the decarbonization of marine shipping by 2050.

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