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DT4GS

Digital Twins for Green Shipping

D1.1: *Value-oriented Analysis in enabling Shipping Decarbonisation*

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Executive summary

The deliverable presents a Value-Oriented Analysis of shipping decarbonization with the use of digital twins. This is achieved through framing the key decarbonization drivers and enablers such as regulation, economic factors and enabling technologies in the context of the digital twin technology. The purpose of the deliverable is to apply a Value Analysis methodology for the potential contribution of digital twins to shipping decarbonization. A Value Proposition Mapping is performed, identifying the value added by Digital Twin models to energy efficiency Improvement and CO2e reduction.

The innovation aspects that this report introduces is twofold:

- It establishes a link between the main shipping decarbonization transition challenges and the cornerstone of the DT4GS project, which is the digital twin.
- The Value Proposition Mapping method identifies the value of digital twins to the different types of stakeholders in shipping sector, as represented by the Project's Living Labs.

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Glossary of terms and acronyms used

Table 1: Glossary of acronyms and terms.

Acronym / Term	Description
AI	Artificial Intelligence
DT	Digital Twin
LL	Living Lab
ML	Machine Learning
VA	Value Analysis
IoT	Internet of Things
KPI	Key Performance Indicator
ETS	Emission Trading Scheme
GHG	Greenhouse Gases
AER	Annual Efficiency Ratio
NB	Newbuild
TCO	Total Cost of Ownership
WASP	Wind-Assisted Propulsion
ERP	Enterprise Resource Planning
ECA	Emission Control Area
CAGR	Compound Annual Growth Rate
M/E	Main Engine
A/E	Auxiliary Engine
CAPEX	Capital Expenses
OPEX	Operational Expenses
GA	Grant Agreement

1 Introduction

As digitalisation in the shipping industry has been maturing over the recent years, DT adoption will be dependent on establishing trusted and convincing DT application exemplars and ensuring that ship operators and other industry stakeholders can set up their own DTs based on their own business models, building their own confidential knowledge at reasonable cost. This requirement is at the heart of the DT4GS approach as illustrated in the Figure 1 below.

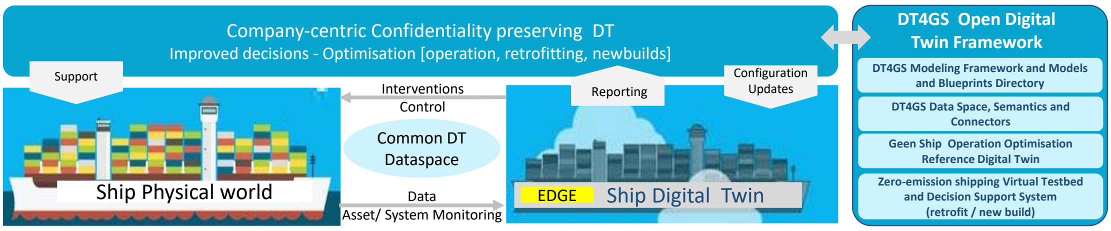

Figure 1: DT4GS approach

DT4GS will develop DTs that are virtual representations of ships and physical transport entities with a bi-directional communication links from sensing to actuation/control and data driven simulation and AI based decision support to shipping industry stakeholders.

This document describes research conducted in Workpackage 1 ''DT4GS Modelling Framework'' and focuses on delivering a value-oriented analysis on the use of Shipping Digital Twins for the decarbonisation of shipping in areas such as:

- innovative ship operation performance optimisation,
- simulation based planning and design of retrofitting with GS technologies and
- planning and designing Green Smart New-Builds (vessels).

Additionally, WP1 aims to deliver strategic DT use cases and datasets drawn from the Project's LLs.

In this report we present the results of Value Proposition Mapping for digital twins in shipping decarbonisation, and identify and quantify all enablers and challenges of deploying and using DT models for the different shipping community stakeholders

1.1 Mapping DT4GS Outputs

The purpose of this section is to map DT4GS Grant Agreement commitments, both within the formal Deliverable and Task description, against the current document.

Table 2: Adherence to DT4GS Grant Agreement deliverable and work description.

DT4GS GA Component Title	DT4GS GA Component Outline	Respective Document Chapter(s)	Justification
DELIVERABLE			
***D1.1* DT4GS Value-oriented Analysis in enabling Shipping Decarbonisation**	Value Oriented Analysis, LLs Scenarios, Transition Challenges, and high-level scenarios Requirements. This deliverable includes the outputs of T1.1.	*Sections 2, 3, 4 and 7*	*Value oriented analysis is described in Section 2.* *Decarbonisation challenges are discussed in Section 3.1* *High level scenario requirements are discussed in Section 7.*
TASK			
ST1.1.1 DT4GS Living Labs Scenarios and Strategic Case Studies	Scenarios and strategic case studies for the LLs, each LL will produce one (1) overarching scenario, and at a minimum two (2) case studies involving the **DT4GS Core Services**, defining the user acceptance criteria, and delivering a reference guide for cooperation between the shipping stakeholder groups and the consortium partners.	*Sections 4.2 and 7*	*Section 4.2 describes DT scenarios. Section 7 describes specific high level requirements and case studies per LL.*

ST1.1.2 Transition Challenges, Enabling Factors & DT4GS actors	Define the macro-environment enablers and challenges for DT4GS. Elicit methods, models and governance related to the economic viability of DT4GS, considering financial levers (i.e., carbon credits, Green Taxes, Transition Finance) in the context of the latest EU disclosures, and adoption strategies in line with the UN SDG's.	*Section 3.1 and 4.3.1*	*The macro-environment enabler and adoption strategies for DTs are discussed in Section 3.1. DT challenges are discussed in Section 4.3.1*
ST1.1.3 High-level Requirements Specification for DT4GS.	Establish key requirements to drive project developments.	*Section 7*	Key requirements both generic (across LLs) as well as specific ones (per LL) are discussed in Section 7.

1.2 Deliverable Overview and Report Structure

This deliverable analyses shipping industry decarbonization from the perspective of the digital twin (DT) technology, its risks and opportunities, potential transition challenges, enablers and stakeholders.

The contribution of this deliverable is to:

- establish a link between the main decarbonization transition challenges and the cornerstone of the project, which is the DT, by elaborating on how the challenges are addressed by the DT.
- present a Value Proposition Mapping of the business value of DT for each shipping sector stakeholder.

This section of the document provides a description of the deliverable structure and an outline of the respective sections and their content. The deliverable is organised as follows:

- Section 1: It provides an overview of how the deliverable links to the work package and tasks as described in the Grant Agreement.
- Section 2: It presents the Value Analysis methodology used.
- Section 3: It sets the business context for the Value analysis methodology.
- Section 4: It presents the concept of ship digital twin and its contribution to ship decarbonisation.
- Section 5: It identifies the different types of shipping stakeholders receiving value from using DTs in shipping decarbonisation
- Section 6: It analyses the value of DTs per shipping application/use case
- Section 7: It presents high level requirements for the application of digital twins in the Living Labs.
- Section 8: It summarises the main takings and conclusions of this work.

2 Methodology

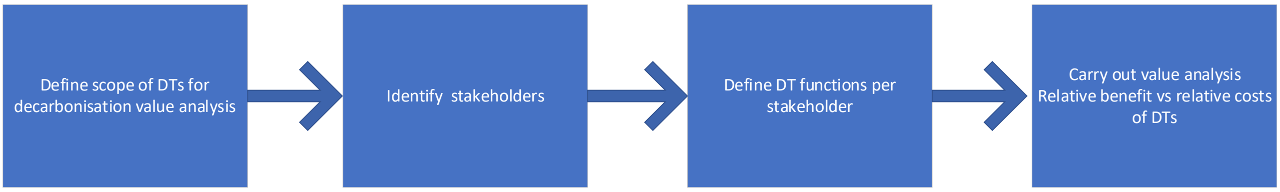

Figure 2: The Framework for Value Analysis

The section presents a value analysis methodology to realise the WP1.1. objectives. The value proposition mapping process steps are as follows (Figure 2):

Define the Scope of the value Analysis

This is done on terms of business (legislation, finance) and technology dimensions. The business dimensions are discussed in Section 3.4 while the technological dimension (digital twin) in Section 4.

Identify all classes of stakeholders

Define the different types of shipping sector entities that can potentially benefit, directly or indirectly from the deployment of DTs (Section 5).

Define DT functions per stakeholder

Define the different application areas/use cases for DTs for shipping decarbonisation. Associate different applications and use cases with the project's Living Labs (Section 6).

Map value proposition of DTs to stakeholders

Build a stakeholder segment matrix and associate DT benefits and risks with each different segment.
Classify DT stakeholders from the *supply side perspective and from the (end) user side.*
Decompose the DTs into different functions, and for each function, define benefits but also the drawbacks of DTs are identified for the end user.

2.1 Value Proposition Mapping

Value Proposition mapping (VPC) is a mapping tool which provides an analysis of a product / solution based on who is providing the solution, what additional value and benefits that solution brings to specific end-users and In parallel, the end-users carry out specific tasks which emerge specific gains and pains that are addressed by the product offered by the solution provider.

We have used the Value Proposition Canvas (VPC), an innovative model to identify the value proposition of DTs to specific types of end-users. VPC breaks down each product or solution into specific jobs undertaken by a specific interested party which has gains and pains impacting the end-user. Our analysis identifies the end user which is expected to be mostly benefited by the application of DTs and maps the DT value proposition to specific user needs and requirements.

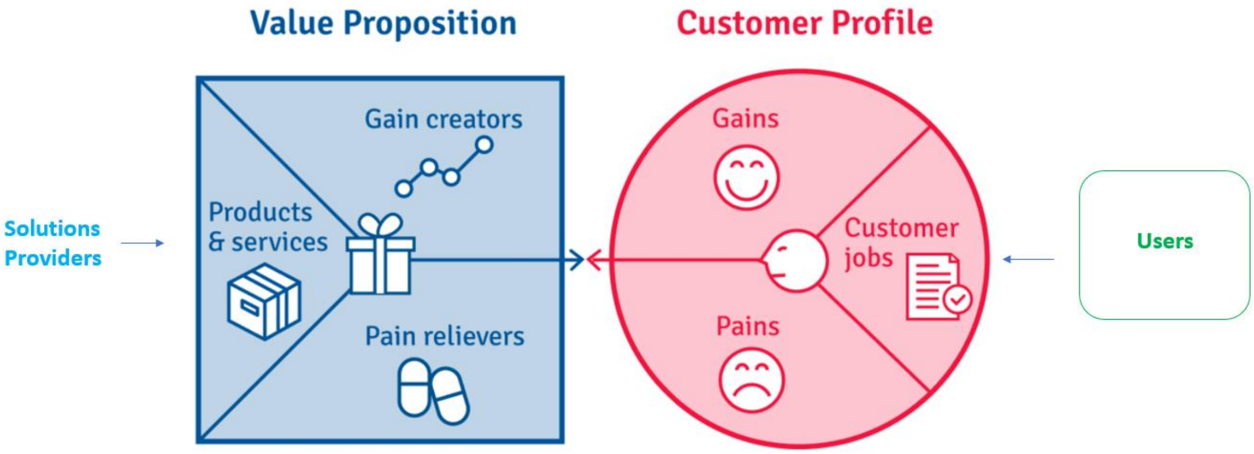

Figure 3: Value Proposition Canvas

3 Value analysis context

Through the subsections of this section, we set the context required for Value Analysis, namely:

- The shipping decarbonisation business/legislative/financial context of the value analysis.
- What is the analysed product (Digital Twin)
- Who are the beneficiaries (users/stakeholders) of that value
- The trade-offs between benefits and costs/risks (gains vs pains) for the stakeholders.

3.1 Decarbonisation in Shipping

Maritime transport emits 940 million tonnes of CO2 annually, accounting for circa 2.7% of the global CO2, an output of around 7% of SOx and 12.5% of NOx emissions (European Commission - 'Reducing emissions from the shipping sector'). Maritime shipping plays also a major role in European transport sector. It accounts for 75% of the EU's external trade and 36% of intra-EU trade flows by volume. Maritime emissions represented 13% of the EU's transport emissions in 2018. Shipping's global emissions are also expected to increase by up to 50% between now and 2050 (Transport and Environment, 2021). However, this contribution has slightly stabilized over the last 5 years however showing a similar trend for the next couple of years. Regulation is certainly underpinning this trend together with industry's realization about the need to decarbonise shipping (Figure 4) (Source: Euronav analysis).

Moreover, shipping decarbonisation and digitalization have always been a core focus policy area for European authorities tying in principle with the EU Green and Digital Transformation strategy. Digital tools applied to building, testing and operating vessels are enabling information and data sharing between the vessel, the infrastructure (Sea2Shore) and people facilitating decision-making towards low carbon economy. Therefore, digitalization could serve as a mean to achieve lower carbon impact in the shipping sector which currently accounts for 3% of global emissions.

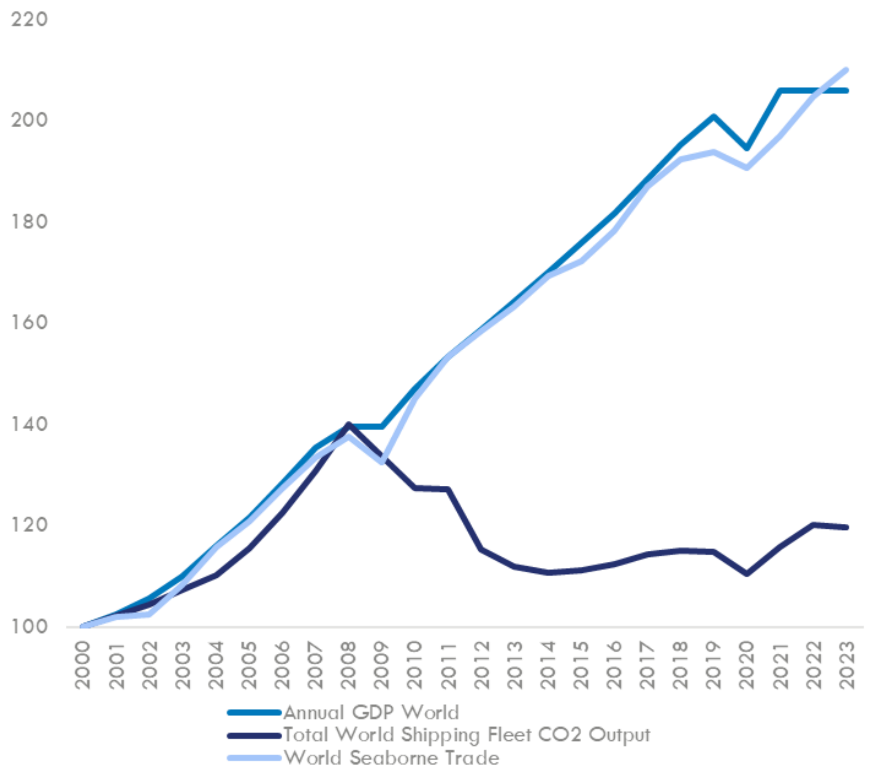

Figure 4: Shipping emissions vs. Global GDP and trade

Shipping finds itself in an odd juxtaposition between a perceived reluctance to take affirmative action on climate change and the actual planned reduction in GHG emissions. This reputation has been driven by the sector's absence from the Paris Agreement on climate change. However, a true picture of the environmental attributes of shipping emerges when it is compared against the other major transportation methods. Shipping is seven times more efficient than rail, sixteen times more than road transportation and a massive eighty-five times more efficient than air transport (IMO, 2009). For a global industry to emit just 2.7% of the world's carbon emissions, this is not only a very efficient process but the least impactful on the environment, particularly when taking into account the quantities and services it transports. For an economic region such as the European Union, shipping accounts for 80% of total exports and imports by volume, and some 50% by value. Shipping is the key transportation sector reflected in the International Chamber of Shipping's website (source: https://www.icsshipping.org/shipping-fact/shipping-and-world-trade-drivingprosperity/).

Since 2019, the total value of the annual world shipping trade had reached more than 14 trillion euros. Shipping's capacity to transfer goods and materials from where they are produced to where they are used or consumed underpins modern life (Bloomberg 1.1.21, International Chamber of Shipping).

Shipping segment size and emission generation are not always proportional. That applies for larger, ocean vessels. The greatest source of GHG emissions within shipping are from container ships, bulk carriers and oil tankers, as shown in Figure 5 (Source: Balcombe et al. 2019).

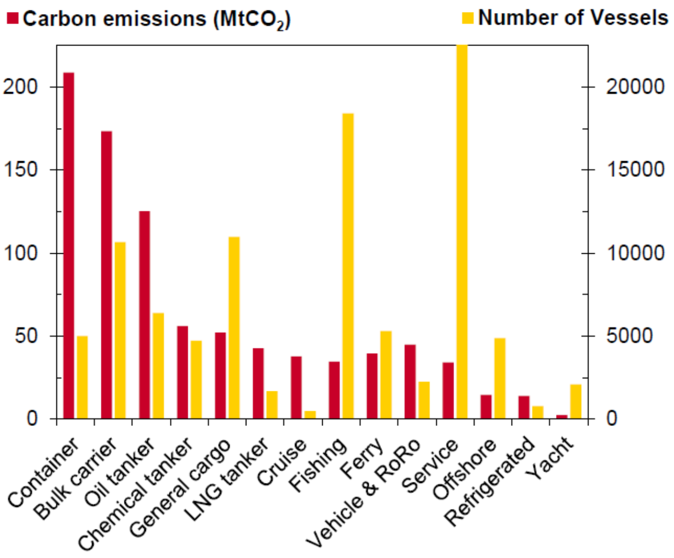

Figure 5: Number of ships and their carbon emissions, by category in 2017

Recognizing the need to reduce emissions from shipping operations, the International Maritime Organization (IMO), the global shipping regulatory body, has established emission reduction pathways that are reviewed regularly. It is expected that next review round will be in the next 2-3 years. Currently IMO targets anticipate a reduction of 50% in the absolute emissions from shipping operations between 2008 and 2050. Moreover, the IMO has also set carbon intensity emissions as well where it is expected that global fleet's intensity will be reduced by 40% in 2030 and by 70% in 2050 both compared to 2008 reference baseline. In the Figure 6 (Source: Poseidon Principles) below, the different trajectories under IMO targets with red line representing the official – to –date – emission reduction trajectory by the IMO.

Many shipping players have launched pilots although at small scale, with important learnings being collected across the industry. In many shipowners' strategies the route to 2030 could serve as an era of energy efficiency improvements stemming not only from retrofits but also from new technologies and digital transformation. Shipping digitalization enables informed decision making by operators, crews and ship managers based on quality data. This leads, in turn, into vast improvements in fuel and energy efficiency.

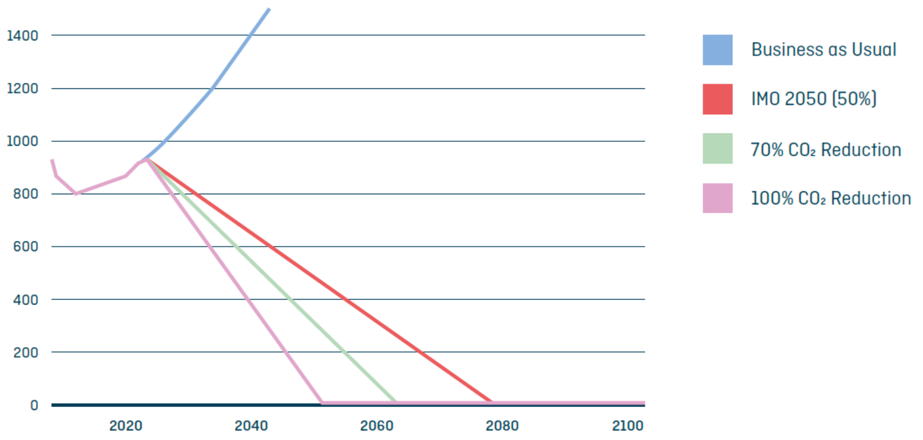

Figure 6: Global fleet's CO2 targets and trajectories under IMO targets (million tonnes of CO2)

A key driver for shipping decarbonisation is fleet modernization. Transition strategies however entail difficult choices between newbuilds and retrofit options. Early adopters may face expensive future retrofits, while on the contrary, shipping players who wait for the fuel category killers may lose part of their customer segment who aim to be at the forefront of the climate agenda.

EU shipping could reduce a third of its emissions by 2050 by mainly leveraging its technical and operational energy efficiency. This can be achieved by installing energy saving devices such as wind-assisted propulsion or air lubrication, but also through operational measures such as optimizing voyage speed, or streamlining supply chain activities (e.g., so called Just-In-Time arrival). Among the sustainable fuels, green ammonia appears to be the most promising zero-emission fuel to decarbonise the EU-related shipping with green liquid hydrogen. To fully decarbonise by 2050, EU-related shipping needs to deploy green fuels as soon as possible. Below (Source: Transport and Environment 2021), Transport and Environment presents a high and low efficiency scenario regarding shipping decarbonisation pathways for EU shipping. In both cases, a mix of different measures is required to achieve the 2050 goal with fuels holding the lion's share.

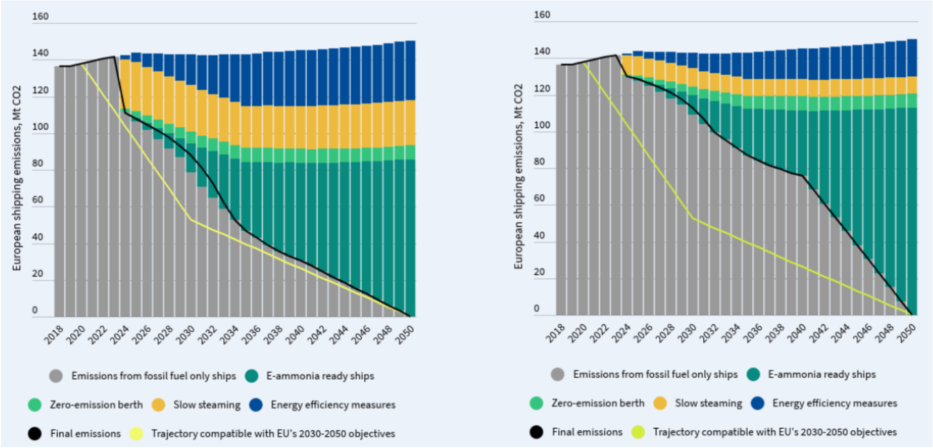

Figure 7: Decarbonisation pathways for EU shipping: high and low energy efficiency scenarios Relevant R&D Projects

Realizing this significance, the EU has put forward specific R&D funding engines to unfold its strategy towards developing a safe, secure and resource-efficient waterborne transport system. In the last years, the waterborne transport programmes have been dedicated to fund a number of innovative solutions in addressing the main challenges of the shipping sector Europe: infrastructure; energy efficient and zero emission vessels; innovative shipbuilding and complex value- added specialized vessels; safer and more efficient waterborne operations; and new and improved waterborne transport concepts.

AQUO (2012) project recognizes the underwater noise impact due to shipping, to prevent negative consequences to marine life.

EU-CARGOEXPRESS (2009) aim has been to prototype a ground-breaking innovative cargo vessel to meet the expectations of green transport and contributing to decongesting of Europe's roads.

ULYSSES (2011) aimed at demonstrating the efficiency potential of the global fleet through a combination of ultra-slow speeds and complementary technologies. In this practical approach with timeless value

SAIL (2010) project developed an integrated ICT tool able to support logistic chain of goods flow and all business operations provided in the port and the dry port areas.

ARIADNA (2009) developed a Volumetric Navigation System (VNS) with new traffic navigation solutions considering certain scenarios in which all the vehicles share information in order to be part of a collaborative navigation network.

DOCKINGASSIST (2011) developed a cost-effective location system, covering the complete port/harbour zone, to provide efficient and safe manoeuvring within the entire port area enhancing vessel trajectory, and providing constant monitoring for moored/docked vessels improving port traffic management, reducing operating expenses, CO2 emissions and fuel usage.

AUTODROP project (2010) addressed the need for an improved method for accurate and inexpensive deployment and retrieval of seabed sensors and equipment as addressed by

LINCOLN (2016) presented three new concepts of added-value specialized vessels able to run requested services for several maritime sectors in the most effective, efficient, economic valuable and eco-friendly way. Those concepts have been serving like vessel platforms through dynamic simulation testing.

TRITON (2013) focused on increasing the trustworthiness of on-board instrumentation used to report vessel information to the control organisms.

MINICHIP (2013) addressed the research gap in marine operations by developing mathematical formulations of marine shipping operations as a stochastic optimisation problem to minimise carbon footprint whilst optimising service level and cost with a use of decision support tool. Furthermore, focus has been shed on the engine capabilities and propulsion to gradually reduce the environmental impact from shipping.

GASVESSEL (2017) proved the techno-economic feasibility of a new CNG transport concept enabled by a novel patented Pressure Vessel manufacturing technology and a new conceptual ship design including safe on- and offloading solution.

RotorDEMO (2017) enhanced the complete propulsion system of a vessel by using wind as an auxiliary propulsion measure.

DEECON (2011) created a modular, on-board, after-treatment unit that combines different sub-units, each of which is optimized to remove a specific primary pollutant.

Later projects have been addressing several aspects of green and digital shipping (EU CINEA, 2021):

Infrastructure:

- The Port of the future (PIXEL, PortForward, COREALIS, DocksTheFuture)

- Green airports and ports as multimodal hubs for sustainable and smart mobility (PIONEERS, MAGPIE)

Innovative shipbuilding and value-added specialized vessels:

- System modelling and lifecycle cost optimisation for waterborne assets (SHIPLYS, HOLISHIP)
- Development, production and use of high performance and lightweight materials for vessels and equipment (FIBRESHIP, RAMSSES)
- High value-added specialised vessel concepts enabling more efficient servicing of emerging coastal and offshore activities (LINCOLN, NEXUS)
- Complex and value-added specialised vessels (HYSEASIII, TrAM, NAVAIS)
- Improved Production and Maintenance Processes in Shipyards (Mari4_YARD, FIBRE4YEARDS, RESURGAM)

New and improved waterborne transport concepts:

- Preparing for the future innovative offshore economy (MARIBE)
- Delivering the sub-sea technologies for new services at sea (DexROV, BRIDGES)
- New and improved transport concepts in waterborne transport (GASVESSEL, NOVIMAR)
- Unmanned and autonomous survey activities at sea (ENDURUNS)
- The Autonomous Ship (AUTOSHIP)
- Moving freight by Water: Sustainable Infrastructure and Innovative Vessels (IWNET, NOVIMOVE, AEGIS, MOSES)

Energy-efficient and zero emission vessels:

- HEMOS, Zhenit, Optiwise, and Copropel are projects investigating energy efficiency.
- Towards the energy efficient and emission free vessel (E-FERRY, LeanShips, HERCULES-2)
- Promoting innovation in the Inland Waterways Transport (IWT) sector (PROMINENT)
- Innovations for energy efficiency and emission control in waterborne transport (AIRCOAT, HYMETHSHIP)
- InCo flagship on reduction of transport impact on air quality (SCIPPER)
- Ship emission control scenarios, marine environmental impact and mitigation (EMERGE)
- Retrofit Solutions and Next Generation Propulsion for Waterborne Transport (Nautilus, FASTWATER, GATERS, SeaTech)
- Structuring R&I towards zero emission waterborne transport (STEERER)
- Under water noise mitigation and environmental impact (SATURN)
- Improving impact and broadening stakeholder engagement in support of transport research and innovation (LASTING, PLATINA 3)

- Decarbonising long distance shipping (CHEK, ENGIMMONIA)
- GREEN RAY project assessing and mitigating methane slip in LNG engines to enable clean waterborne transport.

Safer and more efficient waterborne operations:

- Safer and more efficient waterborne operations through new technologies and smarter traffic management (EfficienSea2, LYNCEUS2MARKET)
- Response to oil spills and marine pollutions (GRACE)
- Safer waterborne transport and maritime operations (SEDNA)
- Marine Accident Response (LASHFIRE, SAFEPASS, FLARE, PALAEMON)
- Human Factors in Transport Safety (SAFEMODE)

3.2 Shipping Decarb Legislation and Regulations

International shipping needs to align with IMO's GHG strategy and that is only possible through zero-emission fuels becoming the main fuel source by the mid-2030s, gradually phasing out current fossil fuels. However, a significant competitiveness gap is recorded between incumbent fossil fuels and alternative zero-emission options. This gap is the result of the existence of market barriers and failures, but mainly the lack of supply and demand, a lack of regulation on safety, as well as the price difference in the fuels. As a result, there is an urgent need for policy to bridge the competitiveness void and ensure shipping meets its decarbonisation ambition. One of the key drivers for shipping decarbonisation is regulations established by the IMO and the EU.

The maritime industry already takes actions to respond to the challenge of reducing its emissions. Serving 2015 Paris Agreement as a basis, IMO announced the goal of reducing GHG emissions by 50% by 2050 back in 2018 compared to emissions baseline of 2008. Besides regulations aiming at mitigating air pollutants such as sulphur dioxide and particulate matter, other measures targeting greenhouse gases are:

- EEDI (Energy Efficiency Design Index) for new ships. The goal of the EEDI is an improvement in average annual efficiency from 2015 to 2025.
- CII (Carbon Intensity Index) which provides ship operators with the pace by which they must reduce CO2 emissions annually to ensure compliance with regulations. The CII must be implemented within each operator's Ship Energy Efficiency Management Plan (SEEMP). CII will be effective as of 2023 with a reporting kick off data in January 2024. CII index will be used to rate ships on a scale: A, B, C, D and E, from best to worst performing. This is shaped to drive improvements in vessel operations, e.g., by technology upgrades.
- EEXI (Energy Efficiency Existing Ship Index): this is also coming into force on 1 January 2023. The EEXI is applied to existing ships outside EEDI regulations. Emissions are defined per cargo tonne and mile.

The anticipated EEXI compliance based on the current global fleet status is (Bureau Veritas, 2021):

- Bulk: 60%
- Tankers: 70%
- Container ships: 30%
- Gas carriers: 55%

- LNG carriers (without steam turbines): 100%
- Cargo ships: 80%

IMO expects that EEXI, EEDI and CII will reduce the annual emissions of global maritime shipping by at least 25% vs. baseline (Richardson, 2021). In 2021 the Marine Environment Protection Committee (MEPC) of the IMO set new targets to reduce CO2 emissions per unit of transport work: a 40% reduction by 2030 a 40% decrease and 70% reduction by 2050 compared to 2008 emissions (IMO, 2021). The reduction path is designed by optimising operations, reducing speed, retrofitting vessels with energy-efficient technology and propulsion and gradually switching to lower or zero emission fuels.

As of 2010, the IMO revised International Convention for the Prevention of Pollution from Ships (MARPOL, Annex VI), aimed at a reduction in emissions of sulphur, nitrogen and particular matter (PM). It also introduced special emission control areas (ECAs) with emissions limits for those pollutants. Two ECAs were established in EU, the Baltic Sea and the North Sea. The revised MARPOL anticipated a reduction in the limit for SOx and PM in ECAs to 0.1 % from 1 January 2015. IMO also announced a global 'sulphur cap' of 0.5 % in all waters from 1 January 2020. It banned even the carriage of non-compliant fuels on board for ships without an exhaust cleaning system. The EU transposed the IMO SOx limits into Directive EU/2016/802. Use of marine fuels with a maximum 0.1 % sulphur content is mandatory in the EU ECAs from 2015. EU also set the same limit for ships calling at EU ports and a 0.5 % limit for all other EU waters from 1 January 2020.

The IMO also introduced reductions of nitrogen oxides (NOx), by setting limits for marine diesel engines on new-built ships. From January 2021, all ships use the mandatory standards or equivalent NOx emission reduction technologies to adhere to NOx emission levels. In 2016, the IMO incorporated Baltic Sea and North Sea to the existing NOx Emission Control Areas (Ricardo, 2022).

EU adopted a system for monitoring, reporting and verification of CO2 emissions from maritime transport ('MRV Regulation' 2015/757/EU), as a first step towards monitoring GHG emissions in EU. It mandates ships above 5,000 tonnes calling at ports in the European Economic Area (EEA) to collect and report their CO2 emission data, based on their fuel consumption. However, data collection under the global IMO DCS started in 2019 and thus, companies are obliged to report similar data twice.

The EU Emissions Trading Scheme operates on the basis of a cap-and-trade system. This means that the total GHG emissions emitted by the ETS parties are capped and there is a gradual reduction in the maximum amount of emissions per year at a specific pace. Participants must report their emissions annually and then surrender quotas purchased to meet their level of GHG emissions. The aim of the system is to reduce total emissions by 43% by 2030. European Commission in its continental carbon target framework considers increasing the GHG reduction target to -55 % by 2030 and integrate maritime sector into the EU ETS as of 2023. The shipowners participating into EU ETS must propose a monitoring plan which is built in accordance with the European Commission's monitoring and reporting regulation and be approved by an inspection body. Participants are required to report their emissions data which are verified by an accredited external verifier.

Below, a combined map of past and upcoming IMO and EU shipping regulations is presented (Source: JP Morgan).

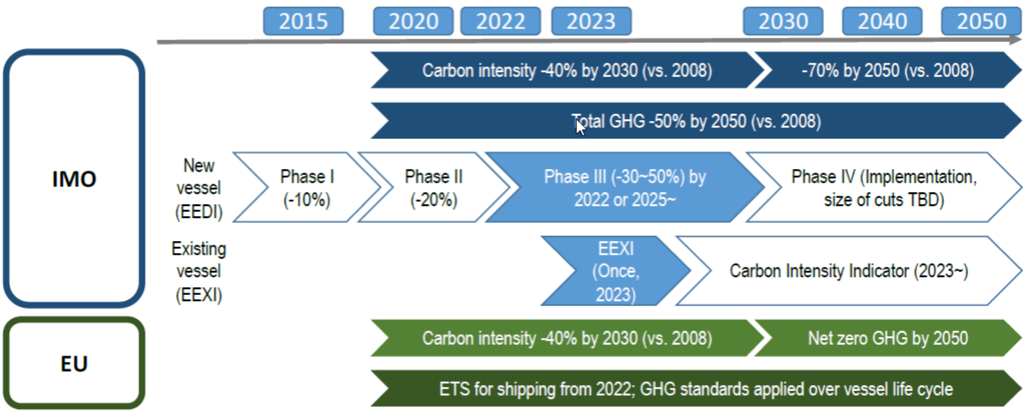

Figure 8: IMO and EU shipping regulations

4 Digital Twins

This section discusses the concept of Digital twin and its value proposition for shipping industry decarbonisation. Recent advancements in artificial intelligence, sensors, machine learning, and the Internet of Things are moving digital twin technology beyond the concept stage to where it is emerging as an invaluable took to aid the shipping industry decarbonisation. In this section we outline the technology's value proposition in areas such as voyage optimisation, ship maintenance and operations, environmental impact and sustainability.

Three business drivers justify the need for digital twins: creating a shared source of asset (i.e. vessel) data that can serve as a single source of 'truth'; supporting investment decision making; and accelerating continuous process optimization [1].

4.1 How a digital twin is constructed

A digital twin can be used across each stage of a vessel's life cycle, from testing what if scenario in financing, ship designs, to reduce human error, to ship building, commissioning operations and decommissioning. Various ship models are integrated into the digital twin and when populated with actual ship data make the digital twin a true replica of the physical ship.

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[1] How digital twin technology is transforming supply chains | EY - Global

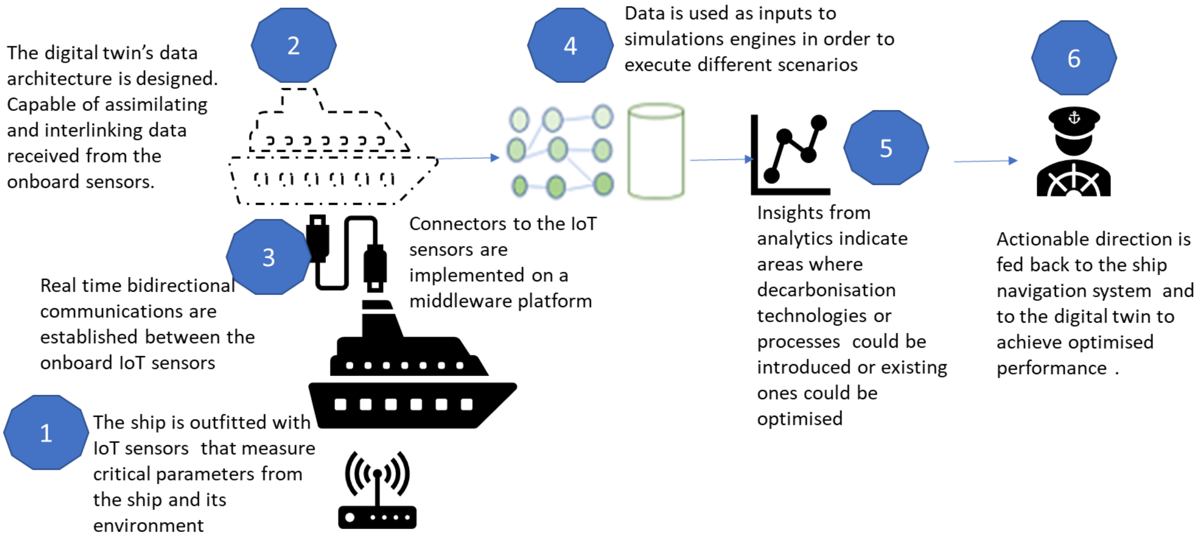

Figure 9: Digital twin construction and operation lifecycle

As Figure 9 illustrates, a digital twin model is essentially, an interlinking (knowledge graph) of various types of ship models that are populated by data that correspond to ship designs, operational data and even data from the ship's environment. In the ship's operational phase, such data are collected by Internet of Things (IoT) sensors installed onboard the ship. The ship's models populated with data are used to analyse, predict and control the ship's behaviour using an ensemble of simulation and machine learning techniques. The ultimate objective is to optimise some of the ship's operating parameters with the aim of reducing the ship's environmental footprint.

Various optimisation areas can be explored such as the ship's navigation and routing as well as keeping the ship in optimal operating condition that minimises fuel consumption, via preventive maintenance. The business value of a ship's digital twin is therefore many-fold and addresses the needs and business models of multiple stakeholders. Moreover, as business priorities are constantly evolving over the life cycle of a ship, a digital twin that remains up to date can support an agile approach to decision-making and management.

4.2 How a ship digital twin is used

As explained in the previous section, a digital twin is a digital replica of the physical ship and can be used to perform analyses and answer 'what if' questions in a manner that is impossible (or prohibitively expensive) to carry out on the real ship. The initial digital twin model (base model) is a 'normalised' ship model, where normalised means that it consists of the ships design and operational configuration data as specified by the ship's designers and constructors (shipyard, subsystem manufacturers etc).

The data sets of the digital twin consist of nominal data and values obtained from manufacturers data sheets, public data repositories etc. The base model will be used as the 'ground truth' to validate any machine learning predictions, source of simulation data and as comparison point for subsequent more elaborate and specific data models (e.g., digital twins).

4.2.1 Simulations/'what if' scenarios

To simulate 'what if' scenarios, a model is required which operates on input parameters to calculate output parameters. Each set of input parameters can represent a hypothetical ('what if') scenario.

MODEL: this is a ship (or ship subsystem's) physical model, i.e., a model containing the mechanical interactions or energy exchanges between the ship subsystems and/or the environment.

INPUT parameters: the independent (e.g., ship performance related) variables.

OUTPUT parameters: The variable we want to understand e.g., ship speed under different operating scenarios.

Variables can easily be introduced into performance models to build scenarios that can provide responsive solutions to changing regulations. To test for example compliance with various emissions regulations.

4.2.2 Assess Energy savings from a decarbonisation solution

Simulations can also be used with available real performance data, to assess the effectiveness of a decarbonisation solution, without actually fitting the solution on the ship.

Required models:

- A digital twin of the ship before the decarbonisation solution (BEFORE-TWIN)
- A blackbox ship performance model (BLACKBOX-PERFORMANCE-MODEL)
- A digital twin (or several) of the ship with the decarbonisation solution installed (AFTER-TWINS)

STEPS:

- Train the BLACKBOX-PERFORMANCE-MODEL using the BEFORE-TWIN
- Predict the energy consumption/emissions/etc using as input data from the AFTER-TWIN(s) to match conditions and to compare equal with equal.
- Compare the predicted consumption/emission with the actual to estimate any savings.

4.3 Building the Digital Twin

Before building the DT model, it is important to set the framework in which the model will be built and deployed. DT models consist of co-dependent and real-time interacting physical assets and digital representations. These simulation platforms require significant amount of data in order to optimize the operational environment (ship building or shipping operations) and therefore a Digital Twin Framework to replicate the real-life activities as accurately as possible. Main applications of DT may be navigation management, route optimisation and hull/propeller optimisation, integrated machinery performance, etc. The DT of a vessel is a complex virtual model of a vessel, and its main application is having better prediction of the vessel's performance (i.e., bunker consumption) given her current physical condition and external factors.

4.3.1 DT Challenges

Building comprehensive digital twins of ships requires vessel data (e.g., cargo tanks data, fuel containment specifications, main and auxiliary engine specifications, etc), voyage data (speed, RPM, type of fuel, bunker consumption) and external data (weather and environmental conditions). Moreover, other information is also useful to increase the model's output accuracy (regulatory constraints – technical or emissions, carbon prices/taxes, etc.) which should be converted in digestible format (input) to be able the DT to process it.

High quality data are a prerequisite to voyage and vessel optimisations, fuel safety and security and energy saving technologies. To ensure valuable outputs from digital platforms, data input must be of high-quality, standardized, valid, interoperable, and more transparent. Fuel consumption models and data must be accurate and informed. Technology can help support these decisions as optimisation and voyage speed variations have been seen to improve fuel reduction considerably.

There is an uneven playing field with regards to how companies are dealing with data in shipping. Noon reports include a huge range of data points, including average speed since the last noon report, propeller slip, engine RPM, weather and sea condition, distance. Because these reports are produced manually, often in accordance with individual shipping company, charterer, or ship management, the diversity and quality of their input can vary widely. Adding complexity to this is that much data can be unreliable, sometimes even "skewed" to protect commercial interests. This poses a challenge for anyone looking to optimize voyages, vessels, fuel, energy use, bunker and emissions. Therefore, a first step towards improving the accuracy of vessel performance could be i.e., to standardize noon reports. There are several entities currently working to standardize definition of terms which will also help in the future with data collection and sharing.

Additional challenges during the processes of DT models creation, training, validation, on-board implementation and "establishment" as decision making tools. However, taking into consideration the enablers of shipping decarbonization, coming from multiple different sectors, it is of the utmost importance to deal with the majority of challenges through an efficient collaboration between the supply (i.e., market) and the demand (i.e., user segments) sides. Both sides have as common objective the decarbonization of shipping industry, each one for different reasons, through energy efficiency improvements (i.e., MWh/year or MWh) and GHG emissions reduction (i.e. CO2 emissions reduction). As already mentioned, this common target derives both from market/commercial needs but also from global regulations, so the outcome of the DT4GS project can be proven really meaningful and applicable not only for shipping companies which provide their LLs, but for the broader shipping sector.

4.4 Data Sources for the Digital Twins

The Digital Twins are built based on various data sources. The major source will be the vessels but also some data from the office IT infrastructure will be needed, as well as external data from internet services. Below, there is a brief presentation of the data requirements for this project, split into five different types.

i. General information, drawings (e.g., Sea Trials Report, M/E and DGs Shop Tests and NOx Technical Files, etc.) particulars and the like required to "define" the DT
ii. Data from office core systems that will facilitate the creation of the vessel digital schema, for example a tree structure describing vessel assets/machinery. Possible sources of such information may be the ERP system used for spare parts requisition/handling.
iii. Available past data to be used as basis for model development and evaluation. High-frequency past data will be used for data-driven models training.
iv. Real time data to be used to feed the DT model inputs and display as Digital Shadow
v. External data from the internet, especially weather data.

In the below Figure 10 the most important parameters required are listed.

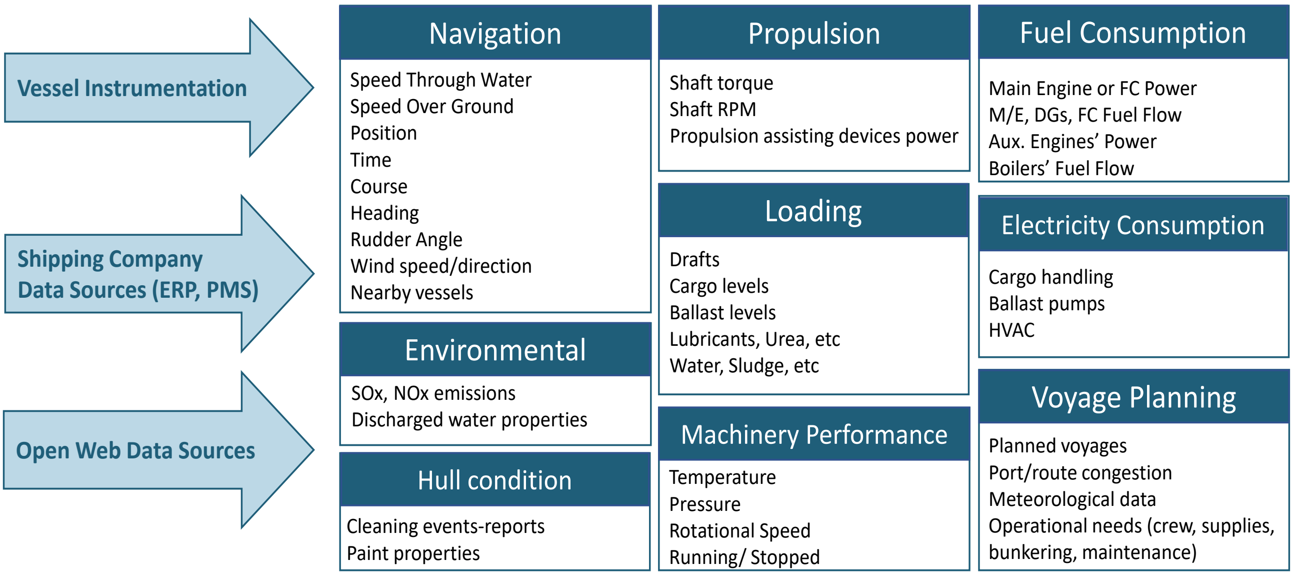

Figure 10: Data required for the formulation of digital twin

4.5 Applications of DTs in Shipping

This section discusses the most important types of DT applications for shipping.

4.5.1 Voyage Optimization

Voyage optimization can be considered as a solution for improving the operation of the vessel and leading to better efficiency, mainly by means of reducing the fuel oil consumption of the vessel and therefore her environmental footprint. In fact, with voyage optimization the route and speed profiles for any sea passage are optimized, of course taking into consideration operational constraints and the current weather conditions. The concept is based on a dynamic routing where the calculations are real-time and can be adapted by the user (i.e., the Master) according to operational needs and his point of view. In this project, the idea is to include all the following aspects of voyage optimization: Route planning, Weather routing, Speed optimization, Consumption optimization, Just In Time Arrival (JIT), Bunkering optimization and Trim Optimization, depending on the Living Lab requirements.

4.5.2 Event recognition for Predictive Maintenance

One of the most important factors to consider when discussing the operational optimisation of a vessel and her performance is the ship hull and propeller fouling. During a vessel's operation there is some degree of fouling, resulting in lower or higher increases in resistance (i.e., frictional) and power requirement. In that way, the fuel consumption of the vessel increases and therefore the fuel costs and the GHG emissions. Except for the aforementioned, the more fouling a ship has, the more challenging is for her to achieve the design and charter party speeds and also the CII ratings, leading many times to failures and then to lack of commercial competitiveness. In addition to the commercial considerations, a ship may also become unsafe when navigating in adverse conditions (Liu et al., 2021), which is the most important reason for taking measures since it could lead to catastrophic failures, such as grounding and collision accidents. In order to avoid the aforementioned and have an energy efficient vessel the proper hull maintenance and fouling management should be adopted.

Counter measures that could be taken to ensure the normal operation and health condition of equipment and mechanical systems, include:

- reactive maintenance by replacing/repairing failed components;
- planned preventive time-based maintenance;
- condition-based maintenance based on regular inspection;
- condition-based predictive maintenance based on continuous monitoring.

From the above maintenance strategies only the first one, that of reactive maintenance, cannot be applied within the fouling management. In fact, planned preventive time-based maintenance includes the dry-docking activities every three or five years and the third schema of condition-based maintenance based on regular inspection means that a diver inspects the ship's condition, which requires a logistics arrangement, and the results are heavily dependent on the diver's experience and report (US Navy, 2006). There is also condition-based predictive maintenance based on continuous monitoring that has started to gain more and more attention. As a matter of fact, ISO has developed a standard (ISO 19030) on measuring the changes in hull and propeller performance (ISO 19030, 2016). This enables the operators to better detect the need for hull and propeller maintenance, repair and retrofit. Examining the different maintenance schemes, it is understood that the optimal pathway is the minimum amount of work necessary to ensure the ship provides the optimal level of speed, fuel and emission performance to ensure it is competitive on the market. Thus, the ship owner and/or operator must figure out the optimal maintenance frequency (Liu et al., 2021).

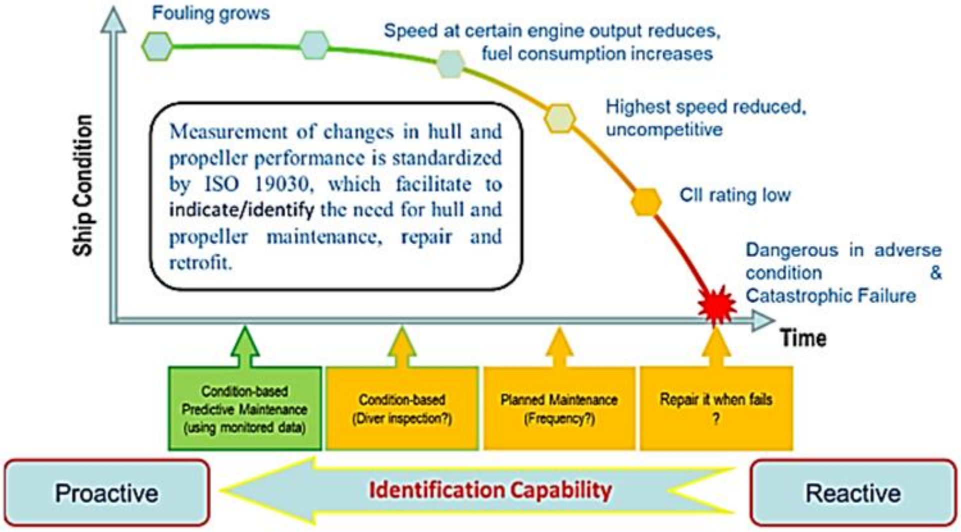

Figure 11: Ship condition degradation and alternative maintenance schemas

4.5.3 Carbon neutral fuels

The objective here is the development of digital twins of the power generation plant, containment system and fuel supply system. The deployment of these DTs will enable simulations of the vessel responses in actual voyages with regards to engine response, consumptions (daily rate and total), boil-off rates and power demands for the fuel supply. After the generation of an adequate number of design variants each of them can be assessed by simulation of the DT, and a multi-objective decision making and design selection based on the deriving Pareto fronts can be conducted with the use of utility functions.

4.5.4 Energy production/storage/conversion:

The development of DTs for the energy production and conversion process of fuel cells, generators and coupled steam turbines, can further enhance the ship system DT and widen the global design space creating design modularity, scalability and flexibility

Energy storage: DTs of batteries and supercapacitors coupled in the global DT will enable the improvement of excess energy/power production and smoothening of the power demand during peak and transient conditions.

Thermal energy recovery/conversion: DTs covering combined cycle arrangements, heat recovery, Organic Rankine Cycle waste heat recover etc., can enable the ship system simulation to drive further down energy demands. The overall energy reduction can lead into the sizing of smaller machinery components and thus help to reduce the building and thus acquisition cost proportionally.

Green propulsion technologies: DTs of wind-assisted power saving technologies (wings, sails, rotors, kites etc.) coupled with corresponding vessel hydrodynamic models, and shaft generators on the main engine interact with the global DT through a holistic context considering the total route energy optimization. The routing and speed optimization is critical here in order to identify routes where the wind assisted technology will have the maximum produced thrust leading to considerable savings. Since this will be a holistic and integrated approach on the global DT, the vessel's lines, propeller and appendices design as well as machinery configurations (e.g., use of shaft generator) will be adjusted to the technology and the resulting optimal routes, speeds and corresponding environmental conditions.

5 Stakeholder identification

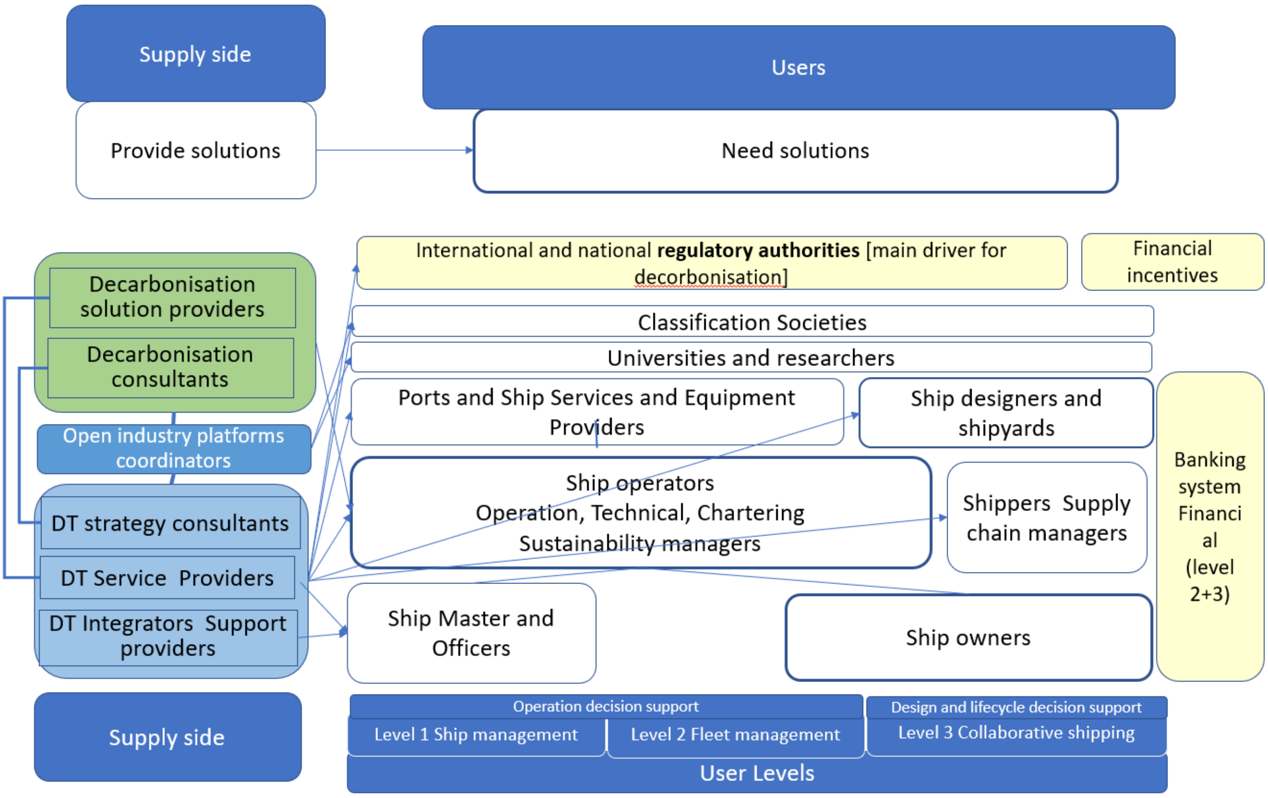

Figure 12: DT stakeholders

Figure 12 identifies the key classes of stakeholders for DTs in shipping decarbonisation, both from the supply side and from the end-user side.

The **providers of decarbonisation solutions**, as well as the decarbonisation consultants benefit from the use of digital twins. Decarbonisation technology providers can validate their products on DTs, rather than on physical ships, which results in cost reductions and better efficiency. Similarly, the decarbonisation consultants can use DTs to analyse and compare different decarbonisation offerings on the DTs of their clients.

From the end user side, there is a hierarchy of stakeholder classes that either directly or indirectly benefit from the use of DTs.

The direct beneficiaries include **ship operators** and **ship owners** that can utilise DTs both for single ship operations optimisation as well as for entire fleet management optimisation.

Shipowners and ship operators can achieve, in the short term, full ship operational efficiency optimisations and producing improved evidence-based new digitized SEEMP (Ship Energy Efficiency Management Plans). Also, ship owners, managers and operators may capitalise on the DT potential to increase ship efficiencies to constantly reduce CO2e, and to support sound investment decisions - retrofit/newbuilds - in the longer term.

Other supply chain participants (**supply chain managers**) can indirectly benefit from the additional visibility about a ship (e.g. its location, voyage condition potential issues, expected arrival times, etc) that a DT can make available.

Further up the hierarchy, **ship designers and shipyards** can utilise DTs to create more streamlined vessel designs that meet decarbonisation targets.

Port authorities can benefit by enjoy Virtual Testbed and Decision Support System, creating a collective capability of the waterborne industry to harmonise efforts and increase synergies between DT applications. Finally, ship operators and ship crew can reap the benefits of a next-generation user led solution for total ship operational optimisation based on DT technology capable of adaptation according to ship type and increasing ship automation, thus delivering superior cost effectiveness.

As per Figure 12, regulatory **authorities** can benefit from the use of DT model outputs by understanding ship design and ship operational parameters, transition potential, cost structures, technical and technological perspectives of vessels (fuel containment systems, pipelines, cargo tanks, engine specifications) which would lead to the development of safety policies and procedures together with new training skills. enable authorities to map their regulatory performance and compliance by the industry. Similarly, classification **societies** are interested in working with industry and regulators in order to devise technological standards around ship design, support regulation development and the design and implementation of technical solutions, improving methods for new vessel design, manufacturing and operation incorporating non-polluting systems and autonomous technologies covering all aspects of asset lifecycle and integration with smart green supply chains. DT model is a brilliant tool to inform their expertise regarding ship design (hull, engines, cargo tanks, ballast water treatment systems, etc.).

On **the academic side**, DT further fuels the research and development efforts on ship design science, advancing research, refreshing knowledge and helping that sector to thrive and offer back to society and industry as well. Also, the DT4GS Decarbonisation knowledge Hub should provide a trusted observatory of key decarbonisation solutions which is another value drop for **universities and researchers**.

6 Value Analysis per DT application area

The main Value Indicators are as per Table 3. There are two different KPIs that will be used to measure the performance of the possible different use cases: energy efficiency improvement (=MWh/year or MWh) and GHG (= CO2e reduction).

Table 3: DT Value per application area

DT application areas	Navigation Management	Integrated Machinery performance management and remote control	Integrated ship energy production, distribution, recovery and management	Digital Twin for Ship Hull and loading	Voyage Optimisation	Life Cycle Assessment Management
Efficiency improvement	3-8%	3-8%	5-15%	3-10%	3-10%	3-10%
Average CO2e Reduction	5%	5%	10%	5%	5%	5%

Source: DT4GS Grant Agreement

Table 3 therefore shows average improvements in energy efficiency and emissions reduction due to the introduction of DT supported vessel improvements across its lifecycle (design, operation and retirement).

For each specific stakeholder, the implementation of a single or combination of the above DT based improvements, will be guided by the analysis of its particular strategy and business model. In the DT4GS project, the participating user companies conducted a preliminary evaluation of the DT applications and through a cost benefit analysis prioritised certain application areas that will be further evaluated in the LLs. Their DT related high level requirements are discussed in the following section.

7 High Level Requirements Specification

In this section we identify key high level requirements for DTs as elicited from the Project's LLs. These are classified as general requirements (applying to all LLs/use cases) and LL specific requirements. The high-level requirements are further decomposed into more specific requirements by LL tasks and activities.

7.1 General requirements

Data availability requirements

This requirement states that the data used to construct the DT must be available to the DT designers/developers/maintainers. There are several reasons for data unavailability, such as the data have not been collected in the past (lack of historical data) ; it is not feasible to collect the data; the data are not shared due to lack of sharing policies/culture (information silos); the data are not available because they are proprietary.

Data integration requirements

Data need to be integrated with the rest of the DTs subsystems and functions. This means that data must be in a format that allows their ingestion, potential transformation and incorporation (importation) in DT's modules.

Data quality requirements

Data must be fit for purpose. Data quality relates to aspects such as completeness, timeliness accuracy and correctness. Moreover, their quality must remain consistent over time Any defects in the data sets must be completely known so that remedial actions can be taken (such as data cleaning) if possible.

Data Security requirements

Potentially, some of the data used by the DT will be commercially sensitive. Measures should be taken that such data are protected when they reside inside the DT databases and systems. Also it should be ensured that such data do not inadvertently become accessible by unauthorised users when they interact with the DT.

DT presentation (UI) requirements

All user interfaces of the DT should meet the relevant Human Computer Interaction (HCI) and usability standards. This is particularly important when the DT is used as part of vessels operation (steering, navigation).

7.2 Requirements per Living lab/Use case

Specific requirements per Living Lab were elicited by applying the Value Analysis method to each specific Living lab. As a result, the DT applications/use cases that deliver the highest value for the specific organisation(s) involved in the LL were identified. The following tables present the results of the value analysis for each Living Lab.

Table 4: Tanker Living Lab Value Analysis

DT Application type	Functional Requirement
Voyage optimization;	DT must be used to calculate minimum consumption routes, resulting to minimum CO2 emissions route DT must be used to calculate the fastest route DT must be used to calculate the Best Time Charter Equivalent (TCE) route
Event recognition – predictive maintenance – Hull degradation	DT must be used to assist on-time hull cleaning decision making DT must be used to plan optimal hull maintenance process with lower costs DT must be used to achieve compliance with vessel maintenance contracts

Table 5: Container Living Lab Value Analysis

DT Application type	Functional requirement
Voyage optimization;	DT must be used for voyage planning optimisation.
Event Recognition for predictive maintenance and safety	DT must be used in combination with different technologies (IoT, AI, other DANAOS technologies) to increase data validity DT must be used for safety monitoring for people and containers DT must be used for ship machinery event recognition and analytics

Table 6: ROPAX Living Lab Value Analysis

DT Application	Functional requirement
Voyage optimization; Trim optimization	DT must be used for Fuel consumption optimization DT must be used for carbon intensity Index (CII) monitoring and optimization
Event Recognition for Predictive & Preventive Maintenance	DT must be used for optimization of under-water cleaning DT must be used for Improving fuel consumption DT must be used to detect systems failure in timely manner

Table 7: Bulk Carrier Living Lab Value Analysis

DT application area	Functional Requirement
Monitor & measure sea growths development in underwater body	DT must be used for better monitoring and visualisation of sea growth on the hull DT must be used for optimisation of cleanliness of cargo holds. DT must be used for recognition and analysis of the dirtiness status DT must be used for continuous monitoring throw-out the process DT must be used for continuous calibration of cleaning operations.

8 Conclusions

This deliverable presented a value-oriented analysis of digital twins used for shipping decarbonisation. This work realises the Project’s objective to guide the specification of high-level requirements for the project’s research and development activities including relevant scenarios and case studies for GHG reduction strategies and solutions, as well as associated challenges and enabling factors

- The main conclusions drawn from this report are as follows:
- The decarbonisation of the shipping industry is a multifaceted issue that involves policy, business, financial and technological domains and their interplays.
- Decarbonisation will require synergetic actions across the industry’s stakeholders.
- Decarbonisation enabling technologies such as the digital twin, need to be further analysed and understood in real settings and contexts.
- The digital twin approach allows experimentation with decarbonisation technologies and with understanding their actual potential, in a more flexible and lower cost manner compared with conventional approaches.
- Additionally, digital twins can serve for raising awareness about decarbonisation issues, best practices and emerging solutions, amongst the industry stakeholders.

In addition, the deliverable has identified high level requirements for digital twin deployment in the Project’s Living Labs.

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