17th Symposium on

High-Performance Marine Vehicles

HIPER'25

Tullamore, 5-7 May 2025

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Edited by Volker Bertram

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Alternative Fuels and Direct Electric Powering for Shipping

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Abstract

This paper surveys key options for fuels to decarbonize shipping, including biofuels, methanol, ammonia, hydrogen, and nuclear fuels. Direct electric powering in the form of batteries and cold ironing is discussed as a related alternative. Key features, pros and cons, selected projects, and references give an introduction in layman's terms, intended as simple introduction to this rapidly evolving field. Methanol and biofuels are mature options now, ammonia is lagging a decade behind in maturity, nuclear two decades. Hydrogen and battery power are mainly options for local transport and workboats.

1. Introduction

Decarbonization of shipping is foremost on IMO's agenda, <u>https://www.imo.org/en/OurWork/Environ-ment/Pages/2023-IMO-Strategy-on-Reduction-of-GHG-Emissions-from-Ships.aspx</u>. The larger goals as such are clear, but what exactly do we have to achieve in the short and medium term and how do we collectively achieve this best is still very much subject to debate in scientific, business and political circles.

In principle, there are four approaches to address the carbon footprint of shipping:

1. Lower carbon content of fuels

Low/no-carbon fuels address the problem at the source. For a fair assessment, the carbon footprint of a fuel should be assessed including its production, storage and transport, before it reaches the ship, i.e. a well-to-wake assessment as outlined in IMO's 2023 guidelines, Fig.1. Nuclear fuels and direct battery power may be included under this heading.

- Lower fuel consumption
 Future fuel prices (including CO₂ surcharges and taxes, as e.g. the EU ETS, <u>https://climate.ec.</u>europa.eu/eu-action/eu-emissions-trading-system-eu-ets_en) will be significantly higher than
 on the past and motivate high focus on energy efficiency. Energy efficiency is likely to be the
 dominant contributor to decarbonizing shipping in the short term (i.e. next decade), not least as
 many energy saving measures pay for themselves. Recommended starting points for energy
 efficiency measures including notably wind assisted propulsion systems are the MCN guide line, *Marioth and Wesnigk (2023)*, and IMO's GloMEEP website, <u>https://glomeep.imo.org/</u>.
- Lower emissions to air through capturing CO₂ Onboard carbon capture and storage (CCS) is gaining interest as one option to reduce carbon emissions from ships, <u>https://www.dnv.com/focus-areas/ccs/onboard-carbon-capture-and-stor-age-on-ships/</u>, DNV (2024b). While the technology is not a silver bullet that would allow shipping to continue with business as usual, it may become an essential element in the decarbonization of shipping.
- 4. <u>Lower net CO₂ in atmosphere through compensating measures</u> Economic frameworks (market-based measures), such as emission trading schemes, may invest received money into CO₂ reduction measures outside shipping, improving the overall global carbon footprint, e.g. into reforestation.

None of these four approaches alone will solve the medium-term or long-term challenges in decarbonizing shipping. Which of the four approaches is used to what extent will depend on various factors, most notably ship type and time horizon. *Løvstad and Bertram* (2022) give an example for bulk carriers.

In the following, we will focus on the first item, namely "new" fuels and battery power technology currently considered in the context of decarbonizing shipping.



Fig.1: Carbon footprint of fuel with well-to-tank (blue) and tank-to-propeller (green) consideration



Fig.2: Associated carbon footprints for various fuels

2. Fuel options

2.1. Introduction to fuels

Many stakeholders in the industry ask which fuel and machinery they should plan for. Unfortunately, the best we can offer are educated guesses, with transparent reasoning of factors influencing the predictions, and updates of our predictions and roadmaps as we move ahead. DNV does this in its yearly updated Energy Transition Outlook - Maritime Forecast to 2050. The key message, in essence, is that "no single fuel or technology dominates in any scenario, emphasizing the complexity of choice that the industry will continue to face", DNV (2024a). In this report, we look at different socio-political scenarios and perform sensitivity analyses. While no clear recommendation for one single fuel can be given, the report in its latest edition is recommended for detailed studies.

See the Appendix for a quick introduction to what colours (green, blue, etc.) for (usually colourless) fuels mean, and a few other terms for the brave new world of fuels for decarbonizing shipping.

We will not discuss LNG (Liquefied Natural Gas) as a shipping fuel here, as it is arguably not an alternative fuel, but an established fuel by now, and was discussed in *Bertram (2021)*. LNG is an important bridging technology for the next one or two decades. *DNV (2024a)* predicts a significant decline by 2050, possibly phasing out, of all fossil fuels, including fossil LNG. However, we may use methane as a fuel for longer, then in form of biogas or synthetic gas.

Synthetic fuels (a.k.a. electrofuels or e-fuels) are man-made fuels. Their lifecycle CO_2 emissions depend on the production pathway for both principal source materials as well as the electricity used for the synthesis. Synthetic fuels containing carbon can at best be carbon neutral, meaning that captured carbon dioxide used in the fuel production is again emitted when the fuel is used. The principal advantage for these is that existing infrastructure for fuel distribution and installation for fuel storage and use can be used without modifications. The manufacturing process for "green" and "blue" synthetic fuels (using renewable energy and carbon dioxide capturing) is costly. While production prices are expected to drop with technological progress in processes and economies of scale, synthetic fuels are expected to remain significantly more expensive than fossil fuels in the past, Fig.3, *DNV* (2024a).



Fig.3: Estimated prices for fuels 2030-2025 (fossil fuel prices do not include carbon surcharges), CN = carbon neutral synthetic fuels, source: DNV(2024a)

2.2. Biofuels

"The use of biofuels in shipping is picking up. As the industry prepares to meet regulations requiring decarbonization, biofuels – in the form of methane, methanol or fuel oils – have been touted as a convenient way for shipping to achieve these goals. Since CO_2 emitted from biofuels during combustion is regarded as potentially carbon neutral as biomass is able to absorb CO_2 during growth, certain biofuels are regarded as sustainable. Biofuels can, therefore, play a significant role in the maritime industry's decarbonization efforts and will reduce shipping's impact on climate change.", *DNV (2023a)*.

Biofuels are a mature option, in terms of technology, regulations and crew training required. Biofuels are mainly used as drop-in fuels, mixing up to 30% with fossil fuels. This is an attractive option to shipowners as it provides them with a flexible way of achieving carbon reductions without having to make large capital investments, *Ejder and Berthelsen (2023)*.

However, while biofuel production capacity is increasing worldwide, biofuels are not available in the quantities required for shipping, nor in worldwide port bunkering availability, *Hsieh and Felby (2017)*.

An interesting perspective are algae-based biofuels, *De Nijs (2018)*. Algae can be cultivated in uncultivable areas and in offshore farming, adding biofuel production capacity that avoids competition with food production. However, algae-based biofuel production is still subject to research and development, needing at least 10-20 years to become industry-mature.

2.3. Methanol

Methanol (a.k.a. methyl alcohol, CH₃OH) is a colourless, volatile and flammable hydrogen-rich liquid fuel that has been advocated as alternative fuel particularly in northern European countries, with pilot projects in shipping since 2016, *Andersson and Salazar (2015)*, *DNV (2023b)*.

Technology and regulations for methanol as a fuel are mature, with more than a decade of experience for ships in operation, Fig.4. Safety and health issues of methanol can be addressed by operational guidelines and are not cause for major concerns. Future zero-carbon methanol may come in the form of bio-methanol or blue methanol. Major concerns for methanol are price and availability. Methanol is not produced in large quantities worldwide. Outside the North Sea and Baltic Sea area, the bunkering in-frastructure is still insufficient for many trade routes. Methanol is more expensive than traditional fuels and requires roughly twice the tank capacity for same range.



Fig.4: Methanol-powered container ship (source: Maersk)

2.4. Ammonia

Ammonia (NH₃) is a prime contender for zero-carbon fuel in future shipping, *DNV* (2020,2023b), *GSP* (2023). Ammonia is rich in hydrogen, but easier to handle than liquid hydrogen in terms of production, storage, and distribution. With a boiling point of -33°C, moderate cryo-technology or pressure (8.6 bar at 20° C) suffice to liquefy ammonia for storage and transport. Typical LPG technology is suitable for handling of ammonia, i.e. the storage technology is mature and widely available.

Ammonia is widely available with large-scale production facilities worldwide (due to the high demand in fertilizers), albeit so far mainly as "brown" ammonia. Machinery for ammonia as a fuel is in prototype maturity, with diesel engines and fuel cells tested in onboard operation, Fig.5. Ammonia's health and safety risks are a key concern for regulations, both for the design and operation of ammonia-powered ships, *GSP (2023)*. Various ship designs have received by now AiP (Approval in Principle) by DNV and the number of concrete projects for ammonia-powered ships to be built and operated is growing, e.g. <u>https://www.nordicinnovation.org/programs/nordic-green-ammonia-powered-ships-nogaps</u>, Fig.6. However, these are generally ships operating under special permits, and in terms of technology maturity, regulatory frameworks, and market take-up, ammonia as marine fuel is about a decade behind methanol.





Fig.5: Ammonia-powered engines for ships

Fig.6: NoGAPS ammonia-powered ship project

2.5. Hydrogen

Hydrogen (H₂) is a tank-to-well zero-carbon fuel, *DNV* (2022). It requires either extremely temperatures (-253°C; liquid hydrogen LH2) or high pressure (350-700 bar; CH2) to liquefy for storage and transport in tanks. Hydrogen can be used as fuel in combustion engines, often in combination with diesel, e.g. *Hoecke et al.* (2021), or fuel cells. Due to the difficulties in storage, hydrogen is likely to be adopted only by vessels that can refuel frequently, like tugboats, inland water vessels, short-distance ferries, such as the Hydra, Fig.6, <u>https://en.wikipedia.org/wiki/MF_Hydra</u>, or possibly short-sea shipping cargo ships, such as e.g. the Hy-Ekotank hydrogen-powered tanker concept, Fig.7. In addition, hydrogen will play a major role in future fuels as a building block in some likely contenders, such as e-methanol, e-ammonia, or blue ammonia, *DNV* (2024a).



Fig.6: MF Hydra



Fig.7: Hy-Ekotank concept, 2023

2.6. Nuclear fuels

Nuclear ship propulsion is used today in large navy ships, submarines and ice breakers. Rigorous safety standards, lack of trained personnel and negative public image have relegated nuclear power for cargo shipping to an obscure backseat in discussions for decades. However, nuclear propulsion for cargo ships has re-entered the discussion as an option for post-2040 shipping, e.g. *DNV (2024a), Houtkoop (2022), De Vries et al. (2024),* Fig.7.

For medium-term scenarios, nuclear power plays mainly an indirect role for shipping, in the production of (pink) e-fuels. Significant research and development would be needed for compact and lighter reactors, auxiliary machinery, design and operational safety regulations, and training for nuclear powered ship operation. "There are obvious concerns with nuclear energy such as nuclear waste as well as societal perception. Additionally, we should be mindful that regulations for marine application are outdated and require significant effort for a successful application", *Houtkoop (2022)* The technology cannot and should not be ruled out, possibly with prototype ships post-2040, but is unlikely to play a major role before the 2050 horizon.



Fig.7: Concept design study for nuclear powered containership, De Vries et al. (2024)

2.7. Direct use of electrical energy

Synthetic e-fuels require electricity to be produced. Even extrapolating technology and economies of scale, in the production of an e-fuel, we need to input 4-6 times the energy of its fuel energy content, Fig.8. It would make a lot more sense to use the electrical energy directly on board.



Fig.8: Energy used per unit delivered to the propeller (kWh/kWh)





Fig.10: Cold ironing in port of Los Angeles

Lithium-ion batteries are a disruptive technology that has altered assorted industry sectors over the last decade, including maritime transportation, *DNV (2016), Hoedemaker (2022)*. Using Lithium-ion batteries and optimized power control can contribute to reducing both fuel consumption and emissions.

However, batteries have relatively low energy density compared to most fuels, and resulting weight and space requirement make batteries a more suitable option for short sea shipping and local operation. By 2024, the largest battery-powered ship in the world was the "Zhong Yuan Hai Yun Lu Shui", Fig.9.

"Cold ironing" denotes the provision of shoreside electrical power to a ship at berth, replacing auxiliary engines and boilers, Fig.10, <u>https://en.wikipedia.org/wiki/Cold_ironing</u>. As generally land-based power can resort to cleaner and more efficient electricity generation, cold ironing can reduce carbon footprint and other emissions to air in port, *Warmann et al. (2024)*. Various regional legislation, e.g. in California and the EU, increasingly forces ports to supply cold ironing and shipping to adopt it in port.

3. Conclusion

The Danish Nobel prize laureate Niels Bohr is credited with the aphorism: "It's difficult to make predictions, especially about the future." For future shipping fuels, this certainly applies. Only the uncertainty seems to be certain. See DNV's energy transition outlook, *DNV (2024a)*, for an in-depth discussion of the many uncertain factors influencing such predictions, such as raw material and electricity prices, governmental interference (taxes and subsidies) and regulatory frameworks.

The uncertainty is a challenge for all stakeholders, but not a stranger to our industry. Uncertainty can be managed. Recipes for success in uncertainty are flexibility and (designing for) fast response. You can also prepare for the general direction and trends. For future shipping fuels, this means:

- We can be certain that future fuels will be more expensive than the fossil fuels of the past. Fuel efficiency possibly gain even more in importance, in design and in operation. If you charter your ships out, expect charterers to focus more on fuel efficiency and to monitor ship performance more closely.
- Most of the discussed future fuels will require more tank capacity for same range and same general design. Fuel efficiency improvement may mitigate to some extent, but most likely concessions on tank space or range will be unavoidable in future designs.
- It is advisable to design for flexibility in the machinery system (main and auxiliary engines, piping, tanks) to ease transitions to future fuels, e.g. with dual-fuel diesel engines, high-temperature fuel cells accepting a wider range of fuels ("methanol-ready", "ammonia-ready", etc.)
- Monitor the technical, regulatory and economic developments for decarbonization closely to avoid being caught offside by any changes. The HIPER conference has been a very good source of information for this, covering assorted evolving technologies with innovative solutions.

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Appendix: Decoding the colour code of fuels and other terminology

The decarbonizing discussion has its own jargon. As always, jargon is practical for concise communication when you understand it, and annoying when you don't understand it.

Biofuels are rather straightforward and virtually everybody understands the basic concept. Sometimes, they are dubbed as 'green' fuels, as 'green' has become synonymous with environmentally friendly.

E-fuels (electrofuels) are synthetic fuel generated from water, air, CO_2 , etc., which are chemically split and recombined to form fuels like methane ("e-LNG"), ammonia, hydrogen, etc., with electric energy as input to the process. Most of the future fuels under current discussion are synthetic fuels. Although the fuels are generally colourless in reality, they appear with a whole rainbow of colours in texts and on presentations, depending on the how they were generated. Let's look for example at hydrogen:

- "Brown hydrogen" is produced using 'dirty' coal through coal gasification (sometimes also called 'black')
- "Green hydrogen" is produced using renewable energy, such as from wind power
- "Pink hydrogen" is produced using nuclear energy
- "Yellow hydrogen" is produced from solar power (but may also be called 'green')
- "Grey hydrogen" is produced from natural gas, leaving carbon waste
- "Blue hydrogen" is like grey hydrogen, but with CCS (carbon [dioxide] capture & storage, where the CO₂ is captured and stored, e.g. pumping it in liquefied form deep below the ocean bed or capturing it on land e.g. in volcanic rock)
- "Turquoise hydrogen" is hydrogen from natural gas using methane pyrolysis (also known as low-carbon hydrogen)
- "Orange hydrogen" is a blend of blue, grey, or green hydrogen

Transforming Sailing Yacht and Wind-Powered Ship Performance with America's Cup Level CFD

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Abstract

This paper describes cutting-edge computational fluid dynamics (CFD) techniques and workflow procedures as applied for wind-powered vessels. While the focus of the illustrative applications lies on America's Cup yachts, the approach and employed software could be applied very similarly to assess and improve the performance of wind-assisted propulsion systems on cargo vessels.

1. Introduction

Designing sailing yachts for optimum performance is in essence not different from usual ship design optimization, but differs in the details due to the specific setting, materials used, dominant wind forces to consider, etc. The common design optimization key tasks are:

- Identifying the operational environment to design a vessel capable of meeting its challenges
- Optimizing vessel's design parameters to achieve the optimum performance in a representative mix of operational/ambient conditions (e.g. top speed)

Quantum leaps in performance may be possible if we leave our traditional design mindset or search space, e.g. by changing to foiling sailing yachts or by using wind-assisted propulsion systems (WAPS) on cargo vessels. In such cases, designers have to abandon experience-based design methods, and employ first-principles methods, such as Computational Fluid Dynamics (CFD).

Two specific events have occupied most of the high-performance sailing world in the past 5 years:

- America's Cup (AC), <u>https://en.wikipedia.org/wiki/America's_Cup</u>
 - In the Barcelona 2024 edition, all teams were preparing, running statistical analysis on weather and sea state forecasts, and designing their vessels for a specific weather window. For the race, CFD was key to designing the fastest and most reliable boat, relegating model testing to history's shelves. Building a strong simulator fed with accurate physics was also a huge advantage in the sailors' preparation.
- Vendee Globe, <u>https://en.wikipedia.org/wiki/Vendée_Globe</u> In this 3-months race, manoeuvring and changing or readjusting the sails require an exhausting amount of energy from the sailor. Reducing unnecessary adjustments by building a precise performance map impacts the performance in the long term. Design philosophy

a precise performance map impacts the performance in the long term. Design philosophy shifted focus on attainable average speeds through better handling of the waves in the Southern Ocean.

Although the two races differ significantly in format (one a "sprint", the other a "marathon"), they both are built on the same two fundamental aspects:

- (1) a design philosophy taking more and more into account the unsteadiness of real-life ambient conditions,
- (2) and a consistent use and trust in CFD simulations as part of the design process.

The CFD tool of choice has been Cadence's Fidelity Fine Marine, <u>https://www.numeca.de/en/products-cfd-solutions/</u>, Fig.1. Its participation in the America's Cup spans over four editions where it has consistently found its way to the main event including three consecutive wins.



Fig.1: America's Cup yacht design using Fidelity Fine Marine, source: Emirates Team New Zealand

Fidelity Fine Marine is CFD software tailored for marine applications. It can be considered as a virtual towing tank. By solving the Reynolds-Averaged Navier Stokes equations (RANSE) for incompressible flows in a Volume of Fluid (VoF) formulation, it aims at modeling the free-surface flows, solving for the body motions in 6 Degrees of Freedom. The design of competitive sailing yachts requires almost the entire range of capabilities available in Fidelity Fine Marine, Fig.2.

Hull

- Hydrodynamic performance
- Aerodynamics performance

Interaction & maneuvers

- Hull / appendage interaction
- Hull / sails interaction
- Hull / free-surface interaction
- Appendage in maneuvers



Fig.2: CFD capabilities required for America's Cup yacht design

2. CFD in sailing yacht (and wind-powered ship) design

How is CFD used in such design projects? We could summarize this through three aspects:

- <u>Understanding and formalizing the conditions</u> in which the boat operates: wind and sea state statistics for intended operational area, over which time period (40 min race, several days, a few months, lifetime of vessel) and how passively/actively the systems can be operated (with associated models for the controller).
- <u>Hull (and WAPS) design</u>: finding a good or the best compromise between the technical constraints (stability, structural strength, class rules) and performance goals.
- <u>Performance studies</u>: Using CFD to map the ship's performance in a representative matrix of operational and ambient conditions as a base for decisions in design, but possibly also later in voyage optimization.

In the following, we will discuss the features required to achieve these goals.

2.1. Meshing

Meshing the geometry accurately is the foundation of any good CFD simulation. Amongst other critical requirements are an accurate representation of the geometry features, a high-quality boundary layer mesh, and a smart volume mesh, allowing a precise capturing of the free-surface and the pressure systems while keeping the cell count under control, Fig.3.



Fig.3: Typical mesh for sailing yacht CFD analysis

The boat motions can only be handled if the mesh can follow them. While the weighted mesh deformation technique is often used in marine CFD applications, sailing vessels can often reach large heel angles, beyond mesh deformability. A powerful alternative is to use the overset mesh approach, where the vessel and its background are meshed separately in different domains, Fig.4 (left). The meshes freely overlap, allowing any relative motion amplitude. The solver then interpolates the solution in between the domains to ensure continuity of the numerical solution. This technique can also be used to for appendages' rotation, like a rudder, opening a wide range of applications. Overset meshing also improves dramatically the mesh quality of hydrofoils, Fig.4 (right), Robin et al. (2022).



Fig.4: Overset mesh technology

2.2. Solving

The basics of hydrodynamic simulations in the marine world is resistance calculation, where typically we model the vessel with 2 degrees of freedom (free to sink and trim), but for yachts with 3 (free to heel as well). The VoF approach allows capturing free-surface deformation including breaking waves, Fig.5. CFD simulations use initial condition at rest and then accelerate to steady speed, similar to model tank tests. Several numerical methods can be used to accelerate the convergence time to quasisteady state.



Fig.5: Free-surface deformation for yacht in CFD simulation using VoF approach, source: finot-conq

Designing for realistic ambient conditions required moving from resistance calculations to seakeeping simulations. Fidelity Fine Marine provides regular and irregular waves generation. Standard spectra (ITTC, JONSWAP, JONSWAP 3, and Pierson-Moskowitz) or a user-defined spectrum can be selected to generate a specific sea state.

CFD seakeeping simulations have been too expensive for many industry applications in the past. Capturing accurately the moving free surface in anticipation required a large number of cells through the entire domain. Fortunately, the Adaptive Grid Refinement (AGR), *Wackers et al. (2022)*, allows dynamic reconfiguration of cells during the simulation, reducing cell counts and computational time dramatically in seakeeping calculations, *Abgrall (2024)*. Cavitation and ventilation can also be predicted accurately using AGR, Fig.7.



Fig.6: AGR mesh for seakeeping



Fig.7: CFD simulation of ventilation at foil (left) and resulting lift compared to experiments (right)

High performance sailing also requires understanding fluid-structure interaction (FSI). The modal approach module in Fidelity Fine Marine provides such capability. After providing the modal structure file for the desired number of modes, the structure deformation can be resolved, Fig.8. While a controlled steady deformation can improve a design's efficiency by putting the geometry in a more efficient configuration at a given operating point, a structure too susceptible to fluttering can start oscillating out of control and be utterly destructive, Fig.9.





Fig.9: Stable and unstable fluttering

2.3. Workflow

One key element of a CFD chain is repeatability and consistency. This gives trust in the obtained results and allows multiplying the simulations with a limited amount of engineering time, removing at the same time the risk of human error.

The C-Wizard has been instrumental in bringing that consistency and automation in the design process. This tool prepares the entire setup for a given list of applications, applying state-of-the-art guidelines for the mesh and simulation setup steps of the CFD chain. Taking only naval-architectural information and conditions as input, the C-Wizard creates in a matter seconds to minutes the entire CFD project, Fig.10, increasing productivity while reducing potential errors. Several of the applications are key to sailing yacht design: resistance, seakeeping, position matrices for hull and foils, center of gravity and mass matrices, cavitation and transition setups for hydrofoils.



Fig.10: Workflow in C-Wizard

The C-Wizard can be run in matrix mode to be used for instance to feed a Velocity Prediction Program (VPP). This allows creating very robustly a large number of simulations varying the position of the boat in a highly consistent way across a pool of geometry variations. In the Sailing Yacht Research Foundation (SYRF) project, Fidelity Fine Marine was instrumented to run an end-to-end automated chain to simulate and analyze a matrix of 150 simulations on 3 geometries. To generate the 150 simulation setups, ready to mesh and simulate, the C-Wizard took only a few minutes.

Sailing yacht designers have always run Velocity Prediction Programs (VPP) to map the boat performances. The standard VPP approach consists in building a large matrix of cases and create a surrogate model to be able to interpolate between configurations. When building the hydrodynamic matrix, 80 to 200 CFD runs are required to have a surrogate model with sufficient quality to be representative, and this quality still depends on the quality of the chosen position samples. The finot-conq's Dynamic VPP does not prescribe the boat's attitude but instead solves the hydrodynamic position of the boat, propelling it using an integrated aerodynamic model, while running a boat speed optimization varying the sail power. As a result, for a given apparent wind angle/speed combination, in a single CFD run, the user retrieves the boat speed, the optimal sail power to reach it, and the solved position.

Since 2025, Fidelity Fine Marine offers the possibility to input directly an aero performance matrix representing any sail or wind assisted propulsion system, such as several sails, rigid sails, Flettner rotors, etc.

3. Commonalities and differences in CFD analyses for yachts and WAPS-powered ships

The discussion so far has been focussed on "America's Cup level" application to sailing yachts. Much of the experience in CFD simulations for sailing yachts can be applied towards WAPS-assisted ships, together with the extensive experience we have with Fidelity Fine Marine for the design and optimization of normal displacement ships.

The approach would differ only in a few aspects:

- The ratio between sail propulsion force and weight of the vessel is much smaller for WAPSassisted. This justifies some simplifications. For example, heel may be neglected, and models may subsequently employ port-starboard symmetry with significant savings in computational effort.
- WAPS-assisted ships will always have rigid sails or rotor-sails. Fluid-structure interaction, ventilation and cavitation can be neglected completely.
- WAPS-assisted ships need a propeller model, just like regular cargo ships. A simplified propeller model using body forces (i.e. replacing the propeller by thrust and rotational forces in the cells where the propeller would be located) generally will suffice.
- Meshing depends on purpose of analysis and wind-assistance devices. Typically, one may use overset meshing strategies as described above. If the focus in on the wind-assistance device, e.g. a Flettner rotor, in an array of same devices, one may be modelled in high resolution, and the others in small resolution.

4. Outlook

In the future, design projects for sailing yachts and wind-assisted ships will benefit from current trends in development of the associated tools:

- <u>Meshing</u>
 - No more struggle with the CAD export formats, import seamlessly and clean the CAD directly in meshing tool.
 - Combination of meshing approaches, exploit the best of each approach into hybrid meshes.
 - Adaptive Grid Refinement will become usable for all hybrid meshes.
- <u>Solving</u>

Mesh and solver improvement will progress hand in hand. The solver will adapt when new meshing technologies require a flow-solver adaptation, and the mesh requirements and guidelines will be adapted when improved numerical algorithms will call for it, ultimately reducing simulation times.

• <u>Meta-modelling</u>

CFD simulations may be used to create fast meta-models. Systematic CFD simulations for applications with a handful of parameters can generate data for training machine-learning algorithms. Once trained, the resulting meta-model can give integral values (such as forces) and flow details (such as pressure and velocity fields) within seconds. The general procedure of CFD-trained meta-models has been successfully applied to propellers, *Albert et al. (2022)*, and planing hulls, *Ahmed et al. (2023)*. It could similarly be applied to e.g. a family of Flettner rotor designs.

• Optimization

Libraries of meta-models for assorted sails and wind-propulsion devices may then be used in modular model generation, as e.g. in Hollenbach et al. (2020), and solving with sufficiently fast response times to apply formal optimization, both in design and operation, e.g. for dedicated wind-assisted ship voyage optimization.

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Towards Net-Zero Container Ships

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Abstract

This paper discusses options in decarbonizing container shipping from now to 2050. The discussion is structured into two phases, short-term to 2030, with tried-and-proven energy efficiency options, and long-term to 2050 using more 'exotic' energy efficiency options and alternative fuels.

1. The CO₂ challenge

IMO is set to cut the carbon footprint of shipping. The Big Zero is the goal to be achieved by or around 2050. Recent milestones in the longer journey were in 2023 the EEXI and CII becoming mandatory. The EEXI is the Energy Efficiency Existing Ship (Design) Index, akin to the EEDI (Energy Efficiency Design Index) for newbuildings, Fig.1, expressing the theoretically achievable energy efficiency for the ship as designed, in prime condition as in initial sea trials. The CII (Carbon Intensity Indicator) is calculated based on IMO's fuel oil DCS (Data Collection System), where the requirement to just monitor is now enhanced by grading the performance each year from A to E. Poor operational performance (E once or three consecutive years D) will entail mandatory action to improve performance, planned, documented, tracked, and audited in a SEEMP (Ship Energy Efficiency Management Plan). The CII will be subject to increasingly stricter thresholds over time, driving the industry towards decarbonization.



Fig.1: EEDI (left) and EEXI (right) baseline curves for container ships. From the 2013 baseline (average over the container ship fleet then), in 3 phases to 2025, the EEDI threshold will be lowered by 10% in each step. Container ship deliveries in 2025 will be on average 30% more energy efficient designs than the 2013 average.









The impact of the EEXI on the world container ship fleet will be negligible to modest. Due to technological progress and economics of scale with newer, larger container ships replacing older

tonnage, the container ship fleet will be able to comply with the EEXI requirements without major changes. EPL (engine power limitation) may be needed in some cases, but this will reduce maximum speed by only 1-2 kn. As especially the older fleet has adopted generally lower speeds, the reduced maximum speeds do not impact the current operational practice in most cases. Fig.2 shows an example of adopted speeds in 2024 for a containership built in 2000 for a design speed of 25 kn. At no time it exceeds 80% of its design speed; *Rutherford (2020)* report similar MCR histograms as found in DNV advisory practice and monitoring, *Stefanatos et al. (2019)*. In some cases, the market will respond with accelerated scrapping of older container ship tonnage.

On the other hand, the Carbon Intensity Indicator (CII) will have a more profound impact, driving design and operational changes both for the existing fleet in service and future newbuildings. Fig.4 shows CII values for container ships in 2019, as analysed by DNV, and CII rating curves for 2026. Across the whole deadweight spectrum, ships lie on the wrong side of the "D" rating. Thus, a large part of the container ship fleet is facing already decarbonization challenges requiring action, i.e. retrofits or changes in operational procedures. With progressively lower CII thresholds, the pressure will increase, and more ships will be affected.



Fig.4: Carbon intensity of container vessels in 2019 and proposed requirements in 2026

In essence, there are four levers to progress toward lower carbon footprints for ships, or in our case container ships, *Bertram* (2025):

- 1. <u>Lower carbon content of fuels</u> "Decarbonization" makes most people think first of alternative fuels, such as biofuels, ammonia, hydrogen, or nuclear fuels, *Bertram (2021)*. These fuels will be significantly more expensive than Heavy Fuel Oil (HFO), the standard shipping fuel of pre-2020 times. Alternative fuels will certainly play a role, increasingly in medium to longterm scenarios.
- Lower fuel consumption Energy efficiency is likely to be the dominant contributor to decarbonizing shipping in the short term (i.e. next 10 years), not least as many energy saving measures pay for themselves. Recommended starting points for energy efficiency measures are the MCN guideline, *Marioth and Wesnigk (2023)*, *MCN (2024)*, IMO's GloMEEP website, <u>https://glomeep.imo.org/</u>, and *DNV (2025a)*.
- Lower emissions to air (capturing CO₂) Carbon capture and storage (CCS), DNV (2024b), <u>https://www.dnv.com/focus-areas/ccs/onboard-carbon-capture-and-storage-on-ships/</u>, is not a silver bullet, but may contribute to addressing decarbonization of shipping.
- 4. <u>Lower net CO₂ in atmosphere through compensating measures</u> CO₂ compensation schemes or surcharges for CO₂ emissions, respectively carbon-content of fuels, will add to the general increase in fuel prices.

In the following, the focus will be on likely measures for container ships, both for the short term (up until around 2030) and the long term (up until 2050).

2. Towards zero-carbon footprint in container carriers

2.1. Short-term perspective (towards 2030)

The first phase of marching towards decarbonizing container shipping will focus on levers that allow us to stay – technically and economically speaking – in our comfort zone, implementing measures which have not yet been fully exploited in the past. The industry will adopt tried and proven, technically mature solutions with low risk and low cost, to improve design (EEDI/EEXI) and operation (CII), as discussed e.g. in *Ahn et al.* (2023), *MCN* (2024).

2.1.1. Design measures

Likely measures adopted for container ships on a wider scale will include:

• <u>Size growth</u> – Larger container ships have better transport efficiency for same utilization rate. The general mechanism is reflected in the Admiralty Formula, *Bertram (2012)*, and in the baseline EEDI curves of IMO. In very simple terms, cargo capacity grows with size (volume), resistance with size to the power of 2/3. The container ship fleet growth of recent years shows moderate increase in ships by numbers, but massive growths by TEU, reflecting the trend towards container ships with very high capacity (>18000 TEU), Fig.5.



Fig.5: Container ship fleet development by ships (left) and TEU (right), source: DNV, IHS Markit

• <u>Hull optimization</u> - One option will be to squeeze everything out of hull design, optimizing automatically for minimum yearly fuel consumption using CFD (Computational Fluid Dynamics), parametric hull modelling and formal optimization algorithms, *Hochkirch et al.* (2024). Typically, 20000-30000 designs are analysed in such a project. 95% of these designs will be worse than a good conventional design, 3-4% will be comparable, and 1-2% will be better. For container ships, improvements of 2-3% are realistic, as baseline designs are generally already of very high efficiency. While obtainable fuel savings are significantly larger for complete hull optimization, optimization of the bulbous bow region alone still offers often very attractive potential fuel efficiency gains. Such projects have enjoyed great popularity in recent years, as the quest for energy efficiency has imposed lower speeds in shipping. As a result, older ships, designed for higher speeds, then were operating in inefficient off-design conditions. In such cases, redesign of bows can offer good business cases, with improvements in excess of 10%, *Hochkirch et al.* (2024), as the older designs were tailored for a single design point with much higher speed than used now.



Fig.6: Bow retrofit (left) based on CFD optimization for new operational profile (right)

- <u>Design speed and sea margin specification</u> Lower design speeds reduce required power of main engine. The so-called "sea margin" (a reserve for both bad weather and increased roughness due to fouling) is traditionally set at 15%, but significantly lower values may suffice for large containerships, *Höppner (2009), Marioth and Julien (2023),* leading also to lower installed power, and subsequently better EEDI values.
- <u>High-performance coatings</u> Low-friction coatings with low surface roughness may improve EEDI values already by 2-3% in sea trials. High-performance coatings may also save fuel in longer periods between dockings, *Sfiris et al. (2023), Farkas et al. (2024).*
- <u>Propulsion Improving Devices (PIDs)</u> The term PID (a.k.a. ESD (Energy Saving Device)) collectively denotes fins and nozzles in the vicinity of the propeller, intended to improve the propeller efficiency, often through partial recuperation of rotational losses, <u>https://glomeep.imo.org/technology/propulsion-improving-devices-pids/</u>. Among the PIDs, a combination of pre-swirl fins with wake equalizing duct (such as the "Becker Twisted Fin", Fig.7) appears to be the most likely option, as it has proven to give the highest savings in independent analyses of PIDs, *Gatin and Kalajdžić (2022), Castagna (2024)*. Propeller boss cap fins (PBCF), Fig.7, reduce losses due to the propeller hub vortex. Rudders can also be improved in energy efficiency, without having to change overall dimensions, *Bertram (2012)*, e.g. twisted rudders, *Echeverry (2016)*, Fig.7. Retrofits are straightforward.
- <u>Bow windshields</u> Bow windshields, Fig.8, may offer moderate savings, possibly 1-2%, *MCN* (2024). Retrofits are straightforward.



Fig.7: Becker Twisted Fin, PBCF, and Becker Twist Rudder, source: Becker Marine



Fig.8: Bow windshield, source: Ocean Network Express (2023)

• <u>Improved engine design and settings</u> – "You can cut fuel consumption by around 3-4% with fuel-efficiency boosting upgrades that modify your engine's fuel injection system and optimize engine parameters. But with radical derating you can go even further and get [...] 10-15% more fuel efficient", *Hamilton (2023)*. Waste heat recovery systems (WHR) recover thermal energy from the exhaust gas and convert it into electrical energy, <u>https://glomeep.imo.org/technology/waste-heat-recovery-systems/</u>. They are limited to newbuildings with engine power above 10 MW, *Diaz-Secades et al. (2023)*. In an expert survey, the saving potential in using WHR was estimated to be 2-7% for ships without power take-in, *Bertram and Tasdemir (2017)*. WHR are generally not a retrofit option, as they require too much space

in engine rooms. In off-design conditions, the energy recuperation potential is usually lower, and vanishes completely at lower MCR.

Alternative fuels – Container ships are the ship type with the highest uptake of alternative fuels in DNV's statistics. Fig.9, albeit with LNG as a bridging technology in the lead so far. Biofuels and methanol are being adopted selectively by some container ship operators. Advanced biofuels may be produced from food waste, used cooking oils, or even algae, DNV (2023). At present, biofuels are used as blend-ins with up to 30% biofuel content. Biofuel blend-ins pose next to no regulatory or technical problems, making them easy to adopt for the existing fleet. Key problems are availability in sufficient quantities and ports. Maersk, CMA CGM, Hapag-Llovd and MSC are among the high-profile container ship operators that have adopted biofuel blend-ins already. Methanol is a fuel with similarly few changes for machinery and crew. The key here is ramping up production and bunkering infrastructure worldwide for clean methanol (not employing fossil fuels in the production). Methanol is already widely established as ship fuel for short sea shipping in the North Sea and Baltic Sea, e.g. https://www.ncl.no/campaigns/sea-change/, Fig.10. "Methanol-fuelled vessels on order are dual fuel, meaning they can operate on conventional fuel and switch to green methanol, once the emissions regulations tighten and the cost of fuels drops to commercially viable levels. The interest for this fuel keeps growing, with large shipping companies like A.P. Moller Maersk signing a number of commercial agreements with methanol producers, securing supply of green methanol for their fleet," Stojanovic (2023), https://www.maersk.com/news/ articles/2023/09/08/equinor-and-maersk-partner-to-supply-first-methanol-enabled-containervessel



Fig.9: Alternative fuels used in DNV Alternative Fuel Insight statistics (2023)



Fig.10: Prototype of future feeder ship using Methanol as fuel, source: NCL

• <u>Engine cooling</u> – Fuel consumption of a typical main engine cooling water pump is 190 t/a corresponding to 150000 USD/a (Klas Reimer of Hoppe Marine in personal communication). Replacing traditional bypass pump systems with frequency-controlled pumps may save only 0.2-0.6% in the overall fuel consumption, *Bertram and Tasdemir (2017)*, but usually offers good business cases with payback times less than 2 years.

• <u>Cargo cooling</u> – Progress in hardware (e.g. inverter systems), software (smart controlling) and arrangement on board, *Filina-Dawidowicz et al.* (2022), has allowed 10-15% energy reduction for modern cooling containers ("reefers").

2.1.2. Operational measures

Typical operational measures implemented in the first phase include:

• <u>Improved hull management</u> - Better hull management is a recommended lever, e.g. *CSC* (2011), <u>https://glomeep.imo.org/</u>. Hull coatings and cleaning technology should be jointly adjusted, e.g. using easy-to-clean coatings and soft frequent cleaning. One example of such coatings are nano-coatings, Fig.11, *Bertram* (2023). For niche areas, ultrasonic protection is an attractive complementary technology, Fig.12, *Kelling and Mayorga* (2020).



Fig.11: 2023 vessel with nano-coating, source: GIT

Fig.12: Ultrasonic transducer, source: Hasytec

- <u>Trim optimization</u> Container ships are the "ship type that so far benefits from trim optimisation the most", *Gatin et al. (2024)*. Considering added ballast water, can lead, counter-intuitively, to additional savings for large container ships. Machine-learning systems may give similarly good results as CFD-based systems, but must be trained properly, which requires more time and crew awareness, *Bertram (2024a)*. As trim optimization software is easily applied to fleets of sister vessels, it is frequently an energy efficiency measure with very good return on investment.
- <u>Slow steaming</u> Fuel consumption per hour goes roughly with the third power of speed near design speed, and the second power of speed for lower speeds, *Bertram and Marioth (2024)*. Lowering speed in operation may lead to significant savings, even if the ship the operates in off-design conditions at lower efficiencies, *Faber et al. (2017), Farkas et al. (2022)*.
- <u>Speed profile</u> Due to the nonlinear speed-power relation, uneven speed profiles lead to net higher fuel consumption. Going 10% faster half of the time, and 10% slower half of the time lets a vessel arrive at same time as going at constant speed, but costs ~2-3% more fuel. A more even speed profile in voyage planning is then a simple option to save fuel.
- <u>Capacity optimization</u> Stowing more containers for a given route generally leads to lower energy consumption per TEU and better CII values. For example, the DNV "Route Specific Container Stowage" looks at intended routes and uses advanced seakeeping analyses to determine lashing forces, and ultimately allow loading more containers for most routes.
- <u>Auxiliary engine load optimization</u> Gensets four-stroke diesel engines are still the standard option for onboard electricity generation, with occasional blend-in from waste heat recovery. Load monitoring and optimization, using e.g. one generator at higher load rather than two at lower loads, Fig.13, is best practice.
- <u>Cold ironing</u> Shore-to-ship power is increasingly available, Fig.14, but much homework is left to be done for many ports and usually the electricity is supplied at higher cost than for on-board generation.



Fig.13: Auxiliary engines running most of the time at 40% load or less, source Hoppe Marine



Fig.14: Cold ironing for container ship in port of Los Angeles (left) and on board (right)

• <u>Improved performance monitoring for assorted consumers</u> – Increased sensor data allows more detailed performance monitoring of assorted equipment, Fig.15. The improved insight can be converted into better decisions in operation, *Reimer (2024)*.



Fig.15: Performance monitoring sensor set-up, source: Hoppe Marine

2.2. Long-term perspective (beyond 2040 towards 2050)

To progress further in decarbonizing container ship shipping, we will have to leave – technically and economically speaking – our comfort zones. We will have to adopt technologies that are now in the R&D stage or "exotic", and in many cases we will have to accept longer payback times or even generally higher costs in shipping. Among the ideas floating around for wider adoption after 2040 are:

• <u>Hull optimization 2.0</u> – The trend toward larger container carriers is likely to continue, not so much in largest size, but in number of 20000+ TEU carriers in the fleet. Hull optimization will become more sophisticated, e.g. looking also at added resistance in waves and sea margins. Together with a trend toward lower speeds, we will see smaller or even disappearing bulbous bows. The 'MSC Tessa', Fig.16, may be indicative of this trend. Asymmetric sterns, Fig.17, and other PIDs may become the norm rather than the exception, where hull, propeller, rudder, and PID are optimized together. For the hull optimization allowing an asymmetric aftbody, *Hochkirch and Krebber (2017)* give 3% additional improvement for a container ship, *Ploeg and Schuiling (2018)* 2%.





Fig.16: MSC Tessa (2023)

Fig.17: CFD simulation on asymmetric stern

• <u>Air lubrication</u>, Fig.18, *Connolly (2022)*, has moved from exotic to commonly accepted in best practice projects over the past 10 years. Shell Shipping had one of the first installations worldwide on a tanker, where long-term performance monitoring by an external provider showed net savings slightly above 5%. For a container ship, we may expect less, as the frictional resistance takes a smaller part in the total resistance and the flat of bottom area a smaller part in the wetted surface area. 3-4% savings may be a realistic estimate.





Fig.18: Air lubrication system, source: Silverstream Technologies

Fig.19: In-transit cleaning robot, source: Nakai

- <u>Advanced antifouling solutions</u> will affect mainly the CII, to a lesser degree the EEDI, *Tan et al. (2022)*. The trend is towards non-biocidal solutions. For most of ship hull, easy-to-clean non-biocidal coatings may be combined with robotic cleaning, *Bertram (2022,2024b)*, even for propellers, *Hermansen (2024)*. In-transit robotic cleaning, *Gerland et al. (2023)*, *Jacob and Nice (2024)*, Fig.19, may develop as a solution for increasing problems with bans of inport cleaning. Niche areas can be addressed by complementary solutions such as ultrasonic protection. Expanding ultrasonic technology from niche areas to full-hull protection of large cargo is subject to research, *Kelling (2021)*.
- <u>Advanced propulsion arrangements</u> Tip-modified propellers, e.g. Kappel propellers, Fig.20, may save 2-4% in container ship trade in overall yearly fuel consumption (based on interviews with propeller experts). Contra-rotating propulsion concepts, e.g. *Pruszko et al.* (2024), Fig.21, may lead to even higher savings, albeit at higher price and complexity.





Fig.20: Kappel propeller

Fig.21: Twin CRP-Pod container ship model, Pruszko et al. (2024)



Fig.22: Feeder with kite (2008)



Fig.23: "Grain de Sail III", source : Grain de Sail

- <u>Wind-assisted Ship Propulsion</u> Container ships are rather unsuited for wind propulsion, due to their high speeds, very limited deck space, and high superstructures (including deck containers). Of the many WASP systems, *Hollenbach et al. (2020), DNV (2025b)*, kites appear most suited, Fig.22, as they may harness wind high above the deck containers. However, rigid sail concepts and Flettner rotors are currently also investigated, e.g. by Hapag-Lloyd and CMA CGM. The "Grain de Sail III" is a 200 TEU container ship designed as cargo sailing vessel, <u>https://graindesail.com/en/content/59-voilier-cargo-grain-de-sail-3</u>, with an expected 90% reduction in carbon footprint, Fig.23,. The saving potential scatters largely between trading routes. Detailed studies on an individual case base are required to assess the business case.
- <u>Alternative fuels</u> Post-2040 goals for decarbonization will require increasingly the use of alternative fuels, *MCN (2024), DNV (2024a), Bertram (2025)*. The fuel mix employed in container shipping will change over time:
 - LNG (Liquefied Natural Gas) is likely to be a popular choice for the next 1-2 decades; LNG as a fuel is most mature and has been adopted by several container ships already. LNG has ~25% less carbon content than fossil fuels like heavy fuel oil, but roughly same well-to-wake carbon footprint. However, bio-LNG may be expected to have 70% lower carbon footprint and should become available to shipping between 2030 and 2035.
 - Biofuels as 30% blend-in are similarly mature and have been adopted by various major container ship operators, e.g. CMA CGM and MSC. Depending on feedstock, production process and additional well-to-tank carbon footprint, 30-60% reduction in well-to-wake carbon footprint is expected.
 - Methanol has been advocated as a future low-carbon or even carbon-neutral fuel (depending on how it is produced). Technology, regulations, and operational know-how are in place by now. In 2023, the first methanol-powered container ship started operation, Fig.24. However, production facilities and bunkering infrastructure for green methanol worldwide are not yet developed to the level required for deep-sea shipping.

- Ammonia (NH₃) is formally carbon-free. Considering well-to-tank carbon footprint and required pilot fuel in diesel engines, 80-90% reduction in carbon footprint compared to HFO is expected. Ammonia is less mature by some 10 years in all aspects, *Bertram* (2025), but will play an increasing role post-2040, with use as fuel outstripping the already large use as fertilizer feedstock. The first ammonia powered container ship is expected in 2026, Fig.25.
- <u>Nuclear power</u> for cargo ships has re-entered the discussion in the maritime community. While recent concept design studies, e.g. *Leurs (2023)*, Fig.26, may fascinate many in the community, assorted regulatory and technical challenges make nuclear power an unlikely option before 2050, *DNV (2024a)*, and then only for large, highly powered ships, such as e.g. 20000+ TEU container ships.





Fig.24: First methanol-powered container ship

Fig.25: Ammonia powered "Yara Eyde" concept



Fig.26: Nuclear powered container ship concept design, Leurs (2023)



For example, for a 5400 TEU container ship, DNV estimated the CII impact on adoption of alternative fuels, Fig.27, (Jan-Olaf Probst in personal communication). CII requirements would be met with LNG as fuel until 2030-2035, with biofuel (30% blend-in) until 2034-2039, but while no longer be viable options. Carbon-neutral e-fuels or nuclear will then have to be adopted on a large scale.

<u>Auxiliary engines</u> – Auxiliary engines for electricity generation (mainly for refer containers) will also gradually adopt alternative fuels, as discussed above for the main engines. In addition, fuel cells offering up to 10% points higher efficiency then 4-stroke gensets may come in time, typically with batteries for peak shaving (e.g. for short-term bow-thruster demand), *Hoedemaker (2022)*. Fully electric container ships, as e.g. 'MV Yara Birkeland', <u>https://en.wikipedia.org/wiki/MV_Yara_Birkeland</u>, will probably remain limited to short-sea shipping applications. The 'Green Water 01', Fig.28, with 50 kWh capacity may be indicative for future larger units for short-sea shipping.





Fig.28: Fully electric container feeder

Fig.29: On-board carbon capturing principle

- <u>Onboard carbon capture and storage</u> (CCS) is gaining interest as one option to reduce carbon emissions from ships, <u>https://www.dnv.com/focus-areas/ccs/onboard-carbon-capture-and-storage-on-ships/</u>, Fig.29, *DNV (2024b)*. While the technology is not a silver bullet that would allow shipping to continue with business as usual, it may contribute in the future to decarbonizing shipping. However, the process of capturing carbon dioxide requires also energy, and captured CO₂ needs to be stored and off-loaded. For example, a 15000 TEU container ship with onboard CCS would need 4 stops for off-loading on a typical Europe-Asia roundtrip.
- <u>Operational measures</u> There are few operational measures beyond what has been discussed already. From 2030 on, cold ironing will be mandatory for container ships in EU ports, and with some delay, it is likely that it will become mandatory in other key regions as well, e.g. in Chinese ports and in Singapore.

3. Conclusions

Predictions are difficult, especially for long-term future developments. I am fascinated by artist visions of future zero-emission container ships, using hydrogen bunkering at offshore wind-power hubs, *Rohde and Sames (2012)*, Fig.30, or wind, solar power and hydrogen fuel cells, like the NYK Super Eco Ship 2030, <u>https://www.no.emb-japan.go.jp/Japanese/KouhoBunka/NTNUHoriuchi.pdf</u>, Fig.31, but I believe the future in container shipping will be more sobering.

The next decade should be devoted to exploiting systematically the existing tried and proven technologies. At the same time, we need to increase R&D activities to lay the foundation for medium and long-term decarbonization, where alternative fuels are expected to carry the decarbonization process to the next level.





Fig.30: ZEM Feeder, Rohde and Sames (2012)

Fig.31: NYK Super Eco Ship, source: NYK

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Maritime Digital Training to Address Challenges from Disruptive Technology – Exemplified for Alternative Fuels

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Abstract

This paper discusses the application of assorted digital technologies to maritime training, where alternative fuels are taken as an illustrative example. First the need for new training solutions is elaborated, both for ship design and ship operations, where the focus lies on the latter. Various digital training technologies, from very simple pdf files to costly and sophisticated VR/AR solutions, are discussed with their pros and cons, and most suitable applications. The conclusion is that while digital training options are increasingly the option of choice, they are not silver bullets and those responsible for training should be aware of their limitations.

1. Introduction – Alternative fuels' challenges & solutions

Decarbonization is at the top of the maritime agenda. No/low carbon fuels are playing an increasing role, *Bertram (2025)*, but the associated technology and operational procedures are largely unfamiliar to the maritime industry. We will use here the theme of "alternative fuels" as an example of disruptive technologies which generally lead to new training needs, as existing and future work forces require new skills to work with these technologies. (The digital transformation with assorted advanced IT technologies is another example, with associated training solutions discussed in *Plowman and Bernhardt (2022)*). Specific challenges of alternative fuels in the maritime industries are:

- In <u>ship design</u>: Ship design is traditionally experience-based, with baseline designs as the starting point for limited modifications to match the design specifications. In a similar vein, "design formulas", e.g. *Schneekluth and Bertram (1998)*, aggregate experience from previous projects for quick and easy predictions in the conceptual design phase. As there is no or at best very little experience for ships with propulsion plants using alternative fuels, the traditional "copy & paste" approach in ship design cannot be applied.
- In <u>ship operation</u>: Similarly, there is no or little operational experience with alternative fuels. For methanol, there is by now a decade of operational experience, but only on very few ships. For ammonia, there is virtually no experience. Crews for new ships using alternative fuel techno-logy generally have not served on the few ships in the existing fleet with such installations. On-board training on ships with alternative fuel technology is a challenge and will mostly be "on the job". Initial, theoretical training can be done in advance.

Where there is a challenge, there is a demand and market for a solution. In our case:

- In <u>ship design</u>: There are various approaches to compensate for the current gap in experience with alternative fuel-powered ships:
 - Simulation can provide "virtual experience", e.g. using energy flow simulation tools like COSSMOS, *Georgopoulou et al. (2021)*, Fig,1, or similar modular-based techno-economic design tools, e.g. *Goh (2023), Sandberg et al. (2023)*.
 - Training can close some knowledge gaps. The available training options for alternative fuels come mostly from engine manufacturers, but classification societies also offer some training with focus on regulations and technology, Fig.2, *Plowman and Bernhardt (2022)*. Training is often in the form of virtual classroom or blended learning.
 - Self-study with publicly available information, e.g. from HIPER conference proceedings, <u>www.hiper-conf.info</u>, white papers, etc.

- In <u>ship operation</u>: IMO's STCW convention addresses required training for crews. For alternative fuels, the guidelines are vague and generic, along the lines of "crew should receive appropriate training and instructions for the specifics of these fuels". What exactly is "appropriate" in terms of content, learning objectives, and scope in a training is left to interpretation by flag states. Details evolve from dialogues between training providers and flag states, and are later formulated into more generally adopted guidelines and standards, e.g.;
 - DNV Standard for competence related to methanol as fuel, DNV (2024a),
 - DNV Recommended Practice of competence related to ammonia as fuel, DNV (2024b),
 - Training Standard for Handling Alternative Fuels in the Maritime Sector, TNI (2024),
 - Recommendations for design and operation of ammonia-fueled vessels, *Maersk* (2023).



Fig.1: Design tool COSSMOS (DNV)

Fig.2: Online teaching on alternative fuels

2. Balance tilts towards "Digital training"

Digital training solutions in the wider sense are on the rise, because they make us an offer we can't refuse: flexibility, *Bertram and Plowman (2019)*. You can have training:

- <u>When you want</u> Traditional classroom training required a critical mass of participants to happen, e.g. 6 paying participants to make break-even with the cost of a trainer and possibly venue and catering. In a highly fragmented industry, where the work force is often scattered globally, classroom courses were often not conducted because there were not sufficient registrations for a given date and location. The problem is aggravated for a classification society like DNV, where certain tasks in surveying and auditing may only be performed if formal training and re-training is proven. If you need a surveyor with certain competence for a customer in your port next week, and you don't have one on site, you either need to train him quickly (not an option with classroom training) or fly in a qualified surveyor from some other station (involving extra cost and unproductive travel time).
- <u>Where you want</u> DNV Maritime has thousands of employees spread around the globe in almost 200 stations. Major hubs like Hamburg, Høvik and Piraeus have larger concentrations of employees, small stations may have only a handful of employees. And they all need training. Traditionally, we tried to cluster trainings regionally, but travel was unavoidable for many employees. The challenge is similar for all large classification societies. Digital solutions now allow training anywhere, as long as you have a computer and internet access (for most solutions). If there is no internet access with sufficient speed and affordable cost, as typically so far on ships at sea, digital solutions can be adapted to have e.g. download in port and offline training at sea.
- <u>What you want</u> Digital solutions generally offer faster training than classroom training. Why is this? Traditional elements in classroom training such as a round of introduction of all participants, coffee and lunch breaks for social bonding cease to apply. But the main reason is

that the trainee can skip parts at will, e.g. because he knows the material already or because it is not relevant to his work. The trainee can self-pace the progress, advancing more rapidly if he is fast at reading and processing the offered material. Classroom training by necessity has been a compromise between the interests, abilities and learning targets of a group of participants. In contrast, digital training comes with the option to tailor target level to individuals.

Most digital training solutions are easy to copy and easy to offer when and where they are needed. However, contrary to wide-spread belief, digital training solutions are always not easy to develop, at least not high-quality digital training solutions. That being said, development time and cost have been significantly reduced over the last 5 years, due to several developments:

- Modular development environments with reduced (but generally sufficient) functionality -"The move from Articulate's Storyline to Rise brought down development times and costs, while at the same time improving trainee satisfaction with the 'look and feel' of the training products", *Plowman and Bertram (2020)*.
- Artificial Intelligence (A.I.) options for base functions While A.I. has failed for larger and more complex training development tasks in our experience, *Gaspar et al. (2023), Plowman and Bertram (2024)*, it has proven to be a time saver for elementary tasks in training development, such as translation, image generation integrated within the e-learning authoring tools, Fig.3, and cartoon-like video generation. Videos with photo-realistic tailored avatars (e.g. wearing a DNV overall and hard hat), speaking lip-sync user-provided text with by now fairly natural sounding voices, can be produced within minutes thanks to the progress in A.I., Fig.4. We use such videos for instance in course introductions. However, the wow factor is wearing off rapidly and such CGI-generated intros may well follow the fate of the MGM logo lion, Fig.5, which no doubt impressed initially, but now looks very dated.



Fig.3: A.I. generated images within RISE for alternative fuel trainings



Fig.4: CGI generated avatar used in course intro



Fig.5: Famous movie intro with roaring lion

The advantages often outweigh the disadvantages, but we all are aware of the disadvantages of digital training:

- <u>Less focus</u> Trainees tire more easily due to lower visual and audio resolution. Digital training forms also require more self-discipline and motivation from trainees, especially in selfpaced training. This is akin to traditional self-paced training that relied on books; the risk is that the book lies around forever, and the trainee does not acquire the knowledge.
- <u>Less clarification</u> Trainees wanting clarification on unclear or even misunderstood items face higher thresholds to expert (trainer) access than in traditional classroom training. Even with chat options and dedicated question & answer time in online training, experience shows that significantly fewer questions are asked in digital training formats than in classic classroom training.
- <u>Less networking</u> While not the primary objective of training, networking between participants and trainers is an important aspect of many trainings, particularly for internal training in DNV. Continued training on the job often involves asking more experienced colleagues where a network of contacts is required, both for identifying the right experts and for lowering the threshold in asking for help or advice.

A recent compromise that we explored at DNV is the use of hybrid classrooms, Fig.6, where some participants physically sit in the classroom, while others follow online. Trainers stand, walk round and use a whiteboard, just as in a regular classroom. Smart cameras follow the trainer automatically and directional microphones with background noise suppression pick up the sound in high quality. General feedback is positive both from trainers and participants, but this approach sacrifices much of the flexibility of pure online training, creating issues e.g. with time zones for remote participants around the globe.



Fig.6: DNV's hybrid classroom; schematic layout (left) and in practice (right)

3. Digital training comes in various forms

Most maritime training involves a theoretical part (e.g. properties, risks, regulations, etc. for alternative fuels), and a practical part (operating machinery, wearing protective gear, giving first aid, etc.)

3.1. "Theoretical" basics

Digital training solutions for the theoretical part of a training are generally straight-forward, and best practice combines various elements:

• Trainer-led learning

The standard solution here is the "virtual classroom". Virtual classrooms are essentially webinars with extended functionality, where participants can interact more with each other (and not just with the trainer, as in webinars), e.g. in chats or breakout rooms for small-group work. Trainer-led learning is best used for interactive parts ', such as Q&A sessions or case study discussion.

Presentation material should, Plowman and Bernhardt (2022):

- Be strongly visual, reducing text to a few keywords, Fig.7. The keywords serve as a

reminder for the trainer, but do not distract from his narrative. For the live online part, the trainer should be the key focus of attention; the slides should be visual aids to support this narrative, not substitute it. Otherwise, the content could just be given as reading material.

- contain relatively frequent interactive elements, e.g. asking questions to participants instead of stating facts to them ("What do you estimate to be..." or "Who of you has already used..."), Fig.8. The interactive elements stimulate the audience to refocus on the topic, reducing the temptation to multi-task (e.g. read incoming emails).



Fig.7: Typical slide with minimum text



Fig.8: Dedicated audience involvement

• <u>Self-paced learning</u>

Self-paced digital learning may come in different forms, *Bertram and Plowman (2019)*. The classic e-learning can be described as PowerPoint or Word documents on steroids. Commercial e-learning platforms, such as Articulate Rise 360, offer easy-to-use standard building blocks to create click-through e-learning modules with a similar look-and-feel to modern websites. Typical building blocks are:

- Text blocks (headings, paragraphs, bullet point lists, embedded text boxes)
- Images (static and animated gifs, galleries)
- Video and audio files (optionally with closed captions; video and audio files may be computer generated or real-life recordings; some e-learnings consist of extended recorded video lectures)
- Interactive blocks (pull-down menus, assorted assessment like multiple-choice questions, etc.)
- Hyperlinks (to websites, attached documents, YouTube videos, etc.)
- Knowledge checks (with automatically graded tasks, typically using multiple-choice or multiple response options)
- Knowledge assessment

Knowledge assessment has become mandatory in many courses due to company quality assurance guidelines or regulatory stipulation. This may also require trainer-supervised human assessment, e.g. for essays or thesis work or presentations of individual or group assignments.

Decarbonization of shipping affects DNV on many levels and in many business segments. Both internally and externally, we perceived a demand for an introductory course providing a basic understanding of the issue, possible pathways and key terminology. In response, we developed a blended course, with 2 half-days of Virtual Classroom and approximately a day's worth of e-learning modules plus text and video libraries for selective drill-down. Figs.9-12 show typical components of the e-learning material for the module on alternative fuels: reading material, Fig.9, interactive elements, Fig.10, assessment quiz, Fig.11, and video lecture from an external expert, Fig.12.



Fig.9: Text material in e-learning

Quiz on Fuels & Converters				SETTINGS
	- 03	What is (real	istically) an alternative fuel?	
Title Screen		Media		
QUESTION ORDER		Pictu	relpng	10
What is not true? Longer chains in hydro- carbons lead to		Correct	Choice Text	Multiple Choice 🛩
What is the main component in natural gas?			Alaza	
What is (realistically) an alternative fuel?		•	AlBac	
What is true for ammonia? [More than one box may need to be ticked]			Corals	
The volume ratio between LNG and natural gas in			Fish	
Low-temperature fuel cells				
ADD OUESTION				

Fig.11: Quiz question in e-learning

Fig.10: Interactive element



Fig.12: Lecture video from library

3.2. "Hands-on"

Not all training relates to theoretical knowledge. For behavioural training, e.g. in machinery operation or firefighting, "hands-on" training approaches are needed. Besides the obvious choice of having drills onboard a real ship, there are options that are at least partially digital:

• <u>Simulators</u>

Hardware-in-the-loop simulators with real control units and simulated rest of the world, akin to nautical simulators, have been used for decades in selected engine room trainings, Fig.13. The advantage is the high degree of realism in handling the machinery, including the haptic sensation of buttons and handles. The downside is that trainees need to travel to a dedicated training centre and have less flexibility regarding when and where to do the training. Another downside is that the simulator centre has only one engine park with given models of machinery. For alternative fuels, often new machinery (dual-fuel engines, fuel cells, etc.) is needed and the mock-up may not have the necessary latest machinery installed to practice this.

• Virtual Reality (VR) simulators

VR simulators offer more flexibility for trainees. They may also offer various "worlds" with different machinery equipment. They are generally only visual, and losing out on the other senses reduces the realism and prevents total immersion. However, touch-screen interaction can be simulated, and trainees generally get quickly used to flicking switches and moving handles virtually. For example, for training monitoring equipment and making the right operational decision, VR simulators can be used successfully, Fig.14.

In both cases, the simulator needs "intel" inside, i.e. a digital twin mimicking the response of the machinery or system. For alternative fuels, digital twins will usually be based on first principles, as we lack experience and data to train digital twins using machine learning. The machinery digital twins may be coupled to other twins, e.g. for propeller or rudder, where the level of detail can be simplified for system parts which are "further away". This is similar to nautical simulators where the maneuvering models for other ships can be simpler than for the own ship.



Fig.13: Hardware-in-the-loop engine room simulator, source: Kongsberg



Fig.14: 3D VR engine room familiarization training simulator, source: Wärtsilä

4. Know Thy Limits

Digital training is more than just e-learning. It may come in many forms, and we like to combine different forms in our trainings at DNV, as diversity reduces fatigue and makes for better pedagogy. New technological developments also affect the training world. They impact the demand for new training content, but new technologies may also lead to new training forms (e.g. VR-based training, Fig.15, *Bertram et al. (2020)*) and faster, cheaper training development (using A.I.).

Digital is not automatically better. We should not forget that training is an area where human factors play an important role, and that training also serves implicitly important tasks in networking and workforce integration. Here, digital training reaches its limits and cases can still be argued for maintaining "old-fashioned" face-to-face classroom encounters.



Fig.15: Human-led VR-based training at DNV

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Monitoring and Enhancing Efficiency and Sustainability for Ro-Pax Vessels

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Abstract

This study compares actual vessel performance of a newbuild Ro-Pax vessel with design estimates. is from the estimated one at design phase. The performance monitoring was based on RINA's SERTICA performance software. The Ro-Pax vessel integrates advanced technologies for emission reduction, energy efficiency, and passenger comfort. During the voyage, various configurations of engine settings and speeds were tested, allowing for a comprehensive analysis of propulsion efficiency and fuel consumption. The primary objective of this study is to determine optimal engine settings for commercial operations, ensuring enhanced efficiency and sustainability. The study found that the vessel's innovative propulsion systems and energy efficiency measures significantly reduce operational emissions and CII compared to older ships in the GNV fleet.

1. Introduction

The IMO, <u>www.imo.org</u>, has set ambitious targets to achieve significant reductions in carbon emissions by 2030 and 2050. These targets are crucial for driving the maritime industry towards more sustainable practices and ensuring compliance with global environmental standards. Within the IMO strategy, the Carbon Intensity Indicator (CII) was introduced to measure and reduce the carbon intensity of shipping operations.

GNV, founded in 1992 and part of the MSC Group, is undergoing a modernization program which entails the delivery of four new Ro-Pax vessels with energy efficiency high standards. During the voyage of one of these four new Ro-Pax ferries, various configurations of engine settings and speeds were tested, allowing a comprehensive analysis of propulsion efficiency and fuel consumption. The study found that the vessel's innovative propulsion systems and energy efficiency measures significantly reduce operational emissions and CII. The adoption of shore connection for cold ironing and advanced energy recovery systems highlights the industry's shift towards sustainability.

The methodology used in the study involves creating performance curves based on voyage sailing conditions and comparing the estimated performance with actual data. Additionally, the study utilizes performance models to provide a detailed description and analysis of the vessel's performance. This approach allows for a comprehensive understanding of the factors influencing the vessel's efficiency and offers insights into potential areas for improvement. The SERTICA performance software used in this study, <u>https://sertica.com/performance/</u>, provides seamless integration with external systems, enabling real-time data ingestion from existing data collection systems. It aggregates data in 5-minute intervals, enriches it with weather data, and performs performance calculations and metrics. Data collected during the voyage were continuously logged and analyzed, confirming the vessel's performance metrics against sea trial benchmarks. This analysis provides valuable insights into optimizing engine settings, contributing to the vessel's sustainable operations. The findings underscore 'GNV Polaris' as a pivotal addition to GNV's fleet modernization and environmental responsibility strategy, setting a benchmark for future maritime projects.

2. The ship

'GNV Polaris' is the first of the four new Ro-Pax vessels designed to enhance the efficiency and sustainability of the GNV fleet, Fig.1. Built by Guangzhou Shipyard International (GSI) in China, it has several class notations for environmental efficiency and comfort: GREEN-PLUS, RINA C, X HULL, X MACH, ro-ro passenger ship, unrestricted navigation, SRTP, AUT-UMS, MON-SHAFT, IWS, COMF-NOISE B, COMF-VIB B, BIOSAFE. Key features include:

- <u>Propulsion and Emission Control</u>: the first two new buildings (NB) feature traditional propulsion (HFO/MGO) with a hybrid scrubber system bypassing the main engines and diesel generators. The third and fourth NB are powered by LNG/MGO. All vessels are equipped with SCR systems to reduce NOX emissions in compliance with MARPOL Tier-III limits.
- <u>Energy Efficiency</u>: Key energy efficiency measures include the use of shore connection for cold ironing, silicone hull coating, waste heat turbine generators, shaft generators, inverters on electric motors, and LED lighting. Additionally, torque meters on shaft lines and mass flow meters on main engines and diesel generators ensure precise consumption monitoring.
- <u>Environmental Compliance</u>: All new ships meet IMO Tier III and EEDI Phase II requirements. They are equipped with exhaust gas cleaning systems (EGCS) and selective catalytic reduction (SCR) to minimize environmental impact.



dwt	45900 GT
length	218.00 m
width	29.60 m
draft	6.45 m
speed	25 kn
capacity	1500 pax
lane cap.	3100 m

Fig.1: 'GNV Polaris'

The introduction of 'GNV Polaris' in the GNV fleet represents a significant advancement in sustainable maritime operations. The vessel's innovative propulsion systems and energy efficiency measures are expected to reduce operational emissions significantly. The incorporation of cold ironing capabilities demonstrates a commitment to minimizing environmental impact during port operations, improving local air quality and reducing noise pollution. Furthermore, the adoption of advanced technologies such as SCR systems and EGCS aligns with international regulations and industry standards, showcasing the vessel's compliance with environmental mandates. The use of silicone hull coatings and waste heat recovery systems highlights the industry's shift towards maximizing energy efficiency and reducing overall carbon footprints.

3. Methodology for Performance Monitoring

This study focuses on monitoring and analyzing the inaugural voyage of 'GNV Polaris' from China to Italy via the African circumnavigation route. Utilizing the SERTICA performance software, this analysis aims to evaluate both the overall and only propulsive performance of the vessel. The primary objective is to determine the optimal engine settings for commercial operations, ensuring enhanced efficiency and sustainability during future voyages.

SERTICA Performance, developed by RINA, is a web-based application designed for the marine sector to support Fleet Managers in optimizing performance. It collects real-time data from automation and other ship systems, elaborates and analyzes them using machine-learning and prediction tools, and provides real-time analytics in a customizable dashboard. This data is paired with external data to provide a comprehensive picture of fleet operational performance. The software offers advantages such as fleet performance optimization, increased efficiency, real time alerts, maintenance cost optimization, and improvements in safety.

3.1. Data collection

Automatic data acquisition systems are typically composed of hardware and software modules, capable of acquiring data continuously from the ship navigation and automation systems or directly from sensors, capable of processing those data advising in real time personnel on board and ashore on performance optimization and/or safety issues. SERTICA performance system foresees an industrial PC with Linux OS installed on board and configured on the ship network, connected to ship navigation and automation systems or directly to sensors if required (high precision inclinometers, torque meters, flow meters, etc.). Typically, the configuration of the hardware kit consists of the components shown in Table I and Fig.2.

Table I: SERTICA	performance – Hardware kit
------------------	----------------------------

	Component Description
1	Industrial PC
2	MOXA Nport IA-5250 2-port RS-232/422/485 serial device server, 10/100MBaseT(X) (RJ45)
3	2x MOXA Nport 5250A 2 port device server, 10/100M Ethernet, RS-232/422/485, DB9 male,
	0.5KV serial surge, 12~48VDC, 0~60°C
4	EDS-208A Unmanaged Ethernet Switch with 8 10/100BaseT(X) ports, -10 to 60°C
5	ioLogik E1240 Remote Ethernet I/O, 8AI, 2-port Switch and SEIKA inclinometer
6	DIN Rail Mounting Kit 35mm, for DE-311/211, NPort 5200/5400, NPort W2250/2150
7	DC/DC 150W
8	Thermoplastic box IP56 240*190*160 with DIN rail
9	AC/DC 30W MOXA power supply
10	Thermoplastic box IP66 300*250*150
11	Cable RS 485 BUS LD 1X2X0,22 (20m)
12	Cable for inclinometer 4*0.75 grey (10m)
13	LAN cable cat 6/FTP 24awg 10m
14	Connector DB9F

Industrial PC and Moxa Nport

Moxa Nport IA

Seika Inclinometer



Fig.2: SERTICA performance hardware kit

The data collector, Fig.3, acquires measurements at customizable sampling frequencies, it filters and processes the data, and stores them in a database with a standard aggregation rate of 5 minutes. Then the data is live streamed to shoreside, where the information from all the vessels are visible in real-time, stored and made available for advanced analysis to the ashore operators. The onboard system also performs data enrichment using external data sources, adding weather data from provisional models or information coming from crew manual inputs such as drafts, displacement, and any other kind of data not automatically available.



Fig.3: SERTICA performance data acquisition process

The signals from the navigation system are expected in NMEA standard - Serial line RS422, to the nearest LAN plug of ship network on the bridge:

- ZDA: Date and Time
- GGA: Geographic Position (or GLL)
- VTG: Track and ground speed
- HDT: Heading True
- VBW: Water Speed
- MWV: Wind Speed and Angle
- RTE, WPL: Route and waypoint from ECDIS

The required signals from the automation system are expected in NMEA or Modbus standard - Serial line RS422/485 directly to the industrial PC:

- Shaft(s) torque, RPM, and power
- Propeller pitch (if CPP)
- Shaft generator(s) power (if available)
- Main Engine(s) Fuel Consumption
- Draft aft / Draft mid / Draft fore (if available)
- For each DG: status/power/fuel consumption
- Boiler status, Boiler fuel consumption (if available)
- Fuel in use/Temperature and specific gravity of fuel (if available)

3.2. Performance analysis

- <u>Propulsion Efficiency</u>: The analysis of propulsion efficiency uses torque meters on shaft lines and mass flow meters on main engines and diesel generators.
- <u>Fuel Consumption:</u> Comparison of fuel consumption under different operating conditions and engine settings.
- <u>Data Trends:</u> Analysis of data to identify trends, anomalies, and areas for improvement in engine performance and fuel efficiency.

4. Comparative analysis

During the voyage, various configurations of engine settings and speeds were tested to assess the vessel's performance under different operational conditions. Performance data collected during the voyage were compared with benchmark power and consumption data obtained from sea trials in order to validate the accuracy and reliability of the performance metrics and to identify the optimal settings for efficient operation, Fig.4 and Fig.5. The sea trials were conducted without silicone paint.

The ship is equipped with two torquemeters (one on each shaft) and two flowmeters (inlet and outlet) on each engine, totaling 16 flowmeters. These instruments enable the real-time recording of shaft power and fuel consumption values.



Fig.4: Sea Trial results: Shaft power vs ship speed



5. Performance analysis during the inaugural voyage

Voyage plan, Fig.6:

- 1. Guangzhou Shipyard Hong Kong (30 October) 72 nm
- 2. Hong Kong Singapore (from 30 October to 3 November) 1488 nm
- 3. Singapore Colombo (Sri Lanka) (from 4 November to 8 November) 1599 nm
- 4. Colombo Durban (South Africa) (from 10 November to 18 November) 3696 nm
- 5. Durban Walvis Bay (Namibia) (from 18 November to 22 November) 1630 nm
- 6. Walvis Bay Las Palmas (Spain) (from 22 November to 1 December) 3946 nm
- 7. Las Palmas Naples (Italy) (from 1 December to 5 December) 1703 nm



Fig.6: 'GNV Polaris' voyage plan

5.1. Singapore – Colombo

The entire leg was from Singapore to Colombo was conducted with four main engines (MMEE) running with shaft generators (SGs) on and diesel generators (DGs) off. The vessel maintained an average speed of 19 kn, with the engines operating at approximately 40% of their Maximum Continuous Rating (MCR).

The speed-power curve, Fig.7, which excludes the power dedicated to generation through shaft generators, confirms the hull/propeller performance recorded during sea trials, with a slight improvement observed.



Fig.8: Singapore - Colombo 4 min engines with shaft generators

The speed/consumption x mile curve, Fig.8, which includes the consumption for generation through shaft generators, also aligns with the predicted values, although the consumption per mile is slightly

higher than expected. At 19 kn, the average consumption is 0.190 t/nm compared to the expected 0.185 t/nm. This discrepancy is likely due to the use of 4 main engines at low power, resulting in higher specific fuel consumption. Interestingly, the consumption per mile generally decreases as speed increases, which seems counterintuitive but can be explained by the engines operating at a point with better Specific Fuel Oil Consumption (SFOC).

5.2. Colombo – Durban

For ~18 hours after departure (from 10 November 10:20 UTC to 11 November 05:20 UTC), navigation was conducted with 2 main engines and 2 diesel engines running (shaft generators off). The remainder of the leg was completed with 4 main engines running. The speed/shaft power curve is similar to that observed with 4 main engines running, as it solely depends on the hull/propeller performance rather than the number of main engines in operation.



The speed/consumption per mile curve is understandably lower than the previous case; at 19 kn, the Key Performance Indicator (KPI) is ~0.17 t/nm. However, when the consumption of the 2 diesel generators is added, the overall consumption per mile is equal to that with 4 main engines running.

5.3. Durban – Walvis Bay

For ~10 hours after departure (from 19 November 07:00 UTC to 19 November 17:00 UTC), navigation was conducted with 4 main engines running with shaft generators on and diesel generators off. During this period, the vessel maintained an average speed of 26 kn, with the engines running at ~75% MCR. The remaining portion of the journey was completed with the 4 main engines operating at roughly 40% MCR, resulting in an average speed of 19 kn.



The speed-shaft power curve, which therefore excludes the power dedicated to generation through shaft generators, confirms the hull/propeller performance observed during sea trials at low speed. However, at higher speed (26-27 kn) the performance is significantly improved compared to sea trials. This improvement can be attributed to the fact that the sea trials were conducted before the application of silicone paint on the hull.

Additionally, the speed/consumption x mile curve demonstrates enhanced fuel efficiency, as the 4 main engines are operating at a point of better specific fuel consumption.

5.4. Walvis Bay – Las Palmas de Gran Canaria

This voyage leg, spanning from 22 November to 1 December, was the longest, lasting ten days. To optimize fuel autonomy, the vessel navigated at an ecospeed of 19 knots, utilizing four main engines and shaft generators operating at 1200 kW each, Fig.13 and Fig.14. No specific tests were conducted during this period, and performance metrics confirmed the results of sea trials.



5.5. Las Palmas de Gran Canaria - Naples

During this leg, the following tests were conducted:

- a) 2 main engines running with shaft generators at 1200 kW each
 - Maximum speed: 14.5-15 kn
 - Limitation in pitch propeller opening due to the shaft generators resulted in higher vibrations and increased consumption compared to sea trials
 - This configuration is not optimal for navigation
- b) 4 main engines running with shaft generators at 1200 kW each at 23 kn, Fig.16
 - This test simulated the Genoa-Palermo line
 - Speed-shaft power curve aligned with sea trials
 - Consumption was slightly higher than sea trials due to suboptimal weather conditions (20-25 kn NE wind, Beaufort scale 4) and fins out





- c) 2 main engines running with shaft generators off, Fig.15
 - Maximum speed: 17.5 kn
 - Performance and consumption closely matched sea trials, showing improvement over the previous configuration

6. Operational results

To optimize regular service operations, it is essential to measure, record, and analyze data to identify more efficient configurations:

- <u>For speeds less than 19 kn</u>, it is preferable to use only 2 main engines instead of 4 to achieve better Specific Fuel Oil Consumption (SFOC). To avoid high vibrations, it is recommended to use diesel generators rather than shaft generators.
- <u>For speeds exceeding 19 knots</u>, the optimal configuration is with 4 main engines running with the shaft generators on.

7. Creation of 'GNV Polaris' performance models and results

A performance model is a powerful tool providing a detailed analysis of a vessel's performance. Performance models can predict the ship performance based on voyage sailing speed and conditions (by considering both weather and ship's loading conditions, not foreseen during design phase). Valuable insight is gained by comparing estimated performance with actual data.

The following two models were created and evaluated:

- 1. <u>Physical Model</u>: created based on physical ship's characteristics in accordance with the ITTC and ISO15016 methodology
- 2. <u>Hybrid Model</u>: created fitting the physical model with machine learning techniques, on the high frequency data acquired.

The physical model was created using physical ship's characteristics in accordance with the ITTC and ISO15016 methodology and the power predicted depends on:

- Ship's loading conditions
- Weather conditions (such as wind, waves and current)
- Ship's characteristics, and in particular:
 - Hull-propeller interaction, evaluated through tank tests results and related to the wake and hull efficiencies at different speeds and drafts
 - Propeller open-water characteristics, which as well come from tank tests result on the propeller's thrust and torque coefficients
 - Hydrostatics, usually obtained through the ship's stability booklet where the displacement and the wetted surface area values are reported at different drafts
 - Speed-power relation basing on sea trial results
 - SFOC-engine MCR correlation, obtained from the ship's engine shop trial results.

Furthermore, in the physical model, it is also possible to include the additional resistance due to the wind by using one of the following models:

- 1. <u>Blendermann</u> is used to describe wind flow over complex surfaces (such as ships) and incorporates the effects of turbulent wind and ship geometry on wind forces.
- 2. <u>Fujiwara</u> assumes more idealized wind profiles, typically neglecting highly turbulent fluctuations and focusing more on the steady wind speed and average relative wind direction.
- 3. <u>STA-JIP</u> considers the wind speed, direction, and ship's geometry to calculate the wind forces acting on the vessel. It focuses on the interaction between the wind and the ship's structure, which influences factors like the ship's heeling, rolling, and pitching.

Finally, it is also possible to keep into account the additional resistance for the waves; of course, the more information that is entered to create the physical model, the more accurate and reliable the model will be.

The creation of physical model for 'GNV Polaris' considered the following information:

- Generic ship's registry information
- Hydrostatic curves
- Hull-propeller interactions data
- Propeller open-water curves
- Shop trials results (SFOC curves)
- Sea trials results
- STA-JIP wind model

The propeller open-water curves used for model's creation are referred to the following P/D values:

- design P/D
- 70% of design P/D
- 80% of design P/D
- 90% of design P/D

The propeller open-water data were only available for the design P/D value, so the others have been retrieved from the tank test results using as starting point those one for design P/D value. It allows us to consider the effect of controllable pitch propeller in the model creation. Furthermore, the combined engine-propeller curves were missing so they were taken out of the sea trials results. At the end, the additional wave resistance has not been included in the model creation.



Fig.17: 'GNV Polaris' Physical Model results vs real data

The physical model was tested using hindcast weather data, steady conditions filters were applied (i.e. the power/speed/course rapid variations are not considered) and the voyage phase Port and Maneuvering were excluded. The entire inaugural voyage of the 'GNV Polaris' was analyzed; for speed range 15.5-21.5 kn, the power prediction is quite good (the model underestimates the real power value with an average of 4%). At low and high-speed ranges (yellow circles in Fig.17), the greatest gap between real and estimated power values can be observed; most likely.

The reason is that tank test results, used for model creation, are usually carried out at operational ship's speed ranges disregarding low and high speed.

At a later stage, a hybrid model was implemented to obtain better power estimation, by fitting the model on real acquired data. Starting from the physical model, high-frequency data were fitted using machine learning and imposing a maximum allowed gap of 20%. The threshold of 20% was chosen to keep the physical behaviour of the previous model. The model was trained on the current dataset available, based on some parameters such as speed over ground, draft values and hindcast weather data (relative current speed/direction, relative wave direction/height, sea state, relative wind speed/direction). Furthermore, the same conditions applied on physical model have been considered (steady conditions on and sea phase).

A significant improvement of power estimated values can be appreciated both for operational and high-speed ranges, with an average error near 0%, Fig.18. There remains a slight gap between estimated and real power values at low-speed ranges. This difference could be reduced using a more accurate physical model taking into account tank test results also at low-speed intervals.



Fig.18: 'GNV Polaris' Hybrid Model results vs real data

8. Conclusions

Digitalization plays a key role in the cooperation between shipowners and suppliers, in order to meet IMO targets by enabling real-time monitoring, data analysis, and optimization of vessel operations. It helps in achieving and maintaining compliance with regulations, monitoring efficiency, and implementing retrofitting actions based on real return on investment.

The monitoring and analysis of inaugural voyage of the 'GNV Polaris' have provided valuable insights into optimizing engine settings for enhanced operational efficiency and sustainability. Key findings include:

- <u>Enhanced Performance with Silicone Paint</u>: the application of silicone paint on the hull significantly improved performance at higher speeds, indicating the importance of hull coating in optimizing vessel efficiency.
- <u>Optimal Engine Settings</u>: operating the engines at approximately 75% MCR resulted in efficient fuel consumption, with speed-to-consumption ratios improving as speed increased.

- <u>Real-Time Monitoring</u>: the use of torquemeters and flowmeters enabled accurate real-time recording of shaft power and fuel consumption, facilitating effective performance analysis.
- <u>Usage of performance models</u>: the use of the performance models has shown that they represent valid tools that provide an accurate estimation which can be used as a benchmark to assess the degradation of the ship's performance over time or as a scenario simulator in case we want to deploy the ship on a different route/scheduling. This may highlight the need for retrofit actions such as hull/propeller cleaning, engines maintenance, etc.
- <u>Benchmarking</u>: comparative analysis with sea trial data validated the performance metrics and highlighted the potential for further optimization of engine settings.

The introduction of the 'GNV Polaris' represents a significant step towards sustainable maritime operations. The vessel's innovative technologies and optimized engine settings are expected to improve fuel efficiency and emissions, setting a benchmark for future projects. Continuous data monitoring and analysis will be crucial in maintaining and improving these performance standards. This ongoing evaluation will also aid in strategic planning for drydock schedules and energy efficiency related maintenance work, ensuring an optimal cost-benefit ratio.

CFD-Based Assessment of the Fuel Savings Potential of a Windshield on a Containership

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Abstract

This paper describes an analysis of the effect of windshields on the fuel consumption of a large containership. High-fidelity CFD simulations are conducted to assess the difference in wind resistance. Windage reduction of up to 25% is possible using windshields. Based on the CFD results, the fuel savings are computed for a specific service utilizing AIS voyage data of the vessels operating on this service and hindsight weather data. As expected, the savings are larger in the west-bound direction where more adverse wind conditions are experienced.

1. Introduction

In the pursuit for ship energy efficiency, the search for improvement measures addresses a wider spectrum, after most of the low-hanging fruits have been harvested. Among the options considered recently for containerships, *Bertram (2025)*, are windshields for containerships to reduce the wind resistance, Fig.1. *MCN (2024)* gives typically savings in the range of 1-2% for overall propulsion power. *Wang et al. (2024)* give 20% on wind resistance reduction in head wind, and lower, but still significant for relative wind directions $\pm 60^{\circ}$ from head wind.



Fig.1: Windshield on containership, source: Tugster

The aim of windshields is to deflect the incoming wind flow to the bow, leading to a much smoother flow, Fig.2. We performed our own analysis on a typical ultra-large container vessel, described in more detail in the following.



Fig.2: Pressure distribution for containership without (left) and with windshield (right)

2. Analysis

2.1. Application case

The application case described here is a retrofit scenario for an ultra-large container vessel where the initial design had no windshield.

- In addition to the base design, two possible candidates for a suitable windshield were investigated. (Previous calculations looked at a set of different windshield designs, before we narrowed down the candidates to those shown in Fig.3.)
- Two different deck cargo variations were investigated.
- The draft was not varied in the geometry model, as both container stack variations for the trade analysed resulted in very similar drafts, justifying the assumption that draft differences are negligible.



Fig.3: Windshield variations; WS02 (left) and WS04 (right)

2.2. Analysis method

To assess the fuel savings potential of a windshield CFD (Computational Fluid Dynamics) computations are performed to solve the stationary Reynolds-averaged Navier-Stokes equations (RANSE) using a k- ω SST turbulence model. The 3D geometry model captured the ship hull above the waterline (treated as a fixed plane), superstructure, deckhouse, container stacks, simplified lashing bridges and windshield variants (including the original design without any windshield). Based on the 3D geometry model, the CFD grid was generated. Unstructured finite-volume meshes of ~20 million cells are used in such computations, leading to high resolution of structural details and flow variations, Fig.4.



Fig.4: Typical CFD surface mesh

Mesh refinement studies have shown that such a grid yields grid-independent CFD results, i.e. a further increase in cell count would not improve the accuracy anymore.

The air resistance was calculated considering five apparent wind angles between 0° (head wind) and 60° for one representative wind speed, specifying an atmospheric boundary layer wind profile at inlet of the CFD grid. The evaluation of hind-cast weather conditions and the AIS operating profiles justified this simplification, as apparent wind angles larger than 60° proved to be insignificant.

Based on the simulation results, the air resistance coefficient as a function of apparent wind angle was derived fitting a smooth function between the five computed values. It was assumed that the effect of the windshield is zero for apparent wind angles larger than 90°. This surrogate model for air resistance then allows rapid calculation of additional or reduced fuel consumption between the original configuration (without windshield) and a given windshield design for any combination of apparent wind angle and apparent wind speed. The fuel savings are calculated for specific vessel voyages based on AIS data, https://en.wikipedia.org/wiki/Automatic_identification_system, and weather conditions. The hindcast weather is based on the Copernicus database, www.copernicus.eu. Data from Copernicus ERA5 database was resampled to 6h-intervals. Track and operational speed-draft profile is generally selected based on ship operator (customer) records and allows to flexibly reflect typical or expected operational conditions.

For simplification (comparably small impact), the calculations assume constant propulsive efficiencies and specific fuel oil consumption. The relative difference between the windshield options is not affected by this assumption since the variations in total resistance are relatively small.

2.3. Results

The average savings across both investigated container stacks and all voyages in different regions were very similar (~2% difference) for both windshields WS02 and WS04, Fig.3, at ~0.8 t/day. WS04 offers a better business case as the large cutout in WS04 leads to ~25% lower steel weight compared to WS02. The computed fuel savings for both windshields are higher for the container stack with more containers. One remarkable result of this study was that while the operational region and sailing direction has some influence on the savings, the savings magnitude is generally very similar.

3. Conclusion

Windshields for container ships can be considered as a robust solution and a low-hanging fruit to improve energy efficiency. CFD simulations are the best tool to guide the design of such windshields. The simulations allow quantification of expected savings along given routes and dates, combining tailored CFD-based surrogate models for wind resistance with weather data bases.

Further improvement potential by optimising the windshield surface for simplified prefabrication while at the same time maintaining the level of attainable savings has been identified as one measure to be looked at in the future.

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Ultrasound - An Effective Non-Biocidal Way to Protect against Fouling

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Abstract

Matching Biofouling Management with the IMO Biofouling Guideline is mandatory for future vessel operation and already crucial when sailing into first mover's territorial waters like Australia, New Zealand, California, Hawaii, and more to come. Innovative, sustainable and overall reliable solutions are required. The paper will focus on development steps of ultrasonic technology, hull fouling protection, and niche areas fouling protection. Case studies of different vessel types illustrate results and benefits.

1. Introduction

Fouling develops in stages. The initial stage is a microscopic fouling, where organisms collectively form a biofilm visible to the human eye, Fig.1. See *Kelling (2017a,2018)* for a more extensive discussion. If the biofilm formation is inhibited, subsequent stages of macrofouling cannot develop. Much of the focus of recent research and development into biofouling management has been focused - rightfully and logically - then on inhibiting biofilm formation and development.



Fig.1: Biofilm as the initial step of marine growth

The classical approach to combat biofouling on ships has been using biocide-containing paints, *Bertram and Yebra (2017), Bertram (2020).* The AFS convention, *IMO (2001)*, has banned so far two biocides in antifouling coating, TBT (tributyltin) and Cybutryne. The Biocidal Products Regulation of the EU, *EU (2012)*, requires approval of biocides and other active substances, <u>https://echa.europa.eu/regulations/biocidal-products-regulation/understanding-bpr</u>, restricting in effect the use of biocides in worldwide shipping. The approval process for new biocides is cumbersome and expensive, if approval is granted at all. As an example, almost no copper-based active substance will get permission to be used in the future. Every system must be approved to be marketed, and environmentally harmful systems shall be sorted out.

This leaves essentially two options:

- taking the risk of using less effective antifouling systems which leads to higher costs for maintenance and repair as well as to higher fuel consumption and emissions to air
- · looking for alternatives to replace the currently used antifouling systems

While robotic cleaning solutions, *Bertram* (2021), are often a cost-effective solution for large, smooth areas, they are unsuited for niche areas. However, niche areas are particularly critical in terms of biofouling and the threat of aquatic invasive species. This is explicitly addressed in the IMO biofouling management guideline, *IMO* (2023). Niche areas are also the focus of inspections of authorities already enforcing biofouling management policies, such as Australia, New Zealand, California and Hawaii. A complementary solution is needed, and the Dynamic Biofilm Protection Intelligent (DBPi), <u>https://hasytec.com/products/dbpi-shipping/</u>, based on ultrasound is the perfect match for the requirements of the IMO biofouling guideline. It will be described in the following.

2. Dynamic Biofilm Protection Intelligent

Biofilms are formed when bacteria adhere to a solid surface, and is a prerequisite for later, more developed and harmful fouling stages. Addressing biofouling already at the biofilm stage avoids numerous issues with macrofouling, such as the complete capture of removed fouling in cleaning operations to avoid the spread of Aquatic Invasive Species (AIS).

Older ultrasound methods followed the idea of getting rid of hard growth which had already attached. Using hard cavitation, this might work in certain situations but may also damage the vessel's steel or coating itself. Consequently, this approach was not accepted by the market. Low-powered ultrasound (avoiding cavitation) destroys the cell structures in biofilm, thus the prerequisite for higher stages of fouling, such as barnacles, shells, and algae. Unlike some coating solutions, ultrasonic antifouling solution are also 100% effective at zero speed, e.g. in longer stays in port or at mooring. Ultrasonic antifouling solutions have enjoyed exponentially growing market acceptance in shipping over the last 10 years. For details on our ultrasonic protection method and its working principles, see e.g. *Kelling (2017b), Kelling and Mayorga (2020)*.

The Dynamic Biofilm Protection based on ultrasonic protection against biofouling may be used for internal spaces, such as pipes, heat exchangers, sea chests, or tanks, Fig.2. But it may also be used for hull protection.



Fig.2: Internal biofouling protection by ultrasonic 'transducers' (indicated by small blue bars)

The ultrasonic vibrations are brought into the water via 'transducers', Fig.3, which are glued to the steel hull on the inside, e.g. in the engine room where electrical supply to the transducers is easy. Transducers are relatively low-powered, e.g. 12 W per transducer for average output, 20 W per transducer for maximum output.



Fig.3: Examples of installed transducers



Fig.4: Sea chest protected by Hasytec transducers and free of fouling after 3.5 years of operation



Fig.5: Tugboat without (top) and with (bottom) ultrasound protection

Fig.4 shows the effectiveness for a sea chest, where the vessel is in a drydock after 3.5 years of operation. The sea chest area is free of fouling thanks to the dynamic biofilm protection, while the hull, 'protected' by biocidal antifouling coating, shows significant macrofouling.

Fig.5 shows the effectiveness for a smaller workboat, *Kelling (2017b)*. Within the CHEK project, *Mayorga and Kelling (2022), Mayorga et al. (2023)*, the effectiveness of large-scale installations for hull and internal equipment of large commercial ships has been investigated with promising results, Fig.6. The effectiveness of dynamic biofilm protection installations was increased significantly harnessing the power of Artificial Intelligence in DBPi, Fig.7, *Mayorga et al. (2023)*.





Fig.6: CHEK cases for full hull ultrasonic protection

Fig.7: DBPi from Hasytec

3. Conclusion

Ultrasonic biofouling management continues to gain traction in the maritime industry. HASYTEC electronics has by now (early 2025) more than 4500 transducers installed, on a total of more than 230 ships. The technology is mature and 'tried-and-proven', and a low-hanging fruit for improving the energy efficiency of ships.

The main areas of applications are now niche areas and appendages, such as propellers. However, our ambition is to develop ultrasonic protection as a technically and economically viable alternative for full cargo ship hulls within the next decade, through continued R&D efforts.

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WHISPER: Energy Transition from Wind and Solar Energy

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Abstract

This paper presents the latest merchant ship concepts developed by the WHISPER Project Consortium under the Horizon Europe framework. The project is managed by Verkis and technically led by Stirling Design International, a naval architecture firm. It showcases innovative Panamax bulk carrier and container feeder designs, achieving up to 30% fuel consumption reduction through the integration of cutting-edge technologies, including OceanWings wing sails, Solbian solar panels, and Sidewind turbines. The paper provides a detailed analysis of the performance prediction, operational challenges, and associated risks. Mitigation strategies employed within the WHISPER Project will also be discussed. One key innovation is the integration of six tiltable OceanWings wing sails, each 363 m², into a Panamax bulk carrier, based on insights from Ant Topic and Marfin Management ship owners. Additionally, the paper presents the integration of two liftable OceanWings sails on a container feeder with an innovative hull design, highlighting results on ship commercial capacity and performance as informed by Samskip and Nav-Tech ship owners. Both designs developed by SDI are practical examples of how renewable wind and solar energy technologies can be effectively incorporated into the shipbuilding and ship repair sectors, offering substantial potential for sustainable maritime operations.

1. Introduction

Global shipping is a large contributor to climate change by emitting for approximately 3 % of global CO2 emissions. To mitigate its consequences, it is essential to drastically reduce these emissions and limit the increase in global temperature below 2°C, as recommended by the IPCC (2018). Consequently, the shipping industry faces increasing pressures to reduce GHG emissions. In response, IMO introduced energy efficiency regulations in 2013, such as the Energy Efficiency Design Index (EEDI) Ship Energy Efficiency Management Plan (SEEMP), https://www.imo.org/ the or en/OurWork/Environment/Pages/Improving%20the%20energy%20efficiency%20of%20ships.aspx. These were the first global measure encouraging the integration of carbon reduction technologies on both retrofit and newbuilding projects. In 2023, IMO introduced stricter short-term regulations such as the Energy Efficiency Existing ship Index (EEXI) and Carbon Intensity Index (CII), aiming to reduce the carbon intensity of the international shipping industry by at least 30% by 2030 (relative to the 2008 levels) with the ambition of achieving near to zero net GHG emissions by the end of the century.



Such a decrease in emissions cannot be achieved by relying solely on conventional propulsion systems. In the last decade, alternative propulsion systems have been identified, with wind-assisted propulsion systems (WAPS) emerging as a promising solution to reduce fuel consumption. These technologies include soft sails, wing sails, Flettner rotors, kite or turbo sails that have been developed and tested on commercial vessels. Fig.1 presents an inventory of existing and on-order ships equipped with WAPS, showing that while Flettner rotors currently dominate the market, rigid sails and suction sails are closing the gap with an increasing number of orders, https://www.dnv.com/maritime/insights/topics/waps-wind-assisted-propulsion-systems/. Fuel savings from WAPS equipped vessels can be significant, ranging from 5% to 25% under average wind conditions according to ship operators, provided that a sufficient number of systems are installed. However, these systems alone cannot completely replace conventional propulsion, additional onboard energy sources are required to meet auxiliary power demands. In this regard, renewable energy devices can be investigated such as solar photovoltaic panels to reduce the auxiliary engine loads during operations. Relevant examples are the 60,000 Gross Tonnage (GT) Auriga Leader built by NYK Line Company in 2011, Fig.2, and a 100-passengers ferry SolarSailor built by OCIUS Technology, Fig.3.



Fig.2: Auriga Leader Ropax ship

Fig.3: SolarSailor ferry ship

The main challenges addressed by the integration of these carbon reduction technologies into a merchant ship design are the economic viability, compliance with the CII, operational efficiency and safety with regards to ship stability requirements, since additional air drafts are induced by WAPS. WAPS performance evaluation is key factor influencing ship owners' decisions, whether for retrofit projects or newbuilds. WAPS performances rely on hydrodynamic and aerodynamic balance analyses, based on empirical methods for evaluating ship manoeuvrability, especially for ships sailing at a drift angle, *Viola et al. (2015), Tillig and Ringsberg (2020), Kramer and Steen (2022).* Their performance can also be evaluated through Computational Fluid Dynamics CFD analysis or model test results using standard series hulls, *Hopes et al. (2021), Kramer and Steen (2022), Van der Kolk et al. (2022).* This matter can also be addressed by Dynamic Velocity Prediction program DVPP, *Kerdraon et al. (2019),* in an unsteady environment. However, these methods, in the case of a WAPS ship in leeway, are computationally expensive.

Other methods are more cost-effective. For example, a system-based approach to study the behaviour of wind-propelled ships with 6 Degrees of Freedom (DOF) has been developed by Ecole Centrale Nantes (ECN), *Charlou et al. (2023)*. This method works as a Power Prediction Program (PPP) or as a Velocity Prediction Program (VPP) and has been implemented into the open-source xWASP_CN model. Comparison of the numerical results with a model scale unit of an 18 ft catamaran equipped with a Flettner rotor showed good agreement for steady-state results. Another 6 DOF PPP, developed by DNV, *Reche-Vilanova et al. (2023)*, leverages semi-empirical methods and WAPS aerodynamic database from scientific literature for rotor sails, rigid wing sails and dynaRigs. The study reveals good agreement between simulations and the sea trials. This work has been extended to a Capesize bulk carrier to assess both its performances and economic viability, *Hansen et al. (2025)*. This work concluded that the economical speed for this vessel is 14 kn and highlighted the importance of the weather routing potential, *Mason (2021)*, for both carbon savings and cost reductions.

Beyond wind propulsion, hybrid solutions integrating both wind and solar power have also been explored. A performance study on a HandySize bulk carrier incorporating both technologies demonstrated a potential CO2 reduction of 36 % at a service speed of 13 kn, *Nyanya et al. (2021)*. However, the study did not take into account the added resistance due to leeway, which can increase total resistance by up to 18%, nor the effect of waves, which can further raise this resistance to 33%, *Kramer and Steen (2022)*.

Despite these advancements, the previous studies have overlooked key operational challenges associated with hybrid wind-solar merchant ships, such as design integration, leeway induced drag on hull and rudder, and aerodynamic interactions between sails. This study aims to bridge these gaps by presenting the methodology to develop fuel efficient merchant ship concepts within the framework of the EU-funded WHISPER project.

The project's objective is to develop, design, manufacture, and test wind-solar hybrid power systems and wind-assisted propulsion systems (WAPS) solutions to improve fuel efficiency of merchant ships, specifically targeting bulk carriers and container feeder ships.

This paper presents numerical performance predictions for two merchant ship concept designs, assessing their impact on both propulsion and auxiliary consumption. The ship designs, developed by SDI and supported by WHISPER consortium, are based on:

- A Panamax bulk carrier, designed with insights from Ant Topic and Marfin Management
- A 1,000 TEU container feeder ship, developed with insights from Samskip and Nav-Tech

The following fuel-saving technologies are integrated into these designs:

- Rigid wing sails provided by OceanWings
- Photovoltaic (PV) panels provided by Solbian
- Wind turbines provided by SIDEWIND

Numerical simulations are conducted using X-WASP PPP. The questions addressed in this study are the following:

- What are expected power savings for wind-solar assisted bulk carriers and container feeder ships?
- How does sail integration impact ship operation at sea and in port?
- What are the most effective sail configurations in terms of power savings both in terms of carbon reduction and economic viability?

2. WHISPER ship concepts

This section introduces the two ship designs under consideration and outlines their operational and technical constraints. The WHISPER project aims to ensure that these ship designs achieve power savings of 30% for the bulk carrier and 15% for the container feeder ship.

2.1. Panamax bulk carrier

2.1.1. Main characteristics and operational profile

For this study, a Panamax bulk carrier, Table I, was designed by naval architect SDI, incorporating insights from ship owner Ant Topic and Marfin management. This vessel type is particularly well suited WAPS installation as it is gearless with the absence of onboard cranes, unlike smaller bulk carrier such as Ultramax vessels. The absence of cargo-handling equipment facilitates loading and unloading operations, ensuring the WAPS are not interfering with onboard gears, thus enhancing operational efficiency.
Service Speed (kn)	12
Length overall (m)	225.0
Moulded depth (m)	18.6
Breadth (m)	32.2
Deadweight (t)	60 000
Transverse metacentric height GM (m)	2.97

Table I: WHISPER Panamax bulk carrier ship: main characteristics

Table II presents the carbon reduction technologies installed onboard, which includes 6 tiltable rigid sails of 363 m² each, provided by OceanWings, 1456 m² of PV panels from Solbian and 5 wind turbines housed in a 20' container, provided by Sidewind.

Table II: Carbon reduction technologies inside Panamax bulk carrier concept

	Units
OceanWings OW363	6
Solbian solar panels (m ²)	1456
20' container - Sidewind Turbines	5

The operational profile of such a ship is shown in Table III for a service speed of 12 kn.

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Engines mean power (kW)	Main	Aux	Days	MWh per year	
At sea (at service speed)	4692	480	210	26067	
At anchorage	0	480	50	576	
At port	0	1160	105	2923.2	
			Total MWh per year	29 566	

Table III: Panamax bulk carrier operational profile

2.1.2. General arrangements

Fig.4 and Fig.5 illustrate the concept design developed by the WHISPER consortium. This design includes six tiltable rigid sails provided by OceanWings. Solar panels from Solbian are installed on top of the hatch covers, while Sidewind turbines are positioned between them.



Fig.4: WHISPER concept: rendered view of the Panamax Bulk carrier (preliminary render)



Fig.5: General arrangements: WHISPER Panamax Bulk carrier hosting 6 OW363 wing sails

2.2. Container feeder ship

2.2.1. Main characteristics and operational profile

For this study, a container feeder ship concept has been designed by naval architect SDI, incorporating insights from Samskip and Nav-Tech. Its main characteristics are presented in Table IV. This concept includes two rigid elevator wing sails of 363 m² each, provided by OceanWings, along with a series of Sidewind containers positioned on the highest container rows.

Service Speed (kn)	16.5
Length overall (m)	147.7
Moulded depth (m)	12.3
Breadth (m)	21.3
Carrying capacity (TEU)	1029
Transverse metacentric height GM (m)	0.65

Table IV: WHISPER container feeder ship: main characteristics

Table V presents the carbon reduction technologies integrated on board, including two rigid sails, each measuring 363 m², which are mounted on an elevator system allowing them to slide inside the ship. Additionally, 255 m² of Solbian PV panels are installed on 24 Sidewind containers.

Table V: Carbon reduction technologies inside WHISPER container feeder ship concept

	Units
OceanWings 363	2
Solbian solar panels (m ²)	255
20' container - Sidewind Turbines	24

Table VI describes the operational profile of the container feeder ship for a service speed of 16.5 kn.

			F F F F F F F F F F F F	
Engines mean power (kW)	Main	Aux	Days	MWh per year
At sea (at service speed)	5424	950	265	40539
At port	0	1200	100	2880
			Total MWh per year	43419

Table VI: Container feeder ship operational profile

2.2.2. General arrangement

Fig.6 and Fig.7 illustrate the container feeder ship concept design developed by the WHISPER consortium, showcasing its general arrangements. In this design, the wings are positioned behind the wheelhouse, ensuring clear visibility and compliance with SOLAS regulations.



Fig.6: WHISPER concept: rendered view of the 1029 TEU container feeder ship (preliminary render)





2.3. Operational and technical limitations

2.3.1 Bulk carriers

The integration of sails on bulk carriers imposes significant limitations. During cargo operations, the rigid sails must be safeguarded against potential accidents or falling cargo. Additionally, integrating

carbon-saving technologies in the bulk carrier impacts both cargo and ballast capacity, as the tilting penetration mechanism of the rigid sails beneath the deck will reduce the available top side tank space. Furthermore, the rigid sails must be positioned to minimise the interferences with ship operations during loading and unloading phases.

2.3.2 Container ships

For container feeder ships, integrating rigid sails is even more complex than for bulk carriers. In addition to ship stability issues resulting from ballast reduction or an increased vertical aerodynamic centre of effort, containers loss due to wing integration must also be considered. For this design, the inclusion of two rigid elevator sails was considered to be an acceptable compromise in terms of cargo-carrying capacity and fuel saving performances.

3. Performance prediction methodology

As mentioned in the introduction, performance assessment on WAPS-equipped ships relies on hydrodynamic and aerodynamic balance analysis. The present section focuses on the aerodynamic modelling, dealing with environmental data characterisation and aerodynamic performances of the rigid sails.

3.1. Aerodynamic modelling

3.1.1. Global wind chart

A normalized global wind chart has been developed, illustrating the probability of wind conditions in relation to the ship's heading along major global trade routes, <u>https://wwwcdn.imo.org/localresources/en/OurWork/Environment/Documents/Air%20pollution/MEPC.1-Circ.896.pdf</u>, Fig.8. The ships operated by Ant Topic have an operational profile very similar to the standard shipping routes studies by IMO unlike Samskip's ships which follow very specific routes as illustrated in Fig.9.



Fig.8: Global shipping routes used for wind chart calculation

Fig.9: Iceland Samskip's ship routes

Based on IMO considerations, the average true wind speed encountered by ships operated on international trading route is 14.4 kn at a height of 10 m above sea level. For Samskip's specific routes, wind statistics have been established based on a 1-year measurement from one of their vessel. Note that the wind statistics from IMO are provided for a reference height of 10 m above the sea level and could be applied if we consider that the wind profile is uniform. However, a more accurate representation considers wind shear, which is modelled using a power law wind profile expressed as:

$$W(z) = W_r \left(\frac{z}{z_r}\right)^{\sigma},\tag{1}$$

W(z) is the true wind speed computed at the vertical coordinate z with respect to the sea surface, W_r is the reference true wind speed at 10 m height above the sea level, z_r is the reference height which is

10 m in this study and σ is the wind shear factor that takes the value $\sigma = 0.14$ according to *Touma* (1977).

For Samskip specific routes, wind data was measured at a height different from 10 m. The data was recalibrated using the wind power law from Eq.(1) to match the same reference height, resulting into an average true wind speed of 14.0 kn. Wind distributions for both global trading routes and Samskip specific routes are presented in Fig.10 at a reference height of 10 m.



Fig.10: Wind speed distribution according to standard IMO regulation and custom measurements on ARNARFELL vessel

3.1.2. Rigid sails

For this study, aerodynamic lift and drag coefficients were computed by OceanWings on a reference ship of similar length to the designs examined in this article. This reference design included six rigid sails arranged in a rectangular configuration as illustrated in Fig.11.



Fig.11 Rigid sail nomenclature applied to the WHISPER Panamax bulk carrier concept

For each apparent wind angle (AWA), it was assumed that the sails operate at their optimal thrust coefficient C_x . However, high C_x values often result in high values of side forces C_y which penalize hydrodynamic performances as the induced drag increases due to leeway, *Kramer and Steen* (2022).

3.2. Hydrodynamic modelling

In this present study, X-WASP PPP is used to evaluate the WAPS ship performances. It is a systembased 6 DOF approach which presents the key advantage of being simple to implement and computationally efficient. Additionally, it is a modular approach, as each sub-system can be described by its own force model. However, its main limitation is that it does not take into account interactions between the different sub-systems. For instance, interactions between the hull and the propellers, as well as the hull and its appendages, are not explicitly modelled; only semi empirical corrections are applied to account for these effects.

3.2.1. Hull modelling

It is possible to evaluate the hydrodynamic behaviour of the hull with X-WASP PPP by using two methods.

A first method consists of modelling the hull excluding appendages as a lifting surface, characterized by its lift coefficient and drag coefficient. These coefficients must then be derived from the literature or Computational Fluid Dynamics (CFD) calculations. However, this method has not been chosen for the current project. Another method appears to be more comprehensive and commonly used, especially in properly addressing the ship's longitudinal balance in drift, which this simplified method does not allow.

The second method involves modelling the hull excluding appendages using its manoeuvrability coefficients, enabling the description and correlation of all forces and moments of the hull based on its movements (forward and drift speeds). CFD simulations at various drift angles allow for the calculation of these coefficients. In this study, manoeuvrability coefficients were estimated using semi empirical methods, *Taimuri et al.* (2020), and CFD calculation on reference vessels.

These coefficients are based on the following governing equation:

$$X'_{Hull} = X'_{vv}v'^{2} + X'_{vr}v'r' + X'_{rr}r'^{2} + X'_{vvvv}v'^{4}$$

$$Y'_{Hull} = Y'_{v}v' + Y'_{r}r' + Y'_{vvv}v'^{3} + Y'_{vvr}v'^{2}r' + Y'_{vrr}v'r'^{2} + Y'_{rrr}r'^{3}$$

$$N'_{Hull} = N'_{v}v' + N'_{vvr}v'^{2}r' + N'_{vvv}v'^{3} + N'_{r}r' + N'_{vrr}v'r'^{2} + N'_{rrr}r'^{3}$$

$$K'_{Hull} = -Y'_{Hull}(0.5T)$$
(2)

 X'_{HULL} , Y'_{HULL} and N'_{HULL} are, respectively, the hull's longitudinal forces, side forces and yaw moment and the right handside terms correspond to the hydrodynamic derivatives. Such equation is similar to the MMG rule, *Yasukawa and Yoshimura (2015)*. Furthermore, in addition to the dynamic forces of the ship in longitudinal direction, the static part, i.e. the ship's resistance curve, is given by Holtrop's method, *Holtrop and Mennen (1982)*, *Holtrop (1984)*.

4. Results

4.1. Bulk carrier ship

This section presents the overall power savings on the Panamax bulk carrier at a service speed of 12 kn. Several wing configurations were analysed, including two types of rigid sails with surface areas of 363 m^2 (OW363) and 588 m^2 (OW588). Fig.12 presents the power savings expressed as a function of the total sail area for different configurations.

4.1.1. Power savings for a new build Panamax bulk carrier

Fig.12 describes the influence of each setup on the global performance of this new build project. If weather routing is taken into account, each individual sail setup can provide increased power savings, up to 60% according to data from scientific literature, *Mason (2021), Dupuy et al. (2023)*.

The WHISPER project targets power savings of at least 30% for bulk carriers and the sails setup allowing this starts from a configuration of 6*OW363 if weather routing is considered. However,

increasing the number of sails beyond this point is not feasible for both retrofit and new build applications because of the lack of deck space for this type of vessel. The dotted curve in Fig.12 represents the power savings assuming no wing-to-wing interaction and no weather routing. Under these conditions, the 6*OW363 configuration achieves a 30% power reduction. However, when wing interactions are accounted for, but without weather routing, savings drop to 18%, highlighting the strong non-linear effect of the wing-to-wing interactions on WAPS performance.



Fig.12: Power savings for the bulk carrier Panamax WHISPER concept at a service speed of 12 kn

However, these results are associated to a slow steaming speed of 12 kn. To account for this effect, power savings on the 6*OW363 sail setup have been calculated at service speeds of 10, 11, 12, 13 and 14 kn using the same assumptions as in Fig.12. Results, presented in Fig.13 indicate that power savings improve as service speed decreases, reaching up to more than 35% at a service speed of 10 kn when both wing-to-wing interactions and weather routing are considered. The economical speed of a ship must be determined at the fleet level, as reducing a single vessel's speed requires increasing the fleet size to maintain service frequency and compensate for longer estimated times of arrival (ETA). According to the WHISPER consortium, a service speed of 12 kn is economically viable, whereas further speed reductions are not acceptable at the fleet scale for economic reasons.



Fig.13: Power savings on bulk carrier Panamax WHISPER concept at different service speeds

4.1.2. Gain assessment for 6 OW 363 at 12 kn

Gain assessment induced by WHISPER technologies are presented in Table VII, showing the updated operational profile with active WAPS. For this setup and this service speed, overall savings of 18.2% are expected, with 16.6% contribution from WAPS and 1.6% from PV panels and wind turbines.

Engines mean power kW)	Main	Aux	Days	MWh per year
At sea	3716.5	425.3	210.0	20874.7
At anchorage	0	425.3	50.0	510.3
At port	0	1105.3	105.0	2785.3
			Total MWh with WHISPER per year	24 170
			Total power savings	18.2%
			Total sail coverage per year (MWh)	4916.4
			Total Sail coverage	16.6%

Table VII: WHISPER gain assessment for the 6*OW363 setup at a service speed of 12 kn

4.2. Container feeder ship

This section presents the overall power savings newbuilding concepts of a container feeder ship based on the insights of ship owner Samskip and Nav-tech. Fuel consumption has been estimated for the following service speeds of respectively: 12.5, 14.5, 16.5 and 18 kn. Several wing setups have been considered; one does not include any sail and includes 24 Sidewind containers. Other configurations include two rigid elevator wing sails and three wing sails.

4.2.1 Power savings for a new build container feeder ship

To choose the best configuration, relative daily fuel consumption per container has been estimated for all the configurations above mentioned, with the reference chosen as the configuration operating at its top speed of 16.5 kn without any sails integrated. Fig.14 shows that the best performing configuration, in terms of daily fuel consumption per containers, is the one including 2 rigid elevator wing sails, for all the considered service speeds.



Fig.14: Relative daily fuel consumption per container for different sail configurations

Consequently, global power savings calculations have been carried out for the same range of service speeds for the "no sails" configuration and the new build concept including 2 elevator rigid sails. Results are shown in Fig.15, showing approximately 3% power savings for "No sails" configuration and approximately up to 18% for the 2*OW363 configuration at a service speed of 12.5 kn, under the assumption of a 15% positive effect of weather routing optimisation.





4.2.2 Gain assessment for 2 OW 363 at 16.5 kn

Table VIII presents gain assessment induced by WHISPER technologies, showing the updated operational profile with active WAPS. For this setup and this service speed, overall savings of 9.7% are expected, with 5.8% contribution from WAPS and 2.9% from PV panels and wind turbines.

Engines mean power (kW)	Main	Aux	Days	MWh per year
At sea	4926.2	828.6	265	36600.9
At port	0	1078.6	100.0	2588.7
			Total MWh with WHISPER per year	39190
			Total power savings	9.7%
			Total sail coverage per year (MWh)	3165.8
			Total Sail coverage	7.3%

Table VIII: WHISPER gain assessment for the 2*OW363 setup at a service speed of 16.5 kn

5. Conclusions

The study presented a methodology for assessing the impact of WAPS and carbon reduction technologies, such as wind turbines and PV panels on fuel savings of two merchant ship designs developed by the WHISPER consortium: a Panamax bulk carrier and a container feeder ship.

The study revealed that for new build Panamax bulk carriers, power savings of up to 30% can be achieved with a six-rigid-sail configuration, but only under the assumption of an optimistic 60% weather routing benefit and a reduced service speed compared to similar vessels (slow steaming from 14 to 12 kn). The results highlighted the strong non-linear impact of the interactions between multiple wings on overall power savings. According to ship owner Ant Topic and Marfin management, a service speed of 12 kn is economically acceptable, but further reductions should not be considered, even if they lead to greater fuel savings.

Regarding container feeder ships, the study revealed that for a service speed of 16.5 kn, configurations without sails resulted in 3% power savings and the design including 2 sails achieved 10% power savings. However, achieving project objectives for this type of vessel appears more challenging due to design constraints making rigid sails less suitable:

- Deck space limitation: Installing sail reduces cargo carrying capacity, requiring careful optimization of the container number to WAPS ratio to maintain fuel efficiency per container unit.
- Course-keeping challenges: The rudder area of these vessels is typically insufficient to ensure course-keeping capability with an increased number of WAPS. Beyond a certain sail area, maintaining equilibrium in the horizontal plane becomes unfeasible.

From a regulatory compliance perspective, this study does not account for CII or stricter EU regulations, such as FuelEU Maritime, <u>https://eurlex.europa.eu/eli/reg/2023/1805/oj/eng</u>, which came in to effect in January 2025 and explicitly accounts for the benefits of wind propulsion.

As part of the WHIPSER project, the next phase will focus on validating these findings through sea trials on a retrofit bulk carrier operated by Ant Topic and a container feeder ship operated by Samskip. Additionally, CAPEX and OPEX assessment will be carried out to quantify the financial impact of WAPS integration. CAPEX is particularly important for retrofit applications, since significant structural modifications are required to integrate WAPS effectively. Furthermore, FuelEU and ETS (Emissions Trading System) calculations will be necessary to assess for the overall financial impact, as these regulation impose penalties on CO2 emissions. Finally, accurate weather routing optimisation will be explored to improve the fuel saving potential of these innovative ship designs.

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Development, Implementation, and Testing of a Hydrodynamic Keel Concept for Modern Wind-Assisted Commercial Ships

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Abstract

Subject is the development and analysis of a special kind of keel system (Wagner Keels) that is suitable for modern ship hull geometries that are restricted by draft limitations and aiming at a cost-efficient solution for tackling the requirements of large wind propulsion system used for primary ship propulsion. The delta-shaped double keels, are based on the vortex-lift principle. Research, based on CFD-RANSE methods as well as towing-tank analysis, was done at TUHH and in the framework of the project TLCSeaT at HEL. The research focus lies on keel performance compared to alternative solutions with respect to optimized sailing capabilities.

1. Introduction

The age of sailing ended with the development of modern diesel engines and their introduction to the shipping sector. At the same time hull forms, that have previously been adapted to the requirements of proportionally large wind propulsion systems, changed dramatically to suit the new requirements of main engine and propeller for thrust generation. Furthermore, hull shapes adapted towards specific cargo demands and the challenges and restrictions posed by new trading routes and seaports. Today we have specialized ships, perfectly adapted to their specific cargo demands. These ships usually have flat bottom hulls without any dead-rise. Dead-rise was formerly incorporated into the hull designs of large sailing vessels for increased stability reasons and for providing lateral resistance in a steadily heeled sailing condition. Keel-rake or aft trim, formerly utilized by sailing vessels in order to align the aero- with the hydrodynamic pressure point, is today considered inefficient, since it increases drag of the engine driven vessel. Both design aspects dead-rise (optionally with bar-keel) and keel-rake or aft trim are not existent anymore in most modern hull designs. If today's commercial fleet is reintroduced to the concept of primary wind propulsion, new keel concepts for handling large side-forces generated by a large wind propulsion system, need to be developed. The topic of this research study is the development of a low aspect-ratio side keel system, based on the principle of vortex lift generation, suitable for modern hulls of nowadays commercial fleet. First basic research on the topic was done during a master thesis of one of the authors, whereby a large variety of keel shape variations and concepts was analysed and compared via CFD-RANSE methods at TUHH. This initial research was continued in the framework of the concept design and scientific research at University of Applied Sciences Emden Leer (HEL) for the design and building of the primarily wind powered sailing cargo ship JUREN-AE in the framework of the IKI funded project 'Transition to Low carbon sea transport' (TLCSeaT) for the Republic of the Marshall Islands (RMI).

2. Physics of sailing - Equilibrium of forces and moments

The basis for evaluating the effectiveness of an appendage system for a primary wind propelled vessel is its ability to counteract the forces and moments resulting from the wind-propulsion system. For large wind propulsion systems, these forces and moments dominate the design of the ship's hydrodynamic layout. For sailing a straight course, forces and moments need to be in balance and the hydrodynamic layout must be adapted accordingly. Since the natural centre of effort for most modern hulls is near the bow, the rudder needs to create a large side-force to align the 'hydrodynamic centre of effort' (CE_H) to the 'aerodynamic centre of effort' (CE_A), Fig.1.



Fig.1: Aero- and hydrodynamic layout for a primary wind propelled ship

Even though the rudder is a very effective device for generating side forces, rudder forces are limited by its relatively small size. Further, the rudder is still needed for manoeuvring of the 'sailing' ship as well. Steady rudder angles above 5° for keeping a straight course should be avoided. Therefore, an efficient keel system is needed to prevent overloading the rudder and to increase total side-force capabilities of the hull. Efficiency of the hydrodynamic system is defined by the 'glide-angle' (γ_A) or 'force-ratio', Fig.2. The higher the force-ratio, the better will be the sailing characteristics of the ship, expressed by smaller angles sailed towards the apparent wind. A large keel system will however also increase the initial drag of the vessel, while sailing in engine mode or downwind where only little side-force is required. The longitudinal positioning of the keel system gives control over the CE_H while its size defines the effective leeway angle as well as initial drag of the ship.



Fig.1: Equilibrium of forces and moments for a sailing ship

3. Basic research at TU Hamburg

Wagner (2011,2015) analysed vortex-lift effects at the raked keels of traditional sailing vessels using CFD, investigating variations in size, position, angle and leading-edge contour on delta-shaped side-keels. The delta shaped side-keels were compared towards two alternative keel design concepts that met the same basic requirements. All appendage variations were attached to a standard hull (without skeg). Apart from cross-force, drag and yaw moment, emphasis was given to analyse behaviour of the different appendage concepts for changing heel angles and effects caused by keel-rake (aft trim) on yaw moment. The study also provides detailed insights into flow conditions as well as force and pressure distributions for the different appendage systems.

3.1. Concept development

Usually, lift is generated by a profiled wing. The higher the aspect ratio of this wing, the lower is the additional induced drag, resulting in high force-ratios and low leeway angles. On top of the technical challenges of a deep retractable wing, operational and maintenance costs pose significant economic challenges for cargo ships with extensive wind propulsion. Instead of conventional lift generation by a profiled foil, the proposed fixed keel concept builds on the idea of using low aspect-ratio delta-wings with vortex-lift capabilities, similar to the delta-wings used for high-speed airplanes, *Luckering (2019)*, to overcome the difficulties concerning draft limitations or additional high expenses for sophisticated technical solutions.

3.1.1. Principle of vortex lift

The concept of vortex lift on a delta wing basically maximizes the tip vortex of the wing and guides this vortex along the slanted leading edge of the wing. The lift is generated by the negative pressure field within this vortex in addition to the potential lift of the surrounding flow, *Polhamus (1966)*. Experiments show that this vortex is not only adding to the generated lift but also effects the boundary layer separation that usually causes the stall of the flow around a conventional profile, *Marchaj (2003)*. Stall leads to drastic reduction of the generated lift or side-force. For delta wings, stall was not observed. Here, the lift reaches its maximum at high angles of attack of 40° to 60°. Further increase of inflow angles results in a gradual transit into the typically separated flow conditions, probably because the accelerated flow inside the attached vortex prevents the formation of a detachment bubble by a steady downstream transport inside the vortex core. Another important characteristic of a low aspect-ratio delta-wing is the comparatively low resistance coefficient at small angles of attack. High-speed aircraft use this quality for reducing drag at high traveling speeds, *Polhamus (1966)*. This low resistance value for small angles of attack could be beneficial for a sailing vessel design that aims at minimized additional drag and operates at relatively small leeway angles.



Fig.2: Vortices forming above the wings of Concorde during landing and take-off



Fig.3: Vortex-Lift effects for delta-wings, Polhamus (1966)

3.1.2. Vortex-lift effects at a traditional yacht hull

Wagner (2011) analysed the principle of vortex-lift for traditional long-keel yachts that show a steady keel-rake. The presence of a significant vortex system creating a low-pressure field within its core - similar to the vortex-systems of a delta-wing airplane - could be demonstrated. For comparison, the empiric analytical concept 'slender-body-theory' (SBT) was applied, showing good agreement up to 10° leeway angle, Fig.5. Above 10°, the calculated curves deviate. The effects of additional vortex-lift and drag could be observed within the CFD results for cross-force and drag and also within the vector-field visualizations.



Fig.4: Vortex at yacht hull with keel rake (right), low-pressure at vortex core (middle), analytical and numeric calculated cross-force and drag (right)

3.1.3. Transferring the delta-wing concept to keels of modern ship hulls

Based on these first findings, *Wagner (2015)* investigated design options of delta-wing keel systems for large commercial cargo ships. The basic idea was to attach the low aspect-ratio delta-shaped keels at both sides of the flat bottom. The sideward attachment does not increase of draft at even keel, but does so in heel, increasing the effectiveness with increasing heel angle. Its position in luv of the hull leads towards a clean and undisturbed inflow. Compared to a cantered keel system where the waterflow is slowed down by the presence of the hull, this sideward position is beneficial for performance of the system. The big question is, if the second keel, positioned behind the hull, will remedy the advantages of the luv-ward positioned keel or if in total a positive benefit remains.



Fig.5: Design concept for delta-wing bilge-keels at a flat-bottom hull for a commercial cargo-ship

The hull itself acts in that sideward attached configuration as a mirror plane. Only one half of the 'theoretical delta-wing' is attached to either sides of the hull. The span of these sideward attached keels is limited by the shape of the hull. If attached in the vicinity of the mainframe, the bilge radius limits the maximum span of the keel. The further these keels are moved towards the aft, the higher can be the effective span of the resulting delta wing whereby aspect-ratio is increased. The total size of such designed keels can be significantly larger, while draft of the vessel is not increased at all. Further, the concept allows to specifically design the keels according to the requirements given by the wind propulsion system by choosing correct size and longitudinal position. The concept can be realized for most modern ship hull geometries. Even retrofits to existing hulls are thinkable, since these completely passive keels are attached solely to the outside of the hull. Inside of the ship no additional space is required.

3.2. Geometries

The basis for the numerical shape variation and investigation is a parametric design environment that allows to create similar shapes by changing single design parameters. For this study a parametric model was created within the design environment of CAESES from Friendship Systems. The base hull is varied by changing keel-rake from zero to two meters. This change affects off course the linesplan of the hull, but main parameters are kept identical: length, beam, average draft, displacement, waterline and area, mainframe, deck and transom are identical for both versions. All appendage systems that are analysed within this study are attached towards this base hull design. In that way the effects of the appendage systems on vessel performance can be analysed and compared, Focus lies on the effects caused by the appendage systems, rather than optimized base hull performance. The basic hull that was used for all calculations is based on the main dimensions of the 'Ecoliner Concept', https://www.dykstra-na.nl/designs/wasp-ecoliner/, Lpp = 130 m, B = 18.2 m, T = 6.5 m, $\Delta = 11000 \text{ t.}$

Since keel-rake is traditionally used to move the CE_H aft, the large majority of calculations is done for a hull including a keel-rake of 2 m. Keel-rake further provides additional draft for the aft-ship region, leading to increased draft for the appendage systems compared to the design variants on even keel.



Fig.6: Bare hull, No keel-rake (0 m)



Fig.8: Bare hull, keel-rake of 2 m

Fig.7: Sections for 2 m keel-rake

For comparison, two other keel concepts were analysed, a centre-skeg variant in combination with standard bilge-keels (CS-v1) and as a more specialized concept a double fin positioned to both sides of the cantered propeller and rudder as far out as possible, similar to the concept used by the E-Ship 1, but in this study the additional fins are considered as fixed structural parts, not rotatable like a rudder (DF-v4). The fins are aligned to the streamlines such that initial drag is minimized on a straight course without leeway angle. Focus lies on two delta shaped bilge-keel variants. The first is a relatively large appendage system that starts forward of the mainframe and extends far aft into the aftship region. This large keel system can create high cross-forces to counter a major wind propulsion system (SK-v4). The second delta-shaped side-keel configuration (SK-v7) is a more moderate version positioned far aft in the aft-ship region but still well forward of propeller and rudder (referred to as SK-v7). The two side-keel variants show exemplary the potential of such a keel system. Any size in between can be realized as well. Table II gives the geometric data for the appendage system variants.



	Angle to vertical	Length	Surface area
Bilge keels for variant CS-v1 and DF-v4	45°	38.1 m	61.7 m ²
Center-skeg for variant CS-v1	0°	39 m	231.8 m ²
Double fin for variant DF-v4 (per fin)	20°	7 m (av.)	90.5 m ²
Delta-shaped side-keel for SK-v4 (per keel)	45°	62.5 m	252.4 m ²
Delta-shaped side-keel for SK-v7 (per keel)	45°	19.8 m	91.6 m ²

Table II: Appendage system data table

3.3. Calculation Environment

In order to evaluate and compare the different keel variants, the hull-polar-curves (Cl-Cd-curve) for each design variant and floating condition were obtained by variation of the leeway-angle in five steps from 0° to 15° . Heel and trim (design keel-rake) was varied for the most promising variants to analyse the effects on vessel performance.

The software used for these calculations was the FreSCo+ code, https://www.tuhh.de/fds/in-housecodes. The grid is basically a large box with the ship at its centre. The volume between ship and the boundaries of the domain box is then discretized with the software HEXPRESS from Numeca. Focus of this study lies on the details happening around the appendage systems and in comparing different design approaches and appendage layouts. To cover all these details a very fine discretization of the calculation domain is required, especially within the vicinity of the appendage systems, leading to a high number of cells of 8-16 million cells for each variant. A high number of cells is located in the hull boundary layer and within the turbulent flow regions of hull and appendage system. For the variations of the leeway angles (creation of the polar curves) the calculation is repeated on the same grid but with changed inflow velocity vectors, whereby errors resulting from changing grids are avoided. All calculations are done in full scale to avoid errors due to scaling effects, especially concerning turbulent flow in the vicinity of the boundary layers and the expected forming of vortices at the appendage systems. In total, more than 150 CFD calculations were performed for a large variety of grid, shape and inflow variations, *Wagner (2015)*.



Fig.13: Calculation domain

Fig.14: Typical grid refinement

Even though the interference effects between appendages and the ship-wave system can be neglected for low Froude numbers, the ship-wave system itself still has significant influence on the total forces and moments. In an additional calculation series for the hull without appendages, but including the free surface (two-phase simulation), the effects caused by the ship-wave system was calculated.



Fig.15: Calculation series for bare hull including free surface effects

By subtracting the results (forces and moments) of the single-phase calculation (domain is cut at water-plane level) from the results obtained by the two-phase calculation series including the free surface effects, the sole effect of the ship wave system is isolated (referred to as 'Rw' in the following diagrams). The resulting forces and moments for the ship-wave-system are then used to compliment the calculated results of all other single-phase calculations. The result of this separated calculation procedure is an efficient way to analyse the appendage systems in greater detail, while computing time is reduced significantly. Due to flow interference effects between hull and any kind of appendages, it is not possible to tell exactly what part of the results (forces and moments) is caused by the flow around the keels (appendages) and what is caused due to the changed flow around the hull triggered by the presence of the attached appendage system. However, some details can be obtained by analysing the 'change' caused by the appendage system, compared to a calculation for the hull without any appendages.



The resulting difference between the two calculations series, results in the isolated effects that the keel system has on the performance of the hull. This difference between the two calculations series includes therefore the effects of the 'keel itself' as well as the 'interference effects' caused by the attached keel on the flow conditions around the hull. Further insights on the generated forces are obtained by virtually cutting the ship longitudinally into sections. This concept allows evaluating the distribution of the generated forces and moments.

3.4. Calculation Results: Compare Variants

3.4.1. Hydrodynamic Lift and Drag Curves

Hydrodynamic lift and drag curves for each series are an excellent basis for comparing the efficiency of the different appendage systems. Together with the separately obtained resistance curve for the hull and suitable concepts for sea-state resistance calculation, these curves can be used for efficient vessel performance predictions. The curves give the initial resistance, induced resistance and cross-force for varying leeway-angles. Initial resistance is the resistance of the hull without any leeway angle (smooth water towing resistance at design speed). As soon as the vessel is heeled to one side, the symmetry is lost, and additional force components are created. A cross-force that is created perpendicular to the direction of the flow and additionally the induced drag, adding to the initial resistance in direction of the flow. The hydrodynamic lift and drag curves are calculated for a steady heeling angle of 5° and for leeway angles of up to 15° .



Fig.19: Cross-force-drag curves: comparing variants, large cross-forces

To classify the results, an approximated cross-force from a large Dynarig wind propulsion system (WPS) is drawn into the diagrams. This cross-force from the WPS needs to be countered by the hydrodynamic layout of the vessel to reach the equilibrium of forces and moments, whereby differences for the centre of efforts need to be equalized by the rudder. The total drag difference of variant SK-v4 and variant DF-v4 compared to variant CS-v1 is ~15%, leading effectively to faster sailing speeds. SK-v7 lies somewhere between with an additional induced drag value of ~7%. Due to the larger keel areas of SK-v4 the leeway angle, required to reach the cross-force demanded by the WPS, is signifi-

cantly lower. If overall performance of the different variants is to be evaluated, then cross-force and induced drag alone are not sufficient since the initial drag values play an important part as well.



Initial drag of the two variants SK-v4 and DF-v4 is larger than for the centre-skeg variant (CS-v1) and the small side-keel variant (SK-v7). Initial drag is important for sailing downwind or in engine mode where no cross-force from the WPS needs to be countered. SK-v7 shows the lowest initial drag values even though its surface area is similar to the double fin variant (DF-v4). SK-v7 gives the best results concerning total drag up to a cross-force level of about 4.0E+5 N. Above that value DF-v4 and SK-v4 perform better as outlined above.

3.4.2. Centre of Effort

For further discussion of the results the CE_H needs to be considered as well. Due to the rather small layout of the rudder, compared to the areas of hull and keel, the yaw checking ability is limited. If the required rudder angle is too large, the reserve for manoeuvring the ship is compromised.



Fig.21: SK-v7 - position hydrodynamic centre of effort, requirements for rudder

The CE_H moves backwards for increasing leeway angles, especially for CS-v1. For small leeway angles the CE_H lies at a far forward position of 92% of L_{PP} for CS-v1. Variants SK-v4 and DF-v4 are already close to the estimated CE_A at the required cross-force level. For SK-v7 and CS-v1 the rudder needs to move the CE_H backwards by ~10% of L_{PP} to equalize the yaw moment of the WPS. Due to its ability to rotate, the rudder itself will have higher force-ratio values than hull and keel together. If cross-force and drag from the rudder is considered, the total efficiency of the hydrodynamic layout is increased, as long as the rudder is not overloaded. The same is true for a double or triple rudder configuration (E-ship 1).

If the moderate side-keel variant (SK-v7) can provide the required cross-forces and CE_H together with a centred rudder at moderate rudder angles, the economic benefit compared to multiple rudder design could make the difference for a commercially attractive system.

3.4.3. Visualization of vector fields

CFD allows detailed insights into the flow conditions. Lambda2 plots (vorticity in x-direction) at hull and appendage systems show the effects of the vortices on the hull surface. The low-pressure trace at the sides of the appendages is a result of the low-pressure cores within these vortices.



Fig.22: CS-v1 - Visualization of vortex systems (left) and pressure on hull-appendage surface (right)

Note the differences between the luv-side (upstream) vortex and the lee-side (downstream) vortex of the two bilge-keels. While the active luv-side vortex is attached to the keel, the lee-side vortex is created by the tip of the keel but almost immediately separates. The large vortex at the centre-skeg stays attached to the skeg and leaves a clearly visible low-pressure field at the side of the skeg. The double fin variant works completely differently in comparison. While the vortices at bow and bilge-keels look almost identically to the centre-skeg version above, the fins function like a normal profile with suction and pressure side. The luv-side fin (starboard) creates high forces, due to the clean inflow conditions. The lee-side fin (port) is clearly compromised due to the presence of the hull upstream.



Fig.23: DF-v4 - pressure on fin surface (left), velocity and pressure slice through fins (right)

A major vortex is created at the active luv-ward side of the delta-shaped side-keel variant (SK-v4). This large vortex creates a low-pressure field at its core and leaves a low-pressure trace at the side of the keel.

The second vortex behind the hull (downstream) creates again a large vortex, but this vortex separates from the hull and trails off with only minor effects on the pressure field of the hull. The difference between the two vortices is made visible by slices through the calculated pressure and velocity fields. The slice series shows the development of the luv-side vortex, attached to the side of the keel with an increasing low-pressure field in its centre. Also, in line with the theory of vortex systems observed for delta wing airplanes, *Polhamus (1966)*, flow is accelerated within the core of this vortex. The lee-side vortex, behind the hull, shows just a minor low-pressure field at the centre of the vortex. Velocity in x-direction within the vortex-core of the lee-side positioned keel is slowed down.







Fig.25: SK-v4 - slice series through velocity and pressure fields at different x-Positions

SK-v7 is designed with much shorter keels (length of only about 20 m). Main difference is the three times higher aspect-ratio compared to the side-keel variant 4, described above.

The low-pressure trace left behind at the keel surface is much more pronounced and covers large parts of the keel. The higher aspect ratio and the more delta-shaped contour of the keel clearly leads towards a faster developing vortex with an even more pronounced low-pressure core at its centre.



Fig.26: CS-v1 - Vortex systems (left) and low-pressure trace on hull-keel surface (right)

3.4.4. Analysis of force distributions from bow to stern

The calculated forces and moments are evaluated section-wise by virtually cutting the ship into sections of 1 m. The resulting force distribution curves show in more detail what is happening along-side the hull due to the presence of the different appendage systems. Figs.28-40 show the data for the submerged part of the hull only, and for 5° heel, without effects caused by the ship-wave system.



Fig.28: Bare-hull cross-force distribution (curves)

The cross-force distribution for the bare hull shows a significant peak directly behind the bow of the vessel. In this region a large part of the total cross-force is generated. Due to the keel-rake of two meters, additional positive cross-force is generated further downstream as well. Behind the section of deepest draft at 40 m, the generated cross-force from the hull becomes negative (due to the absence of centre-skeg and rudder). The negative force created behind section 40 thus counteracts the cross-force provided at the bow. The calculated CE_H for such a bare hull would be far forward of the bow. For the four different appendage systems the cross-force distribution curves are displayed in the same way.



Fig.29: CS-v1 cross-force distribution



Fig.30: CS-v1 cross-force distribution, compare to hull without appendages (RoA)



Fig.31: DF-v4 cross-force distribution



Fig.34: SK-v4 cross-force distribution



Fig.36: SK-v7 cross-force distribution



Fig.32: DF v4 cross-force distribution, compare to hull without appendages (RoA)



Fig.27: SK-v4 cross-force distribution, compare to hull without appendages (RoA)



Fig.28: SK-v7 cross-force distribution, compare to hull without appendages (RoA)

Compared with the force-distribution curves for the bare hull, the negative cross-force field in the aftship region is reduced and partly turned into positive cross-force due to the appendage systems.

Forward of the appendage systems the cross-force distribution curves are identical to the curves for the bare hull. Behind the appendage systems however the curves follow a cross-force distribution for a lower angle (compare red dashed 10° curve with the yellow 10° curve for the bare hull). The calculated difference towards the bare hull is given with the black dashed curves in above diagrams.

For the double fin variant major parts of the generated cross-force are created at the two profiled fins (Naca-0412) behind sec. 10. The two bilge-keels behave identically to the bilge-keels displayed for the centre-skeg variant. The effect of the bilge-keels continues even behind the bilge-keels. The presence of the bilge-keels reduces the inflow angle by ~20% for that specific design (DF-v4). Thus, the bilge-keels have an additional positive influence by reducing the negative contribution of the cross-force created by the hull behind sec. 40. This effect is in the following called the 'hull-appendage interference effect'. Since the two large fins are positioned as far aft as possible, the positive interference effect on the hull is limited to the region of the fins themselves (behind sec. 10).

For the large side-keel variant 4 (SK-v4) the calculated cross-force difference is gradually increasing with its highest value at section 17 (7 m forward of the trailing edge). The angle of attack for the region behind the keels is reduced by 80% due to the presence of the large keel system (compare curves for RoA_10°, RoA_2° and SK-v4_10°). A similar picture can be seen for the smaller side-keel variant SK-v7. The cross-force peak reaches a similar level a few meters forward of the trailing edge. Behind the keels a positive interference effect remains with flow-angle reductions of 70%.

This major interference effect is approximated in Fig.37. The red area represents the approximate part created by the keel system. The yellow part represents the hull-keel interference effects.



Fig.37: SK-v4 cross-force distribution, hull-keel interference effects



Fig.39: SK-v7 cross-force distribution, hull-keel interference effects



Fig.38: SK-v4 - drag-force distribution, compare to hull without appendages (RoA)



Fig.40: SK-v7 drag-force distribution, compare to hull without appendages (RoA)

It looks like the efficiency of this special keel system results in large parts also from the reduction of the negative cross-forces in the aft-ship region created by the hull itself. The same concept for calculating differences towards the bare hull is also applied to the drag-force distributions. For the drag-force distribution the picture is similar than for the cross-force distribution. Forward of the keels, no difference is calculated. Near the keels drag-force is increasing similar to the increase in cross-force. Interestingly is that the difference in drag-force behind the keel-system (dashed grey curve) is close to zero. No additional drag is created behind the delta-shaped appendage systems.



Fig.41: Cross-force-drag coefficient curves for 'appendage plus hull-appendage interference effects'

To complete the picture, the isolated appendage and hull-appendage interference effects are displayed in Fig.41 as cross-force-drag coefficient curves. The dimensionless coefficients are calculated based on water density, vessel speed and the total appendage surface-area. For variant CS-v1 and DF-v4 this means that the bilge-keels are included as well. Compared to the presented cross-force-drag curves for the complete ship, Fig.20, the curves for the 'appendage' plus 'hull-appendage interference effects' clearly show the potential of the delta-shaped side-keel concept. Especially SK-v7 shows comparatively high-performance values. Interestingly to observe is that despite the overall high performance of variant DF-v4, the initial drag coefficient for this appendage variant is significantly higher than for the other three appendage systems.

3.4.5. Behavior due to keel-rake variation

The above discussed appendage variations were calculated for 2 m keel rake KF. In this section, additional series for even keels (KF = 0 m) are analysed compared to data for KF = 2 m. As anticipated, keel rake has a significant influence on performance of the ship. The cross-force drag curves are improved, indicated by total drag reduction for leeway angles above 2° and higher cross-force values. Initial drag at a leeway-angle of zero degrees is increased only slightly for the raked keel variants.



Fig.43: Effect of keel rake on hydrodynamic centre of effort

A major difference can be observed for the calculated position of the CE_H . For all design variants the CE_H is positioned further aft by 7% to18%. Partly this effect is caused by the hull itself. Additionally, the appendage systems can be designed slightly deeper, since draft at AP is increased due to the keel-rake design. The biggest difference is observed for CS-v1. The lowest influence is calculated for the delta-shaped side-keel configuration.

3.4.6. Behaviour due to heel-angle variations

The influence of changing heeling angles has different effects on vessel performance for the different appendage design concepts. displays the effect for an angle variation from 2.5° to 7.5° . While performance increases for SK-v4 (force-ratio increases, no change for the CE_H), the opposite is true for the centre-skeg variant. Force-ratio is reduced for CS-v1 by 9% and the centre of effort moves forward by more than 10%. For the double fin variant (DF-v4) the negative effects due to heeling are only small.



Fig.44: Effect of heel angle on drag, cross-force, force-ratio and the hydrodynamic centre of effort

The different behaviour due to heeling can be further explained by analysing the pressure slices through the vector fields of the three design variants.



Fig.45: Effect of heeling angle on performance, pressure slice

For SK-v4 increased heeling angles lead towards increased draft for the sideward positioned keel. The low-pressure core in the centre of the vortex is slightly increased whereby the induced drag is increased as well. The opposite occurs for CS-v1. Effective draft of the centred keel is reduced. At the same time the bilge (with bilge-keel) moves down for increased heeling angles whereby inflow towards the centre-skeg is disturbed. Resulting from this is the breakdown of the attached vortex at the centre-skeg. The loss of cross-force at the centre-skeg is the reason for the forward shifted centre of effort and the reduced force-ratio. For the double fin variant (DF-v4), a slight reduction of the pressure-field of the leeward (left) fin can be observed. This reduction is made good again by a performance increase for the luv-side fin (starboard) due to increased draft and a more vertical fin position.

3.5. Lessons learned

Three different appendage-design concepts were discussed and analysed in detail. In conclusion it can be stated that the conventional centre-skeg design shows major deficits as soon as the ship is subject to steady heeling angles. The double-fin variant shows significantly higher performance values. Especially if the double fin is realized as a double rudder configuration, the overall performance will

likely be further increased. In case of double rudders, the higher costs need to be considered. For primarily wind powered sailing ships, the most promising concept is the delta-shaped side-keel configuration. This concept has the lowest initial drag values if designed moderately. Further, the side-keels can be combined with an efficient single rudder configuration for increased vessel performance. The concept is completely passive and thus it is cost-efficient and could also be retrofitted to almost any existing modern flat-bottom ship hull, perfectly adapted (size, longitudinal position) to the requirements of the WPS.

4. Research at HEL for the hydrodynamic layout of JUREN AE

In the framework of the project 'Transition to Low Carbon Sea Transport' (TLCSeaT), a bilateral research and development project between Germany and the Republic of the Marshall Islands (RMI), the University of Applied Sciences Emden-Leer developed a concept design for a small primarily wind powered island supply vessel.

The passive but still efficient appendage design concept based on the delta-wing principle was chosen for further design investigations due to its perfect suitability for the anticipated task. The remoteness of the RMI trading area in the middle of the Pacific Ocean requires a solid and robust technology. Draft limitations due to the shallow entrances into the lagoons of the atolls, require a hull and keel design with lowest possible draft. Retractable systems were considered unsafe, since the trading area is poorly charted. Often the vessels navigating the remote outer islands and atolls of RMI need to completely rely on echo sounding devices and often even a lookout is positioned at the bow of the vessels to detect uncharted reefs, while the ship enters or navigates inside the shallow lagoons.

In the framework of the design process for JUREN AE a series of towing tank measurements was carried out to identify the most suited hydrodynamic layout for the ship. The concept for the delta-shaped side-keels was investigated and compared towards two other possible solutions with the goal to verify and improve empiric analytical approximations that are used for vessel performance predictions.

4.1. Hydrodynamic concept design for JUREN-AE

The hydrodynamic layout for JUREN AE foresees medium sized delta shaped bilge-keels that are positioned aft of the mainframe of the vessel. These keels are expected to have several advantages compared to a centred keel. The sideward positioning will not increase the initial draft of the hull, but when the vessel is heeled the keels will become more and more effective the larger the heeling angle is (increasing effective draft). Compared to a centred keel system, this delta-shaped bilge-keel configuration can be smaller in size due to higher efficiency, thus also improving vessel performance in engine mode due to reduced frictional drag, as long as the alignment of the keels is following the streamlines of the hull. As the JUREN AE is a primarily propelled sailing vessel, the hydrodynamic concept needs to be aligned to the aerodynamic design of the ship. Fig.46 shows the concept design including approximate CE_A for the sail-system and superstructure.



Fig.46: 3D model used for initial design and calculations created within CAESES

The hydrodynamic layout is designed with a strong focus on vessel safety against accidental groundings. Retractable dagger-board systems would be the most efficient solution but, in this case, they are excluded due to high risk of accidental damage. Possible appendage systems are therefore the classical centred bar-keel, no keel (deadrise hull with centre-skeg only) or the above discussed deltashaped bilge-keels (Wagner Keels). The centred single rudder is designed rather large in order to contribute to the required side-force. Additionally, the rudder needs to provide enough steering capacities even without the accelerated flow due to the propeller. The recuperating propeller will slow down the approach velocity on the propeller, whereby the generated rudder forces are further reduced in sailing mode.

4.2. Modular towing tank model for the RMI-Design

The modular scale model was fabricated using 3D-print technology. Fig.47 shows the centre-skeg only version, Fig.48 the towing tank model with the bar-keel configuration (left) and the two deltashaped bilge-keels (right). Table III gives data for added draft and surface areas for these two variants. Turbulence is stimulated by sand strips following to ITTC guidelines and recommendations.



Fig.47: Towing-tank model with centre-skeg and rudder, side-view



Fig.48: RMI-Design - towing-tank model with bar keel (left) and delta-shaped bilge-keels (right

rable m: RMI-Design - appendage data					
	Additional surface area Added draft Leng				
only centre-skeg	0 m²	0 m			
bar-keel	14 m²	0.2 m	35 m		
delta-shaped bilge-keels	20.3 m ²	0 m	11 m		

Fable III: RMI-Design - a	appendage (data
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4.3. Preparing for towing-tank testing series

Fig.49 shows the placement of ballast within the model as well as the model guidance on the towing carriage. Below the yaw-angle adjustment unit, the 6-DOF sensory equipment (forces and torque moments) and the cardan joint towards the model can be seen as well. The two pulleys, equipped with spring trolleys, were used to place the ballast in the model according to calculated weight distribution at the two attachment positions.



Fig.49: Placement of ballast inside the model

Trim of the vessel was double-checked by measuring draft at FP and AP. An IMU-Unit is used to measure accelerations in all three axes as well as turning rate, allowing to document the actual floating position as well. The aim of the testing program is to provide input data that can be used within a performance prediction program tool (VPP, PPP). Relevant data in this context is:

- smooth water resistance curve -> Cr, Ct, 1+k
- hull-keel polar curve \rightarrow Cy_{vh}, Cxy_vh, CE_H
- influence of rudder -> validate / adapt analytical formulas, AoA reduction factor

Smooth water resistance was measured according to the ITTC recommendations. The form-factor is measured for the bare hull without bilge-keels. The results for the smooth water towing resistance tests are in the context of evaluating the efficiency of the appendage system only relevant concerning the differences in initial drag (leeway angle of 0°) and are therefore not further discussed here.

4.4. Hydrodynamic polar curves

The hull-keel polar curves are measured for a typical speed (sailing with the WPS) of 9 kn. Since cross-force and induced drag are caused by pressure differences, frictional components can be neglected whereby the measured coefficients (Cy_{vh} and Cxy_{vh}) for the scaled model at a single (typical) speed are also valid for full scale predictions at varying vessel speeds. The formulas used to determine the coefficients are:

$$Cy_{vh} = \frac{Fy_{vh}}{(\frac{rho_h}{2} * Vh^2 * S)} \quad \text{and} \quad Cxy_{vh} = \frac{Fxy_{vh}}{(\frac{rho_h}{2} * Vh^2 * S)}$$

The force component Fxy_{vh} is the difference between the measurement including a varying yaw angle in the coordinate system of vessel motion (Vh) and the measurement at zero yaw angle. Fig.50 shows the predicted cross-force (Fy_{vh}) and induced resistance values (Fxy_{vh}) for the three analysed keel variants. The black dashed curve represents the results based on an analytical calculation (slender body theory) used for later performance calculations within the concept design process.



Fig.50: Cross-force (Fy_vh) and induced resistance (Fxy_vh) prognosis for full scale vessel

The delta-shaped side-keel variant shows the highest cross-force values at moderate induced resistance. The bar-keel shows in this measurement series unexpected high induced resistance values. A clearer picture is given by the cross-force – drag curve. Initial drag is based on the above shown Rt calculation.



Fig.51: Cross-force - drag (left) and force-ratio (right) for full scale vessel without rudder

For an approximated cross-force of 68 kN resulting from the INDOSAIL WPS at beam and upwind courses, the delta shaped bilge keel variant shows significantly reduced induced drag values at lower leeway-angles, leading to increased vessel performance. Force-ratio for the delta-shaped side-keels is increased by 20% to 30% for leeway angles in the relevant range of 5° to 10° .

4.5. Centre of effort

The centre of effort is the relevant information for a velocity prediction calculation to determine required rudder cross-force in order to equalize the yaw moment. Fig.52 shows the CEH for the three keel concepts. The vertical axis shows measured hydrodynamic cross-force. The remaining offset that must be equalized by the rudder depends on the keel-variant. The side-keel concept results in favourable CEH positions of about 10% forward of the CEA while the other two version need to equalize around 25% of L_{PP} .



Fig.52: Compare hydrodynamic centre of effort to requirements from WPS

4.6. Effect of rudder on sailing performance

Rudder measurements were done for a leeway-angle of 7° and also 7° heel. Rudder angles were varied from -20° to $+20^{\circ}$. Important for the rudder calculations is the reduction of the inflow angle at the rudder position due to the appendage layout upstream. This factor is measured by identifying the rudder-angle of zero cross-force. For the RMI-design this factor is approximately 0.5. For the analytical

rudder calculation, the flow speed reduction due to wake needs to be considered. Wake number is estimated with w = 0.1. The measured and calculated rudder cross-forces are given in Fig.53. Fig.54 shows the change in force-ratio if the rudder is considered. Force-ratio is increasing due to the rudder effects for rudder angles of up to 10°. For higher rudder angles, performance of the ship is reduced again. Fig.55 displays the resulting change of the CEH due to the rudder for the side-keel variant. The required position (by the WPS), at 57% of L_{PP}, is reached with 7° rudder angle. This leaves enough room for manoeuvring the vessel, before stall at the rudder occurs.



Fig.53: Measured rudder cross-forces and analytical calculation



Fig.55: Change of hydrodynamic centre of effort due to rudder cross-force



Fig.57: Cross-force-drag curve including rudder and balanced yaw moment



Fig.54: Change of force-ratio due to added rudder forces



Fig.56: JUREN-AE model in towing-tank at Maritime Testing Facilities in Leer



Fig.58: Resulting angle of attack at rudder for equalized yaw moment

If the analytical rudder is included at the required cross-force level the difference between the centreskeg only variant towards the side-keel variant is much smaller. But looking at the angle of attack that is required to balance the yawing moment it becomes clear that the rudder is clearly overloaded for the centre-skeg only variant. Compared to the bar-keel variant a significant total drag reduction can be observed.

5. Conclusion and Outlook

With the delta-shaped bilge-keels, aimed at maximizing vortex-lift effects, a highly efficient and flexible keel system for handling large side-forces induced by a major wind-propulsion system, has been discovered. The system can be used for very different modern hull shapes and can also be retrofitted to most flat-bottom hulls. Major benefit is its cost efficient and passive design that does not increase the draft of the vessel. Necessary for good performance is the alignment towards calculated streamlines in order to minimize initial drag and prevent the forming of vortexes and additional drag at zero leeway angle (engine mode without cross-force).

The implementation of the concept for the JUREN AE revealed high potential so far. Manoeuvring of the ship in engine mode was not compromised by the large keels and the sailing abilities of the vessel revealed an astoundingly good performance. Further performance tests onboard JUREN AE will be conducted in the near future. The keel concept will be part of further comparison studies within our current wind-ship design projects at University of Applied Sciences Emden/Leer.

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The MCN Guide: Ship Efficiency in the Context of International Emission Regulations – An Update

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Abstract

This paper provides an introduction to the current MCN 2024 Guide (formerly known as 'MCN Guideline'), published in September 2024 as a handbook and knowledge base to meet the growing number of requirements related to the EEDI, EEXI, CII, EU ETS and Fuel EU regulations. The Guide provides an overview of technical solutions as well as maintenance and operational measures that can be considered to improve energy efficiency of ships and reduce their greenhouse gas emissions. Furthermore, it describes new and so-called green fuels, highlighting the advantages that "carbon dioxide neutral" fuels may offer, without concealing the associated disadvantages. A revised version of the MCN Guide is expected in autumn 2025. The paper previews the enhancements and new features to be included in the forthcoming release.

1. Introduction

1.1. Creation of the document

The Maritime Cluster Northern Germany (MCN) connects maritime companies and institutions with strong expertise in ship design, supply, and engineering. To harness this knowledge and promote progress toward greener shipping, MCN founded the Expert Group Ship Efficiency in 2014. The group brings together professionals working on technical advancements in ship efficiency and emissions reduction, responding to evolving environmental goals and regulatory requirements such as those from IMO and the EU.

To support shipowners, operators, and other stakeholders, the Expert Group began developing a practical guidance document in 2021 and released the first version in 2022. Since then, the guide has evolved continuously, expanding its scope, structure, and content with each annual edition. It is designed as a living document that adapts to new regulatory frameworks, fuel options, and energy-saving technologies. The fourth edition is currently in preparation for release in autumn 2025, Fig.1.



Fig.1: The MCN 2024 Guide

The guide outlines the regulatory background, available energy carriers, and technical solutions that contribute to more energy-efficient and climate-friendly shipping. It highlights two fundamental pathways to decarbonisation: adopting low- or zero-carbon fuels, and enhancing energy efficiency through operational and technical measures.

1.2. Evolution of the Guide

Since its launch in 2022, the MCN Guide: Ship Efficiency has been continuously developed to reflect the dynamic regulatory and technological landscape of maritime decarbonisation. The first edition, published under the title "Ship Efficiency in the Context of EEDI, EEXI and CII – The MCN Guideline", provided a foundational overview of alternative fuels and retrofit technologies. It was designed as a practical reference to support shipowners and operators in addressing new emission regulations.

In 2023, the second edition introduced a clearer structure by categorizing energy-saving measures into three assessment matrices: operational measures, periodical maintenance, and technical retrofits. It also expanded the range of covered technologies and added content on crew training and the EU Emissions Trading Scheme (EU ETS).

Accompanying these content improvements, the name of the publication was simplified to MCN Guide: Ship Efficiency to better reflect its practical and user-oriented nature. The third edition, released in 2024, further refined the structure and extended the guide to 113 pages. It included revised and new fuel profiles, additional technologies, updated CAPEX estimates and new chapters covering the Fuel EU regulation, ship design changes, carbon dioxide capture and storage (CCS) as well as retrofit benefit tracking. Looking ahead, the 2025 edition is expected to update the content and further broaden the scope.

1.3. Industry Feedback and Survey Results

At the end of 2024 the MCN Ship Efficiency Expert Group conducted a user survey to assess how the "MCN Guide: Ship Efficiency" was perceived by its target audience and where potential improvements could be made. A total of 62 industry professionals participated, representing a range of backgrounds including ship operation, engineering, technology development, and regulatory compliance.

The survey explored how users became aware of the guide, what they found most useful and which areas could be further developed. Most respondents had come across the guide through professional networks, email invitations, industry events, the MCN newsletter and other online social media channels. This outlines the guide's broad dissemination within the maritime sector.



Fig.2: Results, example "New Technologies"

Respondents appreciated the guide's structured format, practical approach and wide coverage of fuels and technologies. Additional questions addressed the usefulness of the technology matrices and fuel comparisons, and gathered feedback on content. Fig.2 shows a sample question of the survey.

Overall, the guide is well received within the industry. About 97% of the survey participants stated they would recommend it to colleagues or business partners. The results of the survey served as a base for a workshop concerning the upcoming 2025 edition and have been taken into account for it.

2. Enablers and Regulatory Aspects of Decarbonisation in Shipping

To achieve lasting improvements in ship efficiency and emissions reduction, multiple supporting elements must align. This chapter outlines the enablers and contextual aspect in the guide that shape the successful adoption of decarbonisation measures.

2.1. Ship Design Evolution – Where it all starts

The guide highlights how ship design has changed over the past decade to improve energy efficiency and support decarbonisation. Core aspects include optimized hull forms, energy-saving appendages, propulsion integration and improved hydrodynamics — driven by regulatory requirements and rising fuel costs. These design improvements are supported by increasingly powerful simulation tools that allow shipbuilders to test efficiency scenarios virtually before construction. While primarily relevant for newbuildings, some elements such as optimized propellers, appendages or improved rudder systems can also be applied to retrofits. Vessel design has a long-lasting impact on performance and emissions, making early-stage decisions critical for future compliance.

2.2. Regulatory Landscape - Evolving Requirements

The regulatory landscape for shipping is developing rapidly with new rules shaping how ships are designed, operated and fuelled. The guide offers a structured overview of major international and European measures, including the IMO's EEDI, EEXI, and CII, as well as the EU Emissions Trading System (EU ETS) and the upcoming FuelEU Maritime regulation. These regulations differ in scope, timing and impact. Some apply at the design and certification stage, others require continuous monitoring or introduce operational cost implications. The guide explains the basic logic and purpose of each regulation and how different technologies impact them.

2.3. Data-Driven Optimization – Measuring and Managing Efficiency

Performance monitoring enables operators to build realistic business cases, detect deviations from expected savings and make data-informed decisions to support long-term decarbonisation goals. In this context accurate performance data is essential. The guide outlines the fundamentals of onboard measurement, highlighting the importance of data quality and regular sensor calibration. Key systems include shaft power meters, fuel flow meters and speed logs, each requiring proper installation and maintenance to ensure reliable results under maritime conditions.

In addition to data collection the guide presents a structured approach to benefit tracking for energysaving devices (ESDs). This includes selecting meaningful performance indicators and comparing preand post-retrofit data, while accounting for variables like biofouling, weather and operational profiles. Particular attention is given to the selection of suitable reference periods to predict the actual effect of a retrofit in an accurate manner.

2.4. Crew Training – Preparing the Human Element

As technologies and fuels evolve, so do the demands placed on crew members. The guide emphasizes that safe and effective use of alternative fuels, new propulsion systems and digital tools, requires updated qualifications and targeted training. Topics such as fuel handling safety, emergency procedures

and sensor operation are increasingly important onboard. The guide also points out that current maritime education programs may not yet fully reflect these requirements. Shipping companies are therefore encouraged to assess training needs in a proactive manner

2.5. Carbon Dioxide Capture and Storage – A Frequently Discussed Alternative

Carbon Dioxide Capture and Storage (CCS) is a topic that resurfaces regularly in discussions on maritime decarbonisation. The 2024 edition of the guide includes a brief overview of the concept, recognizing that while CCS is technically feasible in principle, its application onboard ships remains highly complex. Although no standard systems are commercially available for widespread use, pilot projects and feasibility studies are underway.

The guide outlines key considerations such as space requirements, high energy demand, integration with exhaust systems and the handling of captured CO₂. CCS is included in the document to reflect its ongoing presence in industry discourse and to inform readers of the associated constraints and considerations.

3. Fuels – Options and Considerations for Defossilisation

One of the most visible and impactful levers in maritime decarbonisation is the choice of fuel. The MCN Guide provides an overview of conventional and alternative marine fuels, with particular focus on so-called "future fuels" such as Methanol, Ammonia, and Hydrogen. These are evaluated based on their potential to reduce greenhouse gas emissions, as well as their technical and operational feasibility. The initial idea of reducing CO_2 emissions by switching from heavy fuel oil or marine diesel to Liquefied Natural Gas (LNG) has lost momentum due to stricter emissions targets. Although LNG remains attractive for its lower sulphur and CO₂ output, it no longer meets long-term decarbonisation expectations on its own. The focus has shifted toward full defossilisation, with a growing interest in alternative fuels depending on vessel type, trading profile, and fuel availability. The 2024 edition of the guide expands its fuel section with updated information and includes the following fuels:

- Traditional: HFO, MDO, LNG, LPG, Methanol (from fossil feedstock)
- Alternative/New: Renewable Methanol, Ethanol, Biofuel Oils (FAME, HVO), Ammonia (cooled and pressurized), Hydrogen (liquid LH₂ and gaseous GH₂)

Fuel Type	Origin		Effect on												
		СІІ	EEDVEEXI	FuelEU until 2034	ETS	Availability of Combustion Engines*	Space required/ tanks & machinery & components/Pay- load	Bunker availablity of Fuels	Ships Endurance (range)	Retrofit (from DO)	Bunkering procedure	Storage/ Handling on board	classification rules in power	IMO Goals 2050 0 = neutral	Reputation / Image
HFO	fossile			-		++	+	++	++	n.a.	+	+	++	-	
MDO	fossile			-		++	++	++	++	n.a.	++	++	++		
LNG (content of CH4 varies)	fossile	+	+		+	+		-/0		10 A.	0		++		0
LPG (C3H8 + C4H10)	fossile	-/0	-/0		-/0			0			+	0	++		0
METHANOL fossile	fossile	-	-		-	+	0/+	0/+	0		++	0	+		+
LNG** (pure CH4)	biobased	++	++	+	++	+	-	-/0	-		0	-	++	0	0
LPG** (C3H8 + C4H10)	biobased	++	++	+	++	-		-	-		+	0	++	0	0
METHANOL**	biobased	++	++	+	++	+	0/+	-	0		++	0	+	0	0
ETHANOL**	biobased	++	++	+	++	+	0	-/0	0/+		++	0	+	0	+
Bio Fuel Oil (FAME)**	biobased	++	++	+	++	++	++	-	++	0	++	+	+	0	
HVO Hydrogenated Vegetable Oil** +E-H ₂	biobased	++	++	+	++	+***	++		++	++	++	++	+	0	++
E-Methanol and other PtL-Fuels*	E-fuel	++	++	++	++	+	0/+	-	0		++	0	+	+	0
Ammonia, cooled, from green H2	E-fuel	++	++	++	++	-		-	-		-			++	-
Ammonia, pressurized, from green H2	E-fuel	++	++	++	++	-	-	-	-					++	
Hydrogen, liquid (LH ₂) from electrolysis	E-fuel	++	++	++	++		-						-	++	+
Hydrogen, gaseous (GH ₂) from electrolysis	E-fuel	++	++	++	++		-	-	-	-	-	-	-	++	+

Table I: MCN Guide 2024 Assessment Matrix Marine Fuels

using green/biobased CO:

** All completely biobased and non-fossile hydrogen added fuels "don't emit CO2" according to legislation and therefor have "no" impact on GHG, EED/EEXI and CII *** Engines under development or already in sea trials, releases for HVO and other fuels expected shortly

A structured comparison matrix highlights differences across multiple criteria, including tank-to-wake emissions, relevance for EEDI, EEXI and CII, bunkering logistics, storage and safety issues, onboard handling and engine compatibility. Each fuel is also described in detail across one or two dedicated pages, covering material properties, system requirements and safety aspects. These findings are synthesized in Table I, which presents an overview of the assessment matrix used in the guide.
While no single fuel offers a universal solution, the guide presents all options in a neutral, structured format to support decision-making in a fast-changing environment influenced by both technology development and regulatory pressure such as FuelEU Maritime. A more detailed description of the above points can be found in the MCN 2024 Guide, which contains two pages of explanations for each fuel type in the appendix. These pages include a general description of the fuel, specific physical and chemical characteristics and some action instructions for the crew.

3.1. Side note - On the interpretation of fuel-related emissions

While the guide presents biofuels as one option among several for defossilising ship operations, it is important to note that the classification of such fuels as "CO₂-neutral" needs to be reviewed. From a well-to-wake perspective, production, processing and transport of biogenic fuels can lead to emissions that offset some of their theoretical carbon dioxide neutrality. Their main contribution lies not in reducing atmospheric CO₂, but in avoiding additional fossil-based carbon dioxide release, thus stabilising current levels rather than lowering them. Likewise, even the use of carbon-free fuels such as hydrogen or ammonia does not eliminate all emissions: combustion engines still rely on hydrocarbonbased lubricants, which release additional CO₂ and soot. These aspects illustrate the need for a nuanced interpretation of what terms like "net zero" or "CO₂-neutral" mean in practical shipping contexts.

4. Technology Matrix and One-Pagers

One of the major components of the MCN Guide is a structured overview of technologies that can improve a ship's overall energy efficiency. While design decisions made during the newbuilding phase play a fundamental role in long-term performance, the guide focuses on measures applicable to the existing fleet, particularly retrofits and onboard systems that can be implemented during a vessel's operational life.

Energy losses on ships can arise from various sources: Fouling on the hull or propeller, suboptimal rudder design, parasitic loads in auxiliary systems or inefficient operational routines. To address these issues, the guide compiles a broad range of retrofit and upgrade solutions, including physical modifications, add-on technologies and digital monitoring tools. The technology matrix was split into three distinct categories since the second edition of the guide, which are "Operational Measures", "Periodical Measures" and "Technical Retrofits". An example of an "operational measure" is Hull Performance Monitoring solutions, Fig.3.



Fig.3: Example of changes in hull performance as per ISO 19030-2 on reactively cleaned

While the current version of the matrix does not claim to be exhaustive, it already covers more than 30 technologies and will continue to grow. Table II gives an overview of the technologies now in the guide.



Table II: MCN Guide 2024 - Overview of the included technologies

To support practical decision-making, each technology is assessed using 17 criteria that reflect practical, economic, and technical considerations. These criteria are grouped into three main dimensions:

- <u>Effects on performance and investment</u>, such as energy savings, greenhouse gas reduction potential, and return on investment,
- <u>Application-related factors</u>, including ship type, speed range, sailing area, and operational hours,
- <u>Influence on ship design and operability</u>, covering aspects like required space, handling effort, and integration with existing systems.

The ratings are presented using five-point qualitative scales (e.g. very low to very high), enabling easy visual comparison without requiring detailed vessel-specific input. This approach should support technical managers, shipowners, and decision-makers to identify technologies that may fit their operational profile or investment strategy. While each technology brings its own set of trade-offs, the matrix allows a base understanding of what to expect before initiating deeper technical assessments.

Due to the size and complexity of the full matrix, only a selected outtake is shown in Fig.4 to illustrate the structure and evaluation logic. The complete version is available in the full guide. Apart from the assessment matrix, every technology is also explained in more detail by "one page" descriptions in the appendix of the MCN Guide. This way, it is easier to understand and identify reasonable solutions or combinations of solutions to improve vessel's efficiency.

Technology	Ship type / size	CAPEX			Energy savings			
		New build	Refit	Remark	Propulsion	Aux.	Remark	
Biofilm protection based on Ultrasound Technology	any ship	low	-	depending on ship size and area to be protected; example - shaft propeller: 15-20T€; pod drive: 20T€ per drive; bow thruster: 0- 15 T €; freshwater generator: 10-15 T€	low-medium	very low	biofilm protection on rudder, propp, hull, cooling systems, fresh water systems	
Change from HFO to green Methanol	any ship	high	"high"	depending on conversion concept (approx 4.5 Mio. € for 8-10 MW main engine retrofit incl. fuel supply system & tank coating	+100%	+100%	depending on fuel pricing and CO ₂ tax	
Dynamic Draught and Floating Monitoring	Length > 80m	50 KUSD	50 kUSD	-	none	-	-	
Energy Saving Device: Becker Mewis Duct [®] (MD)	Tankers Bulk Carrier Heavy-Lift MPP	80-300k USD plus Design Package	80-300k USD	depending on aft ship design, propeller diameter, and quantity	high	-	depending on hull design / wakefield	
		<u>.</u>	1					

Fig.4: Snippet of "Assessment Matrix Ship Efficiency"

5. Upcoming MCN 2025 Guide

The next edition of the MCN Guide: Ship Efficiency is scheduled for release in autumn 2025. Building on continuous workgroup sessions the upcoming version will further expand its content while maintaining the structure and practical orientation established in previous editions.

Planned additions to the general section of the guide include an overview of SEEMP-related processes and a section on flexible ship designs such as configurations compatible with multiple fuels or modular, container-based systems. These enhancements, along with practical feedback from ship operators and fleet managers, aim to further align the guide with operational needs and future design considerations.

In the ongoing search for alternatives to oil-based or gas-based marine energy, attention has also turned to nuclear power an energy source that has powered naval vessels for over sixty years. The guide will include a brief overview of the current technological state and considerations related to nuclear propulsion. In addition, the fuel section will be expanded with updated content on biofuels, e-fuels, pyrolysis oil and renewable LNG variants.

On the technology side, the 2025 edition will include new entries such as advanced control systems and updated assessments of existing solutions like waste heat recovery. In addition, the guide may for the first time conceptually address interaction effects between technologies to better reflect the realities of combined retrofit scenarios.

6. Summary, where to get the document and how to contribute

The document is intended to support ship operators, owners, builders, engineers and other maritime professionals in identifying, comparing, and applying technologies and strategies that improve ship efficiency. It also serves as a practical reference to help navigate current and future environmental regulations, particularly those related to IMO and EU decarbonisation targets.

The mission of the Maritime Cluster Northern Germany is to promote, facilitate and consolidate collaboration within the maritime industry. This includes supporting the maritime industry with their efforts in the field of decarbonisation. With this goal in mind, the guide is made freely available to all interested stakeholders. To ensure access to the latest version, the guide is distributed via a simple registration process. Once registered, users receive a download link and will be automatically notified when new editions are published. Registration is available here:



https://www.maritimes-cluster.de/en/topics-and-projects/projects/ship-efficiency-guide/

The guide is revised regularly by the MCN Expert Group Ship Efficiency. Contributions from users, researchers and industry professionals are always welcome—whether in the form of content suggestions, field experience or new ideas for future editions. If you are interested in contributing, please contact Mrs. Jahnke of MCN (ines.jahnke@maritimes-cluster.de).

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User-Centred Design of an LLM-Assisted Fleet Performance Review

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Abstract

This study investigates the integration of Large Language Models (LLMs) into Wärtsilä's Fleet Performance Review (FPR). A proof-of-concept tool was developed to automate structured analysis in the Reporting & Regulatory section. Technical evaluation showed 97.7% alignment with historical reports and uncovered novel, validated insights. A user study with six analysts confirmed improved usability, reduced effort, and enhanced report quality. While challenges remain—such as hallucinations and limited map comprehension—the results demonstrate the potential of LLMs to support, rather than replace, human analysts in maritime reporting workflows.

1. Introduction

The rapid advancements in Artificial Intelligence (AI), particularly in natural language processing, have ushered in a new era of Large Language Models (LLMs). Models such as OpenAI's GPT series, Google's BERT, and Meta's LLaMA have demonstrated remarkable capabilities in processing and generating human-like text, with applications spanning healthcare, finance, and computer science. Among these applications, analytics and reporting stand out as domains where LLMs can significantly enhance efficiency by automating repetitive tasks, generating insights, and improving the quality of reports.

In the maritime industry, data-driven decision-making is critical for optimizing fleet operations, fuel efficiency, and regulatory compliance. Wärtsilä's Fleet Performance Review (FPR) exemplifies this need. The FPR is a recurring process where experts analyse fleet data, tables, charts and maps, to identify trends, setbacks, and areas for improvement in fleet operations, such as fuel usage, route optimization, and data quality. The resulting visual report provides clients with tailored insights to enhance decision-making, but its manual compilation remains time-consuming and resource intensive. LLMs offer a promising solution to this challenge, provided their capabilities align with the specific demands of maritime analytics.

2. Literature Review

A literature review was conducted to assess the state-of-the-art in LLM capabilities for tasks relevant to the FPR, such as chart, map, and table comprehension, as well as insights into the integration of LLMs into data analysis workflows. The findings revealed strong performance in structured tasks like value extraction and basic reasoning, particularly for charts and tables. Techniques such as Chain-of-Thought (CoT) prompting and Retrieval Augmented Generation (RAG) were identified as effective methods to improve accuracy. However, gaps remain in map comprehension, and challenges such as hallucinations, output bias, and context window limitations persist. These insights informed the development of a proof-of-concept (PoC) tool to demonstrate LLM integration into the FPR workflow.

2.1. Chart Comprehension

The literature review revealed that LLMs exhibit strong performance in chart-related tasks, particularly in value extraction and basic reasoning. Models like GPT-4V and specialized frameworks such as OneChart, *Chen et al.* (2024a), achieved high accuracy (93-99%) in reading chart data. Techniques like Chain-of-Thought (CoT) prompting, *Wei et al.* (2022), and programmatic approaches, *Liu and Chu* (2024), improved performance on numerical tasks. However, challenges persist in summarization and open-ended analysis, where accuracy drops due to the subjective nature

of insights, *Hu et al. (2024), Islam et al. (2024)*. Additionally, hallucinations and factual errors remain concerns, particularly when charts lack explicit labels or are low-resolution, Wu et al. (2024).

2.2. Table Comprehension

LLMs demonstrated robust capabilities in table-related tasks, including data retrieval, anomaly detection, and summarization, *Fang et al. (2024), Lu et al. (2024)*. Methods like bracket representation, *Deng et al. (2024)*, and Retrieval Augmented Generation (RAG), *Chen et al. (2024b)*, improved accuracy by simplifying table structures and retrieving relevant rows. GPT-40 outperformed fine-tuned models in question-answering tasks, *Pan et al. (2024)*, but challenges emerged with large tables exceeding context windows, *Guan et al. (2024)*. Hallucinations and bias were noted, emphasizing the need for validation mechanisms.

2.3. Map Comprehension

Research on map comprehension was sparse, with only one study, *Xu and Tao (2024)*, evaluating GPT-4V's ability to interpret geographic data. The model showed promise in extracting textual information and contextual insights from maps but struggled with quantitative analysis and consistency across multiple runs. The lack of standardized benchmarks for maritime-specific maps further limited conclusions, highlighting a critical gap for future research.

2.4. LLMs in Data Analysis Workflows

Studies on LLM integration into data workflows, *Drosos et al. (2024), Guo et al. (2024)*, identified key usability challenges, including output verification difficulties and excessive verbosity in responses. Users preferred embedded AI tools over chat-based interfaces to reduce context-switching, *Weng et al. (2024)*. Structured workflows with predefined tasks, *Inala et al. (2024)*, mitigated prompt engineering demands, while transparency in reasoning steps improved trust. However, concerns about reliability persisted, underscoring the need for hybrid human-AI validation systems.

3. Proof-of-Concept

To assess the feasibility of integrating LLMs into the Fleet Performance Review (FPR), a proof-ofconcept (PoC) tool was developed, focusing on a subsection of the FPR dedicated to auditing the quality of vessel-reported data. This subsection requires the analysis of tables and charts and assessing the quality of the data (e.g. Good or Weak). This section was chosen due to its reliance on structured data and repetitive analytical tasks, making it an ideal candidate for automation. The PoC aimed to demonstrate how LLMs could enhance efficiency by automating insight generation while maintaining alignment with expert workflows. The tool leveraged GPT-40 for its state-of-the-art reasoning capabilities. The role of the tool is to generate a report based on provided fleet data. The report then assists experts in their FPR analysis.

3.1. PoC Design

The design of the PoC was heavily informed by a contextual inquiry conducted with FPR experts. A contextual inquiry entails shadowing experts as they complete the FPR and asking questions to clarify steps and thought processes when necessary. The contextual inquiry revealed key pain points in the workflow. Experts spent significant time manually drafting reports, cross-referencing data, and resolving inconsistencies in subjective interpretations. These observations underscored the need for an LLM tool that could automate repetitive writing tasks, standardize decision-making, and reduce cognitive load.

Insights from the literature review directly shaped the PoC's architecture and functionality. To mitigate hallucinations and improve accuracy, the tool adopted preprocessing techniques such as table

simplification, *Deng et al.* (2024). Chain-of-Thought (CoT) prompting, *Wei et al.* (2022), was employed to enhance logical reasoning, while modular agents were used to decompose complex tasks. The review also cautioned against open-ended interfaces, leading to a structured workflow where the LLM addressed predefined tasks rather than free-form prompts. Insights from the literature review highlighted that users of LLM systems feel overburdened by constantly switching between the system containing the data and the application that interacts with the AI, underscoring the need for integrating the LLM tool into the system that contains the data.

3.2. Technical Framework

The Proof of Concept (PoC) leverages GPT-40 for its strong performance in structured data tasks, making it an ideal choice for rapid prototyping without high resource demands. Designed to assist analysts in the Reporting & Regulatory section of the FPR, the PoC receives data from FOS, preprocesses it, analyzes it using GPT-40 with Chain-of-Thought prompting, and generates a support document. Its layered framework ensures scalability and integration potential, effectively demonstrating how LLMs can be embedded into the FPR workflow.



The PoC's framework, Fig.1, consists of four layers:

1. <u>Data Layer</u>: Manually extracted data (tables and charts) from Wärtsilä's Fleet Optimisation Solution Platform.

- 2. <u>Preprocessing Layer</u>: Simplified tables into bracket representations, and aggregated error types to reduce noise.
- 3. <u>Analytics Layer</u>: Three GPT-40 agents specialized in error analysis, table discrepancy detection, and fuel consumption pattern identification, each using CoT and 8–12 manually selected examples for in-context learning That contain all predefined insights the agents look for.
- 4. <u>Report Layer</u>: Compiled JSON outputs into standardized plaintext reports, including reporting quality status verdicts standard in FPR reports with justifications for traceability.

4. Evaluation

The technical evaluation of the PoC tool involved a comparative analysis between AI-generated reports and historical FPR reports. Historical FPR datasets were recreated using FOS data from the time periods between the last meetings of each FPR. For example, to recreate the dataset for FPR #5, the data from the period between the last meeting of FPR #4 and FPR #5 was used. The GPT-40 model was tasked with generating reports from this data, with default API parameters, but the temperature was set to 0.1 to ensure focused outputs, and the max_tokens parameter was adjusted to 800 for sufficient detail.

AI-generated reports were manually compared to the original FPR reports, assessing quality status verdicts, alignment, novelty, and error rates. Each insight from the AI reports was verified for accuracy and categorized as matching (both reports included the same insight), new (predefined insights not mentioned in the original FPR), or erroneous (hallucinations or missed insights). Special cases involving significant post-FPR data corrections by clients were flagged and analysed separately to account for discrepancies. Insights were also categorized by type, differentiating between those likely identified by the FPR analyst and those excluded from the report for significance reasons.

4.1. Technical Evaluation Results

The technical evaluation was conducted using 37 historical FPR reports. Of these, seven cases involved significant post-FPR data corrections. To maintain consistency and fairness in the evaluation, six of these were retained after excluding the altered insights, while one was removed entirely due to extensive changes. This resulted in a final dataset of 36 report pairs, which were used to compare AI-generated and human-written reports in terms of insight alignment, novelty, and quality verdicts, Fig.2.



Each bar represents one FPR-AI pair of reports

4.1.1. Alignment

The AI tool exhibited strong alignment with human analysts, successfully identifying 84 out of 86 insights documented in the original FPRs—corresponding to a 97.7% recall rate. Insights were considered matching when the AI flagged the same underlying discrepancies as the human report, even if phrased differently. In 50% of the evaluated cases (18 out of 36), the AI-generated reports contained insight sets that were entirely identical to those in the corresponding FPRs. It's important to note that the absence of findings in a particular subsection was not counted as an insight. The two missed insights are addressed separately in the Error Analysis section.

4.1.2. Novelty & Error Analysis

Beyond alignment, the AI tool surfaced 30 novel insights that were not included in the original FPR reports. These were primarily found in the Reporting & Compliance sections and were all manually validated as accurate. A novel insight was defined as one that had previously appeared in at least one FPR historically but was absent in the particular report being evaluated. To assess their relevance, a senior analyst with over five years of FPR experience reviewed each case. While some of these insights may have been identified during the original FPR but excluded for being low in significance, others may reflect discrepancies introduced after the FPR analysis. One notable outlier included an AI-identified case of vessel movement with zero reported engine power—an issue that was both undocumented and beyond the AI's predefined scope, demonstrating the model's capacity for unexpected yet valid discovery.

Two types of errors were identified in the AI-generated reports: hallucinated insights (false positives) and missed insights (false negatives). In total, five hallucinated and two missed insights were recorded. The missed insights involved large data gaps the AI failed to detect. Hallucinations included one false identification of a data gap and four fabricated fuel consumption trends likely caused by misinterpreting visual patterns in the data. Despite these issues, the overall error rate remained low and well-defined.

4.1.3. Quality status verdict comparison

Quality status ratings—classified as "Weak," "Decent," "Good," or "Very Good"—were compared between AI-generated and historical FPR reports. While these verdicts in FPRs are based on the analyst's subjective judgment, typically reflecting the number and severity of detected issues, the AI applied a more systematic approach. The results are shown in Fig 3.



Fig 3. Comparison of Quality Status verdicts between AI generated reports and historical FPR reports

Out of 36 report pairs, 19 showed identical verdicts, while 17 diverged, 14 of which reflected a stricter AI assessment. Verdict shifts were quantified numerically: for example, an AI rating of "Weak" vs. an FPR rating of "Good" resulted in a -2 shift. Positive values indicated more lenient AI judgments.

These discrepancies were mainly driven by the AI identifying novel issues, lacking access to post-FPR data corrections, and being influenced by hallucinated or missed insights. Additionally, historical inconsistencies in how verdicts were assigned contributed to differences. For example, fuel consumption issues heavily influenced the AI verdict but were sometimes excluded by analysts or placed in other sections. Human judgment, influenced by varying experience and interpretation, can yield different conclusions even when reviewing the same dataset, adding another layer of variability to the comparison.

4.2. User study

To evaluate the AI-assisted reporting tool's effectiveness in the FPR workflow, a within-subjects user study was conducted to maximize data depth while controlling for individual differences. The study combined task comparisons, interviews, and questionnaires to assess the tool's impact on effort, productivity, report quality, and user acceptance. This mixed-methods approach provided a well-rounded view of the tool's practical value and limitations.

Six FPR-experienced data analysts (3 female, 3 male) participated in the study, representing the entire available qualified population. One was a junior analyst (<2 years of experience), while the remaining five were senior analysts (>5 years). Each participant completed a mock Reporting & Compliance analysis on two anonymized real-world vessel datasets, assigned to ensure no prior familiarity.

The study followed a two-stage design: first, participants performed a baseline analysis using conventional FPR methods; in the second stage, they repeated the task with access to pre-generated AI reports in text format. This within-subjects setup enabled comparison between traditional and AI-assisted workflows, highlighting productivity gains and the discovery of novel insights. Although reusing datasets introduced a learning effect, this was intentional to better isolate the AI tool's added value.

To simulate integration into the FOS interface, AI reports were presented as if accessed via a button. Participants could view up to ten pre-generated reports to assess variation and were encouraged to think aloud during the task. Afterward, semi-structured interviews and a 5-point Likert scale questionnaire were used to capture perceptions of usability, workflow impact, and report quality. Each session lasted around one hour.

All six participants successfully completed the user study, with both qualitative feedback and questionnaire responses, Fig.4, indicating strong potential for the AI tool to enhance FPR workflows. Despite the tool not being integrated into FOS, participants found the text-based interface easy to use—three "Agreed" and three "Strongly Agreed" on its usability. While some experienced minor logistical challenges and a tendency to reduce manual verification of AI-suggested insights, others reported increased attentiveness due to the AI highlighting unexpected discrepancies. Overall, participants found the tool intuitive and easy to navigate, even within the simulated PoC setup.

Perceptions of the tool's impact were consistently positive across effort, productivity, and report quality. Most participants reported reduced cognitive and manual effort, with comments noting improved focus and decreased mental fatigue. Productivity was also rated highly, with users citing time saved through AI summaries and quicker cross-referencing. Regarding report quality, all participants revised their reports after using the tool, and most felt these revisions improved clarity and depth. The AI's natural language descriptions were especially appreciated, with several participants stating the final outputs were more comprehensive and professionally phrased.



5. Discussion

The PoC demonstrates strong potential for integrating LLMs into the FPR workflow, with both technical and user evaluations highlighting its value in enhancing analytical rigor, reducing cognitive effort, and improving reporting efficiency. Participants praised the tool's ability to automate repetitive tasks in the Reporting & Regulatory section, freeing time for higher-value analysis. User feedback was overwhelmingly positive, with all participants supporting future adoption. While the tool achieved 97.7% alignment with human insights, certain errors—particularly missed and hallucinated data gaps and trends—indicate areas for improvement. These could be addressed through programmatic validation for rule-based checks and embedding visual data in reports to reduce reliance on AI interpretation alone.

However, limitations remain. Some participants showed signs of over-trust, occasionally accepting AI-generated insights without sufficient verification, highlighting the need for training and validation protocols. Despite promising results, full automation of FPRs faces critical challenges, including the need for domain-specific judgment, potential consequences of low error tolerance, and the human analyst's role in strategic synthesis. Still, the PoC's modular architecture offers opportunities for extending LLM integration to other sections of the FPR, where trend detection and validation methods may be adapted. Yet, tasks involving complex visual or contextual interpretation will continue to require human oversight.

The PoC focused narrowly on structured data tasks—specifically table and chart analysis within the Reporting & Regulatory section—where LLMs currently perform best. While this allowed for focused evaluation, it excluded key FPR components like map-based routing and domain-specific visualizations, limiting generalizability. The user study, though promising, was constrained by a small sample size and simulated conditions, raising questions about real-world applicability under pressure. Additionally, the technical evaluation relied on historical reports as ground truth, despite the PoC surfacing valid insights previously missed by analysts. Future work should expand coverage, use larger samples, and establish objective benchmarks for evaluating AI-generated FPR content.

6. Conclusion

This study demonstrated the potential of LLMs to enhance the FPR process through structured task decomposition, user-centred design, and targeted integration into high-value analytical tasks. While

results showed strong alignment, improved productivity, and the discovery of overlooked insights, limitations in map comprehension, hallucination risks, and overreliance underscore the need for further refinement. Future development should focus on expanding task coverage, strengthening validation, and embedding ethical governance into deployment strategies. With continued iteration and real-world testing, LLMs can serve as powerful enablers of digital transformation in maritime analytics.

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Hybrid and Fully Electric Ferries for Green Public Transport

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Abstract

The public transport sector, speaking of passenger ferries, combines some unique conditions which lower the barriers for the decarbonization of the used vessels. Still there are remaining challenges to overcome. The tasks for a successful project grow and they are not only waterborne. Multidisciplinary teams are needed for the development of the vessels and their infrastructure. New business segments for main contractors are in development and a key for a successful project.

1. Introduction

The advantage for the design of ferries with respect to decarbonization is the well-defined schedules and routes the vessel operates on. In addition, the environment, including the berth, is known. The developments of new technologies offer much more design options than combustion engines alone. This means that also the choice and dimensioning of the energy storages and power generation needs to be and thanks to the known schedules, routes and environment can be chosen carefully. This can be done with the help of software like HYDE (ISM GmbH) and other objective measures.

While in former times the design of the power generation was usually based on the maximum scenario, the design of ferries today includes the trade-off between a design for the maximum load and an optimized design with respect to multiple environmental and economic objectives. To simplify the decision-making process on which fuel or power generating technology to use, we have developed a filtering system, which will be presented in the following chapters exemplified by two vessels designed by Schiffstechnik Buchloh.

One of those ships is the ferry type 2030 of the fleet HADAG in Hamburg, Fig.1. It is part of the public transport vessels in the port of Hamburg. There will be three ferries of this kind for different routes. Each vessel is 33.4 m in length and 8 m in breadth and provides space for 250 passengers and several bicycles. The propulsion system consists of two Voith-Schneider-Propellers and two bow thrusters, which makes the berthing easier. The vessel contains approximately 600 kWh of battery capacity and a genset of 440 kW.



Fig.1: Ferry type 2030 of the fleet HADAG

The second vessel is the EPAX city ferry operating between two sides of the river Weser in Germany, Fig.2. Like the HADAG type 2030 it transports pedestrians and cyclists. The ship can carry approximately 60 passengers and is driven fully electric with a battery capacity of 800 kWh. It measures 24.8 m in length and 5.2 m in breadth. To make use of the space on the rooftop, the ship is equipped with solar modules and two rails for charging via a pantograph.



Fig.2: Bicycle ferry EPAX city

2. Filtering system

The broad variety of fuels and power generating technologies increases opportunities and complexity of the design process of ships. To be able to handle this complexity, objective systems like filters need to be applied to find the best feasible solution. In addition, the filtering system can reduce the time of the design process because the right technology will be chosen right away. A possible objective system could be the filter explained below.

At the beginning of the filtering process the most important fuels and power generating systems need to be determined. The most relevant fuels and energy storage systems are:

- Hydrogen
- Ammonia
- Methanol
- Diesel
- Batteries

In addition, two or more of these can be combined in a hybrid system.

The first step of the filtering process is the operational filtering. This filter takes into consideration the operating site and the itinerary of the vessel. Aspects that need to be considered in this step are:

- Availability of bunkering and or charging infrastructure
- Availability of the specific fuel
- Berthing time
- Variance of load (with respect to hydrogen and fuel cells)

In the second step we study the technical feasibility, which includes:

- Available space
- Draft, trim and heeling
- Safety regulations

Finally, the business model is considered and takes the following aspects into account:

- Investment cost (CapEx)
- Operational cost (OpEx)
- Financial risk
- Availability of fuels in the future

In the following chapters the impact of these filters regarding the different fuels and components is discussed.

3. Technical Components

3.1. Power generators

The two main power generating systems in the maritime industry are combustion engines and fuel cells. For the bicycle ferry EPAX city the constant change between cruise and berthing ruled out the choice of a PEM fuel cell, because an operation below 50 % of the nominal power usually reduces the life span of the fuel cell. The passenger ferry in Hamburg was considered suitable for a PEM fuel cell in the future.

- **Hydrogen** Regarding the passenger vessel HADAG type 2030, the design included space for the installation of so called "Tanktainers ", which are designed for carrying liquid hydrogen. Apart from the availability of hydrogen, the second level of the filter plays an important role, since the required space for hydrogen is quite large. This is due to the low volumetric energy density and the required space for storing hydrogen. Furthermore, the technology today is still quite expensive. It might play an important role in the future though and pioneering in this technology might give operators a head start. Moreover, funding programs by governments might lower the investment costs for the operator.
- **Ammonia** Even if there would have been a possible supply of ammonia, it would have been filtered out for both ferries in the second filter, because of the strict safety regulations and the required distances of a blow-off mast for the highly toxic ammonia. Also, the required space for all technical parts including the preparation of the ammonia would exceed the available space on board the ships. The criterion of the available space is especially critical for these ferries because of the size of these vessels. For bigger ships ammonia might be a feasible choice though.
- **Methanol** When it comes to methanol, the aspect of the available spaces is a major factor as well, because the tank needs to be surrounded by a second barrier. In some cases, the use of methanol is still limited by the power range of today's methanol motors. Some ferries have a very low power demand and methanol motors of such low power were not yet well and widely developed at the time of the design phase. On both ferries the use of methanol was filtered out for future operation, because of the direct CO2-emissions.
- **Diesel** On the strive for the decarbonization of the ship industry, a hybrid system consisting of batteries and diesel engines might be a good compromise. In combination with a DC-Link system the diesel generator can be replaced by a different technology in the future. This might be necessary if CO2-emission certificates become more expensive in the future. For the ferry

type 2030 this strategy was chosen, while making sure that the installation of a fuel cell and hydrogen tanks is possible later on.

3.2. Batteries

Ferries usually are very well suited for the use of batteries, since the batteries can be charged frequently. Unlike cargo ships that sail long distances and change position every day, ferries operate in a fixed location. Hence, the installation of a charging infrastructure makes sense and can be used at least once a day if not even several times per day. In contrast to the bunkering process that requires a person to surveil it, the automatic charging of the vessel can be conducted unattended.

Normally batteries pass the first stage of the filtering process because a simple charging infrastructure can be installed with little effort. A short birthing time might be a criterion to rule out a fully electric ferry though. If charging the vessel is not possible due to a short berthing time, the battery capacity needs to be higher, which could result in a bigger battery system that might be too heavy for the safe operation of the ship. This is because batteries have a lower energy density than diesel. Also, the available space (step 2 of the filter) or the cost for a high battery capacity (step 3 of the filter) might lead to the decision for a hybrid system.

Other aspects regarding batteries include the cell chemistry of the battery. NMC batteries might be considered inadequate considering geopolitical events and situations but are better suited for high numbers of charge and discharge in a small bandwidth of the SoC. LFP batteries are considered safer, because of a higher ignition temperature and lower probability of a thermal runaway. Furthermore, penetration tests show that LFP batteries are usually more stable in terms of a thermal runaway than NMC batteries when it comes to mechanical impacts.

The high costs for batteries make it necessary to set up a detailed load profile to keep investment costs low, while making sure that the battery capacity is sufficient for the operation of the ferry. Also, longer distances to a shipyard need to be considered in this process. This load profile needs to be discussed with the battery manufacturer to assess the life span of the battery, which depends on a lot of other factors as well, like temperatures, c-rates, charging cycles etc.

Further considerations involve the interfacing technologies, like the system integration and the charging infrastructure.

3.3. Charging infrastructure and environment

A vital system for fully electric and hybrid ferries is the charging infrastructure. It might in fact decide whether the ferry will be fully electric or hybrid. In the project of the EPAX city ferry the pantograph would make it possible to charge the ferry automatically at every berth on one side of the operational site and with enough charging time, Fig.3.



Fig.3: SoC during the operational day of the EPAX city ferry

Without the automated charging, the crew of the ferry would have to plug in the charging cable 37 times a day. This could have lowered the acceptance of the new ferry and the battery-operated vessel drastically. Another advantage of the pantograph is that the connection for charging is achieved within

10 s, while the crew would probably take more time in average to plug in the charging cable. This would probably lead to less energy transmission overall during the day and thus require higher amounts of battery capacity. Furthermore, a comparison of the costs of the charging technology with similar costs for an additional battery pack, justifies the investment. The prize of the charging system is approx. 130.000 €. This would be 310 kWh (gross) of battery capacity. For a high life span of the battery, it should be kept in a range of 50 % to 90 % approximately. Hence, the net capacity would be 130 kWh. This would spare 5 times of charging, leaving the crew to plug in the charging cable 32 times a day, which might still have a severe impact on the acceptance of the battery-operated vessel.

Regarding the charging technology and the design of it, the environment and the berthing site plays an important role. The pantograph at the operational site of the EPAX ship could be kept quite simple because of the installation of a floating dock. With a ramp the pantograph would have to move with the water level, which involves much more technical effort and much more costs for the charging infrastructure. With the technology of the pantograph the possibility of heeling due to wavey water or bypassing vessels also needs to be considered as charging is not possible at certain angles of heeling.

The topic of charging involves the consideration of the different stops and whether multiple charging stations would make sense. This is a mayor difference between the vessels. While the HADAG type 2030 ferry operates at multiple stops, the EPAX city ferry on the Weser only operates between two stops, Fig.4, which makes it possible to charge the vessel on one side after every round trip. The typical route for the ferry type 2030 connects the stops Landungsbrücken, Altona, Dockland, Neumühlen, Bubendey-Ufer and Finkenwerder, Fig.5.



Fig. 4: Route of the EPAX City ferry



Fig. 5: Typical route for the HADAG ferry type 2030

A frequent charging for the ferry would require several charging stations resulting in higher investment costs. Fig.6 shows a possible scenario for the SoC and the use of the genset during a normal day of the type 2030 ferry.



Fig. 6: SoC during the operational day of the HADAG TYP 2030 ferry

Without the genset the SoC would fall below 20 % of charge which would reduce the life span of the battery drastically if operated like this daily. Moreover, several stops are at floating docks that are also used by other vessels, which might make the charging more difficult. Another challenge is the scenario that the ferry might be used on a different route, which would require charging infrastructure at all 16 stops of the HADAG ferries.

3.4. Energy transmission

Another central part of the electrified ship is the grid. Typically, there are the two choices of a DC grid or an AC grid. The DC gird compared to an AC grid is more complex and more costly. However, it has a lot of advantages over the AC grid, which is the high efficiency and the simplicity to change the power source, for example to change a diesel generator set for a fuel cell in the future, which was the plan for the HADAG 2030 ferry.

4. Conclusion

The discussed variety of technologies and fuels, and the considerations that go along with it show that the energy systems of todays and tomorrows designs open up more opportunities but also become much more complex. This makes the use of filter systems, like the ones explained in this paper more important. Furthermore, it is necessary to stay informed about new technologies and developments on the market. The big variety of technologies makes it impossible for ship owners to make a well-informed decision on their own. This is why the work of engineering offices and the use of software solutions like the program HYDE (ISM GmbH) is of increasing importance for the maritime industry.

Biocides in Antifouling Coatings – Do We Still Need Them?

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Abstract

Biocides are biologically active substances that control the growth of unwanted organisms. For centuries, active substances have been added to hull coatings for marine vessels to protect against fouling organisms. In this paper, we will explore which substances are being used today and why they are being used. The regulatory landscape will be described, and we will touch upon some likely scenarios for the future. Copper is a crucial ingredient in the majority of antifouling coatings and is expected to continue to play a key role in sustainable fouling protection.

1. Introduction

Fouling of ship hulls has been a challenge for mankind ever since ships became too large to lift out of water when not in use. As Fig.1 illustrates, the cleaning and maintenance of a ship in the 19th century was labour intensive and must have been a very costly and time-consuming operation.



Fig.1: HMS Formidable careened (turned on its side for maintenance) in Malta, 1843

The first successful antifouling material to receive general recognition was copper sheathing, *Laidlaw* (1952). The use of copper as an antifoulant was suggested as early as 1625, when a patent was granted for a composition that very probably contained some form of copper. However, it was not until the experiment on H.M.S. Alarm in 1758 that the antifouling qualities of copper were recognized. The report stated three conclusions: that copper provided protection against worms, that it did not injure the planking, and that it did not foul. By 1779, the use of copper became general throughout the British Navy.



Fig.2: Antifouling paint from 1930 containing "2.7% arsenic oxide" in addition to copper and a copy from an ASTM standard of 1928 stating that antifouling paints should contain mercuric oxide

The introduction of iron hulls invalidated the use of copper sheathing because of the corrosive action of copper on iron. From that time on, the number of paints and compositions suggested increased rapidly. By 1865, more than 300 patents for antifouling compositions had been issued in England alone. The principle was "slightly soluble coatings of poisonous materials". All the worst toxins available were used in combination with copper, but primarily lead, arsenic and mercury, Fig.2.

Even though the paints contained extremely toxic chemicals they failed after only a few months as it was difficult to control the dissolution rate of the biocides. The delivery system was improved during the 20th century, and by 1970, the best performing products could provide 18 months protection.

In the 1970s TBT-based paints revolutionized the marine industry by increasing the drydocking interval to 36 months. Later, this was extended to 60 months, primarily due to improved delivery systems. The co-biocide to copper oxide, tributyl tin (TBT), was considered safer than the toxic heavy metals, as it degraded in seawater. However, at a later stage it was discovered that this degradation was far too slow, and the biocide was banned by IMO in 2003.

The third-generation antifouling paints replaced the TBT products around 2000 and these remain in use today. These paints typically comprise copper oxide with co-biocides that have been shown to degrade quickly. These products are often called Self-Polishing Copolymer (SPC) antifouling coatings. Copper-free products are also available. Fouling Release Coatings (FRC) have been available since the 1990s. These use a combination of low surface energy and the release of silicone oils to make it difficult for fouling organisms to attach firmly. The FRC technology works primarily towards animal fouling organisms, hence an algaecide is often added to take care of the plant based organisms.

2. Which biocides are used?

Copper oxide is by far the most commonly used antifouling biocide. It's a broad spectrum biocide, meaning that it has an effect towards most of the 4000-5000 species, both hard and soft fouling organisms, that may settle on the hull. Hard fouling is understood as the shell forming organisms, like barnacles, mussels, oysters and tubeworms. These will need to be removed from the surface by mechanical scraping in the dry dock. Soft fouling is understood as plants (algae), soft animals (tunicates, soft corals etc) and slime (microorganisms forming a biofilm on the surface). These may be removed by high-pressure fresh-water cleaning in the dry dock.

Some algae are quite tolerant towards copper, hence co-biocides are often used in combination with copper. The key algaecides on the market today are copper pyrithione, Zineb and DCOIT. Zinc pyrithione is still being used to some extent.

There are two alternatives to copper oxide, ie. biocides that are effective towards hard fouling organisms, tralopyril and medetomidine. Both are far more potent than copper, hence the volume consumption is lower.

2.1. Copper oxide (Cu₂O)

Copper oxide is used in >90% of all coatings applied for fouling protection of ships and the level in the paint is typically 20-50 w%.

Copper is a naturally occurring substance and is also a micronutrient. It is essential for life and necessary for all living cells. However, at elevated concentrations, the copper ions (Cu^{2+}) are toxic, *ECHA* (2016).

The average copper content in the earth's crust is 55 ppm, *HELCOM (2024)*. The average natural background level of copper is 1 ppb in seawater and 33 ppm in sediments. Erosion of the earth's crust is the main source of copper input to the sea. For example, the riverine input to the Baltic Sea

accounts for 90.7%, the share of atmospheric deposition is 7.8% and releases from direct point sources accounts for 1.5%.

Copper toxicity to aquatic organisms depends on its bioavailability. Water will penetrate the outer surface of an antifouling paint and the copper oxide (Cu₂O) will dissolve and leave the surface as Cu2+ ions. When the ship is laying idle, the concentration of Cu^{2+} in the boundary layer will reach toxic levels, hence it will kill organisms that try to settle on the surface. Cu²⁺ ions are labile and become complexed to organic and inorganic matter in waters and sediments. This affects copper speciation, bioavailability and toxicity. Eventually, the main part of the copper released to the sea is expected to end up the sediments, typically as copper sulphide (CuS), which is insoluble and not bioavailable, Rader et al. (2019).

2.2. Tralopyril (Econea®)

Tralopyril was the first alternative to copper with an effect towards hard fouling organisms. It was launched around 2008. Tralopyril is a halogenated pyrrole, Fig.3, and it is related to the insecticide Chlorfenapyr. Due to reactions with copper oxide, it is primarily used in copper-free products. It requires a co-biocide, typically zinc pyrithione, to give full protection. Tralopyril is 10 times more potent than copper, hence the use level is 3-6 w% in paints. It is off-white in colour which enables light and bright coloured antifoulings that are colour stable. Tralopyril breaks down quickly in seawater by hydrolysis. The half-life was measured to 16 h at 9°C.



Fig.3: Tralopyril

2.3. Medetomidine (Selektope®)

Antifouling paints with medetomidine were launched around 2014. Medetomidine, Fig.4, works selectively towards barnacles and tubeworms. It may be used in copper-free paints, together with cobiocides, but are primarily used in combination with copper oxide as a barnacle fighter. It does not kill the fouling organisms, but induces a physiological response. This results in increased motility of the larva, the settlement stages of barnacles and tubeworms, leading to an anti-settling effect. This effect is reversible. It is extremely potent and the use level is around 0.1 w% and it degrades in seawater. Medetomidine is used in the veterinary medicine as a sedative for dogs and cats.



Fig.4: Medetomidine

2.4. Zinc and Copper pyrithione (CleanBio®, Omadine®, Pyrion®)

The pyrithiones, Fig.5, are primarily used against soft fouling. Both were launched during the 1990s, but currently, copper pyrithione is dominating in volumes, primarily due to the reaction between zinc pyrithione and copper oxide. The typical use level of copper pyrithione as co-biocide to copper oxide is 1-4 w%. When used in biocidal FRC, the concentration is higher, typically 7-9 w%. Both pyrithiones degrade quickly in seawater, primarily via photolysis. Zinc pyrithione was used for many years in anti-dandruff shampoos, but this use has recently declined due to question marks regarding human health.



Fig.5: Pyrithiones

2.5. DCOIT (Sea-Nine®)

Di chloro octyl iso thiazolinone (DCOIT), Fig.6, has a high acute activity towards soft fouling organisms. It was introduced early 1990s to replace TBT. DCOIT works well with copper oxide and is typically used at 2-4 w% level in antifouling paints. It also works well in combination with other biocides, in copper-free products. DCOIT acts as a plasticizer in the coating and can be released rather fast from the surface. It breaks down rapidly in seawater and sediment, primarily via biodegradation. DCOIT is used as a fungicide in house paints; related compounds are used as in-can preservatives in make-up.



Fig.6: DCOIT

2.6. Zineb (Zineb Nautec[®], Perozin Marine[®])

Zinc ethylenebis dithiocarbamate (Zineb) has high activity towards soft fouling organisms. It works well in combination with copper oxide. It has a slow release from the coatings and degrades quickly in seawater. Zineb has been used in plant protection as a fungicide since the 1960s, e.g. when cultivating potatoes.



2.7. Other biocides

The above-mentioned biocides are being used globally. In addition, there are some biocides being used on a smaller scale and in local antifouling coatings only. However, the list is getting shorter every year due to lack of supporting documentation and suppliers. Fig.8 lists antifouling biocides registered in Australia, Brazil, Japan, Malta, UK and USA with the number of formulations and frequency of occurrence (%) in the dataset, *Paz-Villarraga et al.* (2022).



Fig.8: Antifouling biocides registered in Australia, Brazil, Japan, Malta, UK and USA

2.8. Biocide combinations

Copper oxide is the only biocide being used alone in SPC, as it has a broad spectrum of activity. In FRC, copper pyrithione is often used as the sole biocide, as this technology requires an algaecide only. However, most products on the market have a combination of two or more biocides, especially for the shipping market where long-term protection is required.

Fig.9 gives combinations of biocides identified in antifouling coatings registered in Australia, Brazil, Japan, Malta, UK and USA. The scales represent the number of times each biocide has appeared in combination with other biocide(s) and the width of the connections is proportional to the number of paints that have these biocides in their composition, *Paz-Villarraga et al.* (2022).



Fig.9: Combinations of biocides identified in antifouling coatings registered in Australia, Brazil, Japan, Malta, UK and USA

3. Why do we use biocides?

Since 90% of goods traded world-wide are carried over sea, both our planet and the people living on it have a lot to gain from effective control of soft and hard fouling on vessels carrying these products. Preventing such organisms from clinging to the hull of a ship results in lower fuel consumption and helps to safeguard biodiversity.

Marine organisms that cling to a ship cause more friction with water, which can increase fuel consumption and related greenhouse gas emissions by up to 40%. Antifouling coatings significantly increase the fuel efficiency of commercial and naval fleets worldwide. For every kg of copper released to sea, the antifouling is saving the atmosphere four tons of CO_2 (a conservative estimate for a typical merchant vessel), Fig.10.



Fig.10: Emissions of copper to the sea vs. CO_2 emissions for a typical container ship at cruising speed. The ship burns 130 t fuel per day and the underwater hull is protected with an antifouling coating that has a release rate of 20 µg Cu per cm² per day.

Fouling growth on ship hulls usually translates to higher fuel consumption. When a vessel moves through water, it needs to overcome resistance from the water, *Schultz (2007)*. The two dominant resistance parts are wave resistance and frictional resistance, Fig.11.

Resistance type	Influenced By	Examples
Wave making resistance	• Hull design	 Shape of bulbous bow Vessel breadth Trim Other factors affecting design
Frictional resistance	 Area below water Surface condition of hull 	 Amount of underwater area affected during movement in water. (e.g. Tanker vs Container vessel Extent of fouling Roughness of hull Speed of vessel

Fig.11: Resistance from the water on the vessel

Surface roughness plays a key role in determining the boundary layer characteristics and therefore frictional resistance. An increase in the roughness results in a more turbulent flow and in an increased loss of energy from the vessel to the water in the boundary layer.

Hydrodynamic efficiency changes can be expressed in terms of speed loss or speed deviation. Measuring the speed loss over time in a standardized way is the core of the ISO 19030 standard which aims at "Measurement of Changes in Hull and Propeller Performance", *ISO (2016)*.

Fouled ships may carry invasive species between regions. In fact, fouling on the underwater hull is considered to be a vector of equal importance as the ballast tanks. These organisms can be a threat to ecosystems worldwide. 60% of the species that are threatened by extinction are endangered due to the spread of non-indigenous species, *Tedeschi et al. (2024)*. An effective antifouling paint helps to prevent this translocation and to safeguard biodiversity.

4. How to compare biocides?

How should we (fairly) compare biocides?

• By weight?

Biocides are hazardous chemicals and as such the level in antifouling coatings should be minimized. However, a product with 5 w% of biocide A is not necessarily better for the environment than a product with 50 w% of biocide B. We have to evaluate the biocides more closely, and just comparing by weight is not reasonable.

• By toxicity?

A natural starting point for an antifouling biocide is to look at the human toxicity for people handling the paint, and the ecotoxicity for the organisms living in seawater and sediments. In the above example, the biocide A is 100 times more toxic to humans and aquatic organisms than biocide B. Even though the level in the paint is 1/10 only, the toxicity is higher. Which is 'the best'? The ecotox data for single species is used to determine the predicted no-effect concentration (PNEC). This is the concentration of a chemical which marks the limit at which below no adverse effects of exposure in an ecosystem are measured. PNEC values are intended to be conservative and predict the concentration at which a chemical will likely have no toxic effect. Comparing the toxicity data of different biocides is a pure hazard assessment. For the exposure assessment in marine environments there is a need for reliable chemical fate models. Such models must handle the complex transport and exchange processes in coastal environments.

• By risk?

MAMPEC is a marine antifoulant model to predict environmental concentrations, *Van Hattum et al.* (2005). It was developed to predict environmental concentrations (PECs) for the exposure assessment of antifoulants in harbours, rivers, estuaries and open water. MAMPEC is an integrated 2D hydrodynamical and chemical fate model. The exposure assessment model is recognized and used by regulatory authorities and applicants in EU, USA and other OECD countries for antifouling biocides. The model is being developed and maintained by Deltares and the Institute for Environmental Studies with continuing support of the European Paintmakers Association (CEPE). It has the following features:

- Estimation of hydrodynamical exchange in six generalised 'typical' environments (open sea, shipping lane, estuary, commercial harbor, yachting marina, open harbour)
- Compound properties/processes included in model: Kow, Kd, Koc, H, volatilization, speciation, hydrolysis, photolysis, biodegradation. Chemical fate approach in line with EU-TGD
- Emission estimation based on leaching rates, ship hull underwater surface areas, shipping intensities, residence times
- Environmental/hydrodynamical parameters: currents, tides, salinity, density differences, DOC, POC, Chlorophyll, pH, T, SPM, sedimentation, latitude, port dimensions, submerged dams

- Default settings for generic environments, emission scenarios, and compounds
- Inclusion of standard EU (PT-21) and OECD emission scenarios for service-life and non-service life emissions
- Model allows easy comparison of PECs of different compounds
- Multiple run option allowing to run multiple scenario combinations and to facilitate sensitivity analysis
- Analysis of main compound fluxes and significance and contribution of different chemical fate processes

By using this model, we can predict the environmental concentration (PEC) for a certain biocide in a certain environment. As the PNEC is already established, we can calculate the PEC/PNEC ratio. If this ratio is < 1, we can document safe use as the PEC is less than the PNEC. For the above example, the biocide A inside a yachting marina was not considered safe as PEC/PNEC > 1. Biocide B on the other hand, did get a ratio < 1, hence the use was considered safe even though the w% in the paint was 10 times higher than biocide A.

How to compare two antifouling coatings with the same type of biocide? Would product 1 with 5 w% of biocide B be better for the environment than product 2 with 50 w% of biocide B? Not necessarily! It all depends on the efficacy. If product 1 will foul-up more easily than product 2, the environmental 'cost' of the extra consumption of fossil fuel, the extra emissions of greenhouse gases and the extra risk of spreading non-indigenous species will by far overshadow the environmental 'benefit' of releasing less biocide to the sea.

The performance is the key - The antifouling coating with the best performance is always the best for the environment - the better, the greener - of course providing that the ingredients comply with relevant local laws and regulations.

5. Regulatory aspects

Application of antifouling coatings is strictly regulated on a global basis. The IMO ban on organotin (TBT) entered into force in 2003 and Cybutryne (Irgarol®) in 2023, *IMO (2021)*. Ships in operation will need to comply with these requirements by carrying International AFS certificates which state the organotin-free and Cybutryne-free compliance.

In addition, there is a regional and national approval systems in EU and national approval systems in countries like USA, Canada, Australia and New Zealand. The Biocidal Products Regulation (BPR) in Europe is considered to be the most comprehensive and scientific based system.

Biocide	Generic type	Approval	Status		
Dicopper oxide	Broad spectrum	Until 31.12.2025*	Renewal in progress		
Tralopyril	Anti-animal	Until 30.09.2027	Renewal in progress		
Medetomidine	Anti-barnacle	Until 30.06.2025	Renewal in progress		
Copper pyrithione	Algaecide	Until 31.12.2025	Renewal in progress		
Zineb	Algaecide	Until 31.12.2025	Renewal in progress		
DCOIT	Algaecide	Until 31.12.2025	Renewal in progress		
Zinc pyrithione	Algaecide	Pending	Pending		

Table I: Overview of the EU-BPR approvals for the antifouling biocides

*The approval of dicopper oxide includes the use on pleasure crafts <24 m long.

The same biocides are approved in the countries with a national approval system, except for North America where the selection is less, due to a limited size of the markets combined with high registration costs.

In several other countries, like China, Japan and South Korea, there is no approval system, but the antifouling coating to be applied will need to have biocides that are registered in the inventory lists of existing chemicals, the IECSC in China, the ENCS in Japan and the KECL in Korea.

The Ministry of Environment of South Korea includes chemical substances with special hazards into the list of toxic chemical substances, which is regulated by the Chemical Control Act (CCA). Currently, there are more than 2000 compounds on this list. CCA came into effect on January 1, 2015 and focuses on the management of hazardous chemicals and emergency management of chemical incidents. Most antifouling biocides are on this list, hence the shipyards will need to take extra precautions when applying these products to protect the people and the surroundings.

5.1. Trends

Restrictions on biocides are expected to progressively tighten, and the expectation is that the current assortment of biocides available for use will reduce in the years to come, and some restrictions on level of use may be introduced. Historically, it has been the <u>environmental</u> aspect that has been the challenge, e.g. for TBT and cybutryne that are both banned by IMO. The environmental aspect of the 6 key biocides currently being used in industrial coatings is now considered acceptable, as they are all authorized by EU.

What is new is that the <u>human health</u> aspect of biocides has received more attention. Zinc pyrithione is currently under scrutiny in EU and we may expect future restrictions for the other organic biocides. The situation is generally complicated by a multitude of national and regional regulations which are not aligned, with demands for different approaches to assure compliance. EU has the strictest regulatory system globally, and it is expected that other markets will follow and implement restrictions should there be any.

5.2. What about the biocide-less and biocide-free products?

Biocidal FRC follow the same regulations as the conventional antifouling coatings. The biocide-free FRC products on the other hand may be applied without evaluation by the authorities. However, these products often contain ingredients that are covered by other regulations.

Washington State Department of Ecology recently conducted a thorough evaluation of all the available technologies for fouling protection of pleasure crafts, including copper-free and biocide-free products. Their conclusion was: "Ecology is not able to determine that safer and effective alternatives to copper based antifouling paints are feasible, reasonable and readily available", *Ecology (2023)*.

6. Conclusions

Fouling protection of ship hulls is a very challenging task. There are thousands of species waiting to colonise the surface and when settled the environmental cost is high, with increased consumption of fossil fuel, increased emissions of greenhouse gases and increased risk of spreading non-indigenous species.

Antifouling coatings with biocides are the most feasible and reasonable technology available. Safe use of these products should be determined using risk assessment models.

The antifouling coating with the best performance is always the best for the environment – the better, the greener - of course providing that the ingredients comply with relevant local laws and regulations. The performance of antifouling coating should be determined by ISO 19030.

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Behavioural Science Applications in Maritime Operations: Improving Fuel Efficiency Through Crew Engagement

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Abstract

This white paper examines how behavioural science techniques can be leveraged to enhance operational efficiency in maritime shipping. Using data from an 18-vessel chemical tanker fleet, this research demonstrates how structured feedback mechanisms, goal-setting frameworks, and judicious and timely deployment of proven behaviour change techniques can lead to measurable reductions in fuel consumption and vessel emissions. The six-month study observed significant improvements in operational behaviours, particularly in vessel trim optimisation, resulting in over 250 t of fuel and 790 t of CO_2 emissions saved.

1. Introduction

Maritime shipping accounts for approximately 3% of global greenhouse gas emissions according to the International Maritime Organisation. Whilst technological solutions are being developed for long-term decarbonisation, substantial near-term efficiency gains can be achieved through operational improvements. This white paper explores how behavioural science principles can be applied to bridge the gap between vessel performance monitoring and actual fuel-saving behaviours.

2. Research Background

The maritime industry has widely adopted sophisticated monitoring technologies that provide detailed operational data. However, a significant challenge remains in translating performance monitoring into consistent behavioural change among crew members. This research investigates whether established behavioural science techniques, including personalised goal-setting, structured feedback, and targeted incentives, can effectively influence maritime operations.

3. Methodology

3.1. Study Design

The study was conducted across an 18-vessel chemical tanker fleet over six months, engaging 70 crew members. Using existing vessel performance data, Signol's behavioural scientists and data analysts established baseline performance metrics, or behaviours, that applied to all vessels.

Four key operational areas were identified as targets for behaviour change:

- 1. Optimal trim configuration
- 2. Engine maintenance optimisation
- 3. Efficient auxiliary engine use
- 4. Prompt departure procedures

3.2. Implementation Framework

The behavioural intervention consisted of:

1. Personalised Goals: Individual baselines were established for each crew member based on historical performance data

- 2. Regular Feedback: Structured communications delivered via email and a dedicated web application
- 3. Dual Incentive Structure: Achievement recognition coupled with charitable contributions
- 4. Integrated Behavioural Change Techniques: delivered in each communication, including linking the environmental impact of specific operational behaviours

Researchers conducted in-person sessions with crew members before and during the study period to ensure understanding and engagement with the programme.

3.3. Measurement

To assess the indicators of behaviour change, an Econometric analysis was done using a linear regression model, where the primary intent was to obtain values of the coefficients within the equation. This allowed controlling for fixed effects, so any confounding variables were held constant. The fixed effects used were the vessel, the operators, origin/destination/route, weather, month and hull fouling.

4. Results

4.1. Quantitative Findings

The study demonstrated measurable improvements across several key metrics:

- Success rate of the trim behaviour: 16% increase in optimal trim implementation, Fig.1
- Trim Optimisation: Average trim shifted 0.22 m closer to even keel, representing a more efficient configuration for the vessel type, Fig.2
- Fuel Consumption: over 250 t reduction over six months
- Emissions Reduction: over 790 t of CO₂ emissions avoided



Fig.1: Baseline Performance of Optimal Trim Behaviour Pre and Post Signol Launch



Fig.2: The Configuration of Trim Pre and Post Signol Launch

4.2. Qualitative Outcomes

Interviews with crew members revealed several notable qualitative outcomes:

- Integration of efficiency discussions into daily operational meetings
- Increased awareness of how individual actions impact fuel consumption
- Development of collaborative problem-solving approaches to meet efficiency goals
- Enhanced sense of purpose related to environmental impact reduction

One participant noted: "We discuss Signol with the crew in daily meetings [addressing] how we can save fuel. We also talked about Signol in safety meetings. When we receive emails, if we don't meet the goals, we discuss with the crew that we should do something to achieve the goals next time."

5. Discussion

5.1. Behavioural Science Principles in Practice

The research demonstrates how several established behavioural science principles can be effectively applied in maritime operations:

- 1. Goal Setting Theory: Specific, personalised targets based on historical performance provided clear direction
- 2. Feedback Loops: Regular, structured feedback facilitated continuous improvement
- 3. Social Norms: Crew discussions about performance created social reinforcement of desired behaviours
- 4. Intrinsic Motivation: Environmental impact information connected operational behaviours toa broader purpose

5.2. Implementation Considerations

Organisations seeking to implement similar behavioural programmes should consider several factors:

- 1. Data Infrastructure: Sufficient operational data is necessary to establish meaningful baselines
- 2. Leadership Support: Management endorsement facilitates programme acceptance
- 3. Communication Channels: Reliable communication methods are essential for regular feedback
- 4. Cultural Factors: Programme design should account for the existing organisational culture
- 5. Incentive Structure: Alignment with crew values enhances engagement

6. Conclusions

This research demonstrates that behavioural science applications can yield significant operational improvements in maritime shipping. By systematically engaging crew members through personalised goals, regular feedback, and meaningful incentives, organisations can bridge the gap between monitoring capabilities and actual emissions reductions.

The approach detailed in this study offers a complementary strategy to technological solutions, providing immediate efficiency gains whilst longer-term decarbonisation technologies are developed and deployed.

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Optimization of Load Management of Diesel Gensets Using Real-Time Data

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Abstract

This paper focuses on the optimization of gensets load management, particularly through dynamic load balancing. By maintaining generators within their optimal load range fuel efficiency improves. The research incorporates case studies for different ships equipped with real-time data collection service and alarming tools for enhanced control and decision-making.

1. Introduction

Optimizing auxiliary power generation is critical for the efficiency and regulatory compliance of modern vessels of different types (see *Craciun et al. (2024)* for cruise vessels). Traditional diesel generator set (genset) load management often results in excess units running at inefficient low loads, increasing fuel consumption. This study leverages high-frequency, real-time operational data from four identical sister LNGCs (equipped with HHI 6H35DF gensets, operating Oct 2023 – Mar 2025) to address this inefficiency. We quantify potential fuel savings by comparing actual genset usage against a calculated optimum, defined as the minimum number of units required to meet demand while operating below an 85% load threshold (see *Barone et al. (2023)* for different equipment configuration), using empirically derived Specific Fuel Consumption (SFC) models.

Uniquely, this research also evaluates the impact of a practical intervention implemented mid-study, comprising real-time suboptimal operation alarms provided to the crew combined with targeted engagement sessions. This paper presents the methodology, quantifies the initial optimization potential identified, and demonstrates the significant, measurable improvements in fuel efficiency realized following the intervention.

2. Equipment description

This study focuses on the auxiliary power generation systems aboard four identical Liquefied Natural Gas Carrier (LNGC) sisterships. These modern vessels feature dual-fuel main propulsion systems (XDF) and were commissioned recently, incorporating contemporary engine technology and data acquisition capabilities relevant to this research. The analysis specifically targets the performance of the diesel generator sets (gensets) responsible for providing electrical power onboard.

Each of the four sisterships is equipped with an identical auxiliary power plant configuration, comprising four main diesel generator sets. This standardized setup across the fleet allows for comparative analysis and validation of findings under similar operational frameworks. The gensets analyzed each contain four identical diesel generator engines (DGEs):

Engine Manufacturer	Hyundai Heavy Industries (HHI)
Engine Model	6H35DF (Dual-Fuel)
Number per Vessel	4
Rated Power Output (per engine)	2,880 kW
Operating Speed	720 rpm
Generator Manufacturer	Nishishiba Electric Co., Ltd.
Generator Output	6,600 VAC, 60 Hz, 3-Phase
Year of Manufacture	2023

The HHI 6H35DF engines are designed for dual-fuel operation, capable of running on both conventional marine diesel oil and gas fuels, providing operational flexibility. However, this study

primarily focuses on the load management aspects irrespective of the fuel type being used at any given time, concentrating on the electrical load demand and distribution among the running units.

The vessels are equipped with sophisticated data acquisition systems that continuously monitor the operational parameters of the onboard machinery, including the auxiliary gensets. For this study, high-resolution operational data was collected over the following periods (after vessels delivery):

Data Period (Vessel #1)	October, 2023 –31 March, 2025
Data Period (Vessel #2)	December, 2023 –31 March, 2025
Data Period (Vessel #3)	February, 2024 – 17 January, 2025
Data Period (Vessel #4)	March, 2024 – 31 March, 2025
Data Granularity	80 tags per diesel generator engine on each vessel
Sampling Frequency	Data points for each tag were logged at a frequency of 15-60 sec
	and aggregated to 1 hour packages

This comprehensive dataset provides a detailed view of the gensets' dynamic behaviour, including load fluctuations, running hours, start/stop sequences, and various engine performance indicators. The high frequency and multi-parameter nature of the data are crucial for accurately assessing load profiles and the effectiveness of load management strategies in real-time operational scenarios.

Data has been cleaned to ensure only relevant datapoints:

- All points where all DGEs are offline were removed
- All points where DGEs were switched off/on within last 1 hour, i.e. power system was in transitional state, were removed (~3% of initial dataset)

3. Performance Measurements

The primary objective of this study is to assess the effectiveness of real-time genset load management and quantify the potential for fuel savings achievable through optimized dispatch strategies. To this end, a key performance metric, termed "Potential Fuel Savings," was developed and calculated based on the high-resolution operational data collected from the vessels.

3.1. Potential Fuel Savings Metric

The core metric used to evaluate the degree of optimization in genset operation at any given time is the Potential Fuel Savings. This metric represents the difference between the actual measured fuel consumption and a calculated theoretical minimum consumption required to meet the same electrical load demand under an optimized genset configuration. It is calculated as follows:

Potential Fuel Savings = Actual Fuel Consumption - Optimal Fuel Consumption

Actual Fuel Consumption is derived directly from onboard fuel flow meters.

Optimal Fuel Consumption represents the theoretical minimum fuel consumption achievable for the given total electrical load demand at that moment. Its calculation is based on an optimization logic designed to minimize the number of running DGEs while ensuring efficient (no underload) and safe (no overload) operation. The logic proceeds as follows:

- <u>a.</u> <u>Assess Current Load:</u> The total instantaneous electrical load demand on the power plant is determined from the real-time data.
- b. Evaluate Optimization Potential: The system evaluates if the current number of online DGEs (n) can be reduced to n-1 (or fewer) while ensuring that the load distributed among the re-

maining DGEs does not exceed a predefined operational threshold. Based on common operational guidelines for efficiency and engine health; this threshold was set at 85% of the rated capacity (2880 kW) for each individual DGE in this study. This establishes a clear guideline for optimal dispatch based on total load:

Optimal online number = [P / (MCR * t)],

where P is total power demand, MCR the rated power of one DGE, t the maximum load threshold, and [] is rounding up to nearest integer not greater than 4, otherwise 4.

c. Calculate Optimal Consumption:

<u>If Optimization is possible:</u> If reducing the number of online gensets is feasible (i.e., the total load can be handled by fewer units, each operating at $\leq 85\%$ load), the Optimal Fuel Consumption is calculated for this hypothetical, optimized configuration (fewer gensets running, likely at higher, more efficient loads) as:

Optimal Fuel Consumption $[t/h] = \sum_{i=1}^{n} SFC_i * P_i / 10^6$

SFCi is the Specific Fuel consumption of i-th DGE [g/kWh] producing power Pi [kW]. This calculation uses specific performance models (SFC curves) for the DGEs that would be running in this scenario, considering the specific fuel type in use.

<u>If Optimization is Not Possible:</u> If the current number of running gensets is already the minimum required to keep individual unit loads at or below the 85% threshold, the current operational state is considered constrained-optimal for that load level. In this case, Optimal Fuel Consumption is set equal to the Actual Fuel Consumption, and the Potential Fuel Savings is zero.

3.2. Specific Fuel Consumption (SFC) Modelling

The calculation of Optimal Fuel Consumption relies on accurate models of Specific Fuel Consumption (SFC) for each individual engine and for each potential fuel type: LSHFO, LSMGO, LNG. These SFC models predict the fuel consumption rate (in g/kWh) based on the engine's electrical power output.

For this study, SFC curves were empirically derived from the collected operational data using statistical regression techniques. Specifically, a quadratic model was employed (see *Michalopoulos et al. (2022)* for example):

$$SFC = a \times P + b \times P^2 + c$$

SFC is the Specific Fuel Consumption [g/kWh], P the electrical power output of the DGE [kW]. a, b, c are regression coefficients determined empirically for each genset and fuel type combination.

This modelling approach captures the non-linear relationship between engine load and fuel efficiency.

4. Results and Interpretation

This section presents the findings derived from applying the Potential Fuel Savings metric, calculated using the Specific Fuel Consumption (SFC) models developed as described in Section 3, to the operational data from the four sistership LNGCs. Furthermore, it documents the practical application of these findings through system implementation and crew engagement, and the subsequent impact on operational efficiency.
4.1. Initial Assessment and Identification of Optimization Potential

The optimization algorithm described in Section 3 determines the minimum number of generators required to meet the total power demand while keeping each unit at or below 85% of its rated capacity. This establishes a clear guideline for optimal dispatch based on total load:

Optimal online number = [P / (MCR * t)],

P is the total power demand, MCR the rated power of one DGE, t the maximum load threshold, and [] is rounding up to nearest integer (not greater than 4, otherwise, 4)

Fig.1 compares the actual number of online DGEs for each vessel with the calculated optimal number required based on total power demand (red line). Green data points denote optimal loading periods, blue points suboptimal periods. The title of each subplot indicates the proportion (%) of suboptimal operational points recorded.



Fig.1: Load profile for different ships

4.2. Intervention: Real-Time Alarming and Crew Engagement

Based on these initial findings, and to translate the analytical insights into practical improvements, two key actions were taken:

1. **Real-Time Alarms:** An alarm system was configured within the vessels' monitoring platforms. This system utilized the Optimal Number of Online DGEs logic to trigger alerts to the stakeholders when the current genset configuration was identified as suboptimal.

- 2. **Crew Engagement Session:** In April-June 2024, dedicated sessions (interventions) were held between Charterers/Owners and the crews of the vessels. These sessions presented the findings of the load analysis after vessels' delivery, explained the principles of optimal genset dispatch for fuel efficiency, and demonstrated the function of the new alarm system. Main adjustments include:
 - i. Targeting the 82-85% load range per unit where feasible instead of previous thresholds of 75-80%.
 - ii. Increasing the auto-start threshold for standby generators from 80% to 90% of current overall genset load.

4.3. Post-Intervention Performance Analysis

The effectiveness of the alarms and crew engagement was evaluated by analyzing the operational data for the period following the intervention.

- Period Analyzed: July 1, 2024 March 31, 2025.
- Impact on Efficiency: A marked improvement in genset operational efficiency was observed for three of the four vessels (#1, #2, #3). The calculated Potential Fuel Savings decreased significantly, indicating that actual operational practices moved closer to the theoretical optimum.

Table I shows that for vessel #1 the average Potential Fuel Savings metric decreased allowing almost 7% fuel savings on genset operation after intervention. Ship #4 showed a less pronounced economy during this period. Further investigation may be needed to understand contributing factors, which could include differences in operational profiles, crew response, or the shorter baseline data period.

Potential Fuel Savings	ship 1	ship 2	ship 3	ship 4		
before intervention [t/day]	1.08	0.33	0.51	0.16		
after intervention [t/day]	0.24	0.14	0.21	0.12		
difference [t/day]	-0.84	-0.19	-0.30	-0.05		
after intervention total [t]	232	51	61	13		
Average genset consumption before int. [t/day]	12.4	10.5	11.9	9.2		
Consumption changes after intervention [%]	-6.8%	-1.8%	-2.5%	-0.5%		

Table I: Potential fuel savings

Fig.2 shows 30-day moving average of hourly Potential Fuels Savings metric for different ships. Shaded areas show the period of interventions described previously.

This reduction in potential savings directly translates to actual fuel savings being realized onboard. It demonstrates the efficacy of combining data-driven analysis with practical tools (alarms) and targeted crew training. The continuous feedback loop provided by the monitoring system and alarms likely played a key role in sustaining these improved operational habits.

5. Conclusion

This study successfully applied real-time data analysis to quantify and significantly reduce diesel generator set inefficiencies aboard four LNGCs. Initial findings revealed substantial fuel saving potential, exceeding 1 t/day on one vessel, primarily from running surplus generators. The subsequent implementation of real-time alarms based on optimal dispatch logic, coupled with targeted crew training, proved highly effective. This intervention led to a measurable reduction in the identified optimization gap ("Potential Fuel Savings") and decrease of average fuel consumption of over 1.5% for three of the four vessels, directly translating into lower costs, and reduced emissions. These results

underscore the practical value of combining data analytics and automated feedback with proactive crew involvement for enhancing shipboard energy management. While variations in response suggest areas for further investigation (investigation of factors affecting SFC curves, comparing performance of different DGEs), this work confirms that data-driven genset load optimization is a potent strategy for improving the efficiency of high-performance ships.



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Evolution of Ship Design from Energy Efficiency towards Holistic Sustainability

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Abstract

Sustainability is an important design criterion today, and the rule framework is constantly developing. Within the EU, the "fit for 55" framework introduces direct costs for carbon-emitting ships. This highlights the importance of modeling ship energy consumption in operation already during the ship's conceptual design stage and evaluate ship lifetime operational costs. We provide examples of the cost impact of these rules. The model of ship energy flows and consumption is at the heart of the required analysis. We review the development steps taken and the process of sustainable ship design from Deltamarin's perspective.

1. Introduction

Ships have to be designed today for good environmental performance and sustainability, overall. This is an important overlaying theme in developing solutions for the industry. The existing and constantly developing rule framework supports this trend. Globally, the ships must comply within the limits of the carbon intensity indicator CII, and they have to pass the energy efficiency index. In Europe, the "fit for 55" package is a legal framework that also guides maritime transport towards green transition. A part of this framework is the EU emissions trading system (ETS), which defines a price for carbon emissions emitted from ships. Another part of the package is the FuelEU maritime initiative for reducing the carbon intensity of the energy that is utilised onboard ships. In addition to these, the alternative fuels infrastructure (AFIR) regulation focuses on the infrastructure of the recharging or refuelling of ships, and it sets, for instance, demands to arrange shore power for container vessels and passenger ships by 2030.

Nevertheless, the profitability of the ship is always a key criterion for the decisions made for a new building vessel or when upgrading the fleet. The energy efficiency of ships has been an important factor to consider in ship design for a long time, with a direct connection to ship operational costs. Today, ship owners have direct cost consequences also due to the ETS and FuelEU Maritime regulations in the form of carbon tax and penalties for not complying with the ship energy carbon intensity targets.

The new rules, cost pressure, and the overall need and desire to increase ship sustainability introduce many new variables to the process of designing ships. On top of the traditional ship design process, including the optimisation of the ship and her systems technically and managing ship building costs, the process must absorb new analysis criteria. Examples of these are speculations for future rule requirements regarding ship technical performance and especially the economical variables regarding future fuels, carbon emissions and energy prices.

This publication discusses the new requirements for ship design and the development of the process of energy-efficient ship design with examples from Deltamarin's design process and recent projects.

2. Closer look at ETS and FuelEU Maritime

The EU ETS is a cap-and-trade system that has existed for power plants and industry for many years. As of 2024, it is being extended to cover maritime shipping. Under this system, shipowners must purchase and surrender emissions allowances (EUAs) for their CO₂ emissions. Similar to FuelEU

Maritime, the coverage is 100% of emissions for intra-EU voyages and 50% for extra-EU voyages, including emissions at berth. The cap on total allowances will gradually tighten, which typically drives up the price of EUAs.

By incorporating shipping into the ETS, the EU is effectively putting a price on carbon emissions. Over time, as the cap decreases, allowances become scarcer and more expensive, intensifying the financial pressure to cut emissions. Vessels that continue burning fossil fuels will pay increasingly high costs, whereas ships using cleaner fuels or more efficient operations will reduce their EUA requirements and overall expenses.

Currently, the ETS scope is on a Tank-to-Wake basis and includes only CO₂. The scope will expand in 2026 and start covering nitrous oxide and methane emissions as well. The development of the ETS cost is uncertain but expected to increase progressively as the market becomes more constrained.

The FuelEU Maritime is an EU regulation to significantly reduce the carbon intensity of marine fuels used in shipping. The regulation is in effect from 2025 and applies to vessels with a gross tonnage (GT) of 5,000 or more that call at EU/EEA ports. This measure covers all emissions produced during intra-EU voyages, including those at berth, as well as 50% of the emissions for voyages between EU and non-EU ports.

At the core of FuelEU Maritime are its greenhouse gas (GHG) intensity targets. These targets require progressive reductions in well-to-wake CO₂-equivalent emissions, starting from a reference value of 91.16 gCO₂-eq/MJ established in 2020. Over time, the allowable GHG intensity will be tightened, pushing shipowners towards cleaner energy options and more efficient operational practices. Compliance with FuelEU Maritime is enforced through a system of penalties and incentives. Shipowners who exceed the prescribed intensity thresholds will face financial penalties, while those who achieve greater reductions may earn credits. This dual approach is designed to create a strong economic incentive for early movers and effective action in reducing emissions. The non-compliant vessels are charged 2,400€ per ton of VLSFO-equivalent for every unit of energy that exceeds the compliant threshold, resulting in significant financial penalties. Therefore, in many cases, even highcost fuels such as e-fuels will most likely be more economical compared to paying the penalties.

There are multiple options to comply with the regulation. As an example, the surplus credits for overcompliance can be banked for upcoming years and used when needed. Blending more sustainable energy sources into the fuel mix might be a feasible option as well, of course, depending on the availability and infrastructure of such resources. Also, pooling with ships using a more sustainable energy mix is a more economically wise option compared to paying the penalties and likely an easier option than bunkering sustainable fuels. For a sustainable and over-compliant vessel, credits/revenue can be earned by pooling with less sustainable vessels, and thereby balance the cost of a most likely more expensive bio/e-fuel.

3. Money, money, money

How relevant can these new rules be regarding ship operational costs? Fig.1 presents a recent example from EU-project CHEK regarding projected operational costs for a Kamsarmax-sized bulk carrier. The project and simulation results are presented most recently in *Elg et al.* (2024). This kind of ship is designed for global operation, and the rules within the EU might not apply most of the time. Nevertheless, in this example calculation, we assume that the ship would operate a third of her time within the EU. The "Base case" ship in Fig.1 represents a modern ship equipped with traditional fuel and machinery, and "CHEK combo" represents a conceptual design including liquid biogas (LBG) efficient hull, fuel-flexible machinery and a combination of energy saving technologies. The accumulated costs include fuel price, carbon tax and FuelEU Maritime penalty where relevant. It is also assumed that the "CHEK vessel" will get certain benefits from using biofuel and being, thus, overcompliant regarding the fuel's carbon intensity requirements. This kind of vessel can pool surplus compliance

balance with other ships, and the possible impact of pooling on her lifetime energy and compliance costs is estimated in Fig.1.



Fig.1: Operational costs for CHEK bulk carrier

The associated fuel costs are presented in Table I, and sources of assumed costs are presented in Table II.

Table 1. Development of prices for the CHER project calculation in e/ton of fuer						
	2024	2029	2034	2039	2044	2049
LBG	1117	1117	1257	1257	1350	1350
VLSFO	660	549	537	537	537	537
Bio diesel	1193	1452	1730	2008	2267	2525
ETS	70	130	150	200	270	340

Table I: Development of prices for the CHEK project calculation in €/ton of fuel

Table II: Sources of the fuel and ETS Prices assumed in the CHEK bulker and RoPAX examples

Fuel type	Source for price scenario
HVO	It's time to de-risk vessel construction LR
LFO	Fuel Cost Calculator Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping
LBG	CHEK_D8.3 Report on cost comparison for the fuel options_final pdf
ETS	https://doi.org/10.1016/j.apenergy.2021.116914
MDO	23% added on top of LFO prices
LNG	Fuel Cost Calculator Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping
Electricity	10068_LR_Methanol_Institute_White_Paper_200320_4.4.pdf Renewable electricity
-	(The average of lower and upper cost scenario)

Fig.2 illustrates the fuel and regulatory costs separately for the base case vessel, assuming the two different strategies for coping with the rules. We can clearly see that during the early years of operation, a ship such as the CHEK "combo LBG" bulker would create operative savings mainly due to consuming almost 50% less fuel than the baseline vessel. In future decades, the difference might grow three-fold due to the increasing weight of the regulatory costs. The black line in Fig.1 presents the maximum costs, including rule compliance by paying penalties. Nevertheless, another possible scenario is presented regarding operative costs for the baseline ship, including FuelEU maritime rule compliance by blending just enough bio-diesel to avoid triggering the FuelEU penalty. The difference in these two compliance strategies is visible in both Fig.1 and Fig.2, considering the selected price development scenarios in Table I.



Fig.2: Operational costs for CHEK "Base line" bulk carrier separated into energy costs and regulatory costs

4. Anatomy of ship lifetime cost, energy and environmental modelling

For producing the operative cost results illustrated in Fig.1 and Fig.2 for a ship still on the design table, a model regarding FuelEU Maritime rule compliance is required, in addition to data regarding the fuels. In this fuel framework, the ship energy consumption is one of the inputs, as this factor defines the magnitude of the potential penalties or "credits" due to overcompliance to be either given, sold or kept for own later use. Fig.3 illustrates how Deltamarin typically models the various aspects of ship sustainability.



Fig.3: Main processes in ship sustainability and energy modelling

The energy modelling, which is named "DeltaKey" within Deltamarin, is at the core of the sustainability analysis. The energy model requires input from the ship design and systems regarding the energy consumption. DeltaKey and the history of the energy modelling in this context are further explained in Chapter 4. The ship structural and volume model of the ship and the general naval architectural analysis process is illustrated in Fig.3 with light blue color, and it is named as "DeltaWay". For instance, ship hull creation is a part of the DeltaWay process. In general, all ship equipment and dimensions impact the ship's energy consumption due to the energy system interactions and, for instance, the weight included, which influences the ship's propulsion power.

Therefore, certain ship design data is always a starting point for modelling energies.

For ship energy consumption, the ship operational profile is one of the single most important inputs. The operational profile includes knowledge of the ship speed and loading conditions, but also the operational environment including the weather influences on it. Existing ship operational data can be utilised as a direct source of ship speed, draft and location for the energy model. Deltamarin acquires satellite data for this purpose and has created a script that prepares the relevant data for the energy model. The ship propulsion power is modelled as a function of the ship hull resistance, propulsion efficiency and external forces. In some cases, the simplified approach is included in the projects, where a "sea margin" is added on top of ship's calm water propulsion power prediction to cover the environmental loads. Nevertheless, the "DeltaSeas" approach of combining historical or statistical weather data to a vessel's typical operational profile is a necessary approach, especially in modelling ships with sails. The CHEK bulk carrier-related publication also included a brief overview of the DeltaSeas algorithm. (Elg et al., 2024). Fig.4 illustrates how the CHEK vessel propulsion power requirements vary on global routes, even if the simulations expect operation at one selected speed and only two different loading conditions.



Fig.4: CHEK Bulker – All routes. Visualisation of propulsion power demand (kW) at different sections of the route. Left: Base case 2-stroke configuration. Right: CHEK Combo.

As Fig.3 illustrates, ship energy flow simulation may also be the source for "design-based" ship life cycle assessment (LCA), in addition to the decarbonisation related regulatory compliance or cost minimisation. For the ship designer it is relevant to create a modular network of the processes, since the projects are different and not every piece of the analysis is required in every project.

5. Brief history of the energy modelling at Deltamarin

Deltamarin's energy flow simulation tool was developed from the start for quantifying the ship energy flows and analysing the efficiency in ship processes and energy conversions. The model is an engineer's tool for mapping the largest energy consumers and to simulate the yearly fuel consumption of the ship with various design alternatives. As visualised in Fig.3, the ship fuel consumption and emission results are further utilised for analysing the ship's regulatory compliance and costs.

Before the current simulation tool, ship energy balance calculation was performed by simplifying the ship operational profile into various operational modes (such as loading, unloading, port stays and various speed and draft conditions at sea) and the relative total time spent in these modes. The main item which separates the current energy simulation method from the conventional and static energy balance calculations is the possibility to utilise the time-vector. Thus, fuel consumption, power demand and other variables can be monitored at each time step without the need for approximations and averaged values over longer time-periods. The holistic nature of the simulation platform enables

testing different improvements and design alternatives for the ship and their multiplicative effects across the different systems.

Numerous other applications exist for ship energy modelling, such as the COSSMOS environment by DNV, *Dimopoulos et al. (2014)*. Also, the software APROS has been used for simulating ship energy system, *Lepistö et al. (2016)*. *Tillig et al. (2015)* provided a comprehensive but compact overview of the ship energy modelling principles and at the time existing software for the purpose. The paper lists four dimensions according to which the models can be considered. For instance, the level of detail in the model is one of these dimensions, such as white box, black box or grey box models. The other dimensions include model developing time domain, model application time domain and a dimension for model data characteristics.

For ship designer in general, it is relevant to have insight into the processes, and therefore white box modelling has been in the focus for Deltamarin regarding the core processes of the energy model developed. However, the white-box modelling approach is mainly relevant regarding those variables that the designer is in control of and, therefore, the holistic ship energy and emission model may very well be a grey-box model combining parts of black-box models, such as producing response surfaces from measured data as input for a physical process model. This was also demonstrated in the DeltaKey tool recently while absorbing an external model in the form of a functional mock-up unit to describe the ship's machinerys' main functions, *Elg et al. (2024)*.

The roots of Deltamarin's current energy model date back in a joint industry development project SEEE (Ship's Energy Efficiency and Environment) during 2009-2014 under the Finnish research program "Energy and life cycle cost efficient machines" (EFFIMA) funded by Tekes (the Finnish Funding Agency for Technology and Innovation) and FIMECC Ltd. (FinnishMetals and Engineering Competence Cluster). During this project, VTT, Deltamarin and ABB joint forces for compiling a multi-domain, dynamic ship energy flow simulation tool. The tool was configured with Matlab, Simulink and Simscape. Several papers have been published regarding the tool. The most relevant examples are Zou and Tammi (2013) and Zou et al. (2014). These publications also present limited case studies of a cruise ship and container vessel. Deltamarin started to develop its own approach to energy simulations during this project, and in the beginning, the simulation tool was strongly based on the results of the cooperation. Deltamarin's first relevant publication was Elg et al. (2014). The published case involved a bulk carrier. The paper focused on finding energy saving potential with alternative steam system pressures and various cooling system settings. After this, the model was further developed for Deltamarin's own use, and it was utilised to study further efficient ship cooling water systems and multiple energy saving alternatives, including waste heat recovery with Organic Rankine Cycle, *Elg et al.* (2015,2016). The latter studies were performed as a part of a joint industry project, SET (Ship Energy Efficiency Technologies) during 2014-2016, Zou (2017).

Already during the SET project, once performing simulations in Deltamarin's commercial projects, the utilisation of Simscape physical domains was reduced mainly due to the fact that the current setup of auxiliary processes, such as cooling systems, did not scale very well to different sizes of machineries. It also required a lot of manual setup work for the model, such as sizing pipes. In addition to this, the computing times became easily very long since the auxiliary systems were modelled relatively realistically as actual loops.

Later, the focus in the energy modelling has been in integrating efficiently in the model measured data from the ships in growing magnitudes. Another important area has been introducing mathematical optimisation in the ship energy modelling work. Deltamarin's first advancements in this field have been summarised in an extended abstract in the proceedings of development project INTENS, running during the years 2018-2021, *Various (2021)*. The publication included an example of converting the energy model of a RoPAX ship into an executable and running it with a genetic algorithm to evaluate the optimal set-up of installed battery capacity and choosing between waste heat recovery system dimensioning. Another example in the same publication was a cruise ship optimisation case, which was later upgraded into a journal article, *Elg et al. (2023)*. The developed

method allowed assessing thousands of configurations instead of selected pre-set scenarios. This is also the current direction in developing the modelling: developing the model interfaces for various types of input and enabling optimisation in suitable cases.

The energy model is currently compiled with Mathwork's Matlab and Simulink software. The model is utilised especially during ship conceptual design or for retrofit studies. Typically, the time span of these projects is short. Therefore, the model for this use has to be extremely flexible, fast and easily configurable. The current model and its utilisation is a result of an evolution in the focus areas of the energy efficiency improvement work over a decade. It has also evolved in the context of the other digital design layers, such as the propulsion modelling and the current sustainability and decarbonisation-related regulation, and to enable optimisation. The model is constantly being developed to include new devices and operational strategies and to accommodate more efficient working methods for the team. The latest version of the model is rather thoroughly presented in the context of project CHEK with decarbonising cruise ships. The published journal article focused on analysing the impact of several ship energy-saving technologies and hydrogen as fuel to the entire ship energy model in case of a diesel-electric ship and with only Organic Rankine Cycles enabled as a waste heat recovery solution.



Fig.5: DeltaKey energy simulation model high-level factors and elements, Elg et al. (2025)

6. Case example: electrification impact on ship operational costs

In addition to fuels with low carbon intensity, shore power is currently considered as a carbon-free energy source for ships within the FuelEU and ETS framework. For exploring the opportunities of electrification, we present a case of a conceptual RoPAX ship. The ship's main dimensions are presented in Table III. The RoPAX vessel was studied with both LNG as the main fuel alternative and with a fully electric version operating on batteries. This study was performed by assuming simply that all ship heat would be generated with an electrical boiler without analysing further technologies.

Length between perpendiculars	208.10 m
Length overall	221.00 m
Beam	31.80 m
Design draft	7.00 m
Scantling draft	7.20 m
Service speed	22 kn
Lane meters	4080 m

Table III: Main dimensions of the conceptual RoPAX ship





Fig.7: RoPAX ship reference time distribution for different operational modes

For such a vessel, fully electrical operation with the selected battery capacity would be possible, for instance, in the English Channel. The operational profile for the study was received by following a suitable relevant vessel in the English Channel and obtaining the satellite data. Fig.6 and Fig.7 illustrate the main operational speed and operational modes included in the study.

Fig.8 presents the simulated operative costs between an LNG-fuelled alternative and a fully electric vessel, assuming that only 50% of the operation would be considered within the EU rule framework. The calculation assumes that the LNG vessel selects blending LBG in the energy mix for avoiding penalties, but also the scenario of paying penalties is illustrated. A new element is added for the battery vessel to illustrate the theoretical maximum potential of how a low-carbon ship could reduce the FuelEU maritime penalties if pooling with ships within its own fleet. This figure should be understood as "avoided FuelEU penalty costs by other vessels in the fleet" calculated for overcompliant ships. The real-life benefit of pooling ships varies on the compliance avoidance strategies available for the other ships in the pool and any pool administration costs. Thus, it cannot be evaluated without knowing the details of the pool.



Fig.8: Operational costs for RoPAX case with LNG fuel (on the left) and fully battery-operated ship (on the right)

Table IV lists the price-related variables in the study, and sources for price assumptions are summarized in Table II. With the selected prices for energy, the electrical vessel has clearly lower operational costs than the LNG-fuelled ship already due to energy savings and energy costs.

- **						
	2025	2030	2035	2040	2045	2050
LNG	19,3	14,4	14,2	14,1	14,0	13,9
LBG	24,0	27,0	27,0	29,0	29,9	33,0
MDO	18,9	16,6	16,6	16,6	16,6	16,6
Electricity	21	17	17	13	13	10
ETS	100	140	160	210	280	350

Table IV: Development of prices for the RoPAX case calculation in €/GJ of fuel

We can also speculate how the operational cost figures would change if the vessel operation on a similar energy profile would be, if the ship would operate 100% within EU area. Fig.9 illustrates these results.

Fig.9: Operational costs for RoPAX if operating 100% within EU

The regulatory costs (ETS), energy costs and the theoretical fleet penalty avoidance benefit are also illustrated for the best case of the CHEK bulk carrier, adding to the figures discussed in chapter 3.

In all cases, it is clear that while the regulatory cost burden is considerably increased in the later decades, the opportunities for environmentally efficient vessels to generate additional revenue by pooling within own fleet or external pools are largest in the near future.



Fig.10: Operational costs for CHEK bulker's case with best combination of technologies and biofuel

7. Discussion, future work and conclusions

With the case stories reviewed, we can conclude that energy saving and ship electrification can bring considerable fuel and energy savings from day one to ship operators. With conventionally fuelled vessels, the regulatory push is increased during the future decades. For instance, LNG as fuel enables ships to operate with merely the ETS cost impact influencing on the regulatory side until 2035 if methane slip is low. For electric vessels that would be able to utilise shore power, the benefits of both energy costs and regulatory framework materialise faster, and there are opportunities to gain further revenue by pooling compliance balance with less sustainable ships.

Introducing new equipment to the ships inevitably also introduces added weight to the ship and added investment. Also, ship electrification might not be possible in all locations without considerable investment in the infrastructure. Therefore, all projects are very case-dependent. Nevertheless, technically, we evaluated the impact of the most weight-increasing technologies for the CHEK bulker in our article. We concluded that the combined effect of two large sails and LNG machinery, including the fuel storage, compared to the baseline ship, would increase the ship draft by 20 cm. This would increase the propulsion power by 1,6% at the typical operational speed of 12,5kn, which is much less than the achieved fuel savings. In the case of fully electric RoPAX, we estimated that replacing the main propulsion machinery and LNG tanks with 45 MWh batteries would increase the ship's lightweight by a bit more than 200 ton, which is approximately equivalent to 1% of the lightweight. The installation costs have to be analysed as they are case dependent. In some cases, it might also be sensible to prepare the ship for a variety of energy saving technologies or electricity storage, but install some of the capacity later, when the economical calculations support the installation. This is the core idea of future-proof ship design.

Ship sustainability is a broad and complex topic. This article focuses specifically on the cost impact of two European regulations. However, more rules are expected to be implemented in the shipping industry over time. As operational carbon emissions from ships are gradually reduced, attention will inevitably shift toward a more comprehensive evaluation of environmental impact through Life Cycle Assessment (LCA). In line with this, the International Maritime Organization (IMO) has revised its decarbonisation strategy, placing more emphasis on a Well-to-Wake (WTW) approach to assessing greenhouse gas (GHG) emissions.

LCA is a holistic method used to evaluate the environmental impacts of a product, process, or service across its entire life cycle—from raw material extraction and production to use and disposal. In the maritime sector, it is increasingly recommended for estimating the full WTW GHG impact of fuels. It also serves as a valuable tool for assessing overall environmental sustainability.

Applying LCA across all stages of a ship's life cycle is one of the most effective ways to measure sustainability. Among the key indicators are GWP100 and GWP20, which reflect global warming potential over 100- and 20-year time horizons, respectively. These are calculated using methods defined by the Intergovernmental Panel on Climate Change (IPCC).

Fig.11 presents the LCA results for the CHEK bulk carrier project, specifically reporting GWP100 in grams of CO₂-equivalent per ton-nautical mile. Further analysis is available in *Dong et al. (2024)*. While this assessment is limited in its coverage of shipbuilding and end-of-life materials and processes, it offers a valuable glimpse into the future of ship sustainability assessments.

Expanding ship LCAs to include more stages and cost factors could provide a competitive edge for future vessel investments. Although comprehensive LCAs are not yet mandatory across all sustainability categories, they offer deep insights into the most impactful factors. Such analyses enable stakeholders to stay ahead of evolving regulations and make better-informed decisions.



Fig.11: Ship LCA results for CHEK bulk carrier

Regarding FuelEU and ETS regulatory costs from a strategic perspective, compliance is the most cost-effective approach. Early investments will not only offer regulatory flexibility but might also improve the vessel's freight rates and resale value. For global trade, EU regulations apply only partially, and added compliance costs will only be seen when travelling into or out of the EU region.

When predicting the FuelEU compliance costs and carbon costs, there are several sensitivity factors and insecurities. Fluctuations and future development in fuel prices are critical and sensitive factor in

the calculations. There is also uncertainty in infrastructure and regulatory development. The regulation is highly political and therefore vulnerable to, for example, the uncertainty regarding the future development of the political landscape.

By simulating different compliance scenarios in an early phase, one can get a clear idea of future costs and the most suitable compliance strategies. Careful planning of space reservations, system integrations, and structural considerations facilitates a seamless transition to lower-carbon energy sources as infrastructure matures and, in the best case, results in a future-proof vessel. This paper provided some examples how important the holistic view to ship systems is. It is possible to identify solutions which are beneficial in terms of ship energy efficiency, regulatory compliance and costs.

Nomenclature

- AFIR Alternative Fuels Infrastructure
- CII Carbon Intensity Index
- EU European Union
- Eq. equivalent
- ETS Emissions Trading System
- EUA Emissions Allowance
- GT Gross tonnage
- GHG Greenhouse Gas
- GWP Global Warming Potential
- LBG Liquid Bio Gas
- LNG Liquified Natural Gas
- LCA Life Cycle Assessment
- MJ Mega Joule
- IMO International Maritime Organization
- TTW Tank-to-Wake
- WTT Well-to-Tank
- WTW Well-to-Wake
- VLSFO Very Low Sulphur Fuel Oil

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Maritime IoT: Onboard Energy Data as the Key to Operational Optimization and Reporting

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Abstract

The integration of precise sensors and timeseries data acquisition through the Maritime Internet of Things (MIoT) lays foundation for effective energy balancing, operational optimization and reporting. This approach takes a holistic view of measuring onboard energy flows, including fuel consumption, electrical energy, and other key parameters. It incorporates advanced data transmission and various interfacing options, establishing a foundation for many applications both onboard and onshore. With constant monitoring of all signals, providing feedback with hands-on support down to the sensor level, high data quality is maintained, ensuring you get the most out of analysis and reporting.

1. Introduction

In recent years, international and regional regulatory frameworks have increasingly emphasized the need for efficient and environmentally responsible ship operations. The International Maritime Organization (IMO) has adopted a revised GHG Strategy, targeting net-zero greenhouse gas emissions from international shipping by or around 2050. A key short-term instrument in this strategy is the Carbon Intensity Indicator (CII), which evaluates a vessel's operational efficiency and enforces corrective actions if efficiency thresholds are not met, IMO (2023). Simultaneously, the European Union Emissions Trading System (EU ETS) has been extended to maritime transport, requiring shipping companies to monitor, report, and purchase allowances for their CO_2 emissions starting in 2024, EU (2023).

These developments underscore the necessity of effective and efficient ship operation. Optimizing a vessel's performance is no longer an added benefit, it is a prerequisite for regulatory compliance and economic competitiveness. Achieving operational excellence requires availability of accurate, high-quality data. Without a reliable foundation of measured performance indicators, neither real-time optimization nor retrospective efficiency analyses can be meaningfully conducted.

With such a data foundation in place, a wide range of optimization measures can be implemented. Examples include:

- Voyage Optimization
- Hull performance monitoring, identifying biofouling or drag-increasing conditions.
- Trim optimization, using real-time feedback to minimize resistance.
- Load balancing of auxiliary engines, ensuring efficient generator use.
- Evaluation of excessive Sludge Production/ Bad fuel purification and processing
- Development of speed-consumption curves used for benchmarking and comparisons
- Evaluation of Main Engine condition and performance
- Evaluation of CII ratings and emission target alignment over time.

Besides that, there are many measures not focussing the energy efficiency itself but for other purposes like charter party compliance, bunker planning, claim management and incident investigation.

This paper aims to provide a general understanding of our approach to the Maritime Internet of Things (MIoT) as a sensor data acquisition system. It outlines our interpretation of high-quality sensor data and offers insights into how such data quality can be achieved during vessel operation— while also highlighting how critical mistakes in planning and implementing a sensor data infrastructure can be avoided.

Another key objective of this paper is to develop a clearer understanding of which data is worth capturing, and how it should be collected. In this context, we place a particular focus on energy flows, which serve as the foundation for most performance analyses. We aim to demonstrate which types of sensors can be used for this purpose and which design principles should be applied to.

2. Data Quality as a Key Element to Ship Optimization

The quality of data is a fundamental component of data-driven analysis on board ships. To assess data quality, various standards and guidelines exist, including international frameworks such as ISO 8000-8 (numerical data quality measurement), ISO/IEC 25012 (data quality model), VDI/VDE 2650 Part 1 (sensor system evaluation), ISO 13374 (condition monitoring), and the more recent ISO/DIS 8000-210 (data quality characteristics). All these standards provide a method and define criteria to systematically evaluate data quality.

At Hoppe, we align our approach with ISO/DIS 8000-210, as it incorporates practical evaluation methods for both sensor behaviour and data processing routines. This orientation aligns well with our requirements, as it allows us to monitor sensor performance under real operating conditions— conditions that largely determine the reliability and usability of the acquired data.

2.1. Data Quality Characteristics

For our applications, we have developed a custom metric set based on ISO/DIS 8000-210 standard and extended it with characteristics based on our experience, *ISO (2023)*. The quality characteristics we assess include:

- Completeness, Fig.2: Are all expected data points available?
- Validity: A Hoppe characteristic. Are the values within physically and operationally plausible limits?
- Consistency: Do time series progress continuously, without spikes or stuck sensors?
- Dissimilarity, Fig.1: Do correlated signals behave as expected?
- Rule Violation, Fig.1: Physically logical validation based on a fixed rule set.



Fig.2: Implemented anomalies on completeness characteristics, ISO (2023)

Some characteristics and anomalies defined in the underlying ISO standard were intentionally not implemented, as certain types of errors—while potentially relevant for subsequent analysis—are not meaningful when assessing whether a sensor or data signal is functioning correctly and plausibly. An example of this is changes in the logging frequency, which can only be adjusted intentionally through system settings. In addition, we excluded characteristics and metrics that focus on error scenarios which are technically impossible due to our system design and are therefore inherently always fulfilled e.g. incorrect timestamps within a dataset.

One aspect that is not addressed in the underlying ISO standard is the fact that, in the maritime context, we are dealing with moving objects that operate under various operational modes. These different modes can have a significant impact on the behaviour and characteristics of individual sensors. To avoid false positive alerts in data quality assessments, it is therefore essential to consider both the current operational state of the vessel and that of individual machines and subsystems during analysis, <u>https://docs.hoppe-sts.com/docs/hoppe_signal_quality</u>.

An essential aspect of implementing such rules was ensuring that they provide timely feedback on data quality. This is critical to enable early maintenance and monitoring of data quality, so that errors and inconsistencies are identified immediately rather than days or weeks later during downstream data analysis. The corresponding metrics are calculated automatically and consolidated for each signal and each vessel. This allows for a targeted evaluation of signal quality across the fleet, enabling operators to identify and prioritize critical vessels or measurement points within the monitoring process.

One limitation of this method is that potential error sources outside of actual sensor operation—such as inappropriate sensor selection or inadequate system design—are not fully addressed. These issues typically arise during the planning and design phase and are often difficult or even impossible to correct retrospectively. In the following chapters, we will present examples of such cases and outline what should be considered to prevent these issues from occurring in the first place.

3. Identifying Measuring Points with Energy Flows

In our view, the recording of energy flows on board forms the foundation for most performance analyses and sensor-based reporting. Therefore, energy flows must be clearly identified and understood to enable the proper planning and installation of the required infrastructure.

The recording of energy flows using Maritime IoT (MIoT) requires that these flows be systematically identified and structured. This section focuses on identifying the most relevant energy flows, forming the basis for the selection of appropriate MIoT sensors and the overall system design.

Due to the wide variety of propulsion and power supply systems – ranging from conventional directdrive setups to diesel-electric configurations – we adopted a simplified visualization method using Sankey diagrams.

3.1. Energy Flows Illustrated Using Sankey Diagrams

To provide a reference for the following chapter, we present two examples of Sankey diagrams, Fig.3, for a typical container vessel equipped with direct propulsion and shaft generator. One diagram offers a highly detailed breakdown of energy flows, the other presents a more simplified view. The figures shown are qualitative and partially based on operational experience and reasonable assumptions.

The Sankey diagrams include the following elements:

- Color-coded energy forms:
 - Red: Chemical energy
 - Blue: Mechanical energy

- Yellow: Thermal energy
- Green: Electrical energy
- A standardized starting point for energy input (e.g., bunker station or shore power connection)
- A simplified representation of energy losses and conversion efficiencies



Fig.3: Typical energy flows of a container vessel

Sankey Diagram #1 in Fig.3 (left) illustrates a highly detailed energy flow breakdown. It reflects a scenario that would require the installation of extensive sensor and measurement equipment. This diagram is intended to demonstrate what is technically feasible through the installation of various sensors. Sankey Diagram #2 in Fig.3 (right) shows a simplified and commonly used measurement setup, from which basic energy flows can be derived. This can typically be achieved by:

- Measuring fuel flow to the main and auxiliary engines
- Monitoring shaft power from the main engine
- Recording electric power generation and selected consumers (especially those relevant for CII deductions)

The primary difference between the detailed and simplified diagrams lies in the presence of additional instrumentation, such as electrical measurements taken at multiple points within the power distribution network and detailed thermal measurements, including those of cooling water, steam, and exhaust heat. As seen in the second Sankey diagram, a significant portion of the used electricity and heat remains unaccounted for, leaving substantial uncertainty in terms of further optimization potential. Since the simplified setup reflects the current standard, the following chapter will focus on the measurement methods commonly applied in such configurations. However, it is important to keep in mind that even this standard approach leaves many open questions and may overlook potentially critical areas of improvement. This simplified setup will serve as the basis for the next chapter, which focuses on MIoT sensor selection and system design.

4. MIoT Sensors and System Design

This chapter presents suitable measurement technologies and system design approaches for the energy forms identified in Chapter 3. The focus is on the measurement of chemical energy (fuel), mechanical energy (shaft power), and electrical energy—all of which can be captured using MIoT-based sensors and interfaces. The aim is to introduce the most relevant measurement techniques and to highlight the advantages and disadvantages of various technologies and system architectures. Keep in mind that poor measurement techniques or inadequate system design often led to low data quality, even when the sensors themselves function correctly and perform reliable.

4.1. Measurement of Chemical Energy (Fuel)

The key measurement parameter is the energy input to the main consumers, especially the main engine, auxiliary engines, and the boiler. These measurements form the basis for energy balancing and enable further analyses of efficiency and potential losses.

Note: A direct measurement of the fuel's energy content is currently not technically feasible. Instead, fuel consumption is measured, and the corresponding energy flow is derived through calculation. This conversion relies on known fuel parameters such as density, calorific value, and sulfur content. At present, there is no internationally standardized method for the real-time determination of chemical energy.

The calculation of chemical energy, as well as derived values such as CO₂ emissions, remains one of the greatest challenges in performance analysis and emissions reporting, as it depends on manual input at certain stages of the process.

Measurement Technology: There are two common methods for measuring fuel flow, using the following techniques:

- Mass flow measurement (e.g., Coriolis principle), Fig.5: Preferred due to high accuracy and • independence from density and temperature.
- Volumetric flow measurement: Recommended only in exceptional cases, as it requires manual input of correction parameters (e.g., density), leading to a higher risk of inaccuracy. Used e.g. for small consumers using only one fuel type.

System Design: The appropriate measurement strategy depends heavily on the layout of the fuel system. In practice, three typical configurations have emerged:

- Flowmeter in feed line: Single-point measurement in the supply line to the circulation system •
- Flowmeter in circulation line: Supply and return line measurement, with consumption calculated via differential flow
- Mixed Flowmeter setup: Measurement at a shared treatment system, e.g., in retrofitted systems where the main engine and auxiliary engines are supplied together



a) Flowmeter in feed line

Fig.4: Fuel Flowmeter System Design



Fig.5: Example of a Coriolis Flowmeter installation in circulation lines

Configurations 1 and 2 allow clear allocation of flowmeters to the consumption to a specific consumer. In configuration 3, however, dependencies between multiple consumers can occur, which may reduce measurement accuracy and complicate data analysis—as has been observed in past cases.

4.2. Measurement of Mechanical Energy (Shaft Power)

Measurement of mechanical energy is used to determine the power delivered to the propeller which drives the vessel and is a key parameter to evaluate the performance of the engine itself but also of the vessel.

Measurement Technology: Shaft power is determined by combining torque and rotational speed measurements:

- Torque: Indirect measurement via torsional deformation of the shaft
 - Measurement principles: optical, mechanical, or electrical
 - Example: MAIHAK, Fig.6 frequency changes in vibrating strings correlate with shaft elongation
- Rotational speed: Typically measured via Hall sensors



Fig.6: Measuring principle of MAIHAK: torsional deformation measured using two vibrating strings

Note: External factors such as temperature and shaft bending must be compensated for and should always be considered when planning to install a shaft power meter. The MAIHAK system, for example, uses two sensors to avoid temperature influence and a short measuring distance to minimize influences from bending.

System Design: In standard shaft systems, the design is straightforward. However, complexity increases in systems with:

- PTO/PTI configurations (e.g., shaft generators)
- Multiple mechanically coupled engines
- Gearboxes between engine and shaft

4.3. Measurement of Electrical Energy

The measurement of electrical energy can be applied to both energy producers and consumers and relies on well-established, reliable sensor technologies.

In retrofit applications, we primarily use:

- Current transformers (e.g., Rogowski coils)
- Voltage measurement

The combination allows the calculation of active power, reactive power, and energy consumption.



Fig.7: Measurement of electrical power from an auxiliary engine using Rogowski coils

The system design depends heavily on the layout of the electrical system. Currently, targeted measurement of specific generators or consumers is commonly used, such as:

- Auxiliary engines
- Shaft Generators
- Shore connections
- Cargo related consumers like reefers, cargo pumps, and cooling systems (particularly relevant for CII corrections)

5. Data Processing

Data processing becomes essential as soon as data needs to be stored and made available for other applications, making it a central component of the Maritime Internet of Things (MIoT).

5.1. Data Processing Steps

Our so-called "Data Highway" outlines our approach and illustrates the typical data processing workflow on board—from data acquisition at the sensor terminal to its provision in a cloud database.



Fig.8: A typical data processing chain for sensor data.

Overview of major processing steps:

- Sensor and Systems Data Acquisition: Raw data is captured directly from sensors, automation systems, or bus systems.
- Onboard Data Storage: Data is stored in an onboard database, typically at a fixed sampling rate. At this stage, minor filtering and aggregation may already be applied.
- Optional Onboard Interfaces: Data can be made available locally via interfaces such as REST, MQTT or Modbus, for example to feed electronic logs (eLogs), reporting tools, or other performance monitoring applications.

- Export and Encryption: Data selected for export is retrieved from the local database, aggregated to reduce the data volume, and encrypted to ensure secure transmission.
- Data Transfer and Cloud Storage: After transmission, the data is decrypted and stored in a cloud database.
- Cloud Interfaces: The cloud-stored data is then accessible via APIs for analytics, reporting, or visualization purposes.

5.2. Challenges in Filtering and Aggregation

To reduce data volume, filtering and aggregation are applied at two key points:

- At the sensor level, where sensors may be polled at a higher sampling rate (e.g., 5 Hz), but data is stored at a lower frequency, such as every second.
- Prior to export, where aggregation is used to minimize the amount of data to be transmitted.

Export aggregation carries the risk of losing or distorting relevant information if the applied filtering methods are not appropriate for the nature of the signal.

A common example is average filtering (AVG): while useful for aggregating continuous signals, it can lead to significant misinterpretations for other signal types. Examples include:

- Counters: Averaging leads to incorrect values, as one would typically expect the latest (or final) value of the counter.
- Heading data: Circular averaging is mathematically invalid, especially when the heading is near north (e.g., around 0°/360°).
- Position data: Like counters, averaging position data can lead to misleading or unexpected values.
- Outliers and spikes: These can be smoothed out and go undetected, potentially masking underlying issues.

5.3. Impact of Aggregation Interval

The aggregation interval used during data export significantly influences the meaningfulness of the resulting dataset and the analysis of signal quality. A 15-s summary differs greatly from a 1-minute or 5-minute aggregation – both in terms of temporal resolution and correlation between signals.

In many cases, shorter aggregation intervals are advantageous, as they preserve more detail and reduce information loss through smoothing. However, shorter intervals also increase the impact of time-decoupled signals on the analysis, as is often observed when, for example, fuel consumption is measured in the feed line. This can make data quality analysis more challenging, particularly when evaluating dissimilarity between signals.

Therefore, filter types and aggregation intervals must be chosen carefully and tailored to the characteristics of each signal.

6. Maintaining Data Quality

As outlined in the previous chapters, we consider it essential to continuously monitor data quality and to carry out timely corrections or repairs when necessary.

Unlike manual reports, which can often be revised even months later, manual correction of sensor data is generally not possible—and typically not desired, as such systems are deliberately designed as "black boxes". Often the architecture ensures protection against manipulation and guarantees traceability in operational use.

To highlight the practical relevance of data quality, we present several examples experienced in the last 12 months that have impacted signal quality. These examples are not limited to classical technical defects but also include systemic or operational issues that are often more difficult to detect.

6.1. Practical Examples

- Volumetric flow meter without density correction When the fuel type is changed, significantly incorrect SFOC values may result due to faulty volume-to-mass conversion.
- Fuel line bypass accidentally opened Part of the fuel bypasses the flow meter, consistently leading to an underestimation of fuel consumption.
- Sensors or third-party systems freeze or crash Signals become stuck or disappear entirely. Typical causes include communication errors or software failures.
- Software updates in external systems Changes to data protocols or disabled settings result in signal loss or incorrect values—often without prior notice.
- Loose connectors or damaged cables Cause intermittent sensor failures or data gaps in recordings.
- Replacement of hardware components (e.g., ECDIS device) Certain NMEA messages are no longer transmitted after replacement, leading to missing data.
- Changes in the onboard network infrastructure Network modifications by administrators (e.g., IP conflicts, VLAN adjustments) can block data transmission.

These examples illustrate the wide range of potential issues that can negatively impact data quality. Notably, many of these issues are not purely technical in nature but stem from human error, poor communication, or unclear responsibilities.

For instance, during a hardware retrofit, the data format or communication protocol may change without notifying downstream systems. Analysts or controllers may observe missing or implausible values—without any information about the root cause.

6.2. Approaches to Data Quality Management

To ensure consistently high data quality, two key success factors are particularly critical from our perspective:

A Technical Infrastructure for Continuous Monitoring: It is essential to establish suitable methods, metrics, and analysis procedures that meet operational requirements and allow comprehensive monitoring of all relevant signals. The goal is to identify errors or anomalies early and initiate corrective actions without delay. As described in Chapter 2, various approaches and tools are available for this purpose and can be applied flexibly depending on system architecture and data requirements.

A Clear Communication Structure Among All Stakeholders: In addition to technical monitoring, reliable and transparent communication between all involved parties is crucial. Especially in complex shipboard systems with numerous data sources and interfaces, it is essential that all stakeholders are informed about changes and interventions in a timely manner.

Relevant stakeholders include in particular:

- Crew on board
- Technical Inspection and vessel managers
- IT managers and administrators
- System integrators and service partners
- Analysts and controllers on shore

Only when information about maintenance, issues, and operational measures is communicated consistently and systematically can the overall integrity of the data system be maintained in the long term.

A functioning data quality management system is therefore always based on the interplay between technical monitoring, organizational communication, and clearly defined responsibilities.

7. Conclusion and outlook

This paper has described how systematic acquisition, processing, and evaluation of onboard sensor data—particularly related to energy flows—can be done for operational optimization and emission reporting in the maritime sector. The Maritime Internet of Things (MIoT) provides the technological framework to implement such data infrastructures as a flexible foundation to connect many different sources of data and sensors itself.

However, the value of such data is entirely dependent on its quality. As shown, maintaining high data quality is not only a question of proper sensor operation but also of system design, correct configuration, and ongoing monitoring. Data quality must therefore be considered not only during the planning and installation phases but throughout the operational lifecycle of a vessel.

At present, many energy flows on board remain unmeasured, as they are not yet relevant for current analyses or regulatory requirements. However, we should strive for a more holistic understanding of energy-efficient ship operation through comprehensive measurement of all relevant energy flows. As regulations continue to evolve, improving the accuracy and coverage of these measurements will be essential for identifying and assessing energy-saving potential in the mid- to long-term.

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Hybrid Fuel Cell and Battery Powertrain Modelling and Testing for ACUA Pioneer USV

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Abstract

Through the UKs Clean Maritime Demonstration Competition, a demonstration vessel has been built and will be trialled in Plymouth in March 2025. The Uncrewed Surface Vessel (USV) Pioneer is a Small Waterplane Area Twin Hull (SWATH) whose mission is to provide underwater survey support through its reduced motions and large moonpool area. The vessel uses electric propulsion from two rear-mounted three-bladed propellers at the end of each hull and is powered through a hybrid battery and hydrogen fuel cell system. The aim of this paper is to compare a variety of potential power system configurations, including proportions of power supplied by shoreside charging of batteries that can work in combination with the fuel cell. A time domain-based voyage analysis is used for the comparison to evaluate the voyage energy consumption, including the influence of sea state, based on the Pioneer's tank testing and design data. A final part of the paper will include a comparison of the actual time domain measured data from demonstration trials in March with the predicted energy use for the same voyage.

1. Introduction

The International Maritime Organisation (IMO) initially upgraded guidance on emissions regulations and reductions for all vessels across the globe with MEPC 80, *IMO (2023)*, proposing new, more ambitious shipping targets to meet interim emission reductions (20% by 2030, 70% by 2040) and the long-term aim to reach net-zero emissions by 2050. The same initiative was confirmed through MEPC 81, yet the United Kingdom was one of the first to target the elimination of local shipping activities through the introduction of the Clean Maritime Plan, *CMP (2019)*.

To achieve these goals, new vessel builds are required to be mostly zero carbon from 2030-2035 onwards, *Smith et al.* (2021). In general, the maritime industry is conservative in adopting new technologies because of the need for exceptional levels of reliability. The long lifetime of newly built vessels is generally expected to be at least 25 years, *NN* (2020), which requires confidence that decisions made regarding net zero energy sources are future-proof. Regardless of the new fuels selected, a corresponding transition in the bunkering supply and energy infrastructure will be required.

All liquid fuels currently used throughout the maritime sector are remarkable fuels, with only 15-20% of their embedded energy being consumed during production and refining, leaving the great majority of the energy available for useful work, although there are additional transportation losses, *Hall et al.* (2009,2014), *Hawkins Kreps* (2020). The same fuels also offer high volumetric energy density (kWh/L), which is preferred, yet increased volume only has a small influence on propulsive power, *McKinlay et al.* (2024). Fossil fuel tanks only occupy a small fraction of a ship's displacement and volume, *McKinlay et al.* (2020). Understanding and quantifying the whole fuel supply budget in terms of greenhouse gas (GHG) emissivity and the amount of energy input required per GJ delivered to propel and power a ship is essential.

Hydrogen fuel cells combined with battery systems have emerged as promising solutions for clean maritime propulsion, offering the prospect of achieving zero onboard emissions alongside enhanced operational efficiency. Traditionally, these technologies have predominantly been investigated for their applicability in larger, crewed vessels. Nevertheless, small Unmanned Surface Vessels (USVs)

also benefit significantly from such innovations, particularly due to their operational profiles and scale-specific demands. However, the environmental sustainability and economic viability of fuel cell–battery hybrid systems at this reduced scale remain understudied and constitute a significant knowledge gap.

In addressing this gap, the central research question posed by this study is whether fuel cell and battery hybrid power-train systems are economically and environmentally viable for small autonomous maritime vessels. Specifically, the research focuses on a real-world demonstrator: the ACUA Pioneer USV, a 14-metre autonomous vessel equipped with a hybrid propulsion system comprising hydrogen fuel cells and batteries. This study aims to evaluate the operation of this hybrid power-train system, with a methodological approach that was recently developed for a Wind-to-Wake assessment methodology, *Manias et al. (2024)*. To our knowledge, this constitutes the first practical application of the framework within an operational USV demonstrator context, marking a notable advancement in maritime decarbonization research.

While the carbon dioxide equivalent emissions (tCO_{2equiv}) from vessel operations are frequently the primary focus of environmental assessments, it is crucial to recognize the broader spectrum of maritime emissions. Pollutants such as nitrogen oxides (NO_x), sulphur oxides (SO_x), and particulate matter (PM) significantly degrade local air quality and pose substantial health risks to populations in proximity to maritime routes and port areas. Funnel emissions, in particular, have been documented to severely impact local environmental conditions, *Gössling et al. (2021)*, contributing notably to air pollution and responsible for approximately 4.2 million deaths annually. Maritime shipping alone accounts for roughly 15% of global NO_x and SO_x emissions and approximately 2% of global PM emissions, *César et al. (2015)*, *Amoatey et al. (2019)*.

2. Background

Maritime decarbonisation is part of a global decarbonisation effort aimed at reducing greenhouse gas emissions, which is giving rise to the global warming phenomenon. The initiative was made official by the United Nations (UN) Paris Agreement. All members agreed that global warming should be limited to $+2^{\circ}$ C for temperature increase. The IMO, which forms part of the UN's regulatory framework, imposed strict emissions regulations for shipping, aiming for net zero emissions by 2050, *IMO* (2023).

To achieve the net zero ambition, new vessel builds are expected to be mostly zero carbon from 2030 to 2035 onwards. This view is further promoted through the FuelEU directive, <u>https://transport.ec.</u> <u>europa.eu/transport-modes/maritime/decarbonising-maritime-transport-fueleu-maritime_en</u>, where a steady decrease in emissions per unit of energy consumed through the fuels' entire lifecycle must be attained with a final total emission reduction target of 80% by 2055. The maritime industry is expected to be rather hesitant towards adapting to the new fuels and technologies proposed, with its conservative stand resulting from exceptional reliability requirements.

At the same time, with new built vessels generally expected to reach a 25-30 year lifetime, *Bijwaard* and Knapp (2009), confidence is required when making such decisions regarding net zero energy sources. At the same time, a corresponding transition in the bunkering supply and energy infrastructure will be required. It is expected that renewable energy will be employed as a method for producing new fuels instead of carrying on with the utilization of fossil fuels, a continuously depleting source, as indicated by the global Energy Return On Investment (EROI) Index, *Hall et al.* (2009,2014), aside from damaging towards the environment and our population. At the same time, renewable energy sources appear to be a better option in terms of cost per unit of energy provided, *Timilsina* (2021). Consequently, it is essential to undertake objective LCAs for each proposed fuel and powertrain system to identify the fuelling strategy that minimizes the requisite input of renewable energy. Despite its continuously expanding share within the global energy portfolio, the efficient utilization of renewable energy remains critical due to its scarcity compared to conventional fossil fuels. Typically, a comparison of alternative and zero or low-carbon fuels is achieved by predicting

the likely fuel cost (e.g., \$/kg) in the utilisation phase, *Fasihi et al.* (2021), *Harris et al.* (2021). Although this is commonplace for existing fuels, significant uncertainty is involved when this practice is applied to future fuels due to the lack of data to the same extent as fossil fuel distribution networks.

To decrease the uncertainty expected with future fuel predictions, it is proposed to compare the amount of energy required to produce each low or zero-carbon fuel. This is the concept behind the "Wind to Wake" approach, *Manias et al.* (2024), of assessing each fuel according to its total energy requirement along with its subsequent net emissions. Wind is chosen rather than solar, as its embedded CO_{2equiv} footprint required to capture renewable energy from wind is less than solar, *Voorspools et al.* (2000). The study introducing this "Wind to Wake" concept, *Manias et al.* (2024), applied this assessment, finding that hydrogen is the most promising alternative fuel for total renewable energy requirement and total lifecycle emissions, making it an ideal fuel for the USV Pioneer.



Fig.1: Schematic of the process to supply renewable energy onboard an identical ship ordered with increasing WtW ratio. Note that H₂ production is necessary for both e-Ammonia and e-Methanol production.

With an exceptional fuelling source selected to power the USV examined, the boat is also expected to have an equally innovative design. It was decided to produce a Small Waterplane Area Twin Hull (SWATH) vessel due to its superior performance in terms of stability compared to other vessel designs, *Gore (1985), Gupta and Schmidt (1986), Miller (1991)*. The stability is crucial for deploying equipment remotely from the vessel, reducing operational errors compared to a monohull vessel equivalent. The powertrain utilised onboard the USV Pioneer is of equal importance, comprising a Proton Exchange Membrane Fuel Cell (PEMFC) and batteries, which provide high levels of autonomy, as expected by a USV.

With the highly innovative vessel design and fuel supply chain accompanying it, this study aims to forecast the energy demand and fuel consumption of the USV pioneer, for various operational profiles. These case studies will be divided into short-, medium- and long-distance, with various sea states, while the recorded data from the USV pioneer will be used as benchmark, to estimate the final error of the theoretical model developed.

3. Methodology

3.1. USV Pioneer operational assessment methodology

The vessel was being built during the time the tools for assessments proposed, were fabricated. This was done to carefully assess the energy requirements expected for the USV pioneer, prior to installing the appropriate powertrain onboard. The method employed, through which the final powertrain was proposed, is as follows:

- Collect data from towing tank tests conducted on the vessel's model scale hull.
- Extrapolate from the data set collected the power demand values expected for the subsequent target speed in various sea states.
- Include all powertrain efficiency losses throughout the vessel's powertrain by examining each propulsion component individually (e.g., propellers, electric motors, etc.).
- Develop a "voyage compiler" tool to recreate sailing routes of preset distance while also accommodating the various sea states expected.
- Create a powertrain simulation of operation to calculate response rates, consumption and emissions of the suggested powertrain meant to be applied.
- Compare results of the theoretical model with the data recordings gathered from the real vessel.

The two tools, resulting as part of the methodology, were used for developing three different operational scenarios, divided into short-, medium- and long-distance sailing routes, with the long distance sailing route examining an upscaled version of the USV Pioneer under different powertrain configuration.

3.2. USV Pioneer system components

The USV Pioneer, developed by ACUA Ocean Company, is a state-of-the-art Small Waterplane Area Twin Hull (SWATH) vessel optimized for autonomous operations in offshore applications, with the aim of reducing vessel motions.



Fig. 2: The USV Pioneer - Autonomous SWATH Vessel

The vessel's design focuses on minimizing wave-induced motions, ensuring the safe deployment and retrieval of remotely operated vehicles (ROVs) even in challenging sea states. This characteristic makes it ideal for operations in the North Sea offshore oil rig platforms and offshore wind farms. Table I summarises the key dimensions of the USV Pioneer autonomous vessel.

Parameters	USV Pioneer	Units
Overall Length	13.5	m
WL Length	12.25	m
Beam max extents on WL	9.25	m
Draft Amidships	1.6	m
Displacement	24.065	tons
Cut Water Plane Area	5.01	m ²
Service Speed	4.0	Kts
Payloads	4.0	tons
Fuel Cell		
- Rated Power	2 x 45	kW
- Specific fuel consumption	55	g/kWh
- Stack Estimated Lifetime	>20,000	hrs
- Weight	200	kg
- Peak Efficiency	58	%
Battery (Li-ion 21700)		
- Nominal Energy	2 x 63	kWh
- Discharging Power	250	kW
- Weight	2 x 393	kg
- Nominal Voltage	364	V
- Operating Voltage (min.)	297	V
- Operating Voltage (max.)	407	V
- Expected Service Life	3000	Cycle
Hydrogen Storage		
- Carbon Fiber composite tank	6 (+3)	420L each at 350bar (9.96 kg) of Hydrogen Capacity
E-motors	2 x 124	kW

Table I: Dimensions of the USV Pioneer.

The vessel is designed with a hybrid propulsion system combining Proton Exchange Membrane Fuel Cells (PEMFCs) and lithium-ion batteries. This energy-efficient centric system utilizes compressed hydrogen (H₂) as its primary fuel source. With two installed PEMFCs, yielding a combined capacity of 45 kW each and two 63 kWh lithium-ion batteries, the USV Pioneer achieves optimal performance at a cruising speed of around 4.0 knots. Unlike other vessel case studies, the fuel cells employed on board the USV Pioneer, are meant to serve as battery preservers, not as the main demand responders.



Fig.3: Fuel Cell Electric Powertrain of the USV Pioneer

The main control panel is responsible for managing and directing the power output of the fuel cell to the battery and from the battery to the propulsion powertrain. Important to note is how the battery typically acts as a "buffer" between the fuel cell and the vessel's propulsion power demands, yet this is not the case for the USV Pioneer. That said, a simulation will be carried out where the USV Pioneer's powertrain will operate as such.

The vessel's propulsion system and energy requirements are calculated using parameters provided in Table II. The calculations incorporate wake fraction, thrust deduction, relative rotative efficiency, open water efficiency, and transmission losses to determine ship-delivered power, service power, and installed brake power. The equations used for these calculations are outlined below:

Table II: Parameters for power calculations					
Wake fraction	0.0047	w_T			
Thrust deduction	0.0012	t			
Relative rotative efficiency*	1	η_R			
Open water efficiency*	0.5	η_0			
Transmission losses*	0.98	η_T			
Sea margin [*]	0.3	-			

Table II: Parameters for power calculations

*Assumed values

The following equations are used:

$$\eta_{H} = \frac{1-t}{1-w_{T}} (1)$$

$$\eta_{D} = \eta_{H} * \eta_{R} * \eta_{O} (2)$$

$$P_{D} = P_{E}/\eta_{D} (3)$$

$$P_{S} = P_{D}/\eta_{T} (4)$$

$$P_{I} = P_{S} * sea margin (5)$$

 η_H is hull efficiency, t is thrust deduction factor and w_T is wake fraction. η_D is propulsive coefficient, P_D is delivered power, P_E is effective power, P_S is service power, and P_I is installed power.



Fig. 4: ACUA Vessel expected service power for the subsequent sailing speed. Note: The service power results from the towing tank testing recordings of the model scale hull after considering the total system efficiency losses from the propeller to the fuel cells.

The relationship between vessel speed and service power was analysed using polynomial fitting methods to better understand the power demand as a speed function. A third-degree polynomial was selected as the best fit based on its high R^2 value (0.9947), which captures the data's non-linear behaviour.

The equation derived from the polynomial fitting is:

$$P_{S} = 0.1137 \times v^{4} - 0.245 \times v^{3} - 0.502 \times v^{2} + 1.3113 \times v - 0.0217$$
(6)

where P_S is the service power in kilowatts (kW) and v the vessel speed in knots. This equation can be used to estimate the service power requirement for vessels with speeds up to 10 knots.

3.3. USV Pioneer powertrain simulation of operation

A time-domain-based model of powertrain operation, coded in Python, which follows a bottom-up approach, assesses the energy supply requirement to propel the ship for a specified energy demand allows the comparison of the voyage consumption and emission profile for the fuel selected. Such approach has been used previously to evaluate several vessel case studies and types, *McKinlay et al.* (2021), *Manias et al.* (2024), *Turnock et al.* (2024). The same approach is adopted here, except that the recording time step was refined to 1 s, allowing the time response of the various components to be captured in detail.

Depending on the power demand on board, the target power, P_{target} output for the fuel cells is altered. The target power for the fuel cell (Eq.7), is firstly set according to the "on-going" demand, where the time step for the code's domain is set according to the desired operational mode (steady state or dynamic load following).

$$P_{Target} = avg(P_C, P_{C-n})$$
(7)

 P_C is the current time recording processed within the main code; P_{C-n} is the power recording processed *n* seconds ago. Depending on the time interval *n*, Fuel cells can operate in either dynamic following mode or a steady state, depending on *n*, as the frequency of change in the target power is initially set by it and then according to the batteries' state of charge.

The following equations are used within the code to set up the power ramping rates and fuel consumption, which are the result of data made available by a marine fuel cell manufacturer, *NN* (2024), and the battery characteristics are provided by *Kaur et al.* (2022), *Turnock et al.* (2024):

$$P_{Battery} = P_{max} * \tanh(0.5 * t)$$
(8)
$$P_{FuelCell} = P_{max} * \tanh(0.12 * t^{0.8})$$
(9)

t is time (s); $P_{Battery}$ is the power output for a battery (kW); $P_{FuelCell}$ is the power output for a fuel cell (kW); P_{max} is the maximum rated power of the device (kW). The same equations can be used for estimating the time required for the powertrain system to meet the demand required. The structure is as follows:

$$\frac{P_{FuelCell}}{P_{max}} = \tanh(0.12 * t^{0.8})$$
$$\tanh^{-1}\left(\frac{P_{FuelCell}}{P_{max}}\right) = \frac{3}{25} * t^{\frac{4}{5}}$$
$$\frac{4}{5}\ln(t) = \ln\left(\frac{25}{3} \tanh^{-1}\left(\frac{P_{FuelCell}}{P_{max}}\right)\right)$$
$$t = \left(\frac{25}{3} * \tanh^{-1}\left(\frac{P_{FuelCell}}{P_{max}}\right)\right)^{\frac{5}{4}} (10)$$

t is the time expected for the fuel cell to reach its maximum power rating, from a given output.

The specific fuel (in g/kWh_e) for a given power output of the fuel cell system, can be found in:

$$s. f. c._{PEM} = 80 * p^4 - 240 * p^3 + 244 * p^2 - 88.8 * p + 61.943 (11)$$

p is the loading ratio of the fuel cell units, expressed as a ratio of their instantaneous power output to their maximum rating.

Since the batteries act like buffers in the current powertrain proposition, the state of charge is set by:

$$P_{Battery} = P_{tot} - P_{FuelCell}$$
(12)
$$SoC_{1} = SoC_{0} - \frac{P_{Bat} * \delta T}{n}$$
(13)

 P_{tot} is the total power demand on board, *SoC* is the batteries' state of charge and δT is the time passed for a given interval. Each interval is set when the power of the fuel cells exceeds or succeeds the power demand of the vessel, until it does not. Finally, the fuel cells are set to dynamically ramp their power output, according to the batteries' level of charge or according to the level of power demand with respect to the fuel cell's minimum and maximum power output. Two separate simulations were carried out, to investigate how the different fuel cell operational technique affect battery demand.

This is done via "*If*" loops connected to set operational "response" modes within the python script. One example of such an operational mode is where the fuel cells are set to maximize their power output when the level of charge is below 60%, while the follow-up response mode targets the optimum fuel cell power rating for when the level of charge is above 75%. Based on the same "if" loop concepts and associated response mode again, fuel cells are set to respond by reducing power output to their minimum when batteries reach 90% charge. For the main vessel case study however, the fuel cells will only be operated at their minimum rated power output. It is only in the latter case study which the full capabilities of the "*If*" loops and the set operational "response" modes will be showcased.

3.3. Sea-State Criteria

The USV Pioneer vessel is expected to operate under different sea state conditions over the year, even for the same route selected. Different wave heights and periods will be examined as part of the expected sea states the USV Pioneer will undergo. A numerical seakeeping model of the SWATH is used to evaluate added resistance in waves, based on data collected from model scale towing tank tests, for a number of representative sea states based on wave statistics in the region of operation. The results are used to generate a representative 1-hour time series of the added resistance, which is then incorporated into the voyage model. The 1-hour time series is repeated for the full duration of each voyage developed.

For the short routes, where the vessel is expected to be tested, the sea state will be that of calm waters while for the projected service trip between Plymouth and Scilly Isles, an extreme sea state is also considered, based on the relevant weather criteria and data collected.

3.4 Voyage compiling tool

For the various operational profiles examined here, required the development of a voyage compiling tool, meant for replicating realistic sea states for each of the voyages examined. This tool is based on the data collected from the USV Pioneer's model scale testing with separate power demand profiles developed relative to the expected service conditions of the USV Pioneer. Some examples include: Port Idle, Manoeuvring, Slow speed sailing & intermediate speed increase whilst leaving port, Sailing with various sea-states included as per route case study examined, and Approaching Port.

4. Results:

4.1 Short distance, calm water operational profile

A representative testing route is expected to be calm weather sea state, within a well-protected area, with a total distance of \sim 42 miles. The USV Pioneer's power profile, as a result of the target sailing speed (4-4.2 knots).



Fig.5: Power demand forecast for target speed and operation during short route operation(top). Magnified view of operational demand during sailing (bottom left) and while leaving port (bottom right)



Fig.6: Battery and fuel cell power output (left) with subsequent State of Charge (right). Note: As per the USV Pioneer's operational characteristics, the battery serves as the main demand responder, supplying the vessel's energy, until a SoC of below 30% is reached, which is when the fuel cell stacks are switched on.

The USV Pioneer's powertrain is expected to utilize the fuel cell stacks as preservers for the main battery. This suggests that fuel cells will be operated at a steady state, once the batteries reach a battery State of Charge, below a preset value, in this case 30% of its total rated charge capacity. Again, this is achieved through the implementation of "if" loops within the main Python script used to simulate the powertrain operation. The total consumption for this trip was 1.17 kg of Hydrogen, as well as 88.2 kWhe from the battery.

4.2. Medium distance, bad-sea state operational profile

The sea state criteria for which the USV Pioneer was examined, were for an extreme scenario (Jonswap Spectrum $T_0=4s$, $H_{1/3}=2.0m$). The added resistance was determined for a 1-hour time segment, which was then repeated for the duration of the voyage.



Fig.7: Power demand forecast for target speed and operation during medium distance route (Plymouth to Scilly Isles) operation, at rough sea state (left). Magnified view of operational power demand fluctuation during sailing (right).

The total trip was almost 120 nm, and final hydrogen consumption of the vessel was 11.2 kg of Hydrogen and 98.9 kWhe from the battery, which was needed to complete the round trip between Plymouth and Scilly Isles. Again, the fuel cells were set up to operate as battery preservers, constantly operating at 11kW, which for the bad sea state examined in this scenario, is not sufficient.



Fig.8: Battery and fuel cell power output (left) with subsequent State of Charge (right). Note: As per the USV Pioneer's operational characteristics, the battery serves as the main demand responder, supplying the vessel's energy, until a SoC of below 30% is reached, which is when the fuel cell stacks are switched on. For the bad sea state scenario examined here, it appears that the USV Pioneer's powertrain is unable to rely just on the fuel cells' set power output, further discharging the battery, bellow its critical minimum.
4.3. Alternative Powertrain simulation of operation

The owners of the USV Pioneer decided to investigate the possibility of scaling up the current vessel to accommodate a higher cargo capacity on board. The case study selected would be one for a cargo route, serving between UK mainland and a remote island, 120 nm away. A regular sea state would be selected for this route (Jonswap Spectrum $T_0=10s$, $H_{1/3}=1.5m$). The upscaling would be completed by a factor of 2, with a consequent total volume of the vessel being 8 times bigger than the USV Pioneer, as the vessel volume is linked quadratically to the vessel's length increase.



Fig.9: Power demand forecast for target speed and operation during long distance cargo route case study examined, at regular sea state (left). Magnified view of operational power demand fluctuation during sailing (right).



Fig.10: Power demand forecast for target speed and operation during long distance cargo route case study examined, at regular sea state (top left). Magnified view of operational power demand fluctuation during sailing (top right). Fuel cell power ramp up whilst sailing away from initial port stay against power output (bottom).

It is assumed that the vessel's total structure mass will be scaled up by a conservative factor of 6 times instead of 8, as it is believed that less structural reinforcement will be used per unit of volume. The powertrain itself, however, will be scaled up by a factor of 2, as the powertrain of the current vessel is already significantly bigger than what is required for the vessel's needs. The batteries and electric motors sizing will remain the same for the same reason. Fuelling capacity is required to increase drastically, as the power demand is also expected to increase 10 times. At that point, the vessel would benefit from liquid hydrogen storage placed within the vessel's hull, yet this would require a different fuel production plant. The round voyage was expected to take 240 nm each way, 110 h in total, as well as 506.3kg of H_2 .

5. Conclusion

The USV Pioneer is expected to serve many purposes during its service. As its name suggests, the vessel is pioneering in many aspects surrounding its operation, from its fuel supply relying on hydrogen, to its remotely operated powertrain onboard being comprised of fuel cells and batteries. Previous studies examining the most suitable future fuel used the powertrain simulation of operation applied in this study. Despite, the final consumption values gathered being relevant to the efficiency of the fuel cell battery powertrain, it is deemed important to benchmark simulation results with actual data gathered from a real hydrogen powered vessel.

As the USV Pioneer's powertrain is expected to operate in a conservative manner, with the fuel cells' serving as energy preservers to the batteries which act as the main demand responders, the simulation of powertrain operation examined, is simplified when compared to other case studies examined in the past.

Finally, the same fuel cell operation of simulation employed in other case studies is used to predict fuel consumption for an upscaled version of the USV Pioneer, showcasing the fuel cells acting as the main power responders instead of the batteries and indicating how demand is still successfully met.

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Exploring Data-Driven RUL Methods for Marine Systems Using a Lab-Scale Ship Machinery Plant

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Abstract

Accurate prediction of the Remaining Useful Life (RUL) of ship systems is essential for maritime safety, reliability, and cost-effectiveness. Traditional RUL research relies on simulated and historical data, lacking hardware-based failure data. To address this, Dr. Stephen A. Olson developed a lab-scale electric ship machinery plant at the University of Michigan, featuring various systems and real-time control. This study aims to: evaluate current RUL techniques, like Long Short-Term Memory (LSTM) and Convolutional Neural Networks (CNN), using hardware-based data; and explore how the plant's data sources impact and can enhance RUL method development.

1. Introduction

Predictive maintenance has become a cornerstone of modern maritime operations, where accurate estimation of the Remaining Useful Life (RUL) of ship components is essential for ensuring operational safety, reducing costs, and improving efficiency. Traditional maintenance strategies in the maritime sector, such as reactive repairs and scheduled interventions, often result in unplanned downtime or unnecessary replacements, leading to significant financial and operational challenges. Recent advancements in sensor technology and data-driven modeling have paved the way for condition-based maintenance approaches, enabling more precise predictions of component degradation and failure timelines. This shift is particularly critical for high-value assets like azimuth thrusters, turbochargers, and diesel generators, which are subject to harsh environmental conditions and complex operational loads, *Velasco-Gallego et al. (2023), Kongsberg (2025a,b)*.

Despite these advances, accurate RUL prediction remains challenging due to the scale and heterogeneity of shipboard machinery. Many vessels employ manufacturer-specific monitoring protocols that silo sensor data, limit cross-system analysis, and force diagnostics to the component level. Additional challenges include satellite bandwidth constraints, sensor data loss, and inconsistent sampling rates, all of which complicate holistic vessel health prognostics.

This study utilizes the datasets developed by Dr. Stephen A. Olson, for his dissertation, whose work focused on an artificial intelligence framework to predict the operational availability of a laboratory-scale ship machinery plant, *Olson et al. (2022), Olson (2024)*. The data used in this study was generated from the Marine Engineering Laboratory at the University of Michigan. Olson's statistical methods demonstrated the feasibility of fault prognostics but were limited in their ability to address nonlinear trajectories and multimodal sensor inputs under variable maritime conditions. These limitations underscore the need for more sophisticated approaches capable of capturing complex temporal dependencies and spatial interactions within sensor data. Recent advancements in deep learning architectures offer promising solutions to these challenges by enabling automated feature extraction and improved temporal modeling.

Additionally, this study utilizing Olson's data and his case study on RUL, compares three advanced neural network architectures: an LSTM only model, an Auto-CNN-LSTM prediction model, and a Directed Acyclic Graph (DAG) network that combines CNNs with LSTMs, *Ren et al.* (2021), *Li et al.* (2019), *Yang et al.* (2022). The LSTM-based approach proposes a new method for predicting the remaining useful life of rolling bearings, using long-short term memory (LSTM) with uncertainty

quantification and a fusion metric for degradation monitoring, to address difficulties in real-time monitoring and external uncertainties, demonstrating its effectiveness with the PHM2012 dataset, *Yang et al.* (2022). The Auto-CNN-LSTM model integrates convolutional layers for spatial feature extraction with LSTM layers for temporal sequence modeling to extract deeper insights from limited data, *Ren et al.* (2021). Finally, the Directed Acyclic Graph (DAG)-CNN-LSTM hybrid model further enhances prognostic accuracy by explicitly modeling multivariate dependencies among sensors, *Li et al.* (2019). This makes it particularly effective for predicting wear propagation across interconnected components.

By extending Olson's initial work into a new era of adaptive machine learning frameworks, this study aims to bridge the gap between theoretical advancements and operational implementation in marine asset management. These advancements underscore the potential of adaptive neural architectures to overcome legacy fragmentation in maritime RUL prediction, providing a pathway toward fleetwide predictive maintenance frameworks. Subsequent sections detail the technical information on the deep learning models used, along with the integration of Olson's data and case study for reproducibility.

2. Background

The following sections will detail the necessary background for this manuscript. The following sections detail information about the Marine Engineering Laboratory, the data used for this study, and remaining useful life.

2.1. Marine Engineering Laboratory Testing Bed

The Marine Engineering Laboratory was designed and developed by Dr. Stephen A. Olson and Prof. Timothy McCoy at the University of Michigan's Department of Naval Architecture and Marine Engineering, *Olson et al. (2024)*. There are six coupled systems, which are combined together to emulate shipboard machinery systems. An image of the lab is presented below in Fig.1. For his thesis, Dr. Olson examined two of these systems to develop an initial prognostic system to identify when the platform would fail, *Olson (2024)*. These two systems were the cooling and the fueling systems.



Fig.1: The Marine Engineering Laboratory, located at the University of Michigan within the Department of Naval Architecture and Marine Engineering. There are a total of six interconnected systems: cooling, fueling, propulsion, mission, and control.

2.1.1. Cooling System

The cooling system depicted in Fig.2 features two parallel cooling circuits. Each circuit is equipped with a pump that circulates water through a 3kW electric heater. This heater is integrated with the propulsion system, allowing it to heat the water based on the output of the propulsion system, thereby simulating the thermal management of the propulsion components. The pumps intake water from a designated ocean tank and channel it to a separate tank designated for used water. Each cooling circuit is also designed to initiate faults on demand, as represented by the clog and leak valves. The clog

simulation valves can clog the pipe at various rates ranging from 0.025V to 0.2V. The leak simulation valves are binary concerning how much of a leak there is. Furthermore, the system includes pressure, flow rate, and current sensors. In Fig.2, the service pumps are fitted with current sensors, while sensors labeled P1_1, P1_2, P2_1, and P2_2 correspond to pressure measurement. Flow rate sensors are identified as F1_1 and F2_1, and temperature sensors situated on either side of the heaters are marked T1_1, T1_2, T2_1, and T2_2.



Fig.2: Cooling system diagram. Drawing contains available sensors and fault capabilities of system

2.1.2. Fueling System

The fueling system is designed with two parallel lines that mimic the process of fueling a propulsion system, as illustrated in Fig.3. Instead of using combustible fuel, this system utilizes water to replicate the characteristics of a traditional fueling operation. Each line is equipped with a pump that transports water through a pipe toward a diesel injection system. An injection pump pushes the water through a pipe to an injection simulation valve within each diesel injection system. The water, which is treated as if it were fuel, then passes through and returns to the storage tank. The mission control system controls the amount of water "burned" during this process.

To monitor the operation, the system includes various sensors that assess the status of its components. Each pump is fitted with a current sensor, and there is a pressure sensor located after each service pump, positioned before the clog and leak valves in each line. Following the clog and leak valves, a flow rate sensor and another pressure sensor are installed before the diesel injection systems. Inside the diesel injection systems, current sensors are attached to the injection pumps, with a flow rate and pressure sensor situated after the internal clog and leak simulation valves.

Moreover, the system incorporates fault simulation mechanisms akin to those in the cooling system, enabling faults to be induced on demand. These fault simulation valves mirror those found in the cooling system. The clog simulation valves can obstruct the pipe at varying rates from 0.025V to 0.2V, while the leak simulation valves operate in a binary fashion to signify the presence of a leak. Clog and leak valves are placed in each line after the service pumps, before the diesel injection systems, and within the diesel injection systems themselves after the injection pumps and before the injection simulation valves. This fueling system effectively emulates the functionality of an engine's fueling process while allowing for the intentional activation of faults.



Fig.3: Fueling system diagram. Drawing contains available sensors and fault capabilities of system

2.1.3. Run-to-Failure Datasets

Dr. Olson generated 300 total failure runs using the Marine Engineering Laboratory. These failure runs were based on a series of 100 failure profiles repeated for laboratory three operational profiles. Each failure run consisted of up to 10 10-s steady-state snapshots of the laboratory plant as it progressed towards failure as specified by its associated failure profile. For the 100 failure profiles, clog and leaks were randomly distributed amongst them. The failure progression for clogging failures for each failure profile was randomly distributed such that the laboratory plant would fail between the 7th and 10th sequence. Leak-based failures were designed to fail within the first five sequence points, as the leak-based failures in the plant caused the plant to rapidly fail. The distribution of these plant-wide failures is presented below in Fig.4 as taken from Dr. Olson's thesis *Olson (2024)*. In total, there were 68 clog-based failures and 32 leak-based failures. Due to being primarily interested in predicting the remaining useful life of the plant and the immediately visible effects of leaks in the plant, only the clog-based failures were used in the study presented in the following sections.



Fig.4: Sequence point failure distribution for the laboratory plant. The effects of the different operational profiles on the plant's sequence point failures can be clearly observed.

The three operational profiles defined the overall plant's settings during data collection. The operational profiles defined the load on the mission system, the propulsion rate, and the mean continuous power rating (MCR) of the generator system, which affected the waste heat rejection. These operational profiles are defined below in Table I. It can be noted that operational profile B had the largest waste heat rejection due to the electrical mission system's load being at 100% and the MCR of the generator system being at 97%. This is contrasted with operational profile 1 which places a comparatively light load on the propulsion system and no load on the mission system. In between these two operational

profiles, operational profile 3 set the propulsion rate higher than operational profile 2 but reduced the mission load to 0%, resulting in a waste energy percentage between operational profiles 1 and 2.

Tuble 1. Simulated Ship Operational Tromes				
Operational Profile	Mission Load	Propulsion Rate	MCR	Waste Energy
1	0%	20 Hz	47%	42%
2	100%	30 Hz	97%	100%
3	0%	60 Hz	82%	67%

Table I: Simulated Ship Operational Profiles

2.2. Remaining Useful Life

Remaining Useful Life (RUL) refers to the estimated time a machine or its components can operate before requiring repair or replacement. It is a critical metric in prognostics and health management (PHM) systems, enabling predictive maintenance strategies that optimize operational efficiency, reduce downtime, and minimize costs. RUL predictions rely on condition monitoring data, degradation models, and advanced algorithms to forecast machinery health and failure timelines, *Baru et al. (2023), Das et al. (2010).*

For rotating machinery, such as bearings and pumps, RUL estimation often incorporates techniques like vibration analysis, frequency domain transformations, and artificial intelligence models to detect anomalies and predict degradation patterns, *Huang et al. (2024), Mulay et al. (2022), Zhang et al. (2021), Nair et al. (2019).* These methods are particularly valuable in dynamic environments where operational conditions vary significantly, *Liu et al. (2024).*

Shipboard machinery operates under unique and demanding conditions, including exposure to harsh marine environments, fluctuating loads, and continuous operation. These factors make effective maintenance planning essential for ensuring reliability and safety. RUL estimation plays a pivotal role in shipboard reliability programs by providing actionable insights into the health of critical components such as engines, pumps, and propulsion systems, *Singh* (*n.d.*).

By leveraging real-time sensor data and machine learning algorithms, ship operators can detect early signs of wear or failure, schedule maintenance proactively, and extend the intervals between overhauls beyond manufacturer recommendations, Singh(n.d.). This approach not only reduces operational costs but also enhances compliance with stringent environmental regulations.

Recent advancements in RUL prediction methods have improved accuracy and adaptability for shipboard applications. Techniques such as deep learning-based health indicators, Wiener process modeling, and gated attention networks are increasingly employed to account for transient fluctuations and time-varying operational conditions, *Qin (2017), Li et al. (2024)*. These innovations enable more precise predictions even under complex regimes encountered in maritime operations.

Additionally, hybrid approaches combining condition-based maintenance (CBM) with prognostic evaluations further enhance reliability by integrating diagnostics with predictive analytics, *Das* (2010). Such systems provide dynamic RUL estimates that support adaptive maintenance scheduling based on real-time risk assessments. These methods also utilize techniques such as Kalman filters, *Bechhoefer et al.* (2021) and telemetric data, *Soni et al.* (2025).

Despite its benefits, implementing RUL prediction for shipboard machinery presents challenges such as data variability due to changing operating conditions and the need for robust models capable of handling these fluctuations, *Liu et al.* (2024). However, advancements in artificial intelligence and Industrial Internet of Things (IIoT) technologies offer opportunities to overcome these limitations. By utilizing comprehensive monitoring systems and adaptive algorithms, ship operators can achieve higher prediction accuracy and optimize machinery performance over extended lifecycles, *Li et al.* (2024), *Singh* (*n.d.*).

3. Methodology

The following section details the methods of the ascribed RUL models, and the case study details, including how the data was prepared and how the models were trained and tested. All models were recreated using PyTorch, a popular deep learning library in Python, *Paszke et al.* (2019).

3.1. LSTM-based Model from Stephen A. Olson's Thesis

Dr. Olson developed an LSTM-based model to identify when failures occur in the laboratory plant, *Olson (2024)*. The model layers are presented below in Table II. There are two total layers: an LSTM layer followed by a fully connected, hidden layer that outputs the predicted failure label. This LSTM model was built using Dr. Olson's experience during the development of the Marine Engineering Lab's testbed. The model's parameters are in Table III. Here, root-mean-square error (RMSE) is defined by:

$$RMSE = \sqrt{\sum_{y=1}^{n} (y_i - \hat{y}_i)^2}$$

Table II: LSTM-based RUL model from Dr. Olson's thesis Olson (2024)

Layer Type	Layer Parameters
(1) LSTM	Hidden Units = 200 , # of Layers = 1
(2) Fully Connected Layer	Input Size = 200 , Output Size = 1

 y_i is the true label of sequence *i* and \hat{y}_i the model's predicted label for sequence *i*, *Hodson* (2022). During training, using the model which recorded the minimal loss on the validation set was selected.

Parameter	Value
Learning Rate	0.005
Number of Epochs	500
Optimizer	Adam
Loss Function	Root-Mean-Square Error
Model Selection	Best Validation Loss

Table III: Base LSTM Model Parameters

3.2. LSTM-based Model by Yang et al.

This LSTM-based RUL model was originally developed for ball bearings, *Yang et al. (2022)*. The model utilizes two LSTM layers combined with two fully connected, hidden layers, with two dropout layers interspersed, to predict the RUL. The model's layers are presented in Table IV. An important deviation from the original model is that the dropout layer's parameter p, or the probability that an element is set to 0. This modification was due to observing an overall decrease in model performance when p > 0. In the original specification of the model, Yang et al. set p = 0.5. Additionally, in the first fully connected layer, the input size is the result of flattening the output of the LSTM, which is a function of the number of hidden units and the size of the input sequence, *seq_size*.

Table IV. LS IN-based Wodel Layers from Tang et al. (2022)		
Layer Type	Layer Parameters	
(1) LSTM	Hidden Units = 200 , # of Layers = 2	
(2) Dropout	p = 0.0	
(3) LSTM	Hidden Units = 200 , # of Layers = 2	
(4) Fully Connected Layer	Input Size = 200 * <i>seq_size</i> , Output Size = 100	
(5) Dropout	p = 0.0	
(6) Fully Connected	Input Size = 100 , Output Size = 1	

Table IV: LSTM-based Model Layers from Yang et al. (2022)

The model's parameters are presented in Table V. The only difference between this LSTM-based model's parameters and the previous model's parameters is the number of epochs required for training. The number of epochs was increased to 750 to allow the more complex model to appropriately learn the RUL task.

Table V: LSTM Model Parameters		
Parameter	Value	
Learning Rate	0.005	
Number of Epochs	750	
Optimizer	Adam	
Loss Function	Root-Mean-Square Error	
Model Selection	Best Validation Loss	

3.3. LSTM-CNN-Autoencoder Model by Ren et al.

The previous literature from which this model was derived from was trying to predict the RUL of lithium-ion batteries and achieved 95% accuracy on the NASA Prognostics Center of Excellence dataset, Ren et al. (2021). This model uses an over-complete autoencoder to generate large dimensional latent representations of the data for each timestep, this is used to derive 50-dimensional features. The first table specifies the parameters to the self-supervised autoencoder.

(let L be the number of sensors used)

Layer Type	Layer Parameters	
(1) Fully Connected Layer	Input = L, Output = L	
(2) Relu		
(3) Fully Connected Layer	Input = L, Output = 50	
(4) Relu		
(5) Fully Connected Layer	Input = 50, $Output = L$	
(6) Sigmoid		
(7) Fully Connected Layer	Input = L, $Output = L$	

Table VI: Over-Complete Autoencoder Parameters

Table VII: Over-Complete Autoencoder Hyperparameters

Parameter	Value
Learning Rate	0.1
Number of Epochs	1000
Optimizer	Adam
Loss Function	MSE

After the data is transformed from this autoencoder, it runs in parallel through two differing sections (table VIII and table IX). Then the outputs are concatenated into the final deep neural network that decides the RUL (table X). The model parameters are in Table XI.

Table VIII: LST M-Portion Parameters		
Layer Type	Layer Parameters	
(1) LSTM	Input = 50, Hidden = 100	
(2) Dropout	P = 0.2	
(3) LSTM	Input = 100 , Hidden = 4	
(4) Dropout	P =0.2	

Layer Type	Layer Parameters
(1) Conv	Input Channels = 1; Output Channels = 30
	Kernel = (3,3)
	Padding = $(1,1)$
	Stride = $(1,1)$
(2) Relu	
(3) Max Pool	Kernel = (2,2)
	Stride = (2,2)
(4) Conv	Input Channels = 30 ; Output Channels = 60
	Kernel = (3,3)
	Padding = $(1,1)$
	Stride = $(1,1)$
(5) Relu	
(6) Max Pool	Kernel = (2,2)
	Stride = (2,2)
(7) Conv	Input Channels = 60 ; Output Channels = 120
	Kernel = (2,2)
	Padding = $(0,0)$
	Stride = $(1,1)$
(8) Relu	
(9) Flatten	

Table IX: CNN-Portion Parameters

Table X: Deep Neural Network Parameters

Layer Type	Layer Parameters
(1) Fully Connected Layer	Input = 484 , output = 504
(2) Relu	
(3) Dropout	P = 0.59
(4) Fully Connected Layer	Input = 504 , output = 280
(5) Relu	
(6) Dropout	P = 0.59
(7) Fully Connected Layer	Input = 280 , output = 180
(8) Rela	
(9) Dropout	P = 0.589
(10) Fully Connected Layer	Input = 180 , output = 89
(11) Relu	
(12) Dropout	P = 0.591
(13) Fully Connected Layer	Input = 89 , output = 50
(14) Relu	
(15) Dropout	P = 0.59
(16) Fully Connected Layer	Input = 50, output = 29
(17) Relu	
(18) Dropout	P = 0.59
(19) Fully Connected Layer	Input = 29 , output = 1

Table XI: RUL Prediction Hyperparameters

Parameter	Value
Learning Rate	0.005
Number of Epochs	500
Optimizer	Adam
Loss Function	Root-Mean-Square Error
Model Selection	Best Validation Loss

3.4. LSTM-CNN-DAG Model by Li et al.

Like previous model, the previous literature from which this model was derived from trying to predict the RUL for turbofan engines using the C-MAPSS dataset, *Li et al. (2019)*. This model was compared side by side with 11 other literature-based models and was the highest performing. This model computes two parallel paths and then combines via element-wise addition and then their output and runs through some final layers. The two parallel paths are described in the first two tables that follow. The last table describes the layers for combining. Table XV contains the model's parameters.

(let L be the number of sensors used) Table XII: LSTM portion

I	Layer Type	Layer Parameters
	(5) Flatten	
	(6) LSTM	Output Size = $3*$ floor(L/2)

Table XIII: CNN portion

Layer Type	Layer Parameters
(10) Conv	Output Channels = 3
	Kernel = (2,3)
	Padding = $(0,1)$
	Stride = $(1,1)$
(11) Max Pool	Kernel = (2,2)
	Stride = $(2,2)$
(12) Flatten	

Table XIV: Fusing portion

Layer Type	Layer Parameters
(20) LSTM	Input Size = 3^* floor(L/2); Output Size = 10
(21) Fully Connected Layer	Input Size = 10; Output Size = 1

Table XV:	: RUL	Prediction	Hyperparameters
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Parameter	Value
Learning Rate	0.005
Number of Epochs	500
Optimizer	Adam
Loss Function	Root-Mean-Square Error
Model Selection	Best Validation Loss

3.5. Data Preprocessing

The data from the Marine Engineering Lab testbed went through several stages of preprocessing. First, the data was partitioned between the two independent plants of the lab's testbed. Next, several of the sensors from the fueling and cooling systems detailed in Sections 2.1.1 and 2.1.2 were transformed. Then, the sensors were assigned to specific groups, as detailed in Dr. Olson's thesis. Finally, the data was rescaled to the range [0, 1]. Both the unscaled and rescaled data were fed into the models to evaluate and compare their performance. Finally, the data was separated into sequences of sizes 4, 5, and 6.

Since there are two parallel, independent lines in the Marine Engineering Test Bed, only one of these lines was selected. To maintain consistency with the case studies performed in Dr. Olson's thesis, only the first plant was utilized.

Next, within the cooling system, the temperature sensors and pressure sensors were transformed to create a delta temperature input and a delta pressure input. The delta temperature input was calculated

by taking temperature sensors T1_1 and T1_2 and subtracting T1_1 from T1_2. This calculated value represented the amount of waste heat being produced by the plant and being absorbed by the cooling system. The delta pressure input was calculated using pressure sensors P1_1 and P1_2 and subtracting P1_1 from P1_2. This calculated value represented the change in pressure in the cooling system, as centered around the clogging and leaking failure valves.

Then, the sensors were assigned to groups as detailed below in Table XVI. Signal group 1 includes all sensors, signal group 2 includes all pressure and current sensors, and signal group 3 includes only the current sensors. The heater temperature sensor is in degrees Celsius, the flow rate sensors are in liters per minute (LPM), the pressure sensors are in pounds per square inch (PSI), and the current sensors are the root mean square of their recorded amperage (A_{RMS}). These sensor groups are used to examine the importance of certain sensors and their impact on the models' RUL capabilities.

Signal Name	System	Unit	Signal Group
Heater Temperature Delta	Cooling	Degrees Celsius	1
Flow	Cooling	LPM	1
Pump Current	Cooling	A _{RMS}	1, 2, 3
Pressure Delta	Cooling	PSI	1, 2
Flow – LP	Fuel	LPM	1
Flow – HP Rail	Fuel	LPM	1
Flow – HP Relief	Fuel	LPM	1
Pressure – LP	Fuel	PSI	1, 2
Pressure – HP	Fuel	PSI	1, 2
Pump Current – LP	Fuel	A _{RMS}	1, 2, 3
Pump Current – HP	Fuel	A _{RMS}	1, 2, 3

Table VVI	Input Data	Signals on	d thair	Ground
	mput Data	Signals an		Oloups

These data signals were then rescaled to the range [0,1] using the following formula:

$$scaled_val = \frac{val - min_val}{max_val - min_val}$$

where *val* is the original sensor value, *min_val* is the absolute minimum of the sensor value range, and *max_val* is the absolute maximum of the sensor range. This rescaling was done to normalize the data and minimize the impacts of the Marine Engineering Lab's testing environment not being constant, as pressure and temperature changes within the room affected the starting values of various sensors. For comparison, both the original sensor data and the rescaled data was fed into the RUL prediction models to identify the impacts of data normalization on prognostic output.

Finally, to determine how much data is required to make an accurate RUL prediction, the data was further partitioned into input sequences of the first 4, 5, or 6 timesteps.

The two CNN-based models required a higher resolution of data than the LSTM models, as detailed in Sections 3.3 and 3.4. To approximate the data that would have existed if data samples were taken at a higher frequency, a data interpolation method was employed. First, a quadratic function was fit to the original data, and then data points were sampled at an even interval between the first and last data point until the required number of data points were acquired. A quadratic function was chosen due to the shape of the testbed's failure profiles.

3.6. Model Training and Testing Procedures

Due to the limited quantity of training data, to properly validate the results, the following training method was implemented. First, three partitions of the data were created to identify the impacts of varying quantities of training, testing, and validation data, Table XVII. Partition A represents the usage

of the most amount of training data, partition B with the least amount of training data, and partition C more training data than partition B but less training data than partition A.

Table XVII: Data Partition Splits						
Partition	Training	Validation	Testing			
А	80%	10%	10%			
В	60%	20%	20%			
С	70%	15%	15%			

T 11

Then, due to only having 68 total failure profiles, to verify that the model worked generally on not just on a particular set of training, validation, and test data, the following scheme was utilized. First, each partition was assigned a corresponding percentage of testing failure profiles. Then the remaining failure profiles were split between training and validation sets according to Table XVII. Subsequently, the training and validation sets were randomized for a total of 50 times. For each of these 50 splits of training and validation data, the testing set remained static.

Each model was trained on each of the 50 generated training, validation, and test splits for each data partition. Additionally, models were trained on the specific operational profiles detailed earlier in Table I and for input sequences of size 4, 5, and 6. Therefore, a total of 10,800 models were trained across all models, partitions, input sequence sizes, operational profiles, and for regular and normalized data. All models were trained using the model parameters as defined above in Sections 3.1 to 3.4.

The resulting models were then tested on the set training partitions. To ensure that model results were comparable to one another, the RMSE was used as a loss function over all models. For each model, the accuracy and loss were recorded.

4. Results

To preface the following section, results could only be obtained from three of the four detailed models. Dr Olson's LSTM model, Yang et al.'s LSTM model, and Li et al.'s models were successfully trained on the data from the Marine Engineering Lab's testbed, referred to as "Base," "LSTM," and "LSTMCNN" respectively in the following charts. Ren et al.'s CNN-LSTM-Autoencoder-based model was not successfully trained. This will be thoroughly discussed in Section 5.

The following charts are presented as with the following common features. All three trained models are detailed on each chart, in order of Base, LSTM, and LSTMCNN. For each presented model, the data corresponding to input sensor group 1 is assigned blue and referred to as "s1 g1" along the right side of the chart, where "s1" refers to the first plant within the testbed and "g1" refers to group 1. Sensor groups 2 and 3 are presented in a similar manner as red and green respectively. Along the x-axis, the first row contains the aspect of the model being examined, and the second row contains the type of model. These models output floating point numbers. Our training labels are integers, thus, to get a reasonable sense of accuracy score for these models, we round their outputs to the nearest integer to compute the classification accuracy.



Fig.5: Average model accuracy & loss between normalized (minmax) and non-normalized data (regular)

Fig.5 compares model performance between normalized data, labeled as "minmax," and the original, unmodified data, labeled as "regular." Based on the clear performance differential between the normalized and unmodified data, the subsequent figures all utilized the normalized data.

Fig.6 compares model performance using normalized data between data partitions A, B, and C, as detailed in Table VII. From these figures, the models perform the best with partition C.



Fig.6: Average model accuracy & loss between data partitions for normalized data

Fig.7 details model performance using the original sequence length of the data. For the LSTM-CNN model, the specified sequence lengths correspond to the original data before it was interpolated to the required size.



Fig.7: Average model accuracy & loss between sequence lengths for normalized data for partition C

Fig.8 compares model performance with operational profiles 1, 2, and 3.



Fig.8: Average model Accuracy & loss between operational profiles for normalized data

5. Discussion

The Marine Engineering Lab's testbed provides an excellent environment for developing and testing RUL methodologies. When developing these RUL methods for the testbed, and for the maritime environment generally, it is important to consider how the data and the testing environment affect model performance.

5.1. Data and Data Processing

As seen in Fig.5, across all sensor groups, the models performed better on the normalized data compared to the non-normalized data, with model accuracy being higher for normalized data than their corresponding models for non-normalized data. Additionally, model loss was substantially lower for normalized data than models for non-normalized data. This performance difference is consistent with expected model behavior due to data normalization enabling. This falls in line with expectations in

normal machine learning practices, as batch normalization techniques allow models to account for less with respect to covariate shifts of data.

Another important facet of the model results is the quantity of training data that was available. One of the primary challenges associated with a limited amount of training data for machine learning is the risk of overfitting, where the model learns to recognize the noise in the training set rather than the underlying patterns. This results in poor generalization to unseen data, as the model becomes overly specialized to the specific examples it was trained on. Additionally, with insufficient data, there is a higher likelihood of introducing bias, which can lead to inaccurate predictions if the training set does not adequately represent the diversity of real-world scenarios. This limitation also hampers the model's ability to accurately capture complex relationships in the data, reducing its overall effectiveness and reliability. Moreover, a small dataset may be less capable of accommodating variations and anomalies, further complicating the model's training process and diminishing its robustness in application. These behaviors can be observed most acutely in Fig.6, as the loss for partition C was significantly lower than the loss for partitions A and B. Partition A had 80% of the data available for training and 10% of the data for testing. Partition B had 60% of the data available for training and 20% of the data available for testing. Consequently, it is reasonable to conclude that the performance difference between partition A and C was the result of partition A not having enough training data to encompass the small subset of behavior that was included in the testing and evaluation sets. For partitions B and C, partition B has a larger testing set, but the training set was significantly smaller than partition A. Therefore, more of the overall behavior was present in the testing set, but the reduced size of an already small training set decreased the overall size testbed's behavior encapsulated in the training set. For this set of data, partition C resulted in the best model performance due to striking a balance between the size of the training and test sets in this context of a small amount of data.

Across all the above figures, it is evident that the types of sensors included in the models' impact model performance to varying degrees. When examining the performance difference between data partitions and between operational profiles in Figs.6 and 8, there is often a large gap between model accuracy for sensor group 3 and sensor groups 1 and 2. However, when taken into consideration with overall model loss in Figs.6 and 8, model performance across all three sensor groups is very similar to one another. This model behavior is also represented in Fig.7, but with more variance, primarily due to the varying size of the sequential input and being applied across all operational profiles. In total, these results indicate that all three sensor groups are viable in identifying the RUL, but the final accuracy number shows a large discrepancy due to the small number of failure profiles in the testing set. If models misclassify a single failure profile that is near the rounding threshold, then the accuracy will drop greatly. Therefore, it would be expected for the model accuracy for each sensor group to equalize if there were more data points. Consequently, it is evident that the sensors in sensor group 3, the current sensors, are a primary driver of detecting the RUL of the system. The other sensors found in groups 1 and 2 provide additional information compared to the current sensors, but do not provide an overwhelming difference in model performance. Additional investigations will need to be conducted to investigate if other sensor combinations, when isolated as the current sensors in sensor group 3, perform similarly. This information will be valuable when deciding which information sources are the most important for RUL in the maritime space.

5.2. Operational Variance

Fig.8 illustrates the impacts of the testbed's operational profile on model effectiveness. Maritime systems are not static, and their input control sequences will vary based on the specific task being performed. Additionally, these operational settings impact how various systems within the platform will respond. Consequently, there is a variance in how the testbed behaves for each operational profile, which translates into differing model effectiveness. Generally, the models performed the best on operational profile 2, which placed the highest load on the testbed, whereas the models generally performed the worst on operational profile 1, which placed the lowest load on the testbed. These differing model performances are indicative of where additional data is needed within to enhance model effectiveness. Additionally, this difference also highlights the need for evaluating the performance of a

single model that can identify the RUL of systems across all operational profiles. There are several approaches that could be used, including applying the existing models to the entire dataset, independent of operational profile, and utilizing the system control inputs as additional model inputs, to contextualize the data the models observe.

5.3 Sequential Accumulation

As seen in Fig.7 (left), performance generally increased when increasing the amount of timesteps the model was allowed to know. In Fig.7 (right), the expected trend is the average loss monotonically decreases. However, there is no discernable trend. This suggests that relative to the ground truth, the models reduced their bias when trained, hence the accuracy increase. However, their variance may have increased. This is expected to not be the case if the number of timesteps to draw on becomes significantly larger than just 4, 5, and 6 and there is a larger quantity of training data.

5.4 Unsuccessful Model

The Auto-CNN-LSTM model did not train effectively, despite the author's attempts to tweak the regularization factors, such as dropout, in the model. When the model was evaluated, its learned output was constant with regards to its input. It is believed to be the case that one of the layers in the DNN portion had their weights vanish. This is signifying that the latent representations of the data generated by the autoencoder did not yield meaningful features of the data, which the authors believe was caused by a lack of data.

6. Conclusions

This study has demonstrated the significant impact of the Marine Engineering Lab's testbed for RUL in maritime systems. It examined the impact of data normalization, training data quantity, sensor selection, operational variance, and sequential timing on the performance of machine learning models designed within the testbed's context to enable future RUL development on non-simulated, real-world data. The findings indicate testbed's feasibility in developing RUL systems and identified challenges that need to be addressed, such as the current amount of available data.

Furthermore, the exploration of different sensor groups within the testbed reveals that while all sensors can effectively contribute to RUL identification, the current sensors in sensor group 3 are crucial drivers of performance. The variability in model effectiveness across different operational profiles underscores the dynamic nature of maritime systems and the need for tailored data strategies to enhance model robustness across various conditions. Lastly, the investigation into sequential input accumulation indicates a positive correlation between the number of timesteps used and model performance, although challenges remain in achieving consistent decreases in loss.

Overall, these insights not only contribute to the understanding of machine learning applications within maritime contexts but also provide a foundation for future research aimed at improving model generalization and effectiveness through more comprehensive data collection and analysis strategies.

Code

Code based for reproducibility: <u>https://github.com/Advanced-Naval-Concepts-Research/HIPER-25-RUL</u>

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Spectral Analysis of Maritime Communication Systems of Vessel Engine and Control Room

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Abstract

The maritime industry is increasing autonomy, reliability and energy efficiency by installing more digital equipment onboard. The number of sensors, computing resources and human interfaces is increasing, while the traditional way to interconnect equipment is through cabling. The use of wireless technology for onboard equipment interconnection is an interesting option to decrease installation costs, but the industry is reluctant due to uncertainty of performance and reliability of such technology. This paper presents the results of an on-ship test campaign measuring the electromagnetic spectrum in the control room and the engine room of a ship. The objective is to find out the variation of the spectrum, if there are significant disturbances visible from onboard equipment and based on this make an estimate on the applicability of wireless technology.

1. Introduction

The transition toward unmanned engine rooms on modern vessels introduces not only operational advantages but also substantial technical and economic challenges. Achieving autonomous machinery spaces requires the integration of a dense network of wireless sensors and communication nodes capable of reliably monitoring equipment conditions in real time. While wireless systems reduce dependence on traditional cabling, lowering material, installation, and maintenance costs, the overall system design must meet strict reliability demands. For mission-critical functions, such as real-time diagnostics and condition monitoring, the acceptable failure rate for wireless data transmission must be as low as 10⁻⁹ to ensure operational safety and viability for commercial deployment, *Pradhan (2024), Panić (2018).* These requirements incline towards the importance of robust wireless architecture and interference-resilient communication protocols, particularly in environments as electromagnetically complex and physically obstructed as ship engine rooms, *Alqurashi et al. (2022).*

The rise of Internet-of-Things (IoT) technologies in mission-critical maritime applications has led to the development of the Internet-of-Ships (IoS) concept, *Aslam (2020)*. IoS represents a specialized branch of IoT, encompassing a network of intelligent, interconnected maritime assets—ranging from shipboard devices to port infrastructure and transport networks. Its primary objective is to enhance the shipping industry's safety, efficiency, and environmental sustainability.

Effective spectrum management in maritime communication technologies is essential for ensuring reliability and preventing interference. These systems are responsible for monitoring and verifying communication frequencies, ensuring that signals come from authorized onboard equipment to maintain their integrity. The traditional wired communication systems on large vessels present challenges due to the extensive cabling required for connectivity. The maintenance and installation of such cabling are often cumbersome and costly, making it less practical for modern maritime applications. To overcome these limitations, the maritime industry is shifting towards wireless communication methods, including radio communications and Wi-Fi. These technologies offer greater flexibility, reduced infrastructure complexity, and improved adaptability to evolving maritime communication needs. By integrating spectrum monitoring with advanced wireless solutions, maritime operations can achieve enhanced connectivity and operational resilience.

Recent advancements in technologies such as Free Space Optical (FSO) communication and Intelligent Reflecting Surfaces (IRS) have shown significant promise in addressing the limitations of traditional radio frequency-based systems. *Fan et al.* (2024) propose a method for coarse frequency offset estimation using short-time spectrum analysis, aiming to enhance the reliability of FSO systems under variable maritime conditions. Similarly, *Cao et al.* (2024) explore the optimization of IRS-assisted joint sensing and communication systems for maritime settings. These emerging technologies suggest new frontiers for high-speed, energy-efficient communication systems that can complement existing maritime networks.

Leveraging this evolution, *Alqurashi et al.* (2022) provide a comprehensive survey of modern maritime communication systems, identifying both opportunities and persistent challenges. Their review emphasizes the integration of heterogeneous technologies—such as satellite links, high-altitude platforms, and underwater acoustic systems—into a unified maritime communication architecture. Notably, they emphasize the complexity of maintaining coverage across diverse environments, including open sea, coastal zones, and port infrastructure. The study also discusses the need for dynamic spectrum management and energy-efficient protocols to meet the increasing demands of Internet-of-Ships applications, smart port logistics, and real-time safety monitoring. These insights reinforce the urgency of developing robust, adaptable communication frameworks for maritime operations.

The objective of this study was to capture and analyse spectrum data within both the control and engine room environments, near one of the Wärtsilä 8v31 engines, of the Aurora Bothnia ferry, <u>https://www.wasaline.com/en/our-ferry/</u>. This process involved systematically recording network traffic across the frequency range from 0 GHz to 6 GHz. The collected data was then examined to identify, classify, and interpret recurring frequency patterns that repeatedly appeared within the spectrum. These repetitive frequencies aimed to gain insights into the characteristics of network communication within these operational environments, contributing to an understanding of the overall network performance.

2. Background and Motivation

Modern maritime operations rely increasingly on wireless communication networks to support both operational tasks and safety-critical services. Given the structural and environmental challenges unique to vessels, selecting and implementing suitable communication protocols is essential for ensuring reliable connectivity. The following sections first outline the key wireless standards applicable in maritime contexts and then examine recent research evaluating their real-world performance and adaptability in ship environments.

2.1 Wireless Communication Standards and Protocols in Maritime Environments

Marine communication networks must ensure reliable access to both data and essential services, particularly in situations where such access becomes critical for the vessel's operations and mission. Many maritime communication protocols support relatively low data transfer rates, meaning that availability often depends on hardware capabilities and system configurations that enable data transmission at the highest possible rate allowed by the protocol.

For effective data exchange, heterogeneous devices, often operating across different networks, must conform to standardized wireless communication protocols, such as IEEE 802.11 (Wi-Fi) and Bluetooth, to ensure reliable connectivity and interoperability between components. Commonly used standards include IEEE 802.11, Bluetooth, Zigbee, and LoRaWAN, *Kanthavel (2021)*. These protocols define the rules for device communication, ensuring compatibility and consistent data transmission between systems.

However, as *Wang (2018)* emphasized, applying these protocols in maritime settings requires careful adaptation. Unlike land-based environments, ships pose distinct challenges for wireless communication due to their steel construction, constant movement, and physical barriers that can obstruct signals and

disrupt transmission quality. Their study highlights the need for customised wireless channel models that reflect these conditions, ensuring that standards like IEEE 802.11 and LoRaWAN can function reliably onboard. This modelling is vital for maintaining stable connectivity and effective data exchange in the dynamic and constrained conditions of maritime communication.

The applicability of these protocols has been further evaluated in recent experimental studies and simulation-based models, which provide deeper insight into their real-world performance aboard maritime vessels.

2.2 Performance Evaluations and Implementations of Maritime Wireless Networks

IEEE 802.11, supports high-speed wireless connections, making it suitable for environments requiring fast data transfer. Bluetooth, known for its short-range communication capability, is widely used for connecting devices in proximity. Zigbee, a low-power protocol designed for short-range communication, is particularly useful in sensor networks and similar low-energy applications. LoRaWAN, by contrast, offers long-range communication with low power consumption, making it ideal for scenarios requiring wide-area coverage, such as remote monitoring and smart infrastructure, *Tabish (2024). Jung (2023)* evaluated Wi-Fi 6 multi-hop network performance in confined spaces aboard container ships. Results showed that signal strength fluctuated due to structural obstacles like closed steel doors, affecting high-quality video transmission, however, lower-resolution streams remained stable. Ships under construction offered better performance due to fewer obstructions. Dual-band use and strategic placement of mesh nodes were found to be necessary for maintaining reliable connectivity.

Lopes (2014) conducted a performance evaluation of IEEE 802.11n networks operating in the 5.8 GHz band within a maritime environment. Their study established a point-to-point link between a fishing vessel and the shore, demonstrating that communication links up to 7 km at 1 Mbit/s are achievable. This finding highlights the potential of utilizing long-range IEEE 802.11 links for broadband maritime communications, thereby addressing the limitations of traditional maritime communication protocols that often support relatively low data transfer rates.

Song (2023) developed a wireless network coverage visualization model specifically for dynamic and random ship environments. Their work marks the influence of vessel layout and motion on communication coverage, providing tools to simulate and optimize connectivity across a ship's structure. Moreover, *Horsmanheimo et al. (2024)* present a practical implementation of a 5G multi-hop maritime communication testbed in indoor ship environments. Their evaluation demonstrated that with proper node placement and relay strategy, consistent connectivity can be achieved.

3. Methodology: Spectrum Data Collection

For our testing, we used CRFS RFeye node, <u>https://pages.crfs.com/hubfs/datasheets/node-20-6-datasheet.pdf</u>, for signal analysis. RFeye is a remote, robust, real-time spectral analysis system capable of monitoring frequencies in the range 10 MHz to 6 GHz. It was used with the CRFS RFLive software to visualise the frequencies in real time. Due to licensing limitations, the range of compatible software for interacting with the RFeye was restricted, and we did not have access to an exclusive data logging software.

To receive signals, we used a directional antenna to better identify the direction of transmission and only focus on signals visible at certain angles. While the RFeye software was used to visualize the frequency spectrum, Open Broadcast Software was used to record the screen during our measurements.

Our measurements started in the control room of the Cruise ferry Aurora Botnia, where we set up the equipment with the antenna, represented by the green cones in Fig.1, initially oriented towards the control room (right green cones), with the engine room located further ahead in the vessel. We recorded for two hours, covering approximately half of the cruise ship's route. Subsequently, the antenna was rotated to face the opposite side of the vessel floor, as shown in the map, to observe any differences in

signals visible on the spectrum based on heading orientation. The second recording continued until the end of the route.



Fig.1: Map of engine floor with measurement locations and angles marked. The map was drawn from memory. The first measurement was taken in control room (right) and second in the engine observation room (left)

During the trip along the same route, the equipment was relocated to the observation room overlooking the engine room and one of the engines. The antenna was angled towards the closest engine, as visualized in Fig.1 (left green cone). The recordings taken from the control room span the full radio spectrum.

4. Analysis of Spectral Data

This section is divided into two subchapters. The first details the process used for extracting and reconstructing signal data from screen-captured video recordings of frequency spectra. The second subchapter presents a spectrogram-based analysis of the reconstructed signals, focusing on the identification and interpretation of dominant frequency components over time.

4.1 Signal Extraction and Spectral Reconstruction from Video Recordings

The signal data of network traffic were collected as screen capture recordings showing the frequency domain spectra up to 6 GHz. Signal data was extracted by binarizing the individual video frames using a set threshold brightness value of 0.452 in the HSV colour space. This binarization process is illustrated in Fig.2, where the left panel shows the binary mask used to isolate the signal trace. The recorded signal data were displayed as wide lines with non-unique intensity components due to the down-sampling effect, which resulted from the lower video resolution compared to the higher resolution of frequency intensity measurements.



Fig.2: Binary mask for signal trace isolation (left) and mean trace points used for spectral line reconstruction (right)

To reconstruct the frequency domain data, the mean y-positions of the detected signal trace were computed for each x-coordinate in the binary mask. These mean positions, marked as blue dots in the right panel of Fig.2, represent the central tendency of the spectral trace. A continuous spectral line was then derived for each frame using interpolation across these points. The reconstructed spectral lines from all video frames were combined into a time-frequency representation in the form of a spectrogram, enabling the visualization of spectral density variations over time. Although the x- and y-axis scales of the two images in Fig.2 are the same and both plot the signal in pixel coordinates, they can be readily normalised to a linear mapping to display the correct frequency and intensity range during post-processing.

It is acknowledged that the process of estimating mean signal intensity values led to a partial loss of spectral detail, attenuating some sharp features and broadening certain peaks. Nevertheless, given that the primary objective of this study is to identify recurring patterns of dominant intensity over a relatively broad frequency range, this trade-off was considered acceptable and unlikely to compromise the overall validity of the analysis.

4.2 Analysis of Dominant Frequency Components Using Spectrogram Visualization

The following spectrograms present measurements conducted in the engine room of a cruise ship during its operational phase, with the data acquired through a series of consecutive video recordings, each capturing a different portion of the radio frequency spectrum. These recordings were not collected simultaneously but iteratively, using the same measurement setup repositioned across defined frequency bands ranging from 0-6 GHz. For research purposes, and due to computational constraints, only the first 260 s of each recording were analysed and visualised. The spectrograms reflect the spectral environment as recorded from a fixed location within the ship's engine room while in motion, offering insight into the presence, distribution, and temporal stability of the radio signals across frequency range. In each spectrogram, time is displayed on the horizontal axis (0–260 s), frequency is plotted on the vertical axis, and signal intensity is colour-coded using a dBm scale, with values typically ranging from approximately -115 dBm (low intensity, violet) to -70 dBm (high intensity, yellow). Together, these visualizations offer a segmented view of the electromagnetic activity present in the shipboard environment.



Fig.3: Full Spectrum Overview: 0-6000 MHz

The spectrogram in Fig.3 provides a comprehensive overview of the signal environment in the engine room, covering frequency range from 0 to 6000 MHz. Repetitive narrowband activity is observed below 1000 MHz, with standout signals in the VHF (30–300 MHz) and UHF (300–1000 MHz) bands. These

are likely associated with marine VHF communications, AIS transponders (around 162 MHz), and terrestrial broadcast or control signals. A particularly structured and intense band is seen between 2400–2500 MHz, which aligns with the 2.4 GHz ISM band commonly used by Wi-Fi (IEEE 802.11b/g/n), Bluetooth, and Zigbee systems. Above 3000 MHz, the spectrum becomes noisier and less structured, though faint traces may suggest radar emissions, 5G mid-band activity, or interference from onboard electronic systems.

Fig.4 displays a zoomed-in view of the 0–1000 MHz band. Narrow horizontal traces are observed in the 150–170 MHz range, potentially corresponding to maritime VHF radio and marine safety channels. Activity around 450–470 MHz may reflect private mobile radio systems, often used for shipboard communications, port coordination, or engineering staff radios. A strong transient at approximately 470 MHz 470 MHz (possibly a ping between two radios) was generally visible throughout the recording period and particularly intense at around 180 s. This may indicate a burst transmission potentially originating from a handheld or temporary radio source. Broader radio signals below 100 MHz could come from broadcast FM radio, which may still be present depending on proximity to shore.



Fig.5. Subband Focus: 1800-2900 MHz

Within the band of 1800-2900 MHz present in Fig.5, the spectrogram reveals intense activity near 2400–2483.5 MHz, which corresponds to the 2.4 GHz ISM band. This region is commonly used by protocols such as Wi-Fi (IEEE 802.11), Bluetooth, and Zigbee. The consistency and strength of the signal suggest active use of onboard wireless networks, likely supporting crew communication systems, passenger internet services, or industrial sensor telemetry operating in proximity to the measurement site. In the lower part of the band, diffuse and weaker radio signals are visible between 1800–2200 MHz, which may correspond to LTE Bands 3 (1800 MHz) and 7 (2600 MHz)—bands frequently deployed in maritime and nearshore environments for mobile broadband access. These may originate from nearby base stations or shipboard signal repeaters designed to extend mobile coverage into metallic interior spaces.

Additionally, intermittent activity around 2600–2700 MHz could correspond to LTE Bands 38 and 41, often used for Time Division Duplex LTE in industrial applications. Their less structured appearance suggests non-continuous or burst-type usage, potentially reflecting fluctuating data demands or background machine-to-machine communications. The variety of signal strengths and temporal fluctuations within this subband highlights a complex, heterogeneous RF environment arising from both human activity and automated shipboard systems.



Fig. 6. Subband Focus: 2800-6000 MHz

This upper-frequency band in Fig.6 appears sparse in structured emissions. The lower portion (2800–4000 MHz) includes weak vertical signals likely caused by transient emissions or non-persistent onboard wireless activity, while the segment above 5000 MHz reveals weak horizontal components near 5180–5805 MHz, indicative of 5 GHz Wi-Fi channels (particularly 802.11ac). The general spectral diffuseness suggests that this range is either underutilised onboard or affected by structural attenuation, with occasional signals possibly originating from radar systems or equipment operating on higher unlicensed bands.

5. Discussion

Electromagnetic interference (EMI) can significantly impair critical maritime systems, including navigation, communication, and engine controls. Disruptions in these systems may lead to navigational errors, miscommunication, and potential safety hazards. For instance, compromised communication systems can hinder coordination during emergencies, escalating risks to both crew and the vessel itself. Therefore, maintaining electromagnetic compatibility (EMC) is essential to ensure the seamless operation of onboard electronic systems. EMI aboard vessels can originate from various sources,

including engine components, control systems, and onboard electronics. High-power machinery, such as engines and generators, often emit substantial electromagnetic fields that can interfere with nearby electronic devices. Additionally, wireless communication equipment and other electronic devices may contribute to the EMI environment, potentially affecting the performance of sensitive systems.

To reduce EMI, several strategies are employed in maritime settings:

- Shielding: Enclosing sensitive equipment with conductive or magnetic materials to block external electromagnetic fields
- Filtering: Implementing filters using capacitors and inductors to attenuate unwanted frequencies within electrical systems.
- Grounding: Establishing effective grounding systems to minimize potential differences and reduce interference.
- Design Practices: Careful layout of wiring and components, such as spacing conductors and using twisted pairs, to lower the risk of EMI.

Adhering to EMC standards during the design and installation of equipment is crucial to prevent interference and ensure the reliability of vessel operations. The International Electrotechnical Commission (IEC) provides guidelines, such as IEC 60533:2015, which specifies minimum requirements for EMC in ships with metallic hulls.

Maintaining reliable wireless communication in areas with high EMI, such as control and engine rooms, involves several approaches:

- Use of Robust Communication Protocols: Employing protocols designed to withstand interference and ensure data integrity.
- Strategic Placement of Antennas: Positioning antennas to optimize signal strength while minimizing exposure to interference sources.
- Regular Spectrum Monitoring: Continuously monitoring the electromagnetic spectrum to identify and address potential interference issues proactively.
- Compliance with EMC Standards: Ensuring all wireless equipment meets established EMC standards to minimize the risk of interference.

Electromagnetic interference (EMI) presents a substantial threat to the safety and reliability of maritime operations by affecting critical electronic systems. Effective mitigation requires a combination of technical strategies, such as shielding, filtering, and grounding, alongside adherence to established EMC standards. Scientific research supports the need for proactive EMI management, emphasising the importance of proper system design and regular spectrum monitoring. Ultimately, maintaining electromagnetic compatibility is essential for ensuring the operational integrity and safety of modern vessels in increasingly complex electromagnetic environments. Maintaining reliable wireless communication in areas with high EMI involves using robust communication protocols, strategic placement of antennas, regular spectrum monitoring, and ensuring all wireless equipment meets established EMC standards. These measures are essential to minimize the risk of interference and maintain the seamless operation of onboard electronic systems.

6. Conclusion

The spectrogram analyses provide a comprehensive snapshot of the radio frequency environment in the engine room of a cruise ship during active operation. Across the 0–6000 MHz range, both persistent and transient radio signals were observed, reflecting a mix of maritime communication systems, onboard wireless infrastructure, and incidental signal activity.

The lower spectrum (below 1000 MHz) showed consistent narrowband signals, likely linked to marine VHF, AIS, and shipboard radio systems. The 2.4 GHz ISM band exhibited strong, continuous radio

signals indicative of active Wi-Fi, Bluetooth, and Zigbee usage, supporting onboard connectivity and telemetry. In contrast, the higher spectrum (above 2800 MHz) appeared largely underutilized, with only faint activity in the 5 GHz Wi-Fi range and minimal structured signals elsewhere, suggesting attenuation or limited deployment.

The segmented measurement approach enabled targeted identification of active bands and signal patterns, offering insights for communication system design, interference management, and future spectrum planning in maritime. Moreover, the observed spectral activity—particularly in the 2.4 GHz ISM band—suggests the presence of multiple wireless systems actively transmitting data from onboard machinery. This supports the growing role of wireless connectivity in enabling reliable condition monitoring, equipment status tracking, and remote supervision, contributing to more informed and proactive vessel operations.

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Development, Construction and Operation of the Primarily Wind-Powered Cargo-ship JUREN-AE for the Republic of Marshall Islands

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Abstract

This paper presents the development process of the sail cargo vessel JUREN AE, from needs analysis, concept development, optimization, and construction of the vessel, to the delivery and first voyage. The vessel is designed for operation in the Pacific Ocean in the small-scale island trade of the Republic of the Marshall Islands. The challenges for the vessel in this trading area include remote operation, lack of port infrastructure on the outer islands, the requirement of fully self-sufficient cargo operations, very high fuel costs, and ambitious emission reduction goals. The vessel was designed and optimized with "zero-emission" potential as a prototype for climate-friendly island supply vessels utilizing all renewable energy sources available in the trading area of the Marshall Islands. Sea trials and first operational experience indicate good alignment with the design goals and performance predictions.

1. Introduction

In July 2024, the German Society for International Cooperation (GIZ) handed over the newly constructed island supply vessel SV JUREN AE with sail propulsion for largely climate-neutral operation to the state-owned Marshall Islands Shipping Corporation (MISC). The vessel was developed, designed, and built as part of the international climate initiative project "Transitioning to Low Carbon Sea Transport", with technical support and coordination of the University of Applied Sciences Emden/Leer (HEL). GIZ is implementing the bilateral project in close cooperation with the Government of the Marshall Islands. The project is funded by the International Climate Initiative (IKI). The vessel was built by the shipyard Asia Shipbuilding Co. Ltd. in cooperation with the ship design office KOSTEC Co. Ltd. in Geoje, South Korea. The design process was supported by HEL and the Hamburg-based design office SDC. Having completed the sea trials, the vessel was transferred to Majuro on 23 July and ceremonially welcomed. Other participants in the project are Briese Research in Leer, Germany, which assisted with the plan approval process, and ERG, a Hamburg-based law firm, which was responsible for contractual advice and the registration of the vessel in the International Register of the Marshall Islands.

2. The Marshall Islands trading area

Before starting the design process for a new vessel, the transport task and all the conditions to be considered were analysed and described in a baseline report, which served as the basis for the needs analysis for the new vessel, *Oxley (2018)*.

The sea area of the Marshall Islands consists of a total of 29 atolls, arranged in two island chains in the Pacific. The capital, Majuro, serves as a transport hub, handling all of the country's imports and exports. The island supplier's role is to provide a flow of cargo from Majuro, consisting of palletised and loose general cargo (some of it frozen), to the outer islands, and a return flow of sacked copra (dried coconut meat) to the capital, Majuro, for further processing into coconut oil. This is the Marshall Islands' main export, and copra production is the main agricultural activity that supports life on the outer islands.



Fig.1: Atolls of the Marshall Islands, https://www.worldatlas.com/maps/marshall-islands

Port infrastructure on the outer islands is mostly non-existent, so it is necessary to anchor or drift offshore and lighten the cargo with small tenders. The boats are unloaded and loaded on the beach by hand. This is a time-consuming process that requires a large crew. The vessel therefore has ample accommodation for a large crew and has long periods of cargo operation.



Fig.2: Delivery of general cargo for outer islands (left) and copra loading on outer islands (right)



Fig.3: Shares of operational modes in RMI, Oxley (2018)

The Marshall Islands lies within the pattern of the north-east trade winds in the Pacific Ocean. There is a seasonal change from summer to winter, with stronger winds and less precipitation during winter and lighter winds during summer, as the inter-tropical convergence zone moves in north-south direction. This pattern yields rather stable wind conditions, with very consistent east-north-easterly wind directions and slightly varying wind speeds from season to season. The geographic location of the atolls provides excellent conditions for using wind power as a main source of energy for ship propulsion with favorable beam-wind routes. Further, solar power is reliably available throughout the year. The high PV potential can be used to cover at least part of the hotel load's energy demand.



Fig.4: Prevailing wind conditions in Majuro, Marshall Islands, <u>https://www.meteoblue.com/en/</u> weather/historyclimate/climatemodelled/marshall-islands-international-airport_marshall-islands_4040398

3. Concept and ship design

Based on the data collected in the baseline report, several options for reducing emissions from maritime transport in the Marshall Islands were developed and evaluated, *Vahs et al. (2019)*, including retrofitting the existing fleet. The design and construction of a new vessel was chosen for the project, as this new vessel could be optimized for the needs of the remote trading area and serve as a prototype for other small island states with similar transport and emissions challenges.

The main task of the ship design was to achieve maximum fuel and emission savings. In a preliminary study, various technical and operational options were considered and evaluated for their savings potential. These included different sail sizes, hydrodynamic features such as keels and daggerboards. Due to the relatively constant winds between the subtropical high and the equatorial low, the savings potential for a large wind propulsion system is very high. The lack of availability of green fuels or charging infrastructure for larger battery capacities in the Pacific Island regions further limits the options and leads to concepts for the direct use of renewable energy. The evaluation of all influencing variables and boundary conditions led to the selection of the INDOSAIL system. In particular, the combination of performance potential, low construction costs and high operational reliability supported the decision.

A parametric model was used for rapid design variations during the concept phase, Figs.5-8. The model was directly linked to empirical analytical calculation tools that could be implemented in the CAD software. The 3-masted INDOSAIL system with Wagner keels and skeg provided the best combination of performance, reliability, cargo gear integration, and cost. This optimised concept was then used as the basis for the tender design as the project progressed.

In addition to the vessel's main task of supplying the outer islands with general cargo and collecting copra on the return voyage, the vessel is also designed to carry special cargoes such as frozen food in 3 freezer rooms, fuel drums on deck, fresh water for water supply during prolonged droughts (using the RO fresh water production system), a 'supermarket' with goods for daily use and access to money transactions by a representative of the National Bank on board.



Fig.5: Parametric variations, 2 masts, 300 m² sails



Fig.7: Parametric variations, 3 masts, 700 m² sails with genoa



Fig.6: Parametric variations, 3 masts, 500 m² sail, dagger-boards



Fig.8: Increased level of details with SolidWorks volume model



Fig.9: General Arrangement Plan, source: KOSTEC Co., Ltd.

The vessel has a capacity of 12 passengers for inter-island trips. The vessel will also be used for training purposes to support local maritime education, particularly in the operation of environmentally friendly technologies. The focus will be on carbon-neutral propulsion and auxiliary systems with an emphasis on wind propulsion technology. There is accommodation for 6 trainees to support the training program on board.

Due to its international classification, the vessel can be used not only for domestic supply, but also for specialised transport between the Marshall Islands and neighbouring countries. As most of the islands have no harbour infrastructure, the vessel is equipped with 2 tender boats to transfer cargo to and from the beach. The vessel is equipped with light cargo derricks, which are used for cargo operations and lift the tender boats into the water or to the stowage position on the forward hatch cover.

While the ship is primarily wind-powered, photovoltaic modules with an output of ~11 kWp are installed to support auxiliary operations. A 24-volt battery bank stores the energy and also fulfills the requirements of an emergency generator. In addition to the 24-volt distribution, the 110-volt and 440volt distributions can also be supplied.

The definition of an economic budget with a cost cap was also crucial to the shipbuilding concept. The type of ship to be developed should reflect the general economic conditions and have an easy-to-finance cost structure for subsequent builds. The cost cap for the international tender in 2022 was set at EUR 3.9 million. A further 10% of the construction price was set aside as a contingency and for additional investment in a particularly high standard of environmental protection (ballast water treatment, SCR catalytic converter).

The ship design is based on the characteristics of the existing fleet, which has evolved due to the specific requirements and conditions of the trade. One of the objectives was to continue the good practice of the existing fleet. The newbuildings have therefore been designed with coupled cargo gear and tender boats. The Union Purchase cargo gear is particularly advantageous for cargo operations in swell, as the load can be kept stable in the transverse direction by using 2 coupled derricks. Table I gives the main particulars of the vessel. The vessel was classified with Korean Register as +KRS1 - CARGO SHIP CLEAN1 CDG LG ES-WIND +KRM1 -BWT.

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Length o.a.	48.00 m	Displacement	800 t	
Length b.p.	43.40 m	Cargo hold volume	600 m ³	
Beam mld.	8.70 m	Speed @ 100% NCR <bft, engine="" only<="" td=""><td>9.7 kn</td></bft,>	9.7 kn	
Depth mld.	4.10 m	Speed potential @ full sails, no engine	12.0 kn	
Draught mld. Design	2.70 m	Air draught in ballast condition	30.5 m	
Draught mld. scantling	3.20 m	Tonnage	481 GT 157 NT	
Deadweight	337 tdw			

Table I: JUREN AE main dimensions

4. Hydrodynamics and performance prediction

Considerable development work had to be done on the hydrodynamic optimization of the hull. A good coordination of the aerodynamic forces of the sail system and the hull with the hydrodynamic forces is a prerequisite for good propulsion performance and steering characteristics under sail. The sail system not only generates propulsion forces but also lateral forces, which cause drift as well as yaw moments around the vertical axis. This affects the course and steering behavior of the ship and influences the rudder design and size. The lateral force of the sails also generates a heeling moment, which has a significant effect on stability under sail. One of the design objectives was to minimize drift and yawing moments due to high lateral counter forces of the hull and a good coordination of the hydrodynamic pressure point with the sail pressure point in the longitudinal direction of the ship. The lines of the ship, in particular the bow and stern shape with skeg and the balanced spade rudder, were optimized for this

purpose. A particularly effective element for reducing drift and yaw moments is the Wagner keels, which are designed as large bilge keels with a delta-wing profile in the aft section of the ship.



Fig.10: Cross-section through the flow field of Wagner keels with the formation of a controlled vortex and pronounced negative pressure field (left) and excessive x-speed on the active keel (right), *Wagner* (2015)

In a second step, the hull shape and appendages were used to make a performance and power prediction (PPP) for the design, based on both an analytical approach and measured data from a towing tank test series at the University of Applied Sciences Emden/Leer. The tool was coded directly into the CAD design environment and used data from the parametric concept design model as input. This made it possible to compare different design variants. The PPP tool is coded using the feature programming tool provided by Friendship Systems' CAESES software. It is based on a four-degree-of-freedom calculation that balances aero- and hydrodynamic forces and moments in an iterative process, *Wagner (1967)*. Forces in the direction of ship motion, transverse forces, heeling and righting moments, and yaw angle are considered by iterating the required rudder angle. The propeller thrust is approximated by the Wageningen polynomial. Some constraints are also imposed by limiting the heeling angle to 10° (reducing the sail area if too large) and by limiting the maximum engine power (reducing the ship's speed). The minimum speed is set at 7 kn.





Fig.14: PPP - delivered power

Fig.15: PPP - leeway-angle

Fig.11-15 show key design parameters calculated by the PPP tool for varying wind speeds from 2 kn to 26 kn (colours). The polar diagram shows the predicted ship speed. The other graphs show the main parameters calculated by the tool. Each colour represents one wind speed. The x-axis shows the true wind angle from 0° to 180°. The y-axis shows the various parameters. The PPP results are used to evaluate and compare different ideas for the concept design. The tool was used throughout the design process to evaluate different design ideas and compare design variants. Another advantage of the keel system is its low complexity and the resulting relatively low construction costs, as the keels do not require active control, unlike additional rudders (E-Ship 1) or centreboards (Canopée). The arrangement of the keels does not increase the draught.



Fig.16: JUREN AE keel construction

The effectiveness of the concept was confirmed during sea trials under engine and sail. The vessel showed very good course keeping and steering ability under sail. Very good manoeuvrability under engine power was also demonstrated in turning circle tests and Zigzag manoeuvres during the sea trials.

5. Propulsion and auxiliary power

The vessel is a wind-powered cargo vessel, so the sail rig is considered the main propulsion system. With this in mind, the main engine, a DOOSAN L126TI diesel engine, delivers only 240 kW NCR at 1931 rpm and acts via a gearbox on a 3-blade propeller with a diameter of 1650 mm. The propulsion train therefore has sufficient sea margin to achieve the required minimum speed of 7 kn in winds and seas up to Beaufort 5 and to ensure operation in all weather conditions. The predicted speed for sailing operation shows a potential of approximately 12 kn. Experience to date in the moderate wind speeds typical of the area shows that the vessel can sail at the required minimum speed of 7 kn, which means that it can often be operated without engine power and achieve high savings. The small size of the main engine ensures high efficiency in hybrid operation.


Fig.17: Energy concept of SV JUREN AE

For sailing in restricted waters, e.g. within the lagoons, where partly uncharted shallows dictate slower speeds, an electric motor with an output of approx. 50 kW can optionally be connected to the shaft as a PTI via a parallel hybrid transmission (PHT). In good conditions and at speeds above 7 kn in sailing mode, the electric motor can be switched on as a shaft generator (PTO) and feed the onboard power supply. Depending on the wind conditions, a maximum input of approximately 35 kW can be expected. In this mode, the vessel can temporarily achieve 'zero emission' status for propulsion and auxiliary operation. The onboard power supply is also supported by an 11 kWp PV system with a connected battery bank, which further extends the use of renewable energy. The statistical distribution of the different propulsion and auxiliary modes is the subject of a long-term test programme.

6. Sail system

The development of the JUREN AE's sail system is based on the design and experience of the Indosail rig, which was designed and built by Peter Schenzle and his team at the HSVA in the 1980s and 1990s as part of a development cooperation with Indonesia. The rig can be built by the shipyard in steel or aluminium and uses mostly standard industry parts, making it easy to maintain and affordable. A particular feature is the two large rectangular sails (fore and main) with a fixed gaff and pre-tensioned rig structure, providing high performance despite a simple and inexpensive sail cut. The sails can be adjusted to the wind conditions without changing course by using the furling system. The triangular cut furling sails arranged fore and aft (jib, mizzen) are heavy weather sails and can be made in heavy sail-cloth, making them suitable for storm conditions. All sail control functions are operated by electric winches, both from the local station on the mast and from the control panel on the bridge.



Fig.18: JUREN AE winch diagram

A special safety feature is 'Emergency Depowering', which opens all sheets immediately at the touch of a button on the bridge, allowing the sails to depower almost effortlessly in the event of a sudden overload. All functions can be operated manually in the event of a malfunction or power failure. The safety concept has been carefully coordinated and verified with the Korean Register Classification Society as part of the 'ES Wind' additional class notation.



Fig.19: Overview and Schematic Operation of the INDOSAIL system, NN (n.d.)

The INDOSAIL rig also differs from conventional rigs in terms of statics. The arrangement of the shrouds allows the booms to swing out to 90° for greater sail thrust in following winds. This is also useful during cargo operations, when the booms are fixed in the 90° position for rigging the union purchase cargo derricks and full access to the cargo holds. This gives flexibility for cargo handling on the leeward side when the vessel is at anchor. The design of the INDOSAIL system is based on the suspension bridge principle. The sails are positioned in a pre-tensioned frame formed by the trailing, kicking and topping straps, boom and gaff. Triangular sails (jib and mizzen) follow the same principle but lack the gaff and topping straps. This separates the horizontal and vertical forces, making it easier to control the shape of the sail. It also reduces the forces on the sailcloth, increasing sail life.

The masts are made from steel to reduce cost and ease of manufacture, while the boom and gaff are made from aluminium to reduce the mass of moving parts and improve stability. The sails are made from Dacron, a widely available standard sailcloth.



Fig.20: JUREN AE sail plan

Standard industrial components were used in the construction of the rig, e.g. in the selection of the electric winches. The KOSTEC design office was responsible for the structural design. An in-house specialised workshop was able to deliver the steel structure and mechanical components with short lead times. Design and certification was supported and the University of Applied Sciences Emden/Leer. During the first year of operation, extensive data will be collected in order to further optimise the system for possible follow-up constructions. Based on sensor and measurement technology, a higher degree of automation of the system is planned as the next development goal, e.g. for use on small cruise ships.

7. Stability

Ships with wind propulsion are subject to stability loads due to additional transverse forces. Sufficient stability must therefore be demonstrated by additional stability criteria. These are defined by the classification society. In addition to the IMO stability criteria, the Korean Register requires compliance with the so-called IMO weather criterion, taking into account the actual set sail area, but with reduced wind forces. The ship's command must adjust the sail area to the wind conditions in such a way that the weather criterion for the prevailing wind force is met at all times. The Stability Manual contains the relevant reefing tables, information and calculation schemes, as well as examples for the standard loading conditions of the ship.

COND.	COND.	SAILING	WIND SCALE (BFT)										
NO.	DESCRIPTION	CONDITION	0	1	2	3	4	5	6	7	8	9	10
4	HOMO.LOAD DESIGN DEP.	SAILS STRUCK	Α	Α	Α	Α	Α	Α	Α	Α	Α	Α	Α
4.1		REEF-3	Α	Α	Α	Α	Α	Α	Α	Α	Ν	Ν	Ν
4.2		REEF-2	Α	Α	Α	Α	Α	Α	Ν	Ν	Ν	Ν	Ν
4.3		REEF-1	Α	Α	Α	Α	Α	Α	Ν	Ν	Ν	Ν	Ν
4.4		ALL SAILS	Α	Α	Α	Α	Α	Ν	Ν	Ν	Ν	Ν	Ν

Fig.21: Reefing table for homogeneous loading condition at departure, example from the Stability Manual, source: KOSTEC Co., Ltd.

In addition, the ship is equipped with a loading calculator for quick and easy stability calculations, which also shows the additional criteria and associated reefing tables. In addition to the Stability Manual, a 'Sail Operations Manual' has been produced which contains instructions for the operation and maintenance of the sail system, as well as specifications for the operational control of the ship's stability.



Fig.22: JUREN AE reefing conditions, source: KOSTEC Co., Ltd.

To increase the usable range of wind speeds for the sailing system and thus the savings potential, a total of ~77 t of permanent ballast was added to the ship's empty cells and double bottom tanks, in addition to the ballast water tanks, to reduce the ship's centre of gravity and thus improve stability. During development, it became clear that stability is a key issue when designing cargo ships with relatively high sailing performance. Various options, including variation of the ship's hydrostatics through shape parameters, lightweight construction for higher structures such as the superstructure and sail rigging, and additional permanent ballast, must be weighed during optimisation, taking into account the impact on the ship's performance criteria and cost structure.

8. Cargo hold and cargo gear

The two cargo holds have a volume of approximately 300 m^3 each, making them suitable for transporting general cargo with high stowage factors. Hydraulic steel folding hatch covers allow quick opening and closing in adverse weather conditions. The holds are ventilated to provide the 6 air changes per hour required for bagged copra. The holds are approved for the transport of Class 4 dangerous goods. This is necessary for the stowage of copra, which has a risk of self-ignition due to its high oil content.



Fig.23: Cargo hatches, freezers, fuel drum storage on deck, source: KOSTEC Co., Ltd.

Fuel for the outer islands can be carried as cargo in standard 200 litre drums on deck in designated locations along the bulwark, which allows for easy handling, stowage and securing of the drums. The large quantities of frozen goods can be stored in 3 walk-in freezers. One is located on the main deck, and two additional freezers on the tank top utilise the space between the engine room and the hold, accessible by an electric hoist from the main deck.



Fig.24: Union Purchase Gear: Configuration to operate the tender boats on both sides, source: KOSTEC Co., Ltd.

Both hatches are equipped with derricks for loading and unloading. The sail masts are used to hoist the derricks, which are typically used in a combined operation (union purchase). This allows cargo to be moved to both sides of the vessel, which is particularly useful when the vessel is swinging at anchor. The small tender boats can always be loaded on the leeward side, depending on the motion of the vessel. The load distribution of the union purchase configuration also has a damping effect on swinging cargo on a rolling vessel, improving safe cargo handling in areas with little or no shelter from Pacific swells.

Each pair of derricks is operated by 3 winches, one winch lifts both derricks to the appropriate height and one runner winch per derrick operates the combined hook to the cargo. The operator is free to move around the working platform with a remote control for the winches, giving the best possible view of the hold and both sides of the vessel.



Fig.25: Setup of the cargo gear in the RMI

On completion of cargo operations, the derricks are lowered to a horizontal position and secured in designated storage positions. The sail frame can then be returned to the midships position, ready to set sails. All hoisting and lowering is performed by captive winches, reducing the time required to change from cargo to sail operation or vice versa.

9. Navigation and communication

The vessel is equipped in accordance with SOLAS requirements for international voyages. In addition to the GMDSS radio systems for the required A3 sea area, a Starlink satellite communication system has been installed to transmit data from the long-term trials, provide up-to-date weather forecasts for optimum use of the sailing system, and for administrative communication and contact with the next ports of call. In addition, satellite communication provides crew and passengers with an improved standard of private communication, which is important for long-term crew retention.

Navigation is mainly based on paper charts and publications. In addition, an ECDIS and an ECS are installed to facilitate route planning and monitoring in a trading area that is not extensively charted in detail. An echosounder installed forward in the hull assists in detecting shallow areas. In addition, a lookout can be ordered to the top of the foremast in the mast basket to identify shallow reefs when sailing in the sheltered lagoons of uncharted waters.

A special feature is the camera system as a look-ahead function, which provides the required line of sight from the bridge under sail. It was installed in consultation with KR to achieve ES-Wind certification. The screen, located directly at the helm, transmits the image from a pan-tilt camera installed on the foredeck.

10. Accommodation

The crew accommodation meets the requirements of the Maritime Labour Convention (MLC) and flag state regulations in terms of size and equipment. This results in cabins that are quite spacious for the size of the vessel, which is a great benefit to the crew's comfort. To reduce energy consumption, the usual air conditioning system has been replaced by air coolers. These can be operated locally only when

needed, reducing energy consumption and costs both during construction and operation. Only the navigation bridge is air-conditioned, due to the strong solar radiation and waste heat from the equipment, and to provide a low-humidity environment for the onboard electronics.

Crew accommodation consists of single and double cabins on the upper deck and tween deck forward and aft. There is an additional cabin for 6 trainees on the forward tween deck. The crew mess is located on the poop deck aft, close to the galley, at the stern of the vessel in an area protected from wind, sun and rain. The outdoor mess reduces the need for air conditioning and is more comfortable for the crew in tropical waters. There is an additional area for day guests on the upper deck aft, which is sheltered by the large PV installation providing power as well as shade and rain cover.

11. Sea Trials and delivery

Due to the innovative nature of the vessel, the sea trial programme was spread over several days. The standard classification society programme was completed during the first sea trials. The sail system was tested during an additional sea trial. During this time the vessel demonstrated excellent manoeuvrability and course stability. Aerodynamic and hydrodynamic forces were well balanced, and only very small rudder angles were required to compensate for yaw moments. The vessel showed particularly good turning behaviour under sail. The ship's resistance values predicted from the towing tank tests were confirmed. During the speed trials, the vessel achieved a smooth water speed of 9.7 kn with a design draught of 2.70 m. The effectiveness of the rudder was demonstrated with the standard turning circles and zig-zag manoeuvres, all of which met the required criteria. The results of the manoeuvring tests are shown in the wheelhouse poster below.



MANEUVERING CHARACTERISTICS for S/V JUREN AE

Fig.26: Sea trial results: Wheelhouse Poster

However, due to the prevailing wind conditions, shipyard sea trials will only provide a very limited picture of the overall performance of a vessel with a sailing system. To fully assess sailing performance and other relevant characteristics, new approaches to safety testing and valid performance assessment are needed, e.g. a combination of one-day sea trials, longer-term in-service data collection and results from modelling and simulation. Further development work is required and is underway.



Fig.27: JUREN AE on delivery voyage

The long delivery voyage from the shipyard in South Korea to the Marshall Islands was the first real test of the concept and all the systems on board. It was successfully completed and the vessel was very well received in its home port of Majuro.

12. Outlook

Evaluation of JUREN AE's performance under sail is currently underway. The vessel is making its first voyages under realistic conditions, providing many learning opportunities and new experiences for the shipping company, the crew on board, and other stakeholders in the region interested in the success of this prototype. A long-term measurement campaign is needed to thoroughly investigate the performance of the new vessel and validate the models created during the design process. The data required to assess real-world performance is notoriously difficult to obtain in the challenging environment of the high seas, but with sensors on board and the continued presence of the project team in Majuro and aboard JUREN AE, good progress is being made in this regard and promising results are already being returned.

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On the Optimal Spatial Discretization of Sea Routing Algorithms

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Abstract

Navigation algorithms developed for sea routing face a distinct challenge absent in traditional landbased routing with roads and intersections: how to discretize the sea into a manageable yet sufficiently dense network of navigation nodes to ensure optimal routing? While fewer nodes speed up calculations, a higher node concentration ensures the optimal path is actually found. In this paper, through the use of Zelin in-house software Green Sea Routing®, which takes into consideration wind assisted ship propulsion, the influence of the grid resolution on numerical results and costs is studied.

1. Introduction

The development of a Green Sea Routing® (GSR®), a sea weather routing tool for wind-assisted commercial shipping, addresses critical societal, technological, and strategic challenges. From an environmental standpoint, it supports the decarbonization of maritime transport – a sector responsible for significant global CO_2 emissions. By combining wind propulsion with optimized routing, it reduces greenhouse gases and air pollutants, contributing to climate goals and more sustainable trade practices. The broader ambition is to accelerate the wind-assisted shipping sector through an accurate, high-performance routing solution. This tool leverages 3D numerical simulations, machine learning, onboard sensing, and novel weather models to deliver more accurate, real-time routing decisions that improve energy efficiency, safety, and cost-effectiveness.

GSR® relies on multi-dimensional dynamic programming to find the most fuel-efficient routes, accounting for sea weather – wind, waves, currents. Dynamic programming operates on a discretized maritime map, where a compromise must be made between computational cost and route optimality. The paper presents an analysis of key parameter trade-offs, aiming to evaluate the convergence of current settings and to identify opportunities for coarsening parameters that have limited impact on optimality, in order to reduce computational cost.

2. Method

To evaluate the impact of various parameters on routing accuracy and computational cost, this section first presents the routing algorithm, then defines the key parameters under study, and finally outlines the experimental design used for the analysis.

2.1. Routing algorithm and grid

By definition, the dynamic programming algorithm of GSR® discretizes the search space as a succession of *stages*, each of them consisting of <u>states</u> that describe the condition of the ship, for instance position, time. The states space mesh uses a "hammock" discretization scheme. *K* stages are spaced with period Δx along the great circle trajectory from departure to destination. The states of each stage can take *N* positions, they are spaced by Δy . The aspect ratio of the grid is then:

$$\zeta = K \Delta x / N \Delta y$$

The parameter q determines the connections between stages: each position of a stage can lead to 2q+1 positions of the next stage, as illustrated by Fig.1.

Finally, time discretization is performed by assigning J time slots with fixed time Δt to each state. The algorithm iterates, on voyage progress (stages), position and time (states of the current stage). From each position-time state of stage k, trip segments are evaluated towards 2q+1 states of the following stage k+1. Along each segment, the vessel's progress and fuel consumption is integrated using local weather predictions, and surrogate models of the vessel's hull propulsion systems. This integration process is performed at intervals Δt_f along the segments, with suffix f for fuel. Overall, this discretization yields an $O(JKNq/\Delta t_f)$ computational complexity, hence the need for parametric optimization.



2.1.1. Input parameters

Table I summarizes the parameters of the routing algorithm (dimensionless parameters are denoted by a dash). All parameters are explored in this study, except for time_tolerance, which acts in the algorithm as a fuel/time tradeoff parameter: the larger the time window, the more optimal trajectories can be found, at the expense of total travel time. This value depends on the user context and is not covered by this work.

Table I: Routing parameters				
Parameter	Definition			
waypoints	Departure and arrival coordinates (lon°, lat°)			
zeta	Grid aspect ratio ζ (-)			
q	Number of states that can be reached on port			
	side or on starboard side (-)			
dx_max	Maximum possible value of Δx (km)			
dy_max	Maximum possible value of Δy (km)			
time_setpoint	Departure time (h)			
time_tolerance	Time window: ETA +- time_tolerance (h)			
delta_t	Grid timestep Δt (h)			
delta_t_f	Fuel integration timestep Δt_f (h)			

2.1.2. Output variables

The execution of the algorithm generates the optimal path from departure to arrival, along with its complete history at each integration timestep Δt_f : local weather predictions, propulsive power, speed over ground etc. The sensitivity analysis focuses particularly on macroscopic outputs, summarized in Table II.

Table II: Output variables				
Output	Definition			
Total fuel	Total consumed fuel (t)			
CPU time	Computation time (min)			
Deviation	Discretized angle amplitudes from each state (°)			
Course change	Course change from a segment of the route to the following one (°)			

2.2. Design of experiments

The sensitivity analysis considers the following main effects: grid width, time discretization, deviation discretization, and space discretization. For each configuration, route optimization was performed on a batch of travels from Melbourne, USA, to Saint-Nazaire/France to Melbourne/USA, twice per month over the course of 2022, adding up to 12 routes per batch. Those iterations over months were performed to account for seasonal effects. Table III summarizes the design of experiments – all parameters are normalized by their default values.

	sign of experiments
Effect	Number of batches
Aspect ratio	4
Time	5
Deviation	1
Space	24

Table III Design of experiments

3. Results

The design of experiments generated 408 trajectories, Fig.2.



Evaluated trajectories

In order to assess the optimality and performance of each configuration, relative errors and CPU time are the chosen metrics. When results are labelled as normalized, they are divided by the results of the equivalent route for default parameters.

- <u>Relative errors</u> For each analysis, a reference batch is chosen the finest, and for each pair of batches, relative errors are computed between routes with the same departure time and co-ordinates.
- <u>CPU time -</u> CPU time is computed by setting aside constant computational overheads required for loading weather predictions and post-processing routes, to correctly estimate the time complexity of the algorithm.

3.1. Grid aspect ratio

Regarding grid aspect ratio, the reference batch is the one with the widest grid, because of its larger search space to find optimal routes. Zeta is normalized by the default value. Fig.3 shows the relative errors with respect to the reference batch for each route. Fig.4 shows the overall average and maximum unsigned relative errors for the same batches.



Fig. 3: Monthly relative error of optimal fuel consumption with respect to the reference batch

Fig.3 shows that the average and maximum unsigned relative error stabilize at 0 for normalized values of zeta of 2 and above). These batches generate the same exact trajectories with a denser and wider grid, which makes their CPU cost disproportionate. Upon a closer analysis of the routes that yield the largest relative errors, it appears they venture just outside the range of the default value of zeta (as already illustrated by Fig.2). Fig.4 displays the computation time against zeta, both normalized by the default batch.



The effect of q and zeta are conflated in this graph: it is not possible to discriminate clearly between them because both increase. The first point with a 50% increase of zeta compared to default translates to a very meager rise in CPU time. However, the following points, with rising values of q, clearly have higher CPU times.

3.2. Time discretization

Concerning time discretization, the reference batch is chosen to have the shortest timesteps. The numbers of timesteps are normalized by the default value. Fig.5 shows the relative errors with respect to the reference batch for each route, and the overall average and maximum unsigned relative errors for the same batches are shown in Fig.6.



Fig.5: Monthly relative error of optimal fuel consumption with respect to the reference batch

Fig.6: Average and maximum unsigned relative error of optimal fuel consumption with respect to the reference batch

Fig.5 shows that default parameters produce converged results (relative errors below 1%). It is made apparent by Fig.6 that the default parameter values generate temporally converged results. The following figure displays the computation time against the number of timesteps, both normalized by the default batch.



The linear growth of computational cost with the number of timesteps is clearly visible in Fig.7.

3.3. Deviations discretization

Considering the discretization of deviations, all batches whose parameters generate deviations that are different from the default case were considered. The following figure displays the maximum values of course change over all trajectories, against the maximum course changes allowed by the grid.



Fig.8: Maximum and average effective course change

Fig.8 shows that the maximum effective course change plateaus at 90°. High possible course changes are actually associated with low effective course changes. A trajectory with a harsh course change is represented in Fig.9.



Fig.9: Trajectory with maximum course change of 74°

This course change amplitude of 74° is large but plotted over the scale of the whole trajectory it seems due to a manoeuvre to avoid unfavorable weather conditions.

3.4. Space discretization

Regarding space discretization, the reference is the batch with the smallest space increments in Δx and Δy . The numbers of grid points are normalized by the default value. Fig.10 shows the relative errors with respect to the reference batch for each route, and the overall average and maximum unsigned relative errors for the same batches are shown in Fig.11.

Fig.10 shows that, globally, a finer grid enables lower fuel costs, which makes relative errors positives. There are two exceptions on eastbound routes, with negative relative errors. One possible explanation is that grid points don't exactly overlap from one batch to the next, so local optima may exist between two refinement levels. Given the results in Fig.11, the default parameters result in absolute relative errors above 1%, which indicates a lack of convergence. Fig.12 displays the computation time against the number of grid points, both normalized by the default batch.



Fig.10: Monthly relative error of optimal fuel consumption with respect to reference

Fig.11: Average and maximum unsigned relative error of optimal fuel consumption with respect to reference batch



Once again, computation time is a linear function of the number of grid points. Additionally, analyses were led on anisotropic grid refinement, i.e. changing the value of dx_max with fixed dy_max , or the opposite. For those analyses, the batch of overall finest dx_max with fixed dy_max is still chosen as reference because of its fine grid resolution.



Fig.13: Monthly relative error of optimal fuel consumption with respect to the reference batch

Fig.13 shows the relative errors with respect to the reference batch for each route; the value of dx_max is normalized by that of the default batch. Note that for a constant dy_max , from left to right, the deviation angles become increasingly narrow. Overall, for values of dx_max_adim ranging from 0.5 to 1, the total fuel consumption remains similar; outside this range, however, the algorithm is less efficient. On the left, the grid is very fine, but the path is constrained to go almost straight because the minimum deviation angles are too large. On the right, the grid is very coarse, and the path again tends to go straight, this time because the maximum deviation angles are too small.

Fig.14 displays the computation time against dx_max , both normalized by the default batch. The CPU time does not grow linearly with K, as travel segments between successive stages become shorter and therefore fewer integration steps are needed between each stage.



Fig.15 shows the relative errors for each route; dy_max is normalized by the default value. Note that for a constant dx_max , as one moves along the x-axis from left to right, the deviation angles become increasingly coarse. On the left side, the grid is very fine, but the trajectory remains almost straight because the maximum deviation angles are too small. On the right side, the grid is coarse, and in addition, the minimum deviation angles are too large, which again results in a nearly straight path. Consequently, the error curves exhibit a similar shape to those observed when varying dx_max .



Fig.15: Monthly relative error of optimal fuel consumption with respect to the reference batch

Fig.16 displays the computation time against dx_max , both normalized by the default batch. As for the CPU time, when dy_max is smaller, the grid diffuses less towards its outer bounds, so in practice, the CPU time does not increase linearly with N either.



3.5. Overall optimality-CPU time balance

To analyze the global optimality/computational cost tradeoff, the batch with finest dx_max and dy_max is chosen as reference because its spatial discretization is the finest, offering the largest search space. Fig.17 displays the average relative error of fuel consumption between all batches and the reference batch, and CPU time is normalized using the default batch.



Fig.17: Average unsigned relative error of optimal fuel consumption with respect to the reference batch, for each other batch, against average computation time of each batch

Batches with finer timesteps theoretically achieve better fuel consumption *precision*, because their integration timestep is shorter, however the spatial grid remains the same as that of the default batch, and relative errors retain the same magnitude. The batch of largest CPU time has very fine deviation resolution and high deviation amplitude: it achieves on average 4% lower fuel consumption than default but is prohibitively expensive.

4. Conclusion

This paper presented a sensitivity analysis on the key parameters of GSR®. It was found that the largest investigated aspect ratios were computationally inefficient. The results also showed that convergence along temporal parameters is rather computationally inexpensive to achieve. However, reaching convergence in the number of grid points is quite expensive. Finally, anisotropic variation of dx and dy discretization demonstrated that the deviations discretization has a first order effect on the optimality of results, therefore refining the grid in one direction only doesn't necessarily enable more accurate results.

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Aero-Hydrodynamic Interactions for Wind Powered Ships: Retrofit of a High-Speed Mega RoRo Vessel

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Abstract

This study evaluates the retrofit of a high-speed RoRo vessel with rigid wingsail wind propulsion, focusing on aero-hydrodynamic interactions and real-world performance. A validated lifting line model, enhanced with CFD-derived ship-sail interaction effects, is coupled with a dynamic vessel simulation environment. Using operational data from HUMBRIA SEAWAYS, we simulate fuel savings and vessel response across realistic voyages. Results show median fuel savings of 16% at 18 kn, with effective course-keeping and no major operational penalties. The findings support the viability of wind propulsion retrofits for fast RoRo ships operating on consistent, wind-exposed trade routes.

Nomenclature

∆R_WPS	Change in resistance due to WPS (kg m s ⁻²)
AWA	Apparent wind angle - ship frame (°)
AWS	Apparent wind speed - ship frame (m s ⁻¹)
CII	Carbon Intensity Indicator (gCO ₂ GT ⁻¹ ·nm ⁻¹)
F_WPS	Aerodynamic thrust (kg m s ⁻²)
R_T	Ship resistance including wind and wave resistance (kg m s ⁻²)
Span	Height of wind propulsion system (m)
TB	Thrust benefit (%)
Vs	Ship speed (kn)

1. Introduction

The maritime industry is under intense pressure to rapidly decarbonize. Owners and operators are obliged to improve the efficiency of their ships to comply with emissions regulations. Wind propulsion systems (WPS) stand apart among the near-term retrofit options. Simply put, wind provides carbon-free propulsion. Ships fitted with wind propulsion technologies can maintain speed while reducing fuel consumption. Especially along windy routes, the impact on vessel environmental efficiency metrics such as Carbon Intensity Indicator (CII) can be profound.

Wind propulsion systems (WPS) are increasingly adopted, particularly in deep-sea bulker and tanker fleets which benefit from generally low ship speeds and good available deck space for integration. For RoRo vessels operating at high speeds (Vs greater than ~18 kn), the vessels own speed and apparent wind will detrimentally shift apparent wind angle (AWA) forwards, resulting in predominantly upwind sailing conditions where aerodynamic and sailing efficiency are essential to realise significant fuel savings. RoRo types do offer clear deck space for wind propulsion integration, as well as regular sailing tracks and schedules that allow straightforward techno-economic projections about the benefit of a wind propulsion retrofit or newbuilding option.

Several RoRo vessels have been retrofitted with wind propulsion systems, chief among which is Sea-Cargo's SC CONNECTOR, Fig.1. SC CONECTOR is 154 m long with capacity of approximately 1,775 lane meters and a service speed of around 11 kn. It was retrofitted with two 35 m tiltable Norse-power rotor sails in 2021. According to Sea-Cargo and Norsepower, the vessel is able to operate on wind power alone in favourable conditions, with reported annual yields of approximately 25% along North Sea routes. Utilisation of this ship has changed to maximise the wind-powered contribution to

propulsion, where the shortest-distance route is replaced by active voyage optimisation considering each update to the weather forecast. Furthermore, vessel stability in seaway is much improved due to aerodynamic added-mass and damping effect of the WPS.



Fig.1: Sea-Cargo's SC CONNECTOR fitted with wind propulsion systems. Source: dnv.com

Captain Artur Sylwestrzak of the SC CONNECTOR, highlights both performance and crew benefits. "The vessel behaves much better," he explains, referring to the improved roll damping and overall seakeeping. He describes the ship's motion as "more stable," adding that this directly translates to increased comfort and safety on board. Captain Sylwestrzak also appreciates the operational advantages, stating, "We are now using wind as a free and unlimited source of energy," and emphasizes the importance of his crew's enthusiasm: "Once they understood how it works, they became proud to be part of something innovative," *DNV* (2023).



Fig.2: Newbuilding RoRo's with WPS announced by Louis Dreyfus Armateurs (top-left), source: lda.fr, Willenius Wilhemson (bottom-left) source: walleniuswilhelmsen.com, Neoline (topright) source: neoline.fr, and Stena Line (bottom-right) source: stenaline.com

This encouraging experience suggests that significant wind yields might be within reach for most of the RoRo fleet, sailing in the Northern Sea and elsewhere. Nevertheless, the ability of WPS to deliver high thrust even at significantly higher ships speeds is a crucial element of the business case for wind propulsion. In this respect, rigid wingsails, such as CWS Airfin350, have a significant edge of other WPS, due to their naturally high sailing efficiency. This study builds upon previous techno-economic analyses and hydrodynamic research to incorporate an advanced modelling for wingsail aero-dynamics, including superstructure-disturbed windage and optimal sail control considering aero-dynamic interactions to provide a detailed exploration of integrated aerodynamic and hydrodynamic solutions specifically tailored to the needs of a high-speed RoRo retrofit case, sailing at 17-19 kn.

2. Background

European carriers have initiated significant investments in fleet renewal and retrofitting programs. For example, CLdN introduced LNG dual-fuel vessels specifically designed for European short-sea routes, while DFDS deployed new Jinling-built RoRo ferries optimized for efficiency within European waters. Deep-sea operators based in Europe, such as Wallenius Wilhelmsen and Grimaldi Group, have similarly expanded capacities with next-generation vessels to meet high vehicle transport demands.



Fig.3: HUMBRIA SEAWAYS is a modern mega-RoRo cargo ferry built in 2020 operating on the Gothenburg (Sweden) – Ghent (Belgium) route. WPS retrofit concept shown.

DFDS is one of Europe's leading short-sea RoRo operators, running a pan-European network of freight ferry routes spanning the North Sea, Baltic Sea, English Channel, and Mediterranean. The company places a strong emphasis on decarbonisation, putting sustainability first and investing in innovative technologies to reduce its environmental footprint. DFDS were willing to contribute technical specifications and operational data to this case study including vessel particulars, voyage reports, and one year of AIS tracks.

HUMBRIA SEAWAYS operates a fixed route between Gothenburg and Ghent. The Gothenburg– Ghent corridor presents an operationally relevant test case for evaluating wind-assisted propulsion performance. Spanning approximately 550 nm across the North Sea, the route is characterized by frequent exposure to westerly and south-westerly winds, particularly during the autumn and winter months. Average wind speeds along the corridor range between 6-10 m/s, with persistent moderate sea states, making it suitable for steady-state wind-assist operation. The route's duration of approximately 32 h at a typical service speed of 17-19 kn provides sufficient exposure time for aerodynamic thrust to contribute measurably to propulsion. Additionally, the route avoids narrow passages or air-draft constraints. These conditions, combined with consistent biweekly scheduling and a high-capacity RoRo hull form, position the HUMBRIA SEAWAYS as an ideal candidate for evaluating real-world integration of aerodynamic and hydrodynamic design innovations.

in particulars of DFDS ship.	. Πυνιδκιά
Build Year	2020
Length	237.40 m
Breadth	33.00 m
Draft	6.65 m
Dead Weight (Scantling)	17183 tdw
Gross Tonnage	60465 t
Lane Length	6700 m
Capacity (trailers)	450
Propulsion Power	23.6 MW

Table I: Main particulars of DFDS ship: HUMBRIA SEAWAYS



Fig.4: AIS track of HUMBRIA SEAWAYS route between Gothenburg and Ghent during 2024 (left), wind-rose plot showing distribution of apparent wind on round-trip voyage (right) source: MARIN Blue Route.

An overview of HUMBRIA SEAWAYS operational profile and associated wind conditions is presented in Fig.4. AIS data for q4 2024 data represents 45 voyages, where due to data gaps 28 tracks are retained for analysis. A 30-year representation of apparent wind statistics is shown in top-right, including 18 kn ship speed. The impact of vessel speed on apparent wind condition is clear, with normal transit speed at sea of 17-19 kn. The wind propulsion system and integration with the ship must have superior upwind capabilities.

3. Methodology and Results

Analysis in this paper presents aerodynamic modelling from CWS, and ship modelling and operational analysis from AlbatrosDigital. The following paragraphs outline methodology and results of individual efforts. Coupling between simulation tools followed an iterative approach, where AlbatrosDigital provided initial and revised hydrodynamic cost functions, representing the sailing-induced drag associated with drift force and yawing moment (rudder working). These cost functions were used by CWS to refine the Aerodynamic trim of Airfin350 wingsails in upwind conditions. Finally, the aerodynamic forces and moments of the wingsail arrangement are imposed on the AlbatrosDigital ship model with a 6dof tabular exchange format.

3.1. Aerodynamic Modelling

Precise modelling of aerodynamic interactions is crucial to accurately predict performance of multisail Wind Propulsion System (WPS) configurations, such as CWS Airfin350 wingsails. We began with a fundamental approach to single sail modelling before addressing the complexities of sail-sail and ship-sail interactions.

3.1.1. Aerodynamic Single Sail Modelling

The first layer of the aerodynamic model uses Prandtl's Lifting Line Model (LLM) to predict a reliable performance baseline for a single Airfin350 wingsail. The LLM is a well-established aerodynamic tool that calculates the spanwise lift distribution, considering the influence of trailing vortices. For the Airfin350, LLM was extensively validated against experimental data obtained from wind tunnel tests run at a Reynolds number (Re) of 10⁶, on an isolated Airfin350 wingsail. Measurements took place in the S10 wind tunnel of the Institute Aerotechnique (IAT-CNAM). The LLM predictions showed a satisfactory agreement with the experimental results for the single wingsail, confirming its suitability as a basis for further, more complex modelling. This validated single sail model served as the foundation for developing our multi-sail interaction models and sail-ship hull and superstructure interaction models.

3.1.2. Aerodynamic Sail-Sail Interaction Modelling

Interactions between multiple wingsails are modelled by adding a horseshoe vortex system similar to CORR-SILL, *Malmek et al. (2020)*, to LLM. The algorithm iteratively solves the LLM for each wingsail, considering the induced velocities from other units, until convergence. CORR-SILL has known limitations, particularly in neglecting viscous effects and other terms of the Navier-Stokes equations. This is why several corrections were applied to the CORR-SILL model:

- 1. Pressure Gradient Correction: Following *Malmek et al. (2024)*, a boundary layer correction accounts for changes in local pressure on interacting wingsails, modifying the 2D lift curve used in the LLM and improving stall prediction.
- 2. Wingsail Viscous Wake: a semi-empirical correction, based on *Bordogna et al.* (2016), models the viscous wake downstream of each wingsail, accounting for the velocity deficit related to drag.
- 3. Swirl Velocity Correction Inside the Vortex Core: To better represent tip vortices, which significantly influence interactions, we used the work by *Bhagwat and Leishman (2002)* to adjust swirl velocities within the vortex core, preventing local stall artifacts and improving interaction predictions when wingsails are aligned with the wind.
- 4. Streamwise Velocity Deficit Inside the Vortex Core: A streamwise velocity deficit was introduced within the vortex core, similar to the viscous wake. This also serves to represent the wake of the pedestal on which the wingsail is mounted, which was experimentally observed to have a notable impact on downstream wingsails.

The aerodynamic sails-sail interaction model was then validated and fine-tuned using experimental data from wind tunnel tests. Experiments were run on two large scale models attaining $Re = 10^6$, placed in several different layouts, Experimental results and model validations are extensively described in *Tardif et al.* (2024).

3.1.3. Aerodynamic Ship-Sail Interaction Modelling

A ship-sail interaction model was added to account for the influence of the ship's superstructure on the airflow around the wingsails. Firstly, the perturbed flow field caused by the ship's hull and superstructure was computed with RANS simulation, for a set of wind speeds and directions. These perturbed fields were then used as input for the LLM calculations in the interaction model. This approach is supported by existing literature, such as the work by *Garenaux and Schot (2021)*, which

suggests that wind twist and the effect of the operating settings of the wind propulsor can be neglected in ship-sail interaction analyses. This simplifies the modeling process, allowing us to reduce the number of CFD configurations.



Fig.5a: Streamlines of the CFD flow field around the ship without wingsails



Fig.5b: Streamlines of the CFD flow field around the ship added to the induced velocities computed by the interaction model

It must be acknowledged that this methodology comes with inherent limitations. The perturbation field extracted from CFD corresponds to a steady-state mean flow and is then simply added to the induced velocities computed by the aerodynamic model. This linear superposition neglects potentially significant flow features such as local pressure gradients and turbulence-related phenomena, which could influence the aerodynamic response of the wingsails in a real operating environment.

Nonetheless, this method provides a first-order approximation of the aerodynamic interaction between ship and sails, enabling a more realistic evaluation of wingsail performance while maintaining reasonable computational cost. The superposition of the sail-sail and ship-sail interaction model is illustrated on Fig.5b. Our results confirm conclusions found in the literature: the apparent wind angle is shifted to the beam at low and high wind angles, while the apparent wind speed tends to decrease for beam winds.

3.1.4. CFD Setup Overview

The CFD simulations of the ship are run using OpenFOAM (version 22.12 by OpenCFD, on Ubuntu 22.04 LTS) on the CWS computing cluster. The simulations use the SIMPLE algorithm in combination with the k- ω SST turbulence model. The computational domain is a cylindrical volume with a diameter of 900 m and a height of 130 m. It features a single inlet and a one outlet, with two symmetry planes enclosing the remaining boundaries. A simplified representation of part of the ship above the water is placed at the bottom centre of the domain. The mesh consists of approximately 19 million cells.

Considering the symmetry of the ship, simulations were run on only one side of the vessel. The range of apparent wind angle (AWA) was sampled at every 15° , between 0° and 180° , for a reference apparent wind speed of 10 m/s. The aerodynamic model then applies a 4D linear interpolation across three spatial directions and the AWA to reconstruct the locally disturbed flow along the span of the wingsails. The velocities are scaled by AWS, which assumes flow similarity and neglects potential Reynolds number sensitivity.

3.2. Aerodynamic Results

In this section, we present the aerodynamic results obtained from our models and simulations. We will first examine the airflow perturbations caused by the presence of the ship and then analyze the aerodynamic performance of the complete rig, considering interactions between the sails and the ship.

3.2.1. Ship aerodynamic perturbations

Raw CFD results were analysed to assess whether the main flow trends align with observations from previous studies. Three representative AWA conditions are presented here: 45° , 90° , and 135° .

Fig.6a shows a deviation of the flow above the forward deck, where the wingsails are intended to be installed. This deviation locally shifts the apparent wind angle (AWA) towards a more favourable downwind direction. A slight increase in AWS is also observed in this region. Both effects are expected to improve the aerodynamic performance of the rig by increasing thrust while reducing the side force, compared to a scenario without ship-induced perturbations.



Fig.6a: Top view of streamlines of perturbated flow at AWA = 45° at Z=40 m

Fig.6b provides insight into the vertical distribution of the flow at beam winds (AWA = 90°). While an increase in wind speed is still noticeable above deck, a large recirculating bubble due to

flow separation is clearly visible. Within this region, the flow is highly turbulent and characterized by low velocities, which would significantly reduce the aerodynamic performance of the wingsails operating in this area. As a result, this phenomenon would likely mitigate the beneficial effects of the ship-induced flow acceleration on the wingsails.



Fig.6b: Front view of streamlines of perturbated flow sampled at midship at AWA = 90° at Z=40 m



Fig.6c: Top view of streamlines of the perturbated flow at AWA = 135° . Z=40 m

Finally, Fig.6c shows flow characteristics at AWA of 135°. In this case, both flow deviation and velocity increase are less pronounced than at lower AWA, such as 45°. Additionally, the wake generated by the ship's superstructure would, in certain conditions, directly interact with the wingsails, potentially degrading their aerodynamic performance.

3.2.2. Full rig aerodynamic analysis

Several simulations were run to assess the overall aerodynamic performance of the wingsail rig, and to progressively account for the different interaction effects impacting the flow.

Three levels of modelling were considered. The first one included only the aerodynamic interaction between sails, without considering flow perturbations generated by the ship. In a second step, the

CFD-derived perturbed velocity field was introduced to capture the effect of the ship-sail interaction, considering the distortion of the flow induced by the hull and superstructure. Finally, a hydrodynamic penalty was added to the sail control optimiser, to represent the additional drag generated by the hull and appendages when compensating for the aerodynamic drift force.



Fig.7: Evolution of thrust force (top) and drift force (bottom) as function of apparent wind angle

Fig.7 presents the total aerodynamic forces obtained for all tested configurations, including these different levels of modelling. The results are also compared to a single-sail reference case, which serves as a baseline for assessing the influence of sail-sail and ship-sail interactions.

Under upwind conditions, the interaction between sails significantly reduces the apparent aspect ratio of the rig, resulting in a sizable reduction in thrust. At beam wind conditions (AWA $\approx 90^{\circ}$), the wake shed by the sails on one board of the ship directly impacts the sails located downstream on the opposite board. This leads to a distinct thrust loss around 90° AWA. However, at higher AWAs, the aerodynamic interaction between sails becomes favourable, resulting in a thrust increase compared to the single-sail configuration.

The addition of ship perturbations has a mixed effect on sail performance, depending on AWA. Their influence is most significant at bow and to a lesser extent stern quartering AWA. The CFD velocity fields reveal both a favourable flow deviation and an increase in wind speed in the region where the wingsails are located. This has directly increases the thrust generated by the rig, as confirmed by the interaction model results. At beam wind conditions, the perturbations induced by the ship appear to have a limited effect on the overall aerodynamic forces. The local increase in wind speed above the deck tends to compensate for the performance losses generated at lower heights by the large recirculating bubble induced by flow separation.

Finally, the application of the hydrodynamic penalty mainly affects low AWA conditions (below 40°), where the drift force generated by the rig is the highest. The optimiser tends to reduce the angle of attack of the sails to limit the drift force, resulting in a slight decrease in thrust. Superior aerodynamic efficiency of the CWS Airfin350 profile, means that a significant reduction in drift force

can be achieved with only a moderate impact on thrust. At higher AWAs, where the drift force is naturally lower, the penalty has a negligible effect on the results.

3.3. Operational Performance Simulations

3.3.1. ALBATROSDIGITAL Software

The AlbatrosDigital software is a cloud-based modelling suite of naval architecture and marine engineering tools. At its core, the AlbatrosDigital software uses a constrained-optimization solver that computes a ship's response to maintain a steady course under given environmental conditions, such as ship speed, wind condition and wave condition. An adjustable level of simulation physics is available to match the modelling purpose, or available ship information. The Albatros software is highly customizable, allowing users to easily include their own specific models and requirements. The AlbatrosDigital software provides an assessment of the wind propulsion arrangements on the DFDS vessel HUMBRIA SEAWAYS

The model is deployed on a modern web-based infrastructure, featuring a cloud-native modelling engine that includes rapidly scalable computing resources. This architecture allows for efficient processing of large datasets and complex simulations. The model's flexibility extends to its integration with client data and third-party services, offering bespoke preconditioners and plug-ins that can be customized to meet specific needs. Users can interact with the tool using Jupyter Notebooks for input and output, an API endpoint integration, or a customized interface.

AlbatrosDigital Virtual Voyage makes the link to operational profiles, using HUMBRIA SEAWAYS AIS track provided by DFDS and metocean data to replicate voyages. The ship model comprises a full factorial combination of vessel drafts, vessel speeds, wind conditions, and wave conditions. For this analysis, the resulting fuel table consisting of 167,832 entries describing the vessel response. Along the waypoints of each AIS track, corresponding metocean data is matched to the relevant entry in the fuel table.



Fig.8: Modelling accuracy for AlbatrosDigital baseline model, comparing modelled voyage consumption with reported consumption in 28 DFDS voyage reports during q4 2024

A baseline digital ship model is first compared with consumption data in DFDS voyage reports to validate the composition of the model. Normal consumption is 60-110 t according to the weather encountered on the voyage. Over 28 complete AIS tracks during q4 2024, an MAPE level of 3.63% was reached, see Fig.8.

3.3.2. Concept design for WPS retrofit

A six-wingsail arrangement (three in-line along each deck edge) is proposed as maximal option for wind propulsion retrofit. We consider alternate configurations with three or four wingsails arranged along the centerline that may result in more efficient sailing performance. The leeward systems in the six-wingsail arrangement shown above suffer to a certain extent from the wake of the upwind systems. On the other hand, a six-wingsail arrangement along deck-edge facilitates integration with trailer operations on the upper deck.



Fig.9a: Arrangement of six or three wingsails configuration on the ship deck



Fig.9b: Arrangement of four wingsails configuration on the ship deck

3.3.2. Thrust Benefit as Wind-assist design metric

The thrust benefit (TB) is a convenient performance metric for wind-hybrid vessels, defined as:

$$TB = \frac{F_{WPS}}{R_T + \Delta R_{WPS}}$$

Hence the thrust benefit is the ratio of the aerodynamic driving force produced by the wind propulsion system and the total the total resistance of the ship, including any increase due to the 'sailing condition'. TB, often expressed as a percentage, represents the balance between wind propulsion and the main engine propulsion, and is therefore an approximation for the expected fuel savings. This level of analysis does not consider changes in the propulsion efficiency of the main mover (main engines and propellers).

Sailing performance metrics such as TB are typically presented in polar plots as in Fig.10, in which the vessel performance is given for a range of true wind speed (TWS) and for all wind angles (TWA). The angle is defined in the ship reference frame, relative to the ship heading: the ship is sailing directly into the wind at TWA = 0° (resulting in negative TB due to the added air drag of the wingsails), and with the wind astern for TWA=180°. Observe the iso-line = 0 which defines the extents of the "no-go zone". At AWA = 115°, TB approaches 100% and some wingsail configurations supply enough thrust to propel the ship. The typical transit speeds for HUMBRIA SEAWAYS mean that wind angles are concentrated to "close-hauled" region where wind angles less than 60° are relevant.



Fig.10: Polar diagram showing thrust benefit in terms of True Wind condition for design candidates three wingsails (left), four wingsails (center), and six wingsails (right). (Vs = 18 kn)



Fig.11: Leeway and rudder angle presented as polar diagram for True Wind condition. Bare hull (top) and Anti-drift fin case (bottom). Six wingsails, Vs=18 kn.

Vessel response polar diagrams of heel (using GM =3.5 m), leeway, and rudder angle show no major blocking issues. HUMBRIA SEAWAYS operates at high transit speeds, with ample flow over dual rudders providing steady course-keeping even under wind propulsion drift force. Anti-drift fins are incorporated in the design to improve upwind efficiency and cope with generally small apparent wind angles associated with high transit speeds, following *Jacobi et al. (2024)*. The impact is presented in Fig.11 showing polar diagrams for leeway and rudder angles for the six wingsails configuration.

3.3.3. Operational Profiles and Voyage Simulations

Wind data for the route between Gothenburg and Ghent, expressed as percentiles in a wind scatter matrix, are used to create a weighted sum of the entries in the polar diagram, giving the expected performance of the design candidate sailing along the route.



Fig.12: Percentage of fuel saved per voyage calculated using annual wind statistics showing performance of different sail configurations (left) at vessel speed 18 kn, and impact of vessel speed (right) for six Airfin configuration as maximal retrofit option.

We obtain a rough indication (with fixed speed) of expected voyage fuel savings of approximately 10 ton per voyage, corresponding to between 8% and 19% according to number of wingsails or vessel speed, shown in Fig.12.



Fig.13: Tons of fuel saved per voyage calculated as 28 individual realizations based on AIS voyage tracks of during Q4 2024

Wind propulsion contribution on individual voyages was computed by comparing consumption of the Airfin arrangements with the baseline ship model along voyage AIS tracks. Each result is shown in Fig.13, including resulting statistics for the voyage fuel savings. The median value for individual realisations presented is 16%, with interquartile range of 3.3%-23.6%. In ongoing work, this analysis will be extended to consider seasonal and interannual variation in wind conditions.

4. Discussion & Conclusions

This study demonstrates the technical feasibility and substantial operational benefits of retrofitting high-speed RoRo vessels with rigid wingsail systems. Through advanced aerodynamic modelling, CFD-informed interaction analysis, and validated operational simulations, we find that significant thrust contribution from wind propulsion is achievable even at service speeds around 17–19 kn. The case study of HUMBRIA SEAWAYS shows potential fuel savings of up to 50% on individual

voyages, with a median reduction of 16% over a winter sailing season. Key to unlocking this performance is the aerodynamic efficiency of modern wingsails, especially in upwind conditions where apparent wind angles are small. Integration considerations, such as anti-drift fins and deck layout, also play a vital role in maximising benefit while maintaining vessel operability. This research strengthens the business and technical case for wind-assist retrofits in high-speed RoRo fleets operating along windy, regular trade routes.

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Minimizing Methane Slip from LNG-Powered Vessels

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Abstract

The use of liquefied natural gas (LNG) as fuel for shipping results to negligible sulphur emissions and low NOx and particle emissions together with lower CO_2 emissions compared to diesel-based fuels. Drawback of LNG usage is the unburned fuel i.e. methane can be found in the exhaust. Both, engine technology and aftertreatment technology development ongoing to minimize methane emissions are presented. In addition, the emission detection and quantification are studied since it will play a key role as methane is also becoming regulated.

1. Introduction

When aiming to decarbonize shipping, different types of measures can be implemented to decrease GHG emissions. While there are measures to take e.g., in logistics, digitalization and hydrodynamics, the energy source and related machinery remain the ones which can result to major contributions. New alternative, low carbon or carbon free, fuels would make major benefits for shipping decarbonization. The actual deployment of such fuels depends though on many issues, like the supply dynamics, fuel characteristics, engine related technology advancement, actual well-to-wake performance, economic and socio-politics issues. Also, other emissions than GHG, e.g., air pollution needs to be considered.

One fuel, already widely in use today, that results to lower CO_2 compared to the diesel fuel, which is the main fuel for shipping today, is liquefied natural gas (LNG). LNG utilization has increased in recent years with the most popular way to use LNG in low-pressure dual-fuel (LPDF) engines together with diesel fuel for ignition. Lower sulphur and nitrogen oxides, together with lower particulate emissions are reported with LNG use compared to diesel use. Moreover, CO_2 emissions are lower as well but there is an issue with the methane slip with the LNG used in low-pressure dual fuel engines. The methane being a strong greenhouse gas and regulations introduced to consider methane emissions from ships, have made the engine manufacturers to take further development steps in preventing the methane slip. By minimizing the slip, lower GHG emissions are achievable.

As part of the ongoing GREEN RAY project technologies are being developed to minimize the methane emissions. Both on-engine and aftertreatment technologies development is ongoing. In current paper we focus on four-stroke engines.

Furthermore, we present results of an assessment of methane emissions from LNG vessels that has been done in the GREEN RAY project and also study the different measurement methods to reliably detect and quantify the methane emission. Reliable methane measurement is important as methane is included in regulations aiming to reduce GHG emissions from shipping. The International Maritime Organization (IMO) aims to reduce carbon intensity by 40% by 2030 and net-zero GHG emissions by 2050. The EU has also implemented regulations, including the EU Emissions Trading System (EU ETS) to cover CO_2 emissions from all large ships entering EU ports. Methane and N_2O will be included as from 2026. FuelEU Maritime Regulation sets maximum limits on the yearly GHG intensity of the energy used by a ship. CO_2 , CH_4 and N_2O emissions over the full lifecycle of the fuels is covered.

2. Methane emissions from LNG vessels

2.1 Onboard studies

In present study, methane slip results of all publicly available studies conducted onboard vessels equipped with 4S LPDF engines were collected. This data set was fulfilled with recent onboard studies of the current GREEN RAY project, *Lehtoranta et al. (2023), Kuittinen et al. (2024), Lehtoranta et al. (2025)*. These emission measurements were conducted on-board two state-of-the-art LNG vessels. The first campaign took place on-board a Ro-Pax ferry (built in 2021) operating in the Baltic Sea and the second was conducted on-board a cruise ship (built in 2022) operating in the Mediterranean. During both on-board experiments, one measurement point in the exhaust pipe, located a few meters away from the engine, was used for sampling raw exhaust gas. Sampling lines were heated to 180°C. The speciation of methane was performed using a gas chromatograph (Agilent MicroGC) and Fourier transform infrared spectroscopy (FTIR, DX4000 by Gasmet).

Methane measurements conducted at different engine load modes, with both vessels studied, show lower methane levels at higher engine loads, Fig.1. When looking at the vessel operation data these higher loads are also utilized more than the lower load conditions during the vessel normal operation. However, there are also conditions when varying loads are used like the harbor approach.

When comparing the methane emission data measured in GREEN RAY project, namely from the two engines of the RoPax ferry, ME4 and ME3, *Lehtoranta et al.* (2023), and one engine from the cruise ship, *Kuittinen et al.* (2024), to other published onboard studies, levels are clearly lower than the ones published from engines built before 2020 (with one exception being the Andersson et al. (2015)). Sagot et al. (2025) and Lehtoranta et al. (2025) agree well with the Kuittinen et al. (2024), all those present results from modern cruise ships. More detailed comparisons of the different studies are challenging, since the data set is limited, with limited information about the engine manufacturers and measurement conditions, which can influence the result as well.



Fig.1: Specific methane emissions from on-board measurements conducted on LPDF 4-S engines or vessels built or calibrated after 2020 (in blue and green) and older (in greyscale). The year in the legend refers to the year the engine or vessel was built.

Considering the climate effect, it is an important finding that the current state-of-the-art LPDF engines can result in lower methane levels compared to previous studies. However, it is essential to reduce the

methane slip even more. This can be done either by engine means or with an aftertreatment system. Both technologies are part of the current study and discussed in chapters 3 & 4.

2.2 Measuring methane with different devices

Since methane emissions become regulated and monetized, reliable emission detection and quantification will be in a key role. There is not yet any universally regulated method for measuring methane slip. But various technologies are available for detecting and quantifying methane emissions. As part of the ongoing GREEN RAY project, we have also done experiments to compare these different methane measurement technologies, *Lehtoranta et al.* (2025).

To measure total hydrocarbons (THC), Heated flame ionization detector (HFID) is generally the accepted method (e.g. in ISO 8178, NOx Technical code). However, when thinking of measurements onboard, there might be a challenge of bringing this equipment with the fuel gas (containing hydrogen) onboard some vessels. In FID the sample gas is introduced into a hydrogen flame inside the FID. Any hydrocarbons in the sample will produce ions when they are burnt, creating an electric current which is proportional to concentration. In our current study, we had two different devices utilizing FID method. Horiba MEXA HFID was used and measured total hydrocarbons and CH₄ (with the help of non-methane cutter catalyst, that burns all non-methane hydrocarbons). Combustion FAST FID was also used.

In addition to FID, we applied other methods to measure methane in our study. Gas chromatography (GC) combined with a suitable detector can be used to measure methane and in current study Agilent 490 Micro Gas Chromatograph was utilized. Also infrared spectroscopy can be used to analyze methane. Non-dispersive infrared (NDIR) spectroscopy-based Horiba PG-350GHG analyser, and a MARSIC300 from SICK, were used in present study. In addition, a Fourier transformation infrared (FTIR), namely two Gasmet DX-4000 FTIR devices were in use to measure methane.

Experiments were done in engine laboratory, and involved a state-of-the-art LNG engine, namely Wärtsilä 25 DF, a new 6-cylinder engine from the production line, with a rated power of 345 kW/cylinder summing up to 2070 kW. In addition to measuring methane from engine exhaust, measurements were also performed downstream of a catalyst, namely a methane abatement catalyst (MAC) consisting of a sulphur guard bed (SGB) and a methane oxidation catalyst (MOC).



Fig.2: Methane concentrations (wet) measured with 5 instruments at five different engine loads. Error bars show the standard deviation, *Lehtoranta et al.* (2025)

Measurement of methane from engine out exhaust was conducted with five different instruments and results are presented in Fig.2 as a function of engine load. These concentrations are calculated as averages over the measurement period (min. 30 minutes), together with the standard deviations shown
in Fig.2. An exception to this is the Horiba MEXA for which we only present one value without standard deviations, since the device was equipped with a program averaging measurement results over the 5 minutes time the MEXA was measuring. In general, MikroGC, FTIR and both devices following NDIR (Horiba & SICK) show very similar methane levels, with differences only of few percents, corresponding level to the standard deviation of one instrument. An exception within the instruments is the FID, which shows higher values than any other instrument, resulting in 9-12% higher methane levels compared to the highest level measured with other instruments.

Measurements were also conducted downstream of the MAC system at three different engine loadings of 100%, 75% and 25%. Cambustion FID was measuring THC while Horiba NDIR and Gasmet FTIR were measuring methane. Two Gasmet FTIR devices were in use. Results are collected to Fig.3. Upstream of the MAC system a separate temperature control was done, meaning that the temperatures shown here do not correlate directly with the engine out exhaust temperatures. At 100% engine load the temperature at MAC was 320 °C and obviously not enough for methane oxidation. However, all the measurement instruments showed similar methane levels near 600 ppm and interestingly also the THC level (measured by Cambustion FID) was the same, near 600 ppm. This indicates that the catalyst was though warm enough to oxidize other hydrocarbons (like ethane and propane) and only methane was left downstream of the catalyst. At the two other engine loads the temperature of the MAC was higher (i.e., 370 °C and 400 °C) and the methane levels measured downstream of the MAC were very low. The agreement between the instruments was still good and all instruments could detect the methane conversion efficiency for the MAC, which was found to be above 95%.



Fig.3: Methane concentrations (wet) measured downstream of MAC system with 4 instruments at three different engine loads. Error bars show the standard deviation, *Lehtoranta et al.* (2025)

In general, the different devices used to measure methane were found to show similar results with only a few exceptions. These exceptions might reflect the usage and maintenance of specific devices rather than the devices' capabilities to measure methane accurately. This indicates that as it is important to have reliable methane emission quantification there are also several methods to be used for this quantification. Moreover, it is important to have good and careful maintenance and operation of the devices to secure reliable results.

3. On-engine technology development

Wärtsilä started developing the next generation dual-fuel low pressure concept in 2017. Early research was focusing on solving the main weak points of the lean burn otto combustion: the high sensitiveness to air-fuel ratio and varying cylinder specific condition, the cycle-to-cycle instability, the flame quenching towards the combustion chamber walls, and the crevices dead volumes. These issues are primarily related to the ignition and flame propagation throughout the combustion chamber and leads to a noticeable variation in engine efficiency and to an increase in carbon monoxide and methane emissions. There are three main sources causing engine hydrocarbon emissions, shown in Fig.4: 1)

incomplete combustion at the periphery of the chamber, 2) scavenging losses due to short circuit between intake and exhaust ports, 3) dead crevices in the cylinder, *Delneri et al.* (2023).



Fig.4 : Main sources of hydrocarbon emissions, Delneri et al. (2023)

To address the weak points, a closed loop control concept was developed and tested on a W6L20CR laboratory engine during 2017-2018. Real-time in-cylinder pressure data was used to optimize the combustion event by controlling the injection timing and the flexible valve train from cycle to cycle. The test measurements showed such promising results, 50% reduction on the methane slip and up to 95% for Nox, Fig.5, that it was decided to continue developing the concept, *Delneri et al. (2023)*.



Novel Comb. concept verus std DF

Fig.5: Measured improvements in Methane slip and NOx emissions on the W6L20CR, *Delneri et al.* (2025)

Helped by the European Commission's H2020 co-funded SeaTech project, further development and testing of the concept was done first on the W31 laboratory single cylinder engine (SCE). The focus was first on optimizing the combustion system components and parameters.



Fig.6: Measured improvements in NOx, Methane slip and engine efficiency on the W31SCE, *Delneri* et al. (2025)

Subsequently, performance verification, concept fine-tuning and technology validation was done on the W10V31DF laboratory engine. After successful laboratory validation, it was decided to install a pilot demonstrator on the ME3 engine onboard the Aurora Botnia ferry by end of 2022. This engine is the very ME3-engine described in chapter 2.1, as its emission levels were independently measured within the GREEN RAY project. Wärtsilä has also done own measurements onboard the Aurora Botnia, and the results are very much in line with the data retrieved from the GREEN RAY project, *Delneri et al. (2025)*.



Fig.7: Internal and third-party CH4 measurements done on Aurora Botnia. In light blue NextDF, in orange the reference standard DF, *Delneri et al.* (2025)

The developed concept has been named NextDF and was released for sale for the W31 engine platform in November 2023. After the SeaTech project ended, development of the NextDF concept for the W25 (sales release in October 2024) and W46 platforms has continued under the GREEN RAY umbrella. Measurements are showing a close to 1% remaining methane slip amount compared to combusted gas

fuel, which is drastically below the assumed EU ETS limit of 3.1%, the IMO limit of 3.5%, and the measured (from 34 unique existing ships) current state emission level of 6.4%, *Comer et al. (2024)*. Fig.8 summarizes the CH4 emissions as a percentage of the gas fuel input for the NextDF engine portfolio, *Delneri et al. (2025)*.



Fig.8: Methane slip factor measured on the NextDF portfolio against the EU ETS default value and the ICCT FUMES report findings, *Delneri et al.* (2025)

4. Aftertreatment technology development

Challenge in the development of methane oxidation catalyst (MOC) has been the catalyst deactivation since palladium-based catalysts needed for methane oxidation are very sensitive to sulphur poisoning and as little as 1 ppm SO₂ present in the exhaust has already been found to inhibit the oxidation of methane, *Lampert et al. (1997), Ottinger et al. (2015)*. In present study the catalyst system involves an innovation of a sulphur guard bed to collect the sulphur from the exhaust gas upstream of the actual MOC.

The objective with the Methane Abatement Catalyst system, MAC, is to significantly reduce methane emissions from gas and dual fuel engines through exhaust aftertreatment. The methane is oxidised in the Methane Oxidation Catalyst, MOC, which is based on a chemical composition including noble metals. As noble metals are sensitive to sulphur content in the exhaust, the Methane Abatement Catalyst system, MAC, includes also exhaust pre-conditioning in a Sulphur Guard Bed, SGB, first removing unwanted sulphur from the exhaust before the exhaust enters the MOC. Shell has developed a proprietary SGB formulation that has been tested in the lab and in land-based field demonstration and has proven successful in preventing sulphur from reaching the MOC catalyst. Shell has also developed a proprietary MOC formulation that has been tested in the lab and in land-based field demonstration and has proven successful in converting methane slip from gas engines.

Laboratory tests within the frame of the EU co-funded project GREEN RAY have been performed using a test environment in Wärtsilä's Sustainable Technology Hub in Vaasa/Finland. The test environment consists of an exhaust gas collection system, where exhaust gas is collected from both laboratory- and customer delivery engines running in various test cells, i.e. both marine and power plant engines. The equipment under test is a lab-scale variant of both the MOC and SGB, see Fig.9 and 10.

The exhaust gas emission composition has been varied thanks to the collection of exhaust from various engine types and loads. The dedicated equipment for MAC testing consists of bypass valves, heaters and fans to enable testing with various temperatures and exhaust gas velocities. Obviously, the test environment also contains emission measurement equipment introduced in Chapter 2.2.



Fig.9: Canned MOC for lab-scale testing (left). Integrated SGB and MOC for lab-scale testing (right).



Fig.10: System overview of catalyst test rig in STH, Vaasa, Delneri et al. (2025)

The Methane Abatement Catalyst system shows promising performance in terms of methane emission abatement. Conversion levels well above the GREEN RAY target of 80% were observed throughout the testing period, also for a marine engine. More than 150 hours of operation have been collected, meaning that most de-greening should be behind, i.e. the time when a new catalyst is highly reactive before stabilization. The real-life long-term performance anyhow remains a subject to be analysed as part of an upcoming vessel demo within the scope of project GREEN RAY.

To assess the mechanical strength of the MAC, a dedicated mechanical rig was built to simulate the pulsating forces and induced vibration caused by the engine actual exhaust flow dynamics. In particular

the SGB catalyst durability was tested extensively to assess the resilience of its structure. Tests were carried out at Technobothnia/VAMK in their shaker table test bench, Fig.12, able to generate up to 3g vibration level continuously for 24 hours; the outcome was positive and the SGB catalytic elements showed good stability during the accelerated vibration test.



Inlet MOC Temperature

Fig.11: CH4 conversion efficiency in various operating conditions. Note excessive space velocity for testing purposes, *Delneri et al.* (2025)



Fig.12: Wrapped SGB for vibration bench testing

According to common practice, functionality and safety aspects have been analysed with the help of a Failure Mode and Effect Analysis (FMEA). As a sign of conformity for marine applications, the MAC system has been awarded Approval in Principle by DNV, paving the way for an upcoming full-scale vessel demonstration and market introduction.

5. Conclusions & next steps

In conclusion, the use of liquefied natural gas (LNG) as a fuel for shipping presents significant advantages in terms of reducing sulphur, nitrogen oxides, particulate emissions, and CO2 emissions compared to traditional diesel-based fuels. However, the challenge of methane slip remains a critical issue that needs to be addressed to fully realize the environmental benefits of LNG.

The ongoing development of both on-engine and aftertreatment technologies, as part of the SeaTech and GREEN RAY projects, shows promising results in minimizing methane emissions. The assessment

of methane emissions from LNG vessels and the study of different measurement methods highlight the importance of reliable detection and quantification of methane emissions, especially as regulations become more stringent.

Overall, LNG is considered to be a transition fuel and the technologies developed today should be capable of utilizing biobased gas or a renewable synthetic in origin. Methane slip minimization and avoiding other pollutants produced are not only important today but also for future fuels, even though such fuels could be produced sustainably. Continued research and development in this area are essential to ensure that the shipping industry can meet its environmental goals and contribute to global efforts to reduce greenhouse gas emissions

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Getting Real on Non-Biocidal Coatings: The Current Reality and Future Outlook for Fouling Control in Marine Applications

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Abstract

This article explores the current state and future outlook of antifouling coatings, with a focus on both biocidal and non-biocidal options for marine applications. It delves into the efficacy and environmental impact of biocidal coatings, the challenges faced by non-biocidal technologies, and the need for a holistic life-cycle assessment approach. The regulatory trends and the importance of comprehensive evaluation methodologies are also discussed, highlighting the necessity for ongoing innovation in fouling control solutions.

1. Introduction: Understanding Biocides in Antifouling Coatings

Biocides are active substances incorporated into antifouling coatings to prevent the accumulation of marine organisms on submerged surfaces. These compounds function by either deterring or eliminating biofouling agents such as barnacles, algae, and mussels, which are known to cause significant hydrodynamic drag, operational inefficiencies, and environmental risks.

The regulatory framework for biocides is rigorous and science-based, ensuring that their use is both safe and environmentally responsible. The hazard assessment evaluates the intrinsic properties of the biocide (e.g., toxicity, persistence), while exposure assessment examines the degree and frequency of potential contact with humans and the environment. These two assessments culminate in a comprehensive risk evaluation, guiding safe use conditions under frameworks like the EU Biocidal Products Regulation (BPR) and similar global systems. Modern antifouling biocides undergo extensive testing including ecotoxicological profiling, bioavailability studies, and environmental fate modelling to ensure that they pose minimal risk when used according to guidelines.

2. The Case for Biocidal Antifouling: Efficacy, Impact, and Necessity

Antifouling coatings are essential for maritime operations. Biofouling can increase hull roughness, leading to higher fuel consumption and greenhouse gas (GHG) emissions. Biocidal coatings are the only proven active technology to mitigate this problem at scale. On average, fouling can cause up to a 40% increase in fuel consumption if left unmanaged. Biocidal antifouling coatings can reduce fuel consumption by 10-25%, depending on vessel type and operational profile. This equates to ~250 million tons of CO₂ emissions saved annually across the global fleet.

The societal benefits are substantial. Reduced emissions contribute directly to international decarbonization goals set by the IMO and national governments. Economically, fouling control reduces drydocking frequency, lowers maintenance costs, and extends the operational lifespan of ships. Without effective fouling control, ships require more frequent hull cleanings, leading to increased downtime and operational inefficiency.

There are also environmental risks associated with ineffective fouling control. Fouled vessels are known vectors for the spread of invasive and/or non-indigenous aquatic species. Invasive species such as the zebra mussel (Dreissena polymorpha) in North America have caused economic damage exceeding USD 5 billion due to infrastructure clogging and ecosystem imbalance. Preventing biofouling is a key element of biosecurity for many coastal nations.

Recent analysis from Morningstar Research (2024) demonstrates that ineffective antifouling systems can negatively impact ESG (Environmental, Social, and Governance) performance metrics for shipping

companies. Their report indicates that vessels with suboptimal fouling control systems show an average 12% higher carbon intensity than those with optimal protection, potentially affecting carbon ratings and financial instruments tied to environmental performance targets. This emerging economic dimension of fouling control adds another layer of complexity to decision-making beyond direct operational costs.

3. Market Reality: Biocidal Dominance and Current Limitations

Despite increasing interest in non-biocidal alternatives, the current market remains dominated by biocidal solutions. According to Lloyd's Register, out of 988 type-approved antifouling products, 937 are biocidal coatings. Only 24 are abrasion-resistant non-biocidal coatings used mainly for ice breakers, 24 are biocide-free fouling release coatings, and a mere 3 are biocide-free self-polishing coatings. While approval numbers are not direct indicators of market share, they reflect the industry's reliance on biocidal antifouling systems.

Table I: Distribution of antifouling approvals of Lloyds list between biocidal and non-biocidal coatings

	Number	Percentage
Biocidal coatings	937	94.8
Abrasion resistant biocide free	24	2.4
Fouling Release Coatings biocide free	24	2.4
3 Self Polishing Coatings biocide free	3	0.3

A joint study by I-Tech and Safinah Group (presented at HullPIC 2025) revealed that despite the availability of modern antifouling solutions, drydock inspections continue to show performance variability and insufficient biofouling control in some segments. The table shows for example that under non-polished-through conditions at in-docking 23.6 % of the inspected vessels show more than 20 % of the flat bottom covered with hard fouling like barnacles. Additionally, a recent Riviera Marine Coatings survey showed that while 84% of participants are exploring alternative technologies, most alternatives remain experimental or face deployment barriers.



Table II: Hard fouling found at in-docking (HullPIC 2025)

A similar result can be drawn from a survey conducted by Riviera at their Marine Coatings Webinar the 24th of November 2024. 80 % of the over 200 maritime professionals found that hard fouling like barnacles are either a significant or a huge problem for shipping.



Fig.1: Problem of hard fouling incl. barnacles, source: Riveira Marine Coatings Webinar 24.11.2024

4. Alternatives and Their Limitations

Several non-biocidal fouling control technologies are being developed:

- <u>Fouling Release Silicone coating systems</u> have been available in the market for more than 10 years and thus not under development, but mentioned here to include them in the alternatives.
- <u>Ultrasound systems</u> emit low-frequency sound waves that deter biofouling organisms.
- <u>Electrochemical solutions</u> generate localized biocidal activity but face scaling issues and electrical safety concerns.
- <u>UV light-based systems</u> are promising for niche areas (e.g., niche protection zones), but require constant power and have so far limited underwater penetration.
- <u>Underwater hull cleaning</u> is either reactive or proactive and may increase the risk of invasive species dispersal if not properly managed.

Research from RMIT University and Cape Breton University in 2023 highlighted that while innovative coating technologies such as micro-structured surfaces and biomimetic approaches show laboratory promise, they face significant challenges in scaling to commercial application. The researchers emphasized that laboratory conditions rarely match the complex and variable marine environment, leading to performance discrepancies between controlled testing and real-world deployment.

None of these approaches, alone or in combination, have yet demonstrated the commercial viability, scalability, or reliability needed for widespread use in commercial shipping.

5. The Missing Link: A Holistic Life-Cycle Assessment Approach

A significant challenge in the antifouling debate is the lack of a unified, holistic framework to evaluate coating technologies across their entire life cycle. Environmental evaluations tend to focus on narrow endpoints (e.g., leaching rates) rather than broader system-level impacts such as fuel savings, operational efficiency, prevention of invasive species and contribution to global emission targets.

Stakeholders - including regulators, ship operators, coating manufacturers, and environmental NGOs - often work in silos, each optimizing for different performance indicators. For example, a coating with no active substances may show more benign chemical hazard metrics, but if it results in a 15% increase in fuel use, the net environmental impact may be worse.

Durability, application frequency, and in-service performance significantly affect the overall environmental footprint of a coating system. JRC (2020) explores the complexity of comparing

different antifouling technologies across their complete life cycles, noting that a single-metric approach is inadequate for capturing true sustainability.

Recent work from the University of Newcastle's Marine Coatings Research Group (2024) developed a Multi-Criteria Decision Analysis (MCDA) framework that attempts to balance technical performance, environmental impact, and economic factors in a weighted evaluation system.

Without harmonized metrics that include LCA (life cycle assessment) of antifouling coatings - including production, application, in-service performance, and end-of-life treatment - meaningful comparisons remain elusive.

6. Regulatory Trends and Future Frameworks

The regulatory landscape for antifouling coatings is evolving rapidly, with significant implications for both biocidal and non-biocidal solutions. The 83rd session of the Marine Environment Protection Committee (MEPC) addressed the development of a legally binding framework for the control and management of ships' biofouling. The aim is to establish mandatory requirements to curb the spread of invasive aquatic species through biofouling.

The proposed framework stems from the recognition that invasive species spread through biofouling represents a major environmental threat. Proponents argue that enforceable regulations are necessary for effective global management, as the current voluntary guidelines have resulted in inconsistent implementation. The framework would likely encompass specific requirements for hull cleaning schedules, antifouling system maintenance, and comprehensive record-keeping obligations.

7. Conclusion: Reality Check and Future Directions

Biocidal antifouling coatings, when used according to existing regulatory frameworks, are safe, effective, and currently the most reliable method for controlling marine biofouling. They are essential tools in achieving the maritime sector's environmental, operational, and economic goals, especially in the context of global decarbonization targets.

Despite ongoing innovation, non-biocidal alternatives are not yet ready for mainstream application. The industry must focus not only on exploring new technologies but also on developing comprehensive, holistic evaluation methodologies that consider full-system impacts.

Until such tools exist, the most sustainable path for marine coatings includes responsible use of biocidal antifoulings, continued performance monitoring, and transparent, collaborative efforts to improve assessment frameworks for all fouling control solutions.

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The Power of VR in Design and Training

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Abstract

This paper explains through customer stories how Virtual Reality (VR) is applied effectively as collaborative tool for design review and realistic training. As an illustrative example, in a boat design, more than 30 design flaws were found when using VR in the design project. Another example application uses VR in a man-over-board operation training.

1. Introduction

Digital transformation technologies are major topics in the maritime industry today. But to utilize these new technologies, we need to design the vessels "correctly" and train crews to operate the technologies correctly. How can this be done in a way that doesn't pollute our environment, saves time and money, while ensuring correct HSE with zero damage to personnel and equipment and opens opportunities for realistic collaborating worldwide without time-consuming travels and emissions to the environment?



Fig.1: Use of collaborative VR at Motus Technologies

2. Virtual Reality (VR) explained

To fully understand this paper, it is necessary to explain what this paper means by VR. VR is short for Virtual Reality, which means just that. When you put on the VR equipment you are "transported" from your normal reality and into a virtual reality. In this virtual reality you can communicate with other virtual participants and execute tasks. The other virtual participants may be human, like yourself, or digital avatars that are pre-programmed or are AI controlled. The tasks can be designing vessels, training onboard, planning vessel operations and so on.

Most important, VR itself has no limits to what you can do and how you can operate. Limits are created by the technology, budgets, timelines and you imagination. More on that later in this paper under the headline "Why VR is the best".

VR is a part of the XR (Extended Reality) family, which is VR, AR (augmented reality) and MR (mixed reality). VR is already explained in the beginning of this chapter. Meta Quest 3, Pico and Varjo is such products.



Fig.2: Meta Quest 3 VR set

AR means a combination of reality and graphics, where the graphics doesn't interact with reality. Example: If you "throw" a 3D object into the room it just go "through" any real object, like a table, a chair or even a person without interacting with the objects. XREAL One is such a product.

MR means a combination of reality and graphics, where the graphics interact with reality. Example: If you "throw" a 3D object into the room it will interact when it hits a real object, like a table, a chair or even a person. Microsoft HoloLens and Meta Quest 3 is such products.

A typical VR set consists of a head mask, often called "goggles" and two hand controllers. The VR set can communicate with other VR sets via Wi-Fi or cabled to a computer. The computer then communicates with other VR sets directly, via Wi-Fi, or via another computer with a VR set attached to it. The VR set attached to a computer can use cable or wi-fi, i.e. you always can work "cable-free".



Fig.3: Modern VR sets are easy to use - no cables required!

Different VR sets have different features and different technical specifications. The most obvious one is visual quality. The higher the resolution of the lenses in the VR set, the more realistic the VR experience can be. However, price and resolution are not necessarily comparable. VR sets also have different amount of storage and different CPU's which influences on the price. VR sets have a price-range from \notin 350 to more than \notin 10 000! Usually, you content deliverer will give you good advice regarding which VR set to choose.

The VR sets can contain the software it runs itself, via the computer it is attached to, via a cloudbased service or via a server located somewhere on the internet. Let's investigate the pros and cons by showing some types of projects that are up and running today.

3. Design reviews using VR when planning to build a vessel

Digital ship drawings are huge 3D models. This requires a computer to "crunch" the data before it can be displayed in VR. Typical setup is that all the different participants that are connected to the design of the vessel runs a software, like Spawn, where the data is stored in the "cloud" and shared between the design team (and maybe the vessel owner and future crew members).

4. Planning operations using VR

When a vessel has completed the design phase you may use the vessel drawings to start planning how to operate the vessel.

We still have huge drawings, but these can be optimised to run directly in the VR sets if you want to avoid the "hassle" using a PC running VR software, like Spawn.



Fig.4: Odfjell vessel "Bow Hercules» in VR

4.1. Onboarding new crew members using VR

Your new vessel is to be manned (maybe not in the future). Your existing vessel drawings in VR means that your crew can familiarize itself with the ship, knowing where everything is placed, muster stations, types of equipment used etc. You can still choose to use the "original" huge 3D drawings, run via computers, to the VR sets, but I recommend optimising the drawing so that everything can be stored inside the VR set.

If you want your crew to cooperate during this familiarization phase you can have a server connecting all the different VR sets and distribute data to the different participants. The crew members can be located on different physical places but still work together.

4.2. VR based training onboard a sailing ship

Some months ago, this was impossible because we found that the VR set developers never intended their VR sets to be used in an environment that was moving (sailing). Nagelld was the first ever to

encounter this problem when we were making a lifeboat VR training. This is now fixed. Meta calls this feature "travelling mode" and it must be checked off inside the VR set.

The lifeboat crew now has a local "internet" where a server and several VR sets communicate so that the crew can run training sessions when the vessel is sailing.

We are now testing how it will be to combine VR sets onboard vessels running the Starlink satellite broadband with VR sets ashore. If this works out well, you will be able to run training sessions with sailing crews connected to land-based experts.

4.3. Implementing VR in a customer organisation - Logistics of hardware and software

First an important advice: Your VR project is not an IT department project! You may need the IT department to buy and implement the VR sets and computers into your company network, but the IT department cannot help you choose VR sets, servers or computers needed! To choose correct equipment specifications, you need to talk to your VR content supplier. I cannot stress this enough!

Depending on how many VR applications and VR sets you need, you also need a plan to support and deploy the applications and sets. Most VR suppliers have software to handle this logistics, but many of the solutions are bad and they have a tendency of changing depending on who owns the company. An example here is how the Oculus for Business software was discontinued when Meta bought the company. Meta also made the VR set impossible to use in China because of the Facebook connection.

Several independent logistic solutions are available, like ManageXR and ArborXR. Talk to your content provider or connect to a VR cluster, like VRINN in Norway, they will advise you independently.

5. Research & Development

The most recent R&D projects in VR are "hand tracking", "see-through VR" and a combination of both.

"Hand tracking" means that when you are learning how to operate any type of equipment you don't use the VR controllers anymore, you use your hands instead. Example: To push a button, you simply push the virtual button using your finger and not by pressing a selection button on the controller first. This means that you can "pick-up" tools, "turn" levers, "push" buttons and so on just like you would have done in "real life". This makes the VR experience to become much easier to use.

"See-through" VR means that you can switch between a complete VR experience and a MR experience where 3D objects interact with the real surroundings. Example: you want to "isolate" a valve so you can concentrate on it without having to interact with the rest of the engine room. Maybe you want to call in a land-based expert to show you how to fix the valve and it is easier when the particular piece of equipment is isolated and the expert actually can see both the "real" valve and the 3D model of the valve.

Combine the "see-through" with the "hand-tracking" and you can fix the valve using correct tools directly with your hands in an isolated view. New technology will open for new content which again will open for new ways to work and interact in VR.

6. Why VR is best

Would you like a work environment without any physical limitations in space and time, where you can assemble your team instantly and independent of current physical location of the team members, where nobody is injured and your equipment never is damaged even when your team is training on accidents that may happen. A place where everybody is 100% focused only on the tasks at hand and

you can evaluate everything that has happened. Where you can reset your world and begin again, over and over. Where you can test multiple solutions and design without scrapping any metal. Where you and your sub-suppliers can meet and discuss, test and experience different solutions until they are 100% optimal? Where your crew can train on operations and maintenance over and over.

This world does exist today, and you don't even have to swallow a pill to get there! Let's take a closer look at the different parts that makes up this work environment.

6.1. No physical limitations

I call this feature the "Matrix syndrome". In virtual reality you are only limited by the feature of the VR presentation. You can jump 50 m at the time, you can fly, you can lift any structure, you can poke inside closed gear boxes, you can examine a vessel's running engine – from inside the engine! But you can also be restrained to the world as we know it. Your choice!

A true story related to the subject: A company was ordering a new RIB (rigid inflatable boat) and wanted the crew members to "experience" and comment on the design before it was actually built. We set up a VR experience where the crew members could get a "look & feel" of the boat. The crew found a lot of stuff they wanted to change which resulted in a completely different design based on the operations the crew wanted the boat to carry out.

During the VR experience one of the crew members asks me how he can "physically" look into the hull structure of the boat, maybe we can remove the outer hull or make it transparent, he suggests. The other crew members had similar suggestions. No one suggested to simply put one's head through the outer hull!



Fig.5: RIB vessel in VR

This experience made me realise that most people are like Neo in the Matrix. We are always limited to what we think is possible and not what is actually possible. This is something we must train to overcome when creating VR presentations. (By the way: are you quite sure you can't put your head through the nearest wall?)

6.2. Multi-user collaboration independent of physical location

Covid – yes, I need to mention it. It separated us from working and meeting physically. In VR we can meet and work together without any chance of contagion because we don't have to be physically

located in the same place. We have tested VR several countries and even continents apart. One company has VR rooms in Singapore, Houston and Bergen where people meet to collaborate. This also gives a friendly nod to our environment. You no longer have to make those 2-days-travel-1-hourmeeting journeys. Just meet up in VR.

6.3. No injuries to people and no damage, wear and tear or accidents on your machines

Let's look at cost and ROI (Return On Investment). It costs to develop VR training programs, but the more interesting thing is to look at the ROI. How fast is the investment paying off? Not just in actual costs related to a training session, but also the cost of injuries and machine wear and tear. You can even train on scenarios that are impossible to train on "live", Like capsizing, explosions and severe fire.

One company has a cost of \in 50000 on every training session. They may have 1-2 sessions each week. The entire VR training simulator costed \in 150000. The training sessions are offshore and involves expensive equipment. Each crew trains maybe 10 times per year. For now, they don't train less in physical training, but they train correctly every time because the crews can train in VR as often as possible, honing their skills. The different crews, located along the entire Norwegian North Sea/ Norwegian Sea basin also have the possibility to train together, learning from each other, without needing to meet physically. Now each crew member can train 5-10 times a week.

6.4. 100% focus

Training using VR ensures 100% focus on the task at hand. No disruptions from your mobile phone or other people located around you. No mail to be answered or web pages to be scrolled. VR is so focused that we had to implement a clock showing the real-life time in our VR software. I have been late to countless Teams-meetings because VR erase your internal "clock".

Every time our customers have experienced VR together with us, I ask them about how long time they think they were in the VR experience. So far, no one have been close. I'll share a story for illustration: Some engineers from a customer of ours came into one of our offices to test out a new pump design using our VR equipment. One of the engineers was not too keen on using VR because she had a bad experience earlier (Euro Disney VR experience!). I talked her into trying and within few minutes she was so focused on the task that she completely forgot that she was using VR. When they had tested what they wanted (and found that they had to re-think the entire maintenance operation) I asked her how long she thought she had been in the VR experience. 15-20 minutes maybe, she answered. The correct time was just over one hour!

6.5. True evaluation

VR doesn't allow cheating and shortcuts, if we don't want it to. We all know that walking/standing under a hanging load is a big no-no in the real world. In VR you don't get away with doing that or any other shortcut. The VR experience monitors everybody always and can give you a complete evaluation of every training.

7. VR in design

Do you know the series called 'Deadliest catch' where they fish for snow crab? A Norwegian company is developing such a vessel with a 'clean deck' operation. The vessel has two main cranes. The crane supplier wanted a VR project where the customer could run the cranes in VR to make sure the cranes operated within the specs given. We made the VR project and all seemed fine.

The vessel supplier wanted us to include the entire operation, not just the crane handling. So we set up hatches and winches - and hey! One of the cranes interfered with a hatch in one given point of the operation rendering the entire operation void! We were asked to re-model the hatch, so it didn't interfere. After a new 3D model of the hatch was modelled and implemented by us, everything was fine. I asked them how much they saved and they wouldn't say! This, and many other stories makes we wonder how much time and money is mis-spent when designing a vessel.

There are many considerations to make when designing a vessel. Why not use VR to make all these considerations play together or at least know where the issues are? One of the considerations to make in today's vessel design is which "fuel" that are to be used. The different "fuels" require completely different vessel designs. Whether the vessel is hybrid fuelled, electrical, sails, ammonia, hydrogen, or LNG, to mention some alternatives. Designing in VR makes it possible to "test" different fuel layouts in your vessel design.

In Norway we had an accident where the pilot didn't see the vessel he crashed into because the beam structure hindered view from the pilot seat in some angles. This would never have happened if the pilot could "test" his viewing angles in the design phase using VR because VR gives 1:1 view of your surroundings.



Fig.6: Snow crab vessel in VR

All kinds of lay-outs can be tested and optimised using VR in the design phase:

- How is the accommodation for the crew
- How many containers can my vessel handle and are the container locks placed correctly
- Is the view from the bridge optimised according to work operations
- Does the equipment from sub-contractors connect correctly
- How easy is it to replace or maintain a larger part within the vessel's hull
- Etc. etc.

If you design a vessel today without using VR Design Reviews, chances are 99% that you are wasting time, money and the environment. 100% of all projects, not just ship designs, we have run through VR have had design faults or unwanted operational / maintenance design.

Remember also that a digital 3D model of the ship in VR opens up for other departments to start working with the vessel much earlier than before:

- Operation planning
- Maintenance planning
- Onboarding of crew members

- HSE planning
- Recruiting (HR)
- Showing the vessel to potential customers
- Showing the vessel in exhibitions
- Making a digital twin of the vessel

8. VR in training

The challenge: We want to train a MOB (Man Over Board) crew on operation and communication before we put them in a real boat? The solution: Make a MOB boat training simulator that uses real physics on the 3D models. This simulator requires a rather powerful computer connected to each of the three crew VR sets because the VR sets cannot handle the real-time physics that is calculated when the MOB boat flies across the virtual waves! The simulator trains the crew in communication, operation (steering the boat in all kinds of weather and finding the missing persons) and maintenance. An operator "throws" trouble at the crew in real time, the operator also has the tools to evaluate the session both in real-time and afterwards.



Fig.7: MOB boat in its cradle

Training you personnel using VR is the best way of training, by far! The reasons why we claim this to be true is from messages we get back from our customers. After training in VR, they solve the tasks correctly the first time without wasting any time on pondering how to solve the task and they remember how to solve the task at hand. Using hand-tracking in the VR training can be very realistic because you must pick up the correct tools and use them correctly to solve the task at hand. Just like you would do in real-life.

Star Trek: Kobayashi Maru - When training in VR you can also train "impossible" scenarios or accidents, just to see how your crew react to difficult or no-win scenarios.

Most important when, training in a VR simulator, is that your crew can train over and over, by themselves or with other crew members.



Fig.8: VR collaboration in the NOFO Offshore Oil Spill simulator

9. Extra material

I have often encountered companies and persons that want to buy VR but are stopped because they lack what I call "competence of XR project purchasing". That's why I have added a short helper when purchasing a VR project:

- What issue is the project going to solve? The developer needs to know the issue(s) you are trying to solve in order of manage to price the project. If the project order is "fuzzy" it can become expensive really fast.
- How much does the issue cost me today? Is the issue solved today? What is the cost today? These are important questions when forming a budget.
- What ROI can I expect? The developer should be able to explain the possible ROI of the project. Also beware that some VR projects may open up new business models for your company.
- How is the developed project priced (licensing or one-off payment with support)? Do you want to pay a license fee per person, not owning the solution or do you want to pay "one-off" and own the solution. You usually pay a yearly support fee if you buy a one-off.
- Off-the-shelf solution or a developed solution? Off-the-shelf solutions usually gives you 80% of your solution, if you can find such a product. A developed solutions cost much more but give you control of the content of the product.
- Who owns the IP of the finished product? This depends on the payment model and how exclusive you want to own the product.
- What equipment is needed (VR sets, PCs, etc.) The developer can spec the equipment/hardware you need. Buy the equipment from your local dealer. In that way you get help fast if something stops working.
- Single user or multi-user (or both)? Do you want to collaborate in VR or not. Multi-user is more expensive than single user and usually requires more hardware. The upside is that your team can collaborate directly in VR.
- Who are supplying the digital 3d models needed (customer, sub-contractors, modelled by the VR project supplier)? No 3D models mean no VR project. Who is going to supply the 3D models needed? If you work with a developer that has a lot of 3D models it is usually less expensive than to work with a developer that need to model the 3D models not provided by you or your sub-contractors.

- What is the expected timeline? Always agree on a timeline with milestones. This keeps everybody in the project on its toes and ensures forward momentum. Remember that it is usually the customer and not the developer that slows the project down...
- How much involvement is needed/expected from the buyer? The timeline with milestones will decide this. Working with a developer that knows the industry usually requires less involvement from the buyer.
- Who is testing the product? Testing takes time and money. Decide on a test plan as soon as possible.
- Who is in the project team and why should you avoid your IT department? Put together a team that controls the financing of the project, a product expert / tech. person and the person with the problem. IT departments are only to be involved if needed regarding network security and purchasing of PCs. Usually, the developer and the IT department wants different hardware specs because the IT department wants to streamline all computer equipment, and the developer wants you to buy the equipment that serves the VR project best.

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All VR work presented in this paper is developed by Nagelld. Nagelld is recognized as one of the frontrunners of VR experiences to the maritime industries worldwide. One of our VR training scenarios won "The Jury Award" at Nordic VR Forum 2024. In 2023 we won "Best VR training experience" at Nordic VR Forum for a cruise ship lifeboat VR training experience. Nagelld has also developed Spawn, a metaverse collaboration platform for design reviews and various operation and training scenarios.

Novel Method of Hydrogen Fuelling for Small Ships

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Abstract

As the world transitions to renewables and hydrogen economy, fuel cells will be a crucial part of enabling eco-friendly transportation. However, they are a radical change in propulsion and power generation systems compared to diesel engines, and one of the main barriers to its adoption is the difficulty in bunkering and storage of the hydrogen fuel. In this study, a new method of hydrogen fuelling for vessels is investigated. This technology uses a novel process to generate the hydrogen on board the vessel avoiding the bunkering and storage issues. The viability of the technology in terms of transport, bunkering, shipboard plant, efficiencies and waste handling is examined for a small fishing trawler.

1. Introduction

The move towards viable fossil fuel alternative fuels presents many challenges for the shipping industry. Propulsion equipment suppliers must contend with fuels that are more difficult to make, are less energy dense, have more challenging combustion properties and difficult storage requirements as shown in Fig.1. For ship designers, these alternative fuels require vessels to devote more space for fuel storage but also presents opportunities for vessel arrangements to be optimised around new types of propulsion machinery.

Fuel	Fuel density	Energy density (G)	Energy density (V)	Storage temperature	Storage pressure	Storage factor
	kg/L	MJ/kg	MJ/L	С	bar	(space ratio)
HFO	0.98	39	38.2	60	1	1.1
MDO	0.88	42.7	37.6	25	1	1.0
Diesel (MGO)	0.85	50	42.5	25	1	1.0
LNG (A tanks)	0.45	47	21.2	-163	1	2.5
LNG (C tanks)	0.45	47	21.2	-120	10-20	3.5
Methanol	0.79	19.9	15.7	25	1	3.0
Ammonia (A tanks)	0.68	21.8	14.8	-33	1	3.5
Ammonia (C tanks)	0.68	21.8	14.8	20	8	4.0
LH2	0.071	120	8.5	-253	1	8.0
500bar H2	0.025	120	3.0	25	500	25.0

Fig.1: Properties of current & alternative marine fuels

The author has previously identified hydrogen as the preferred future fuel, due to its better well-to-tank efficiency. The advantage of hydrogen fuel comes from its very high energy per mass density, which is and six times better than either methanol or ammonia and nearly three times better than even fossil fuels. The fundamental reason why the well-to-tank efficiency of hydrogen fuel is better than green fuel alternatives, is that in order to make methanol or ammonia, you first need to have green hydrogen as feed stock as can be seen in Fig.2.

The main motivations for using methanol and ammonia as future green fuels is that these fuels are easier to storage and transport and existing diesel engine machinery can be used with relatively minor modifications to engine fuel and control systems. It should be noted that these engines require about 5-10% of diesel 'pilot' fuel to be injected into the cylinder to start the methanol or ammonia combustion process. These 'green' vessels will therefore still need to carry the same diesel fuel handling and processing equipment as before.



Fig.2: Well-to-tank processes for green fuels, source: Iberdrola

Hyrea is an Australian company developing hydrogen technology that is different from the current methods of producing and transporting hydrogen. The hydrogen fuel itself never needs transporting. Instead, it uses a solid reactant that is produced and transported. The hydrogen fuel is then produced where the fuel will be consumed, in this case directly onboard the vessel, see Fig.3. This paper examines the Hyrea technology for a fishing vessel, cruise ferry and bulk carrier.



Fig.3: Current green hydrogen upstream process (top), Hyrea hydrogen upstream process (bottom)

2. Hyrea Process

The hydrogen gas is produced by a chemical reaction of the solid reactant with water inside a reactor instead of the usual methods of electrolysis of the water or steam reforming of methane. The Hyrea system is particularly well suited for ships, since access to water is readily available. It should be noted that Hyrea's technology also covers the production of the solid reactants, however analysis of these upsteam processes are out of the scope of this study.

2.1.. Hyrea Reactants

Hyrea is experimenting with different types of reactants. The exact formulation of the reactants cannot be disclosed. Reactant A needs a catalyst for the chemical reaction to produce hydrogen gas. Reactant B does not require a catalyst, but the hydrogen yield is lower per mass of reactant. In Fig.4, the various reactants are compared by weight for 1kg of hydrogen gas produced. It can also be seen from Fig.4, that about half of the reactants mass is water. To reduce the mass of reactants that the vessel has to carry, it would be preferable if the water is not carried but taken directly from the sea.

Reactant	Powder density	Reactant input	Water input	Input mass	Heat energy output	Waste output	Hydrogen output	
Reactant A	1.5 g/cm3	7 kg	9 kg	16 kg	24.0 kWh	15 kg	1 kg	
Reactant B	1.2 g/cm3	10 kg	9 kg	19 kg	24.3 kWh	18 kg	1 kg	

Fig.4: Hyrea reactant mass fractions & outputs

Pending further testing, the reactants may be in the form of powder or pods. The reactant is highly reactive with water and must be kept in dry conditions to avoid reaction with moisture in the air. It is envisaged that the powder will be stored in silos built into the ship's hull structure. It will be preferable if the interior of the silos have smooth walls and with minimal if any internal structures.

There are several methods from the food and pharmaceutical industries to transfer the powder reactant. Pneumatic conveyance though pipes or hoses can be used for bunkering or transfer between storage tanks. The powder also can present a dust explosion risk and various precautions are necessary. For more efficient and accurate transfer of the powder, screw feeders can be used, for example between a service hopper and reactor where the hydrogen is produced.

2.2.. Hyrea Reactor

The Hyrea reactor is a key component of the Hyrea process. The reactor combines the solid reactant and water, with the ensuing chemical reaction creating hydrogen gas and a solid by-product waste. The reactor is expected to be slow to respond to rapid change in hydrogen demand and therefore it will be important to have some limited hydrogen storage on-board the vessel that can act as a fuel cache to cope with the fluctuating demands from the vessel's power system.

Although seawater can be used in the reactor, regular flushing of the reactor would be necessary to prevent the accumulation salts as the H_2O is consumed. Such flushing would also remove any catalyst. Therefore, in the case of Reactant A, high purity water is preferred so that reactor flushing and catalyst wastage is minimised. A concept design for the Hyrea reactor system is shown in Fig.5.



Fig.5: Hyrea reactor concept

2.3. Reactor Waste Heat Recovery

The considerable heat released by the chemical reaction can be extracted from the reactor cooling system. Uses for the waste heat include freshwater production, absorption refrigeration and electrical power generation. The heat output for various capacity reactors, based on the hydrogen output needed for a fuel cell with a SFC of 0.07 kg/kWh is shown in Fig.6.

Reactant	PEMFC power	Reactant input	Water input	Input mass	Heat power output	Waste output	Hydrogen output
Reactant A	1000 kWe	504 kg/h	648 kg/h	1152 kg/h	1728 kW	1080 kg/h	72 kg/h
Reactant B	1000 kWe	720 kg/h	648 kg/h	1368 kg/h	1750 kW	1296 kg/h	72 kg/h
Reactant A	500 kWe	252 kg/h	324 kg/h	576 kg/h	864 kW	540 kg/h	36 kg/h
Reactant B	500 kWe	360 kg/h	324 kg/h	684 kg/h	875 kW	648 kg/h	36 kg/h

Fig.6: Hyrea reactor inputs & outputs

A vacuum freshwater generator is commonly used in the marine industry to make fresh water from seawater using waste heat from engine cooling systems. A high efficiency vacuum evaporator water maker only needs about 300 kW of heat to produce 20 t/day of water, which is sufficient freshwater for a 1000 kWe reactor.

Another use of the waste heat is powering an absorption refrigeration system. Such a system could provide cooling for air conditioning or cargo reefer holds which are typically large electrical consumers. The efficiency of an absorption refrigeration using heated water measured as Coefficient Of Performance (COP) is estimated at 0.4. Therefore 1000 kW of heat can be converted into 400 kWr of cooling, sufficient for a typical 50 m fishing vessel with a 650 t fish reefer hold and would save about 270 kWe of electrical power.

Another possible use of waste heat is to generate electricity using Organic Rankine Cycle (ORC) systems as shown in Fig.8. This system uses an organic fluid that vapourises at lower temperatures than steam and drives a turbine to generate electricity. The efficiency of this process depends on the

difference between the waste heat and the seawater temperature used for cooling. It is estimated that approximately 10% of the waste heat can be converted into electricity using ORC.

2.4. Reactor Waste Products

The chemical reaction also creates considerable solid waste. As can be seen in Fig.4, Reactant A will create 15 kg of solid waste for every one kilogram of hydrogen produced. Similarly, Reactant B will create 18 kg of solid waste for every one kilogram of hydrogen produced. Therefore, the weight of waste is actually about twice the weight of the initial solid reactant. It may be possible to discharge this waste overboard, given the waste is non-toxic to sea life, but this would need approval by authorities.

A possible method of storing the solid waste onboard the vessel is to feed the waste back into the reactant silo, Fig.5. An ullage barrier will be needed to separate the solid waste from the unused powder reactant. The solid waste will need to be de-watered and possibly dried to prevent water entering the silo, which could react with the unused powder creating an explosive hazardous mix of hydrogen gas and air.

3. Hyrea Application to Fishing Vessels

Application of Hyrea technology to a fishing vessels has been studied and compared to other alternative fuels. This type of workboat represents many decarbonisation challenges. They are almost all powered by diesel engines for propulsion and power generation as per Fig.7.



Diesel-electric & motors directly driving a propeller Fig.7: Fishing vessel diesel propulsion & power system



Fig.8: Proposed fishing vessel fuel cell power system

One key aspect is that the fuel storage requirements for alternative fuels are demanding of space, which is very limited on these small vessels. Another challenge is the limited availability of high-speed diesel engines that can run on alternative fuels. While the roadmap of available engines is improving, it is assumed for this study that such engines are available and are essentially drop-in replacements of existing diesel engines.

Hydrogen powered fishing vessels could utilise either combustion engines or fuel cells as shown in Fig.8. Previous studies by the Author, have found that the space and weight requirements for a fuel cell powered vessel are similar to combustion engines. Therefore, regardless of the chosen propulsion system, the only difference will be the space necessary for the hydrogen fuel storage. For the Hyrea system, the space and weight for the reactant storage and the reactor system will need to be considered.

3.1. Study Vessel

Commercial fishing vessels under 12 m in length generally have short range and endurance and will most likely utilise battery electric propulsion systems to decarbonise. Vessels between 12 and 24 m in length, are the most numerous type that undertake multi-day voyages in the Australian fleet and consume about 65% of the fleet fuel. The study vessel chosen is a prawn and scallop trawler of 18 m in length as shown in Fig.9 and 10. There are a significant number, estimated at 2000 such vessels in the Australian fleet.



3.2. Fuel Tank Calculation

Generally, these vessels have diesel fuel tanks integrated into hull side voids and within the engine room. Alternative fuels like methanol, ammonia and hydrogen are all gaseous fuels even though they can be stored as liquids. Regulations require any tank storing these alternative fuels to have a void space around the whole tank and as such it will be very difficult to convert any existing diesel fuel tanks into alternative fuel tanks. As mentioned previously, at least some of these diesel tanks would need to be retained for pilot fuel. It is therefore proposed that vessels could be lengthened at the midship with a hull module that includes the new alternative fuel tank.

18m Steel Prawn	Trawler
Length OA	18.2 m
Length WL	16.9 m
Beam	6.0 m
Depth	3.0 m
Draught	2.8 m
Main Engine	350 kW
Gensets	2 x 90 kWe
Diesel Fuel	20,000 L
Fresh Water	3,000 L
Refrigerater Hold	10,000 L
Crew	5 persons
Displacement	100 T



Fig.10: Study vessel principal particulars (left), vessel undertaking fishing operations (right)

To calculation the vessel lengthening needed the following factors were considered:

- Fuel tank capacity of 100%, 75% and 50% relative to the study vessel.
- The new engine fuel efficiency ratio relative to existing engines. This has been set to 1.0 for combustion engines as there is no verified information from engine makers at the moment as to the efficiency of these new alternative fuel gas engines.
- For fuel cells, the efficiency ratio has been set to 0.5 which accounts for both the better energy conversion efficiency of fuel cells (PEMFC 55% compared to ICE 34%) and the increased efficiency of not needing to idle engines or gensets running at low load giving a further 20% reduction.
- The fuel volumetric ratio is the energy density per volume of the alternative fuel as a ratio to the energy density per volume of diesel fuel, see Fig.1.
- The pilot fuel is given as a ratio of diesel to alternative fuel needed to start the combustion process in the engine. The pilot fuel will also reduce the alternative fuel capacity needed.
- The vessels beam is used to determine the width of the alternative fuel tank minus the width of the safety void and insulation on each side of the tank.
- The average hull depth is the height of the alternative fuel tank which considers the shape of the hull bottom which normally has a slight rise from the keel to the turn-of-bilge giving the hull a slight V-shape.
- The tank area is cross sectional area by multiplying the tank width and average depth.
- The tank length is calculated from dividing the tank volume by the tank area then adding the safety void to each end of the tank as shown in Fig.11.
- New Length Overall (LOA) is calculated by adding the tank length to the study vessel LOA.



Fig.11: Fuel tank concept for vessel lengthening

3.3. Alternative Fuel Vessel Variants

Based on the above fuel tank calculation, the vessel lengthening was determined for various alternative fuel and propulsion options as can be seen in Fig.12. For the compressed hydrogen options, it was necessary to modify the calculation for fuel storage in 200 litre gas cylinders.

The lengthening results (New LOA) are highlighted in green if the lengthened vessel is less than 24 m LOA and red if more. It can be seen that the results for compressed hydrogen and LH2 are greatly over 24 m and such a vessel modification would not be feasible technically or economically.

			18	m Vessel wit	h Combus	tion Engine	Propulsion	& Methanol F	uel			
Ref. tank	IC Engine	Methanol	Pilot fuel	Alt. fuel tank	LOA	Beam	Hull depth	Safety voids	Insulation	Tank area	Tank length	New LOA
(m3)	(eff'y ratio)	(fuel vol. ratio)	(fuel ratio)	(m3)	(m)	(m)	(avg. m)	(m)	(m)	(m2)	(m)	(m)
20	1.00	0.37	0.1	48.6	18	6	2.5	0.6	0.05	11.28	5.51	23.51
15	1.00	0.37	0.1	36.5	18	6	2.5	0.6	0.05	11.28	4.43	22.43
10	1.00	0.37	0.1	24.3	18	6	2.5	0.6	0.05	11.28	3.36	21.36
			18	m Vessel wit	h Combust	ion Engine	Propulsion &	Ammonia F	uel			
Ref. tank	IC Engine	Ammonia	Pilot fuel	Alt. fuel tank	LOA	Beam	Hull depth	Safety voids	Insulation	Tank area	Tank length	New LOA
(m3)	(eff'y ratio)	(fuel vol. ratio)	(fuel ratio)	(m3)	(m)	(m)	(avg. m)	(m)	(m)	(m2)	(m)	(m)
20	1.00	0.35	0.15	48.6	18	6	2.5	0.6	0.20	9.24	6.46	24.46
15	1.00	0.35	0.15	36.4	18	6	2.5	0.6	0.20	9.24	5.14	23.14
10	1.00	0.35	0.15	24.3	18	6	2.5	0.6	0.20	9.24	3.83	21.83
			18	m Vessel with	n Combust	ion Engine I	Propulsion 8	500bar H2 I	uel			
	Pow	ver & Fuel Sys	stem		н	ull	50	0bar gas cylin	der	Tank	space	
Ref. tank	IC Engine	500bar H2	Pilot fuel	Alt. fuel tank	LOA	Beam	Volume	Quantity	Area	Area	Length	New LOA
(m3)	(eff'y ratio)	(fuel vol. ratio)	(fuel ratio)	(m3)	(m)	(m)	(m3)	(n)	(m2)	(m2)	(m)	(m)
20	1.00	0.07	0.2	228.6	18	6	0.20	1143	0.30	343	57.1	75.14
15	1.00	0.07	0.2	171.4	18	6	0.20	857	0.30	257	42.9	60.86
10	1.00	0.07	0.2	114.3	18	6	0.20	571	0.30	171	28.6	46.57
	`			18m Vessel	with Comb	ustion Engi	ne Propulsio	n & LH2 Fue	1			
Ref. tank	IC Engine	LH2	Pilot fuel	Alt. fuel tank	LOA	Beam	Hull depth	Safety voids	Insulation	Tank area	Tank length	New LOA
(m3)	(eff'y ratio)	(fuel vol. ratio)	(fuel ratio)	(m3)	(m)	(m)	(avg. m)	(m)	(m)	(m2)	(m)	(m)
20	1.00	0.2	0.2	80.0	18	6	2.5	0.6	0.40	6.80	12.96	30.96
15	1.00	0.2	0.2	60.0	18	6	2.5	0.6	0.40	6.80	10.02	28.02
10	1.00	0.2	0.2	40.0	18	6	2.5	0.6	0.40	6.80	7.08	25.08
				18m Ves	sel with Fu	uel Cell Pov	wer & 500ba	r H2 Fuel		\$		
	Pov	ver & Fuel Sys	stem		н	luli	50	0bar gas cylin	der	Tank	space	
Ref. tank	Fuel cell	500bar H2	Pilot fuel	Alt. fuel tank	LOA	Beam	Volume	Quantity	Area	Area	Length	New LOA
(m3)	(eff'y ratio)	(fuel vol. ratio)	(fuel ratio)	(m3)	(m)	(m)	(m3)	(n)	(m2)	(m2)	(m)	(m)
20	0.50	0.07	0	142.9	18	6	0.20	714	0.30	214	35.7	53.71
15	0.50	0.07	0	107.1	18	6	0.20	536	0.30	161	26.8	44.79
10	0.50	0.07	0	71.4	18	6	0.20	357	0.30	107	17.9	35.86
				18m	Vessel wit	h Fuel Cell I	Power & LH2	Puel				
Ref. tank	Fuel cell	LH2	Pilot fuel	Alt. fuel tank	LOA	Beam	Hull depth	Safety voids	Insulation	Tank area	Tank length	New LOA
(m3)	(eff'y ratio)	(fuel vol. ratio)	(fuel ratio)	(m3)	(m)	(m)	(avg. m)	(m)	(m)	(m2)	(m)	(m)
20	0.50	0.2	0	50.0	18	6	2.5	0.6	0.40	6.80	8.55	26.55

6 Fig.12: Lengthening calculations for alternative fuel options

18

2.5

0.6

0.40

6.80

22.88

4.88

3.4. Hyrea System Vessel Variants

0.2

0

Hydrogen has an energy density of 120 MJ/kg compared to diesel 50 MJ/kg, thus giving a mass ratio of 0.42. From the hydrogen mass, the mass and volume of silicon reactant can be calculated. The silo factor determines how much of the hull section can be taken up by the silo. A silo factor of 0.7 gives a 0.5 m void around the tank sides. It is then possible to determine the lengthening required to store necessary reactant powder.

10

0.50

Note that gaseous alternative fuels require a void at each end of the tank as well as the sides and bottom of the tank to ensure any fuel leaks can be detected and contained in these voids. The Hyrea reactant powder will not leak like a liquid or gas but the side voids are still necessary to protect the silo and reactant from a potential hull breach and ingress of water. The end voids may not be necessary, saving space compared to other alternative fuels, but are included for this study.

The Hyrea system will also require installation of the reactor system as described in Section 2.2. The reactor is best situated adjacent to the powder storage silo to simplify the transfer of powder from the silo to the powder feeder tank as shown in Fig.5. It is estimated that an additional 2 m lengthening in addition to the silo space will be sufficient for reactor and supporting equipment.

18m Vessel with Combustion Engine Propulsion & Hyrea (Reactant A) H2 Fuel												
	Pov	ver & Fuel Sys	stem		Hull			Reactant A		Tank space + Reactor		
Ref. tank	Ref. tank IC Engine H2 to diesel Pilot fuel H2 mas					Beam	Avg. depth	Mass	Volume	Silo factor	Length	New LOA
(m3)	(eff'y ratio)	(mass ratio)	(fuel ratio)	(t)	(m)	(m)	(m)	(t)	(m3)	(area ratio)	(m)	(m)
20	1.00	0.42	0.2	5.7	18	6	2.5	40.0	26.7	0.70	5.5	23.54
15	1.00	0.42	0.2	4.3	18	6	2.5	30.0	20.0	0.70	4.9	22.90
10	1.00	0.42	0.2	2.9	18	6	2.5	20.0	13.3	0.70	4.3	22.27

18m Vessel with Combustion Engine Propulsion & Hyrea (Reactant B) H2 Fuel												
	Pov	ver & Fuel Sys	stem			Hull		Reactant B		Tank space + Reactor		
Ref. tank	IC Engine	H2 to diesel	Pilot fuel	H2 mass	LOA	Beam	Avg. depth	Mass	Volume	Silo factor	Length	New LOA
(m3)	(eff'y ratio)	(mass ratio)	(fuel ratio)	(t)	(m)	(m)	(m)	(t)	(m3)	(area ratio)	(m)	(m)
20	1.00	0.42	0.2	5.7	18	6	2.5	57.1	47.6	0.70	7.5	25.53
15	1.00	0.42	0.2	4.3	18	6	2.5	42.8	35.7	0.70	6.4	24.40
10	1.00	0.42	0.2	2.9	18	6	2.5	28.6	23.8	0.70	5.3	23.27

Fig.13: Lengthening calculations for Hyrea system & combustion engines

18m Vessel with Fuel Cell Power & Hyrea (Reactant A) H2 Fuel												
	Pov	ver & Fuel Sys	stem			Hull		Read	tant A	Tank space	+ Reactor	
Ref. tank	Fuel Cell	H2 to diesel	Pilot fuel	H2 mass	LOA	Beam	Avg. depth	Mass	Volume	Silo factor	Length	New LOA
(m3)	(eff'y ratio)	(mass ratio)	(fuel ratio)	(t)	(m)	(m)	(m)	(t)	(m3)	(area ratio)	(m)	(m)
20	0.50	0.42	0	3.6	18	6	2.5	25.0	16.7	0.70	4.6	22.59
15	0.50	0.42	0	2.7	18	6	2.5	18.7	12.5	0.70	4.2	22.19
10	0.50	0.42	0	1.8	18	6	2.5	12.5	8.3	0.70	3.8	21.79

18m Vessel with Fuel Cell Power & Hyrea (Reactant B) H2 Fuel												
	Pov	ver & Fuel Sys	stem		Hull			Reactant B		Tank space + Reactor		
Ref. tank	Fuel Cell	H2 to diesel	Pilot fuel	H2 mass	LOA	Beam	Avg. depth	Mass	Volume	Silo factor	Length	New LOA
(m3)	(eff'y ratio)	(mass ratio)	(fuel ratio)	(t)	(m)	(m)	(m)	(t)	(m3)	(area ratio)	(m)	(m)
20	0.50	0.42	0	3.6	18	6	2.5	35.7	29.8	0.70	5.8	23.83
15	0.50	0.42	0	2.7	18	6	2.5	26.8	22.3	0.70	5.1	23.13
10	0.50	0.42	0	1.8	18	6	2.5	17.9	14.9	0.70	4.4	22.42

Fig.14: Lengthening calculations for Hyrea system & fuel cells

It can be seen from the above tables in Figs.13 to 14 that the study vessel lengthened with the Hyrea system and fuel cell power is shorter than nearly all the alternative fuel options and shorter than all of them if the 0.5 m void can be removed from the ends of the reactant storage silo. Therefore, if space is the primary consideration, then the Hyrea system is the better option compared to other alternative fuels.

3.5 Study Vessel Arrangement with Hyrea System

The lengthened vessel arrangement with the Hyrea system is proposed. The lengthening will increase the vessel's displacement by about 40 t. A basic weight calculation, Fig.15, was undertaken to check the effect of the Hyrea system on the lengthened vessel.



Fig.15: Study vessel with 4 m module for Hyrea & fuel cell system (left), weight schedule (right)

The weight calculations in Fig.16 shows that the fuel cell system was about 1.5 t lighter than the diesel engine system of the study vessel. The additional weight of the hull module, powder storage and reactor system is about 27 t. Therefore, it will be necessary for the lengthened vessel to carry about 10-15 t of ballast water if the draught is to be maintained for stability. This water could be used during the voyage for producing the hydrogen. The excess buoyancy will also be useful if the Hyrea solid waste is stored on-board for shore discharge instead of being dumped overboard.

					500 1	W Fuel Cell Pro	pulsion & Pov	ver System	
					ltem	Capacity	Quantity	Unit weight	Total weight
500 kW	Diesel Engine	Propulsion & F	Power System				(n)	(kg)	(kg)
ltem	Capacity	Quantity	Unit weight	Total weight	Fuel cells	250 kWe	2	800	1600
		(n)	(kg)	(kg)	Fuel cell converters	250 kWe	2	250	500
Main engine	350 kW	1	2000	2000	Propulsion motors	175 kW	2	300	600
Propulsion gearbox	500 kW	1	1500	1500	Propulsion gearbox	500 kW	1	1500	1500
Gensets	100 kWe	2	1500	3000	Motor drives	175 kWe	2	250	500
Main switchboard	200 kWe	1	500	500	Main switchboard	1000 kWe	1	1000	1000
Ventilation systems		1	500	500	Ventilation systems		1	250	250
Piping systems		1	1250	1250	Piping systems		1	800	800
Electric cables		1	250	250	Electric cables		1	750	750
				9000					7500

Fig.16: Diesel engine system weights (left) and fuel cell system weights (right)

For this 18 m study vessel, there will be many unused spaces or hull voids from this type of lengthening. If a similar capacity trawler was designed from the outset to for a Hyrea system, the length of the resulting vessel would likely only by 2 m longer than the study vessel.

4. Vessel Operations with Hyrea Technology

The Hyrea process of producing hydrogen fuel on-board a vessel is significantly different from other types of liquid fuel handling and the process also involves gas fuel handling between the reactor and end consumer, either a combustion engine or fuel cell. For future vessels operating with Hyrea systems, there are operating issues that would need to be considered for handling the reactant powders, Hyrea reactor plant and hydrogen gas fuel.

Marine engineers and other crew are generally not familiar with bulk powder handling, Fig.17. Powder products do not flow as well as liquids and are subject to blockages in silos and hoses. Clearing such blockages may need redirection of air in pneumatic conveyance systems and in the worst case some form of mechanical intervention may be necessary.



Fig.17: Bulk powder handling system

Keeping the reactant powder from getting wet will be extremely important. Safety systems will be necessary in the case of flooding of the silo creating an uncontrolled chemical reaction releasing hydrogen and huge amounts of heat, but also crew training as to how to deal with such an incident is equally important.

The reactor control system will need to manage both pressure, temperature as the demand for hydrogen gas varies. Although control is expected to be fully automatic, the Hyrea reactor will need to ensure fail safe operation with redundant safety systems. The crew will need training on the reactor plant operation and manual safety overrides.

There is a current lack of published rules and regulations for hydrogen gas fuelled vessels. It is expected that forthcoming rules for hydrogen will be similar to other gaseous fuels like methanol and ammonia. Design features for gas-free non-hazardous engine rooms, Fig.18, include using double-walled piping and enclosed valve trains, purge and inerting gas system and explosion proof motors in hazardous gas zones and ventilation systems.



Fig.18: Non-hazardous engine room for gas engines

5. Conclusions

The Hyrea process for on-board generation of hydrogen fuel and its application to the Australian commercial fishing fleet has been investigated. The study identified many novel aspects of Hyrea technology such as dry bulk material handling and the reactor design issues for onboard hydrogen production that are not common technologies in the maritime industry.

Notwithstanding the novel aspects and the small scale of the current prototyping of Hyrea technology, there does seem to be any technical aspects that cannot be solved with well known engineering solutions to upscale the Hyrea process for fishing vessels.

The Hyrea process produces a considerable amount of waste heat that can be used productively for producing fresh water, powering absorption refrigeration systems or producing electricity. This energy recovery will contribute significantly to overall efficiency of the system and will be easier to implement since the waste heat is released in the reactor only. By comparison, with alternative fuels used in combustion engines, the waste heat is divided into water coolant and engine exhaust streams complicating the waste heat recovery.

Future propulsion and power systems using alternative gaseous fuels such as methanol, ammonia and hydrogen in internal combustion engines were reviewed, noting that these engines still need a small fraction of diesel fuel to start the combustion process. Fuel cell systems using hydrogen are about twice as efficient compared to hydrogen engines and only emit water vapour.

By far the largest segment of the fishing fleet with respect to annual fuel consumption are vessels between 12 and 24 m in length, accounting for 65% of the total fleet consumption. Therefore, this study focused on a typical side trawler in this category. It is estimated that there are about 2000 such vessels in the Australian fishing fleet.

A volumetric comparison between the various alternative fuels including methanol and ammonia has been undertaken. The proposed modification for storage of the alternative fuels is a midship hull lengthening so that the required void protection can be more easily included. The amount of lengthening required was calculated for each alternative fuel and compared to the Hyrea system.

The volumetric comparison found that the Hyrea system required the least amount of hull lengthening, about 4 m, if the vessel used a fuel cell system. The study vessel, an 18 m length trawler could be lengthened and still stay within the AMSA 24 m length. It was also advised that a similar capacity fishing vessel designed from the outset for the Hyrea system would likely be only slightly larger than the original study vessel.

6. Future Studies

This study has confirmed the technical feasibility of implementing Hyrea technology onboard fishing vessels. The next step for Hyrea and the fishing industry is to identify a specific vessel for a full concept design so that the development of the Hyrea reactor and supporting plant equipment can be focused on a full-size prototype system for on-board testing. This development could also be focused on a containerised system for easier deployment and integration on the vessel.

Technical aspects of the Hyrea process that will need further development include:

- Which reactant Hyrea will focus on and the physical characteristics of the powder
- Determining the operating pressure and temperature the reactor to optimise performance
- Design of the reactor control system to ensure reliable and safe operation
- Determining what processing the hydrogen produced from the reactor requires
- Clearing of solid waste from the reactor and de-watering for possible storage on-board

Other shipping segments should be investigated such as bulk carriers and tankers industry since the technical solutions and costs of implementing Hyrea technology may be less challenging. The cruise industry could also be very interesting, since the waste heat can be useful for producing fresh water and cooling for air conditioning systems, both of which are large electrical consumers.

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Maximizing Deployability & Sustainability of On-board Additive Manufacturing

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Abstract

The commercial maritime sector increasingly faces operational challenges related to supply chain disruptions and maintenance delays. Deployable metal additive manufacturing (AM) technologies offer a potential solution by enabling on-board production of critical components. Molten Metal Deposition (MMD) technology provides a safe, energy-efficient, and feedstock-flexible approach suited for such applications. This paper investigates how MMD could contribute to improved operational resilience, reduced logistics dependency, and enhanced sustainability for ships. While promising, the adoption of deployable AM requires careful consideration of technical limitations, integration challenges, and the need for further field validation.

1. Introduction

The operational demands of the maritime industry are intensifying, driven by tighter schedules, rising operational costs, and growing environmental regulations. Ships traversing global routes must often remain self-sufficient for extended periods, facing mechanical failures or unexpected needs that require rapid intervention.

Traditional maintenance strategies involve overstocking a wide range of spare parts, dedicating valuable space on board to inventory and relying on complex logistics chains to deliver missing parts – often at great cost and delay. Similar to defense naval operations, these approaches are increasingly unsustainable.

Commercial vessels – from container ships and offshore carriers to cruise liners – require a paradigm shift: moving towards localized, on-board manufacturing capabilities that ensure self-sufficiency, agility, and reduced environmental impact. This is the main driver for having on-board workshops. Deployable additive manufacturing (AM) technologies, particularly those suited for metal part fabrication, provide a promising avenue to further enhance this.

One example of the reliance on supply chain was demonstrated by a study of Humolco Trans Inc., a Jakarta-based shipping company. Over a series of 36 voyages, the company experienced 22 voyage cancellations with an astonishing 66% cancellation rate-directly attributed to delays in the delivery of critical ship spare parts. These cancellations were not due to cargo delays or port issues, but rather because the ships were rendered unseaworthy while waiting for essential engine or auxiliary components, *Sumali et al. (2018)*.

The operational and financial impacts were severe. Each canceled voyage not only disrupted the company's shipping schedules but also damaged contractual relationships with cargo shippers, resulting in financial penalties and loss of trust. The inability to maintain vessel readiness due to missing or delayed spare parts led to extended periods of vessel downtime, during which the company incurred ongoing operational costs (such as crew wages, port fees, and insurance) without generating any revenue. The research quantified a strong positive correlation (94%) between spare parts delivery delays and voyage cancellations, highlighting how critical timely parts availability is to shipping operations.

This case illustrates the limits of traditional onboard workshops. Even with skilled technicians and standard repair tools, the absence of the correct spare part (often a specialized or obsolete component) meant that repairs could not proceed. The onboard workshops could not fabricate or substitute for these missing parts, underscoring the need for more advanced, flexible manufacturing solutions at sea.

Such incidents are not isolated. Broader industry analyses confirm that delays in spare parts delivery frequently lead to increased off-hire time, disrupting ship operations and causing significant economic losses. The lack of optimal procurement processes and the inability to manufacture certain parts onboard are persistent challenges in the sector, *Pahl (2022), Selasdini et al. (2021).*

Operational delays at sea impact not only the economic value of transported goods but also significantly increase transportation costs and carbon emissions, *UNCTAD (2023)*. A relevant example from the naval sector illustrates this dynamic: Frigates (~124 m length, ~3300–3750 tons displacement) consume several hundred liters of fuel per hour, with fuel consumption varying up to a factor of three depending on speed and payload. Although these ships are equipped with machining workshops (12–20 m²) and large spare part warehouses (up to 160 m² total), logistics challenges remain critical, *Janicke and Peters (2021)*. Two operational scenarios highlight the impact:

- <u>Remote operations:</u> For ships out of helicopter range, a mission-critical delay can result in ships idling with one or two generators running (200–300 L/h diesel each), producing 20–38 tons of CO₂ emissions per day next to the generated operation/consumption costs.
- <u>Helicopter re-supply:</u> When reachable, helicopter supply missions are costly and emission-intensive, with helicopters consuming 200–800 L/h over 2–4.5 hours, generating 1–10 tons of CO₂ per intervention.

2. Value of Additive Manufacturing

Additive manufacturing (AM) has the potential to reduce spare part stock by 15–20%, thereby lowering payload weight and warehouse space requirements, *Rylands (2020)*. While the direct impact on vessel emissions is limited relative to total displacement, the indirect benefits on logistics efficiency are substantial, *Janicke and Peters (2021)*.

Deployable AM technologies onboard significantly reduce the need for urgent resupply missions and idling time, contributing to both cost savings and environmental objectives.

One example is given by *Kostidi and Nikitakos (2024)*, that demonstrates onboard production of a semiopen pump impeller via additive manufacturing could reduce spare part delivery time by almost 180 days and save up to \notin 960 per part in storage and logistics costs. Instead of relying on regional warehouses or port deliveries, a vessel could fabricate critical components like pump impellers directly onboard within a few hours, ensuring rapid repairs and mission continuity. This highlights how AM not only optimizes inventory but also mitigates costly delays associated with traditional maritime supply chains. Another example, a handle of a butterfly valve, *Rohman (2022)*, is shown in Fig.2.



Fig.1: Supply chains for current existing maritime SPSC delivery and proposed delivery with onboard manufacturing further enabled with AM usage, *Kostidi and Nikitakos (2024)*



Fig.2: Example of a butterfly valve handle printed in polymer, Rohman (2022)

3. Hurdles for (Metal) Additive Manufacturing Adoption

Conventional subtractive manufacturing requires a huge diversified feedstock inventory, hampering the ability to rely on it in these offshore situations. Additive manufacturing could be the solution, as it is feedstock-agnostic and consumes significantly less material (thanks to its freedom-of-design and material use where truly needed). However, mainly for metals, the existing AM technologies, such as Laser Powder Bed Fusion (LPBF), Binder Jetting, Direct Energy Deposition (DED), are not deployable enough. Depending on the technology, it requires cumbersome post-treatment, chemicals, extensive power, safety precautions, additional peripheral equipment, specialised maintenance expertise and highly educated operators. Additionally, for many of these technologies, the time-to-part is not same-day-turnaround because of their slow print and/or intensive post-processing time. There is a need for a technology that can address this deployability challenge and especially overcoming the barrier for easy adoption of metal additive manufacturing.

4. Molten Metal Deposition (MMD)

As extensively discussed, deployability is a critical factor for the widespread adoption of additive manufacturing technologies. In this context, deployability encompasses a combination of factors, including energy consumption, ease of operation, learning curve, environmental adaptability, operational safety, feedstock flexibility, cost efficiency, time-to-part availability, and material diversity. Polymer-based additive manufacturing, particularly Fused Filament Fabrication (FFF) — also known as Fused Deposition Modeling (FDM) — has demonstrated considerable potential in addressing these demands. FFF/FDM is a layer-by-layer manufacturing process wherein a thermoplastic filament is heated to a semi-liquid state and extruded through a nozzle to form three-dimensional parts. However, translating this approach to metals presents significant challenges, primarily due to the fundamentally different material properties and processing requirements associated with metallic systems.

Molten Metal Deposition (MMD) is a novel wire-based metal additive manufacturing (AM) technique, developed and patented by ValCUN. With an initial focus on aluminium, MMD involves the direct melting and deposition of wire feedstock onto a heated substrate (see Fig.1). The material solidifies upon deposition, allowing complex geometries to be produced with relatively similar equipment and software as the popular and already demonstrated polymer FDM/FFF process. This method eliminates the need for auxiliary energy sources like lasers, binders, or extensive support structures, thereby reducing thermal stress and enhancing process efficiency. As a direct result, MMD is particularly suited for high-strength aluminium alloys in the 6xxx and 7xxx series, alloys that as sensitive to thermal cracking when using thermal processes such as welding, *Elangeswaran et al. (2023)*.



Fig.3: Principle of ValCUN's Molten Metal Deposition (MMD)

MMD technology directly addresses the 'deployability' challenges. Key features include:

- <u>Feedstock:</u> Unlike traditional powder-based AM, MMD employs simple, safe, and easily storable metal wire. This drastically improves safety and logistics. As the metal is fully molten in the printhead the technology allows the extension towards billets and recycled parts, further enhancing the sustainability and feedstock independency
- <u>Energy Consumption</u>: The insulated printhead reduces energy requirements by a factor of 4–10 compared to other metal AM methods critical for energy-constrained maritime environments.
- <u>Small Footprint and Easy Integration</u>: The compact size as no additional peripheral equipment is required for the printing process, allowing installation in existing ship workshop environment.
- <u>Material Versatility</u>: Beyond aluminum crucial for lightweight marine applications the same machine can print various polymers and potentially other metals, reducing the need for multiple machines within the workshop.
- <u>Single Step Process for Same-Day Part Production:</u> Minimal post-processing ensures that parts can be printed and used within hours vital for operational continuity.
- <u>Safe:</u> lower process temperatures are used as avoiding harmful fumes and loss of alloying elements by evaporation.

A common misconception in the field of Additive Manufacturing (AM) is the assumption that parts are "ready for use" immediately after fabrication. In the case of Molten Metal Deposition (MMD), which is a layer-by-layer additive process, conventional post-processing—such as machining—may still be required to achieve critical surface finishes, including mating interfaces, sealing surfaces, and threaded features. Depending on the specific requirements of the repair or replacement task, the most appropriate and efficient combination of additive and subtractive manufacturing processes should be carefully selected to ensure optimal functionality and performance.

5. Case study

In this section, the fabrication of a real-life component — the thermostat housing of a diesel generator engine — is motivated and demonstrated, Fig.4. Onboard generators are critical assets on naval vessels, providing essential electrical power to maintain operational readiness. Proper engine management is therefore vital, as operating without functional thermostats can lead to severe engine damage and significantly reduce service life.

It is important to emphasize the following considerations:

- Manufacturing this component is only justified when a replacement part is not available within the ship's inventory.
- The original component is designed for casting, its preferred manufacturing method.
- The objective is not to permanently replace the original equipment manufacturer (OEM) part but to provide a temporary solution to complete the mission.

Field conditions were fully considered to assess the deployability of the solution. Only standard onboard tools were used, without reliance on specialized equipment.

The manufacturing process began with the identification of critical functional features: sealing surfaces, hose connection diameter, hole pattern, and sufficient internal volume for thermostat integration. Noncritical features were simplified to enable rapid and efficient design and production. Given that the MMD process yields a near-net-shape part, only the critical surfaces required conventional postmachining. The final post-machined component is shown in Fig.4 alongside the original OEM part. Despite noticeable differences in geometry, the manufactured component performed adequately, serving as a functional replacement until the arrival of a new OEM part.



Fig.4: Example of failed engine thermostat housing. Left: typical thermostat. Middle: aluminium 3D printed by Molten Metal Deposition technology. Right: original (failed) part



Fig.5: Production time comparison of the thermostat housing between Molten Metal Deposition (MMD) and 2 other suitable AM technologies: Laser Powder Bed Fusion (LPBF) and Binder Jetting. All steps from broken part till functional replacement part are taken into account.

The complete process from the identification of the damaged component to the production of a functional replacement is outlined in Fig.5 and compared with two other commonly used and technically suitable metal additive manufacturing (AM) technologies. While powder-bed laser-based methods, such as Laser Powder Bed Fusion (LPBF), offer superior resolution and surface quality, they present significant operational drawbacks. LPBF requires specialized feedstock handling, substantially longer build times, and extensive post-processing, including part removal from the build plate and the elimination of support structures. These factors collectively reduce the practicality of LPBF for rapid, deployable in-field manufacturing scenarios.

Although Binder Jetting and similar technologies offer relatively rapid printing processes, the subsequent debinding and sintering steps required to achieve final part properties substantially extend

the overall time-to-part. In contrast, using the described MMD approach, a functional component can be produced in less than five hours. This is significantly faster—and more cost-effective—compared to the alternative of placing an order with a local warehouse and relying on helicopter-based resupply operations, assuming the ship is within operational reach.

More typical 'spare part' examples, produced with MMD are shown in Fig.6.



Fig.6: Snippets of other parts: brackets, manifolds, heat exchangers, tooling, filters

6. Conclusions

The integration of deployable onboard additive manufacturing (AM) technologies as an extension of existing workshops offers several operational advantages:

- <u>Minimized Spare Parts Inventory</u>: On-demand manufacturing enables significant reductions in the volume of spare parts stored onboard.
- <u>Reduced Downtime</u>: The immediate production of critical components following failure minimizes maintenance-related disruptions.
- <u>Enhanced Operational Autonomy</u>: Vessels operating far from port can maintain mission capability without reliance on emergency resupply.
- <u>Environmental Impact Reduction</u>: Localized production decreases the emissions associated with urgent resupply missions and reduces ship weight due to lower inventory requirements.
- <u>Cost Efficiency</u>: Avoiding costly last-mile delivery services, such as helicopter transport or port diversions, leads to substantial operational savings.

Historically, the deployment of metal AM technologies at sea has been constrained by safety concerns related to metal powder handling, high energy requirements, and the necessity for specialized personnel. These factors have significantly limited the practical adoption of metal AM in maritime environments.

However, deployable metal additive manufacturing has evolved from a conceptual innovation into a viable operational capability. Early field demonstrations, particularly with polymer-based systems, have validated the potential within the commercial maritime sector. Technologies such as the Molten Metal Deposition (MMD) process offer a safe, energy-efficient, and field-deployable solution for onboard metal part fabrication. The integration of such systems into maritime operations promises to enhance vessel autonomy, improve operational resilience, increase maintenance efficiency, and promote more sustainable and flexible logistical practices.

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A Single-Source-Of-Truth for Future Ship Life-Cycle Data

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Abstract

During the last decade the author have been in contact with diverse attempts from the academia (theoretical) and industry (practical) to implement a single-source-of-true for the ship design value chain. This paper compiles some impressions from these attempts, motivated by the existing SEUS EU project on smart shipbuilding, that NTNU and 7 other partners are part of. The paper starts with a discussion on the concept of single source of truth in ship design for closing the ship life cycle loop. This is followed by the idea of database and dashboards able to aggregate six data domains in a unique and coherent structure. The advanced but fragmented present situation of information silos in maritime is exemplified via selected approaches in design, construction and operation. The final section presents a speculation for the future, in which standardization can be driven by the government and/or market, as well as a promising exercise in using LLM for handling event-driven sources of truth.

1. Single Source of Truth in Ship Design, Construction and Operation

The need to study the concept of single source of truth (SSoT) in ship design value chain is currently fomented by the Smart European Shipbuilding EU project (SEUS - seus-project.eu) that the author coordinates. The project aims to develop a digital platform that enhances the efficiency of shipyards by integrating design and management software. Add to it previous experience in industrial research projects aimed at similar data coherence during conceptual ship design for re-use in consequently lifecycle phases, *Keane et al. (2017), Gaspar (2018)*. Moreover, other recent initiatives linked to close the loop from operational to design enhanced the importance of a coherent database all over the lifecycle, closing the loop between operation and design, *Taylor et al. (2024), Gaspar and Bekker (2025)*.



Fig.1: Single source of truth for the ship lifecycle data

SSoT is this here understood here as data, knowledge, information and wisdom (DIKW) from the main activities expected in the ship design value chain, as observed in Fig.1: concepts, CAD/CAE engineering documents, ERP and CAM systems, compliance with classification societies, assembly operations, sea trial, performance validation, operation under diverse mission profiles, monitoring and sensors, emissions compliance, MRO, retrofit and end of life towards recycle.

Note that the discussion of the idea and importance of a unified database for maritime activities is as old as the initial digital implementations from the 1970s. *Wolanyk's (1979)* essay from the 6th Research and Engineering for Automation and Productivity in Shipbuilding Symposium (REAPS) reads as well now as in 1979: "We raised the question of why should a corporation consider their own database (...). To be able to retrieve information and know that it is the most accurate and up to date available. Other reasons are to reduce data redundancy and thereby permit sharing of data among applications and allow data usage restrictions to be applied effectively. Knowing where the data is located, or that it resides in fewer locations, makes it easier to control that data. Finally of course, maintenance of data integrity and data independence issues can be addressed. By data independence issues we mean the ability to change a program or to change a database and not have to change the other, concluding with (...) there are no database management system packages commercially available today that really suit both the commercial and the manufacturing side of an organization as well as the engineering side. However, there is a commonality between the two application areas that should be tied together, perhaps, through interface systems. The second conclusion is that the effort involved in the implementation of a data dictionary is worth it to put the shipyard in position to take advantage of new technology."

Two distinctive SSoT concepts are here analysed. The first, within an organization, as mentioned by Wolanyk, and currently advertised and implemented in diverse maritime companies. In this way, a clear boundary of data ownership is traced. When within a design office, for instance, SSoT would mean access to existing and previous designs; within a shipyard, construction drawings and suppliers' information from delivered ships; from shipowners, operational data and maintenance schedule. The second concept follows the lifecycle of the ship itself, aggregating data from many different stakeholders of the life cycle phases and ownership, within a single coherent database.

It is my belief that the majority of the academic articles and industrial sales pitch focus on big promises connected to the second concept, while justifying the existing challenges to achieve it in the lack of the first one in place. In other words: "We can have the whole digital twin of the ship ready to be accessed, including design, construction and operation, but first you need to implement X, Y and Z in your company... as soon as all other stakeholders do the same, the solution is implemented". The catch is that tools and methods X, Y and Z vary to each service provider, and in reality, we introduce new digital processes in top of existing ones, masking (and increasing) the real fragmentation.

Keane et. al. (2017) correctly points that a solution for the integration challenge may be use of PLM as umbrella, as a basis for emergent technology. The authors also add the criticism that modern PLM fails in the promise to handle multi-taxonomy/disciplinarily issues. In reality, modern PLM systems yet require a semi-fixed hierarchization of the ship design products, system and process, not much different in theory as the SFI group system from the pre-digital era. Such need constrains the understanding of the system by a specific set of rules, which may not work in a different context of market, construction or operation.

To exemplify this challenge, we can use the good explanation of *Semini et. al. (2018)* for the four core strategies that larger ship design firms have when detailing and constructing the vessels, Fig.2. A more detail description of each strategy is observed in *Bronson and Gaspar (2024)*.

A coherent data architecture for strategy I, where the upstream phases are within the same boundaries, can be achieved, as all the decisions have similar context around then, such as regulations, incentives and best-practices. When third parties from other countries enter in the process, such as the cases of strategies II to IV, then the chance that a coherent unified model can exists when managed by multiple stakeholders is close to none. There is a large market of digital engineering conversion in countries like Poland, Romania, Ukraine and Turkey, in which naval architecture offices are contracted to translate the data send from the designer office and supplier towards the modus operandi of the ship yard. The same hull, with the same basic design drawings, will require organization to different taxonomies to be constructed in Norway, Turkey or China.



Fig.2: Shipbuilding Strategies, from Bronson and Gaspar (2024), based on Semini et al. (2018)

The rest of this paper will discuss some of the reasons for this to happen, with an overview of the six key data domains that seems to have the largest importance. Later, an overview of selected existing solutions for coherent database that are being used for design, construction and operation. The proposition for the future of SSoT starts with reminiscences of the past, with the realization that some of the issues raise more than 45 years ago are yet a reality. A brief discussion on event-driven source of truth is then presented, biased by past attempts and current research that the author was/is involved. The role of the invisible hand of the market, or visible hand of the governmental entities is discussed, based on examples from the building industry and the successful implementation of BIM in the last years. The paper closes with some speculation about the role of AI in developing and managing a SSoT and the importance of openness, transparency and traceability.

2. Data Domains and Dashboards - Taxonomies that matter and Path Dictionaries

The challenge in stablishing a SSoT for the maritime sector lies in its high level of customization within a narrow margin to accept risks. As recently summarized by *Yilmaz et al.* (2025), maritime industry fits the profile of project based firms, *Gann and Salter* (2000), in which design and production processes are organized around highly customized solutions, operating with volatile stakeholders in their value chain. Such concept matches well *Erikstad's* (1996) seven aspects preliminary ship design, namely: one of kind, multi-dimensional performance evaluation, high cost of error, shallow knowledge structure, strong domain tradition, complex mapping between form and function and stricter time resources and constraints.

Motivated by the lack of mature discussion on the effects of the disruption from upstream to downstream phases for the maritime systems' digital models, *Bronson et al. (2024)* compiled four existing gaps towards developing a common data platform in the maritime industry: Lack of Open Standards, Non-standardized Data Models, Non-integrated pipeline and Lack of Adoption Strategies. Such gaps are commonly understood as the reason why the maritime industry lacks a common taxonomy able to parse Fig.1 data into a structure that can be accessed and exchanged between the many actors.

One of the attempts of the existing activities of the SEUS project is to investigate which data domains are the more relevant to be considered when gathering and organizing lifecycle data. We converged to six domains, namely: Process, Product, Systems (Functional), Geolocation, People and Contextual (market, rules, regulations). Central to the idea of domains includes the fact that they are highly linked,

and information falling within one domain can be reinterpreted to other domains based on intent and function. Fig.3 presents a mock-up of what could be a dashboard to access these domains during design and construction, *Bronson and Gaspar (2024)*.



Fig.3: Mock-up of a dashboard incorporating the six domains in a unique and coherent structure for the ship design lifecycle, first sketched in *Bronson and Gaspar (2024)*

As an aggregator, the concept from Fig.3 would be acting as a central repository, what in the past could also be called a "data dictionary". This would store the relevant required definition and metadata in a unique location, while the detailed information would be located in an existing silo. In other words, a dashboard with paths to reach more detailed data about a certain element, filtered by tasks, user (people), location, systems and lifecycle phase.

Note that the concept here is not the same as a unified software platform solution, such as PLM, ERM, ERP or CAD/CAE platforms, neither a fleet performance monitoring software. The dashboard

resonates with the idea of aggregators already used by the building industry, such as Synchro 4D, screenshot presented in Fig.4.



Fig.4: Synchro 4D construction management platform (bentley.com/software/synchro/)

Rather than competing with state-of-the-art tools such as CAD suites and project management solutions, such aggregator (or federated model) uses the standardization of building information modelling (BIM) and its .IFC standard widely used in the European building industry. IFC files generated by many actors within different phases of the project are visualized under the same umbrella, with an adequate GUI that facilitates data exploration in diverse important domains, such as:

- Temporal: with an interactive timeline of the phase of the project and the correspondent status of the product, visualized in 3D.
- Activities: with ownership, duration and the connection with the completion of a part of the product of service from a supplier.
- Human, with the persons and service providers performing the work.
- Resources, with a unified list of supplier and raw materials, connected to physical and economic data.
- Links and relations, that is, a hierarchization of the process connected to requirement and criteria that must be achieved in a certain order.
- Gates, milestones and checkpoints.
- Breakdown of the system, with subsystem, components and traceability of ownership.

Coherence in the data taxonomy means having access of the information in a a way that it can be accessed, aggregated and re-arranged according to the needs. Fig.3 is not a proposal for a new digital platform suite or new industrial standard, in the same way that the software from Fig.4 is not a CAD, project management or BIM software. Both used the idea of open and accessible data format to generate an interactive and visual compilation of the data domains until now, heavily making use of the timeline and how the other product varies of the time. In the following section we exemplify the concept based on existing practices in design, construction and operation.

3. Silos and current SSoT attempts in Ship Design, Construction & Operation

There is no doubt that we achieved a high level or digitalization and formalization of difficult and complex ship design, construction and operation tasks within an information silo. Independently, each of us have their own way of organizing information in a way that we can access and re-use. Within small groups the gain in productivity and performance is also well stablished, especially when the department is able to handle tasks of a singular discipline (e.g. CAD for classification compliance, or outfitting). The users (people domain) usually share the same ontology of the task, that is, a set of concepts and categories in a subject area or domain, as well as the relations between their field of work and the external world.

Within different domains and lifecycle phases, however, the challenges discussed in *Gaspar (2018)* seem yet to be valid, as the integration and flexibility promised by modern SSoT systems are not yet delivered in everyday activities. Among its reasons, the cost for purchasing and training users among the life cycle activities in engineering and yard, especially in strategies with work made abroad, Fig.2, seems to play an important role. Other reasons are: limited freedom to customize libraries and adequate tacit knowledge and local procedures to the data standard; additional development cost for customization, macros and APIs able to handle the uniqueness of each company; high cost to acquire, install, train personal and keep servers running; risk of being locked to a system, and losing independence if features and licenses terms changes.

The sales pitch and training materials of computation tools for the maritime usually avoids presenting workarounds that may suggest the use of a competitor tool for a complimentary task, ignoring that experienced professionas have different preferences on how to solve the problem complex problem, and that a certain methodology proposed by the software *X* may not the most effective among the users. Note that this is not a new problem. *Knapp (1980)* presents a discussion in similar tone on the challenges of firstly implementing digital planning in shipbuilding: "(...) the speed of the computer has been harnessed to increase the overall document volume generated by the Planning department, but the sophistication of the software is not being utilized. Instead, the yard's traditional planning techniques are being dropped, with no improved methodologies replacing them. Moreover, the overall experience levels of the planners is on the decline (...) Planning "to suit Production" is replaced with planning "to suit the computer", with the overall approach tending away from the shipbuilding process. (...) No computer software system has been created which understands all of the intricacies of the shipbuilding process, contrary to the assumptions of some planners". I believe that the same is yet true not only in construction, and changing the substantive above for design or operation seems to work well.

In the following, this is exemplified based on my personal experience, and any criticism should not be directed to maritime companies or software developments, as it serves only to illustrate a challenge that has been acknowledged for decades.

Design: Hull design and file formats, related to additional work to convert existing data from *silo A* in the format/tool used by silo B. As example, the use of diverse CAD tools and files to handle the hull and GA. While there are plenty of unified solutions to design, analyse and detail the hull shape and properties, in reality large and serious ship design companies do have high skilled employees spending time in the conversion of models between the disciplines.

Personally, I have been exposed to at least four similar cases in which Rhinoceros is used for the main conceptual design and overall arrangement in the pre-contract phase, shared by engineering and sales, in medium and large European ship design companies, different countries. In all these cases, the companies had access to a complete solution to handle hull design and analyses, such as CADMATIC, NAPA or FORAN/SIEMENS NX, usually used by the structural and hydro engineers. The process goes something like this (my bias): the chief design has a personal collection of previous designs and constructed projects in Rhinoceros, with a very detailed 3D arrangement of the hull, as well as macros to export the concept to fancy 3D renders and architecture-like isometric GAs. Added to it a well calibrated spreadsheet, parametrized to match the Rhinoceros catalogue, fed with decades of data from

previous analyses, towing tank experiments and sea trial data. In this way, a new design could be balanced quickly with interpolation of the existing data, with a precision good enough to assure the client that it is functional. After contract, this Rhinoceros project is then shared with the other departments for compliance, sometimes abroad. The same hull would then be converted to match stability calculations (e.g. NAPA or SARC), structural analyses (e.g. DNV) and seakeeping. Changes would need to be fed back to Rhinoceros, as to keep the sales model updated. Only after the hull is properly balanced that the Rhinoceros model is thus abandoned and the detailed engineering of subsystems is them carried out in the software of choice, as well as the CAD for classification and construction.



Fig.5: Attempt of balanced conceptual design using Rhinoceros, Suhas (2023)

Suhas (2023) touches this topic, attempting to reinvent the wheel into Rhinoceros, as to achieve the initial design balance with scripts via the Grasshopper functionality. His work exemplifies well the advantage of modern CAD software in empower designs to create something unique, and later quickly parametrize right into the 3D environment, while the reality of extremely complexity of introducing in such tools a niche analyses, such as stability and structural compliance, Fig.5. The work shows an impressive compilation of scripts and basic naval architecture procedures for a container vessel. The use for real analyses and compliance, however, is not achieved as the amount of code and interaction grows much faster, as the real number of activities within stability and structural compliance does not allow it to be done by a single person.

Another lesson to be adapted from the Lincoln et al. (1980) discussion from, in relation to the economics of implementing digital tools. The authors conclude from many implementation experiences that "whether it makes sense to use computers in shipyard production control is simply a question of economics, namely, whether the savings from increased control more than cover the cost of the system and provide a reasonable rate of return (...) Generally speaking, for small shops with fewer than 100-200 active jobs at any given time, a well-thought-out manual system is probably the most cost-effective.

Beyond this point automated systems become economically attractive". Again, thinking in terms of design activities, the manual work of the main designer in the CAD tool of her preference (e.g. Rhinoceros) fits well the speech. When, however, the number of tasks raises to include the stability and structural engineering, the manual work should include automation, which in our examples can be translated as the seamless data exchange between different software.

Construction: Product and processes management. The second example is connected to classical connection between the product realization, that is the construction of the ship, and the management of the activities, including personal and supply chain logistics. Again, we do have amazing complete solutions to handle both activities separately. A suit like CADMATIC, for instance, is able to handle a large database of components and assemblies with millions of elements in 3D for the outfitting and ship systems (e.g. HVAC). On the other hand, shipyards have in house planning tools able to store information about building blocks division, workshop planning and stock with control of the information via the supply chain. Communication between these both sides, yet falls in the same conversion work commented in the first case, as the yard has usually a different taxonomy to organize it the ship than the engineering. The first is based on WBS process and resources availability, in a tight schedule balancing use of existing resources and warehouse management. The second is thought in terms of functionalities and technical compliance, in which divisions do not necessarily follows a *physical* constrain.



Fig.6: CADMATIC eShare, handling functional and product structures within the 3D platform

An existing service to tackle this problem is here exemplified by CADMATIC eShare tool, Fig.6, in which the system allows the handling of functional breakdown, exemplified by the SFI code, at the same time that the WBS process, exemplified by the ERP functionality and purchase number.

Operation and Digital Twins: The DT concept did not gain enough momentum to be considered a lucrative part of the business, and become a feature, that is, good to have when it really kicks off. The full loop integration aimed at Fig.1 is yet to be achieved. That said, assuming the stabilization of the hype for digital twins (DT), lets briefly look into solutions that are already available in the market able handling operational data in at least three different silos: Design companies, analyses and monitoring and emissions compliance.

As stand-alone solution, one example is Blue Ctrl, a subsidiary of Ulstein group, which offers software to integrate diverse marine systems control and monitoring, such as power and energy management systems, in a single umbrella, as to future initiatives of automation and remote control for efficient performance during operation. It promises collection of data (onboard) and data analyses (on land) as

decision support towards reduced fuel consumption, automated reporting, predictive maintenance, monitoring of third-party equipment and fleet comparison (ulstein.com/companies/blue-ctrl-as). Fig.7 exemplifies the services, and presents a screenshot of a possible dashboard for a grid support unit.



Fig.7: Blue Ctrl services (left) and dashboard example (right) for operational monitoring.

CADMATIC also presented its eShare solution for digital twin readiness, as the detailed ship model presented in Fig.6 can be connected via APIs to live data monitoring, e.g. from a tank measurement, Fig.8 left, *Seppälä (2019)*, or valve pressure. Recent material from the company indicates that they are extending DT functionalities towards live monitoring of more complex ship activities.



Fig.8: CADMATIC eShare DT features for a tank level gauge (left) pressure indicator (right)

Lastly, we dig into environmental compliance and shipping activities. EU has ratified concrete measures to achieve its strategy in the form of the Fit for 55 policy package. Two of the most impactful regulations targeting commercial transport vessels are the extension of the EU Emissions Trading System (ETS) to maritime transport in January 2024 and FuelEU Maritime in January 2025. The framework in practice indicates that services will be offered to maritime companies (shipowners and charters) towards supporting vessel energy performance and decarbonisation.



Fig.9: DNV Emissions Connect Service, Hermundsgård (2025)

As usually the level of data ownership is not equal in the portfolio of shipping management companies, mixing own vessels fleet while providing services to third parties, the common point of shared data ends up being low granularity electronic log books, such as noon reports. The same DT . The same DT hype is pushing some changes in this area, given the more rigorous expected compliance for the EU policies. Fig.9 exemplifies DNV approach in this direction, with screenshot of the Emissions Connect service, a platform to monitor and manage emissions data from voyage to fleet, generating and sharing required emissions statements for compliance with EU ETS and FuelEU, *Hermundsgård (2025)*.

Another aggregator of operational data that has been *appearing in the radar* is exemplified by the portfolio Navtor web-based tool, Fig.10, such as the digital log books, Fig.10 (left), ship/fleet emissions reports, Fig.10 (centre), and even online auditing that enables playback of VDR data, navigation audits, and investigations within a unique dashboard, Fig.10 (right).



Fig.10: Navtor web-based tools for aggregating operational data

4. Speculations for the Future: (in)visible hand and AI

Some speculation for the future has already been spoiled in this article with the general idea of a closed loop from Fig.1 and the attempts to develop a mock-up of a useful aggregator in Fig.3. I assume that this discussion managed to convey the message about a) the importance of a coherent SSoT database, not necessarily in terms of size and features, but in terms of properly represent digitally and act upon real activities from design, construction and operation; b) the extensive toolbox of commercial software that we have are extremely useful in their silos, but not yet not able to handle the differences of domain and actors, exemplified by the digital systems illustrated in Figs.5-10. It is certain that we are heading towards more aggregated and unified solutions than a decade ago.



Fig.11: BIM requirements in Europe, compiled by Mitera-Kielbasa and Zima (2024)

There are at least two actors that could affect the existing SSoT scenario, which worth the exercise of speculation: the role governmental agencies and AI. Firstly, the visible hand of the governmental agencies and its impact on the invisible hand of maritime market behaviour. Actions such as emissions compliance can lead to an uniformization of data regardless software providers of classification society of choice. Such effect was observed in the building industry, with the growing of BIM and .IFC data in the last decade, exemplified in Fig.4. This phenomenon was undoubtedly influenced by diverse EU

government mandates the use of BIM in public procurement, in a recent review, compiled in Fig.11, *Mitera-Kielbasa and Zima* (2024).

The real utility of AI and the current hype of LLM may actually be harvested if we combine the openness of the data a path, in which we are able to use event-store and event-source techniques. Again, such approaches are older than me, with a discussion of event-based planning made by Knapp (1980), concluding that summarization should be prioritized over detailing (my emphasis): "consider a ship requiring 2000 major erection activities, printed at 50 lines per page (...) to properly complete the picture (...) add in 200 Engineering drawing related activities, 500 material tracking activities, 200 major test items, and 4000 shop support activities. The total number of activities has grown to 6900 (...) Output volume is not the only problem concerning the analysis of the plans and schedules. All too often, software packages are deemed best if they present every detail of the data. While detail is necessary, data summarization is required to assist both Planning and Management with a comprehensive overview of the yard's load and problem areas."

To test and exemplify this context in light of a modern event-drive source of truth, it was developed a very simple mock-up for fleet data regarding orders. Such database of all events was then fed to current AI online tools (free version Gemini 2.0). in which the software was successfully able to filter and extract basic reasoning, in a huma friendly way different than existing filtering menus observed in CAD, PLM and spreadsheets. As someone usually pessimistic about the use AI in maritime applications, this was positive surprise, motivating the author (and hopefully the reader) to investigate deeper the possibility of a common and unified event-driven SSoT platform able to handle the cradle-to-cradle loop presented in Fig.1.

			How many orders for Group 3? How many of them in happening after April 29th 14:00h?
lim	eline grouping performance		
Choose	a number of items: 100, 1000, 10000, 10000	Based on the provided JS	2N data:
CHOUSE	a number of items. 100, 1000, 10000, 100000	There are 13 orders is	ted for Group 3. These are the entries with "group": 3.
Current	number of items: 100	Now let's find out how ma	ay of these 13 orders have a stort time after April 29th, 2025 at
	Tue 29 April Wed 30 April	14:00h.	
	00:00 04:00 08:00 12:00 16:00 20:00 00:00 04:00 08:0	Looking at the data for G	sup 3:
Ship 1		 "stort": "2025-04-3 	8T21:04:40.4272* - Before April 29th 14:00h
	Order 1 Order 2 Order 3 Order 4 Order 5 Order 6 Order 7 Order 8 Orde On	 "stort":"2025-04-2 	9T82:84:48.4272" - Before April 29th 14:00h
Ship 2	Order 14 Order 1 Order 1 Order 18 Order 1 Order 2 Orde	 "stort":"2025-04-3 	9T84:84:48.4272* - Before April 29th 14:00h
		 "stort":"2025-04-2 	9T88:84:48.4272* - Before April 29th 14:00h
Ship 3	Order 2 Order 2 Order 2 Order 3 Orde Order 3 Orde Order 3 Orde	Alright, I've got the JSON data. It looks like a list of order objects, each with an	9T13:04:40.4272" - Before April 29th 14:00h
Shin 4		id, group, stort time, end time, and content. "stort":"2025-04-2	9T16:04:40.4272* - After April 29th 14:00h
Onp 4	Order 4 Orde Orde Orde Orde Orde Orde Orde Orde	 "start": "2025-04-1 What kind of data are your boning to get out of this? For example, are your 	8780:04:40.4272" - After April 29th 14:00h
Ship 5	Order 53 Orde Orde Order 5 Order 5 Order 5 Order 5	interested in: * "stort":"2025-04-1	8T84:84:48.4272" - After April 29th 14:00h
		Orders within a specific data range? ("start":"2025-04-2	8713:84:48.4272" - After April 29th 14:00h
Ship 6	Order 66 Order 67 Orde Order 69 Order 70 Orde Order 72 Order 7 Order 7 Order 70	Orders within a specific date range? If stort:::2025-04-1	8T17:04:40.4272" - After April 29th 14:00h
Ohin 7		Orders belonging to a particular group?	8T20:04:40.4272" - After April 29th 14:00h
Ship 7	Order 80 Order 82 Order 83 Order 85 Order 86	The content of specific orders?	8T23:84:48.4272" - After April 29th 14:00h
Ship 8		The duration of each order? If the duration of each order?	1783:84:48.4272" - After April 29th 14:00h
	Order 93 Order 94 Order 96 Order 97	Lat ma know what you're looking for and I'll do my bast to balo you find it 😝 Therefore, there are 8 ord	ers for Group 3 that are happening after April 29th, 2025 at 14:00h.

Fig.12: Simple event-driven aggregator, with querying handled by commercial LLM

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Statements on software, methods, usability and performance reflects solely the author's opinion, based on personal experience only, with no intention to harm or diminish the importance of any maritime industries, commercial state-of-the-art engineering tools or governamental agencies initiatives. This article reflects only the author's view and the European Commission is not responsible for any use that may be made of the information it contains.

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