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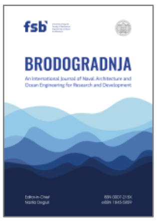

Wind-assisted ship propulsion efficiency prediction: a review of simulation models and decision-support frameworks

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ABSTRACT

Wind-assisted ship propulsion (WASP) technologies are increasingly considered a viable option for reducing fuel consumption and greenhouse gas emissions in maritime transport. Reliable prediction of their performance is essential for supporting design, retrofitting, and operational decisions, yet existing simulation approaches remain fragmented in terms of assumptions, fidelity, validation practices, and practical applicability. This paper presents a comprehensive review of simulation models used to predict the efficiency of WASP systems, including Computational Fluid Dynamics (CFD), empirical and hybrid formulations, experimental validation methods, and Velocity Prediction Programs (VPPs). Beyond the literature review, this work contributes three original elements. First, it proposes a conceptual taxonomy that classifies WASP simulation models according to model fidelity, operational applicability, and level of technological integration. Second, it introduces a structured and weighted decision-support framework to guide model selection across different project phases and data availability levels. Third, it identifies key research gaps related to validation, hull–sail interaction modeling, and operational integration, and outlines directions for future developments. By linking detailed simulation methods with practical engineering requirements, this review provides researchers and practitioners with a clear framework for selecting and applying WASP simulation tools, supporting more robust efficiency predictions and facilitating the effective deployment of wind-assisted propulsion in commercial shipping.

1. Introduction

The maritime sector is undergoing a profound transformation driven by the need to reduce greenhouse gas (GHG) emissions and align with increasingly stringent international regulations. The International Maritime Organization's (IMO) Initial Strategy on the Reduction of GHG Emissions from Ships, adopted at MEPC 73, and its subsequent updates have established progressively ambitious decarbonization targets for the sector [1,2]. The recently approved IMO Net-Zero Framework further introduces mid-term fuel intensity

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limits and market-based measures (MBMs), reinforcing the need for technological and operational solutions capable of delivering measurable emission reductions by 2050 [3]. In this evolving regulatory context, shipowners and designers are required to evaluate a growing portfolio of energy-saving technologies under technical, economic, and operational uncertainty.

Among the available options, wind-assisted ship propulsion (WASP) has re-emerged as a promising solution capable of reducing fuel consumption and emissions by supplementing conventional propulsion systems. Although wind propulsion has historically underpinned maritime transport for centuries, its renewed relevance is driven by contemporary economic pressures, environmental regulations, and advances in materials, automation, and control systems. Several studies indicate that WASP technologies can provide meaningful fuel savings, particularly when deployed along suitable routes and operational profiles, though their large-scale adoption may depend on supportive economic and regulatory frameworks [4,5]. In this sense, WASP occupies a distinctive position within the broader decarbonization landscape, complementing alternative fuels, electrification, and energy-efficiency measures rather than competing with them directly [6–8].

Simulation models play a central role in evaluating the technical and economic viability of wind-assisted propulsion. Over the past decades, numerical and analytical models have been extensively applied to improve ship energy efficiency through measures such as engine optimization and slow steaming [9–11]. More recently, simulation-based assessments have expanded to include alternative fuels, air lubrication systems, and wind propulsion within integrated energy-efficiency strategies [12]. For WASP technologies in particular, simulations are essential to quantify aerodynamic performance, assess hull–sail interactions, and estimate fuel savings under variable environmental conditions. The inherent dependency of wind-assisted propulsion on weather variability further amplifies the importance of modeling tools capable of incorporating route-specific wind and sea-state data, as demonstrated by weather-routing approaches [13].

Beyond technical performance, simulation models increasingly support broader operational and economic analyses. Integrated frameworks combining propulsion modeling with voyage economics enable shipowners to evaluate payback periods, operational savings, and regulatory compliance scenarios [14]. Such capabilities are especially relevant for WASP systems, where benefits depend not only on device efficiency but also on route selection, operational strategies, and interaction with conventional propulsion systems. Technologies such as rotor sails, wing sails, and kite systems have been investigated using a wide range of modeling approaches, from high-fidelity Computational Fluid Dynamics (CFD) to simplified empirical formulations [15]. However, integrating these systems into existing vessels—particularly in retrofit scenarios—introduces additional challenges related to deck layout, control strategies, crew training, and port operations [16,17].

Looking ahead, wind-assisted propulsion is expected to contribute meaningfully to the IMO's long-term decarbonization objectives. Updated targets adopted at MEPC 80 aim to reduce sector-wide emissions by at least 30 % by 2030 (striving for 40 %) and 70 % by 2040 (striving for 80 %) relative to 2008 levels [2]. Achieving these targets will likely require a portfolio of complementary technologies, among which WASP systems—particularly rotor sails, wing sails, and kite-based solutions—are increasingly recognized for their adaptability across ship types and operational profiles [18–22] . The effectiveness of these technologies, however, remains strongly dependent on the quality and applicability of the simulation models used to evaluate them.

Recent studies have further reinforced the growing relevance of wind-assisted propulsion technologies in the context of maritime decarbonization. For instance, recent assessments have highlighted their potential to significantly reduce fuel consumption and emissions under realistic operational conditions, as well as their increasing feasibility from both technical and economic perspectives [23,24]. In parallel, advances in numerical modeling and system-level analyses have improved the understanding of performance and integration challenges associated with these technologies [25], while comprehensive reviews have consolidated their role within broader decarbonization strategies for the shipping sector [26]. These developments further support the need for structured approaches to classify and compare simulation models, as proposed in this work. Despite a rapidly growing body of literature, the modeling landscape for wind-assisted ship propulsion (WASP) remains fragmented. Existing studies employ a wide range of methodologies, including Computational Fluid Dynamics (CFD), empirical and semi-empirical formulations, experimental validation, Velocity Prediction Programs (VPPs), and optimization-based workflows. These approaches differ substantially in terms of underlying assumptions, model fidelity, computational cost, validation practices, and suitability for design, evaluation, or operational decision-making. As a result, direct comparison between modeling approaches is often difficult, and model selection is frequently performed on an ad hoc basis or driven by computational convenience rather than structured engineering criteria. This fragmentation limits the practical usability of simulation results for ship designers, operators, and regulators seeking robust and transparent efficiency predictions.

Against this background, the objective of this paper is to provide a comprehensive and structured review of simulation models used to predict the efficiency of wind-assisted ship propulsion systems. Beyond summarizing existing methodologies, this review introduces three original contributions: (i) a conceptual taxonomy that classifies WASP simulation models according to fidelity, operational applicability, and level of integration; (ii) a structured and weighted decision-support framework to guide model selection across different project phases; and (iii) a critical discussion of current limitations and future research directions, with emphasis on validation, operational integration, and emerging data-driven approaches. By bridging detailed simulation methods with practical engineering needs, this work aims to support more robust efficiency predictions and facilitate the effective deployment of wind-assisted propulsion in commercial shipping.

2. Literature Analysis

2.1 Historical Context

Sailing ships have shaped maritime transport for centuries, as extensively documented by classic works such as Parry [26], Chatterton [27], and Holmes [28]. From the caravels of the Age of Discovery to the fast tea clippers of the 19th century, the history of sail reveals a long trajectory of innovation that only began to decline with the widespread adoption of steam engines. Multiple authors show the resilience of the sailing ships in facing the steam revolution. A great part of the advantages of the sailing ships of this later time was due to the high efficiency of the hulls and the specific routes they took, privileging great circles in long voyages (where the wind was abundant and favourable), such as the Australian coal trade [29] and the immigrants routes. This latter being a function of both uncertainties from the immigrant passenger market and the steam technology itself [30]. After the decline of the Age of Sail, in the mid-19th century, only a few experiments with sail-like technology can be identified applied in merchant vessels. Some iconic examples include the Flettner Rotors, introduced in the 1920s [31], and the Rigid Wing Sails, installed in a prototype vessel in the early 1960s [32] and in Japan in the late 1970s, as noted by Ouchi et al. [33]. Kites, on the other hand, are modern interpretations of the wing sail theory, applied in a highly dynamic environment, and thus only more recently explored in the literature [34]. Numerous studies have explored the potential of WASP technologies, ranging from Flettner rotors to rigid sails. Simulation models have been instrumental in quantifying the efficiency of these systems. By the end of the 19th century, the steam technology was successful in surpassing the sail, but the efficiency of such a resilient technology persists and shows significant signs of recovery in a globalized and low-emission maritime sector at the dawn of the 21st century.

2.2 Methodology

In terms of historical context, this work focuses on more recent and contemporary works on the subject. Methodologically, the research in this work aims to cover a wide range of studies regarding modern WASP technology. More specifically, this work aims to review the ways researchers employ simulation to measure or compare scenarios in which wind-assisted technology is an option for propulsive thrust on ships. To structure the subsections by simulation type, we applied explicit inclusion/exclusion criteria. We included studies that (i) implemented a formal simulation of a WASP device or WASP–ship system (e.g., CFD/RANS, empirical, hybrid, VPP, routing/optimization); (ii) disclosed sufficient methodological detail (governing equations, model structure/parameterization, or algorithmic description) to enable reproducibility; (iii) reported validation or benchmarking (wind tunnel, towing tank, sea trials, or cross-validation); and (iv) provided quantitative outputs convertible to comparable metrics (e.g., CL, CD, thrust/$CX–CY$, fuel/power savings, spin ratio and AWA envelopes). We prioritized works from 2015-2024 and retained pre-2015 seminal papers when foundational to a model class.

For classification by simulation type, we adopt the following working definitions.

1. **CFD (RANS):** physics-based solvers of the Navier–Stokes equations (typically steady or unsteady RANS with a specified turbulence model), producing high-fidelity aero/hydrodynamic coefficients (C_L, C_D) and force/thrust predictions at device or ship scale.

2. **Empirical methods:** algebraic/curve-fit formulations derived from experiments or sea trials; fast to evaluate, low parameterization, limited generalization.

3. **Hybrid empirical–experimental models:** semi-empirical approaches calibrated/validated with wind tunnel or tank data; moderate fidelity and cost, suited for parametric studies.

4. **VPPs and numerically validated methods:** system-level performance models that couple aerodynamic polars (from experiments or RANS) with hydrostatics/resistance and balance, yielding thrust/power and operating envelopes; "numerically validated" indicates polars/maps derived from or cross-checked against CFD.

Papers were assigned to the category that provided their primary performance-prediction engine; when methods were equally balanced, we classified them as hybrid and noted cross-references. Studies without an explicit simulation component were excluded from these subsections.

The database used for this research was the compilation of several sources of technical articles, not limited to the naval architecture area, but also covering economics, mechanical engineering and operational research. The literature survey drew primarily from Scopus-indexed journals published by Elsevier, Springer, Wiley, and MDPI, yielding more than 2960 publications related to wind-assisted ship propulsion, of which over 2300 involve the development or application of simulation-based approaches. Besides, some keywords were applied during the filtering for more focused works. The method PRISMA (short for Preferred Reporting Items for Systematic reviews and Meta-Analyses [35]) were employed for organizing and screening the references analyzed and cited in this paper. Figure 1 illustrates the application of the method from the perspective of the first research database, encompassing the last number of articles referenced directly and in-depth in this paper.

The funnel through which the papers were filtered began with the stage of removal of duplicates, which were in the order of 250 articles that were scattered across different sources. Afterwards, the papers were filtered and organized according to relevance by the title and its abstract, using mostly significant keywords.

The most significant keywords (that resulted in more effective results in aligned works) were "Numerical Simulation Tools", "Computational Fluid Dynamics (CFD)", "Four Degrees of Freedom (4 DOF) Models", "Monte Carlo Simulations", "Wingsail Performance", "Wind-Ship Turbine", always associated with WASP (Wind Assisted Ship Propulsion) systems. This filter resulted in a reduced universe of circa 650 papers to be analyzed in more depth. Finally, 485 articles were excluded due to various reasons, primarily because of the specificity required for this comprehensive review. From the initial articles sample repository, 164 papers were discussed and are included in the bibliography, including methodological references and ship location references. The graphics in Figure 2 illustrate the intensity and growth of research efforts in this area in the last decade, growing approximately exponentially and requiring further comprehensive reviews to update the sector's scientific status, in particular, on how technology is being evaluated.

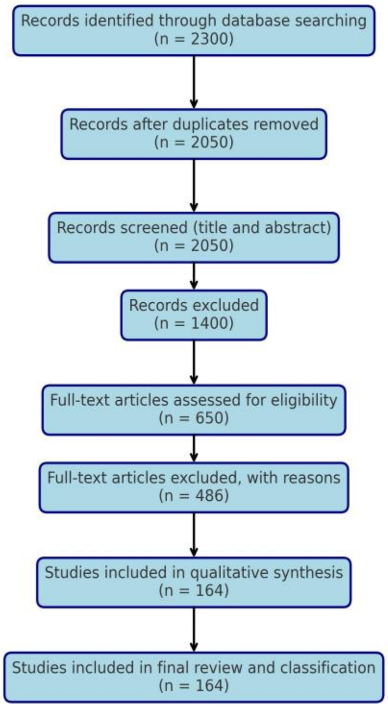
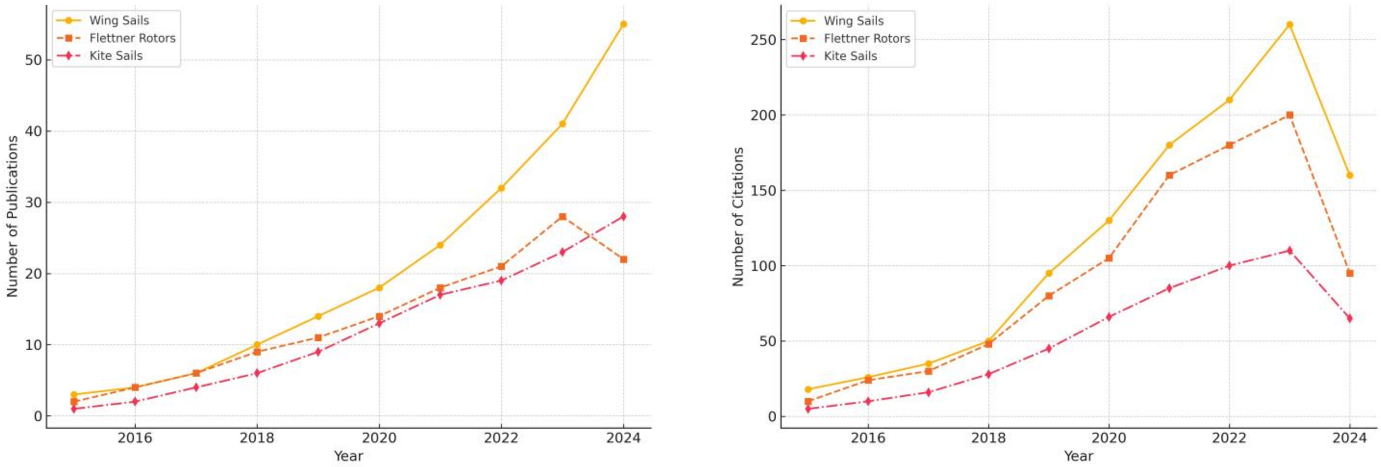


Fig. 1 PRISMA flowchart indicating the number of papers reviewed



(a) (b)

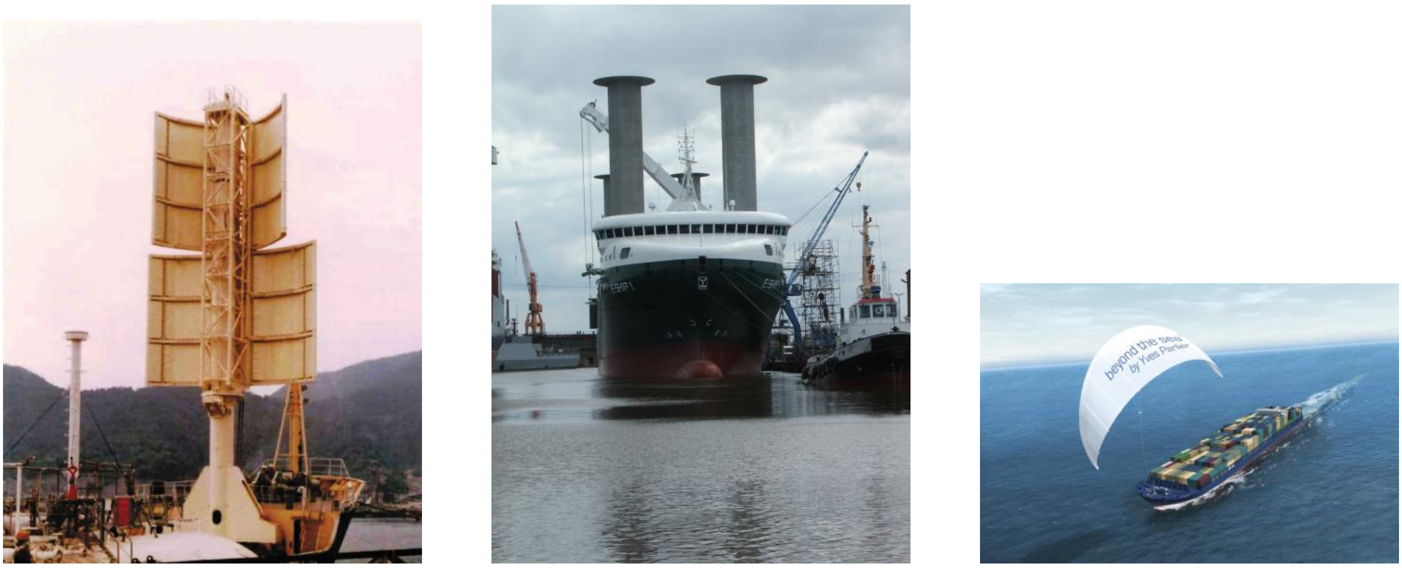
Fig. 2 Annual growth of WASP: (a) publications and (b) citations, based on data from app.dimensions.ai for the period 2015-2024

2.3 Types of WASP

2.4 Wing Sails

Wing sails, also known as rigid sails, generate thrust from the wind passing through an airfoil mounted on a mast. The mast can be rigid, flexible, or hybrid. This configuration creates lift in a direction perpendicular to the sail panel, contributing to the ship's overall thrust. The sailing physics and dynamics of the sailing (wing) theory are very well documented throughout the years and substantially tested in small yachts with canvas sails, despite the differences in hull dynamics when compared to larger merchant vessels. Trials with

Wing Sails have been common since the late 1970s and 1980s, and ships with rigid sails installed above the deck are still the focus of many developers [34]. Figure 3 illustrates real-world applications of some of the most promising WASP technologies. Figure 3a shows one of the Rigid Sails prototypes that was installed in a commercial Japanese ship. Atkinson et al. [36] presents a comprehensible SWOT analysis (short for Strengths, Weaknesses, Opportunities and Threats matrix) for this particular type of sail technology, which may also be representative for the other types of WASP as well.



(a) (b) (c)

Fig. 3 Real-world applications of Wind-Assisted Ship Propulsion (WASP) technologies: (a) Shin Aitoku Maru equipped with rigid wing sails [36] (CC BY 4.0); (b) E-Ship 1 with rotor sails (CC BY-SA 3.0); (c) container ship towed by a kite sail from Beyond the Sea[37] (CC BY-SA 4.0)

As stated by Viola et al. [38], the dynamics of the hull with sails installed as auxiliary or main propulsion should differ from the approach with smaller and lighter vessels due to the behavior of the hull size in the equation of motion. The aerodynamics of airfoils are illustrated in Figure 4 for the example of Soft Canvas (thin airfoils), and are also applicable to Wing Sails. Having the hull a much larger inertial contribution to the rolling motion than sailing yachts (especially regarding the smaller heel angles large ships assume when under sail), it is possible to decouple the heeling movement from the equation of motion, for example. It is crucial to note that, in terms of degree of freedom, the yaw angle is much more significant in larger vessels than the heeling angle, precisely due to the different sensitiveness of such a type of hull when compared to traditional smaller yachts, more widely studied through Velocity Prediction Programs (VPPs) analysis [39,40]. Moreover, according to the cited authors, the installation of Wing Sails may even contribute to the reduction of the roll motion in waves, which may reinforce that this degree of freedom can be neglected in most VPPs, in favor of the calculation of the yaw motion [41].

Another essential insight regarding Wing Sails - and potentially every WASP system - is that reducing the thrust from engines may increase the effectiveness of the Wing Sails, once the engine consumption is lowered and the thrust component from the sails is proportionally augmented simultaneously, as noted by Viola et al. [38]. All in all, it is possible to deduce that the application of Wing Sails remains one of the key competing solutions in the decarbonization of maritime transport among WASP types [39–41]. It can be seen from Table 3 that Wing Sails occupy a significant space in recent WASP installations, possibly due to their inherent system of thrust and similarity to the known sails of the Age of Sail.

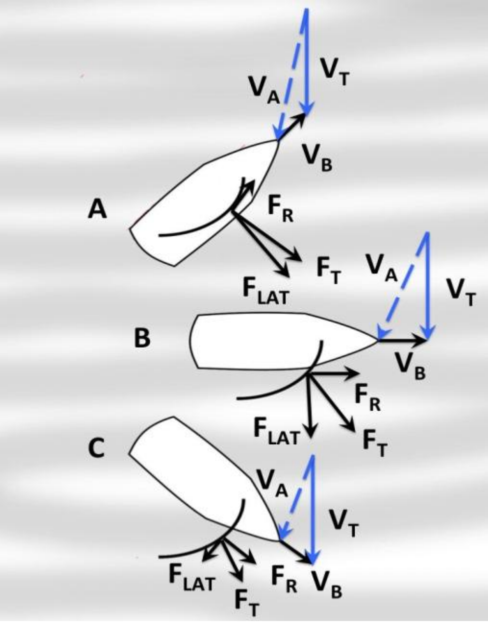


Fig. 4 "Forces on sails for three points of sail". Author: Hopson Road. CC BY-SA 4.0. A, B and C are different ship positions according to the wind direction. V_T is the true wind speed, V_A is the apparent wind speed and V_B the true ship speed. F_R, F_T and F_{LAT} are, respectively, the thrust force, the total aerodynamic force and the lateral force

2.5 Rotor Sails

Rotor sails use the Magnus effect, generating lift by actively rotating a cylinder mounted on the vessel's deck. Figure 5 shows a cross-sectional view of the device, schematically illustrating the flow around the rotating cylinder, with the upper arrow indicating the direction of the resulting lift due to the pressure difference induced by rotation. The aerodynamic performance of the rotor is typically described through lift and drag coefficients, which are strongly dependent on the spin ratio (SR), defined as the ratio between the rotor peripheral speed and the apparent wind speed. As SR increases, the lift coefficient generally rises up to a saturation region, while the drag coefficient also increases due to viscous effects and flow asymmetry. Consequently, the resulting aerodynamic force depends on the SR-dependent balance between lift and drag, affecting both the magnitude and direction of the generated thrust. In addition to Spin Ratio (SR) and Aspect Ratio (AR), the End Plate diameter ratio (De/D) also plays an important role in rotor sail aerodynamic performance. Studies have shown that larger end plates can reduce tip vortex effects and improve lift generation, directly influencing the lift-to-drag ratio and the resulting propulsive efficiency of the device [42–44]. Figure 5 shows a cross-sectional cut of one of these devices, highlighting schematically the flow past the turning cylinder with the top arrow pointing in the direction of the lift created by the difference in pressure caused by the rotation. An example can be seen installed over the deck of E-Ship 1 [45], as shown in Figure 3b. Several studies review such technology, stating the advances and proving the effectiveness of the installation in terms of Return on Investment (ROI) predictions, such as Ammar and Seddiek [45] and Searcy [46], in different contexts. Angelini et al. [47] developed a six degrees of freedom (6 DOF) model for a vessel equipped with two Flettner rotors to assess the performance of this common configuration of wind-assisted sails. The study incorporates weather routing and sea state modeling, offering a comprehensive and realistic approach to real-world applications. This article provides insights into how the behavior of Flettner Rotors integrates with the ship and its deck disposition, altering the flow and consequently, the efficiency of the set of sails. Despite not being taken into account in its experiments, the effect caused by the interference of obstacles such as deck equipment, superstructure, and even other rotors when in the vicinity of the Flettner Rotors and its efficiency in creating lift, was considered important. Other studies place the Flettner Rotors in different routes and evaluate analytically the performance of the set of sails [48–50], depicting the valuable contribution of such WASP technology in the assessed routes. Beyond the cited studies, it is also easy to see how this type of WASP is present in the increasing WASP merchant fleet, with proven examples of vessels sailing commercially (and more efficiently) with the system aboard, as can be seen in Table 2.

The performance of rotor sail plans as auxiliary propulsion - not energy generation - is analyzed by gathering performance prediction parameters from several works in varying types of ships and sizes [51–53]. It is the technology that gets more benefits from available real-world data among the three types of technology described here. Commercial manufacturers are already delivering the technology not as prototypes, but as products tailor-made for each type of ship. Manufacturers map the technical parameters of efficiency to provide a performance fit for every kind of ship regarding its characteristics (hull form, deck space, type, etc) and particulars of the route and operation of the vessel [51]. It is now even possible to depict an average of annual savings using a standard commercial Rotor Sail directly from the website of the sail manufacturer [52], showing how the simulations using this type of technology may be more advanced, in terms of accumulated experience and confidence in the technology, than the other types of WASP.

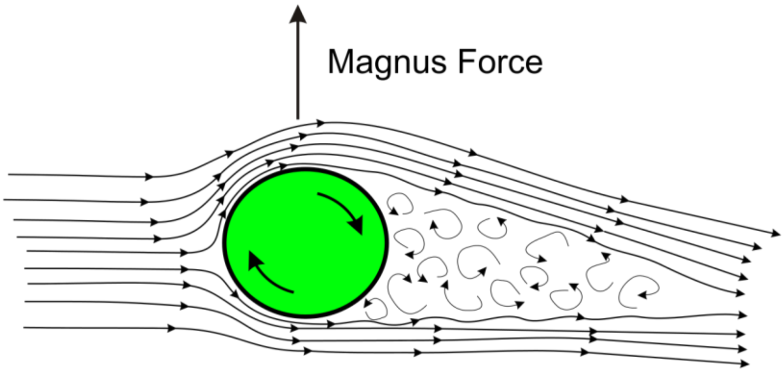


Fig. 5 Magnus effect with a turbulent wake. Author: Chetvorno. CC BY-SA 3.0

Kwon et al. [43] developed a CFD model to analyze the aerodynamic performance of rotors and provided important insights with consistent and validated results for a specific target parametric rotor geometry. For different Spin Ratios, defined as the ratio between the rotor’s rotational speed and the wind’s tangential speed, the results show clear trends in both lift and drag coefficients (as shown in Table 7). The table is not only a valuable reference for future studies on Spin Ratios but also provides a standardized basis that can be extrapolated to different routes and operational characteristics. Its inclusion is therefore essential, as it will support discussion in the following sections on the outcomes of the various simulation types. Another author [42] also iterated different Spin Ratios and the distances between the devices on deck, providing insights on how the distribution of sails and the optimization of the operation of these sails may impact the final emission outcome.

2.6 Kite Sails

From the 1980s, the use of elevated sails as auxiliary propulsion started to be experimented with in scale workboats. Then, the idea of using kites for commercial shipping propulsion was far from reality [35]; however, it proved to be an alternative and a consistent option among WASP systems. Elevated or Kite Sails apply the principle of flying a kite linked to the ship through lines attached to the vessel’s deck, capturing the wind flow several meters above the sea surface. It does not require any mast, but rather a base where the lines attach to the deck. Commercial vessels have already sailed with this technology and are being further developed [53]. Despite the author of the former work states conclusively that this system would be more volatile than the Rotor Flettner in a direct comparison, it occupies less space on deck when in operation and should be considered as a competitor technology among WASP systems, depending on the route, size of the ship and favorable economics of each system, being the Kite Sails possibly more suitable for smaller vessels in shorter voyages, as this type of ship will have less deck space and little autonomy (or rather coastal missions).

The principle of operation relies heavily on automation to keep the kite sail flying in the best trajectory, as shown in Figure 3c - if considering a dynamic sail system, but each manufacturer protects the fine-tuning of the code as an industry asset. The physics behind the flight of the kite, though, relies upon the same lift and drag principle presented previously for both rotor and wing sails, but specially in Figure 4 with the difference that it happens in a moving (flying) kite that operates in a so-called wind window, entangled by the boundaries where the kite experiences the best composition of aerodynamic forces.

In summary, technologies are different in terms of their limitations and applications, but the principles that govern their function - to thrust the ship and reduce engine thrust - are the same. This work aims to elaborate on the applications of simulation across those different devices, so compilation is mandatory to summarize the application of certain simulation techniques in each case. It is imperative to observe that, despite this comparison, simulations may not always be adherent to the same technologies all the time, and the objectives of each study may govern the decision for a specific method or another. Table 1 presents a compilation of the technologies cited in this work, with a primary focus on simulating each technology.

Table 1 Summary of WASP Technologies with Cited References

Technology	Operational Principle	Real-World Applicability
Wing Sails	Airfoil aerodynamics	Trials since the 70s[1]
Rotor Sails	Magnus effect	Commercially available[2]
Kite Sails	Kite flight	First experiments in the 80s[3]

2.7 Applications and Emission Reductions

Several types of carbon and fuel-saving technologies are currently being evaluated with a wide range of approaches. Some of the most important initiatives are summarized in Xing et al. [68], which includes more ecological drip fuels, such as LNG, Hydrogen, and Ammonia, but also alternative sources of power, including electricity from photovoltaic panels and even wind power. However, the discussion tends towards a neutral and indiscernible solution that involves multiple technologies but does not evaluate the single prospect of wind power alone in the context of a comeback to the age of sail. It may be right to state that drip fuels will face increasing barriers in both regulations and infrastructure [68], limitations that the sailing technology will probably not experience. Knowing that no single solution can achieve net zero emissions alone, reinforced by several authors, including Xing et al. [68], Al-Enazi et al. [69] and Julià et al. [70], wind-assisted technologies show a sort of trade-off in this decarbonization scenario, being adopted in the most different contexts and being highly adaptive in various stages of design and operation of the vessels. Even carbon-free shipping considers utilizing wind assistance as an essential source of thrust power, according to Julià et al. [70]. Considering that carbon-free shipping includes all the vessels that have zero emissions during operation, having the sails as a thruster endorses the capability of such technology to drive again, at least in part, the global merchant fleet. In the case studies addressed here, a fixed type of ship on an average route was simulated empirically by the application of VPP, highlighting how the ship routes have to adapt along with the shipping times to allow pure carbon-free vessels to operate. Further studies on different sail-technology configurations for various types of vessels, ranging in size and capacity, should also be simulated to expand the conclusions of this present work.

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[1] Key references: [29,30,33,35–37,54].

[2] Key references: [18,28,41,43–45,50,53–63]

[3] Key references: [42,64–67].

In the last few decades, however, there has been an increasing interest in those major types of WASP technology, not entirely replacing diesel engines, but providing as much thrust as possible, with some important contributions from the industry already entering the commercial phase and being installed aboard real-world fleets. An example of how widespread the technology is, Chou et al. [17], Petković et al. [19], Wang et al. [18], or Comer et al. [71] summarize both real-world and simulated applications of wind-assisted technologies.

New ships are being built or receiving WASP technology each year, as shown in Table 2 for active Flettner Rotor Vessels, Table 3 for vessels with Rigid Sail installed, Table 4 for the only one known active kite installed in a vessel (for tests), Table 5 for vessels that adopted suction wings (which are here considered as an active Wing Sail, once benefit from similar mechanics), and Table 6 for Soft Sail type vessels, including some adapted to cargo or passengers. The effort of compiling such data has already been addressed previously, including the expected fuel savings [18]; hence, this revision aims to illustrate the most recent WASP ships and provide an assessment of the technology's potential. All the tables could already be expanded with the most recent announcements from different shipowners worldwide. Still, those here included are a glimpse of the fast spreading of technology, thanks to the simulation methods. These non-exhaustive lists aim, above all, to present the urgency for the in-depth study of wind-assistance technology, which should follow the increasing demand and the different applications it may have around the maritime sector. It should be noted that the various ship types exhibit the most diverse technology parameters, which, when combined, reveal the immense universe of possible tangible and potentially practical ways to apply WASP technology. The parameters presented in the tables are the Quantity of sails installed and the Dimensions, in meters (height x diameter for Rotor Sails, height x width for Wing Sails and the total sail or kite area for both Canvas and Kite Sails), whenever the data is available. If data is not available, the dimensions are shortened. An example is that some data will show only the height of sails in the case of Wing and Suction sails.

Tables 2, 3, 4, 5 and 6 are a glimpse of the over 45 mapped vessels already sailing with wind assistance in the world fleet, according to Bureau Veritas [72], IWSA [73] and Consulting [72]. The tables consider only vessels with a deadweight (DWT) above 500 (excluding some relevant initiatives, such as Grain de Sail I and II vessels [74]). Besides, yachts have been neglected in this study. This perspective, according to the cited studies, is to have between 30 to 40 % of the world fleet with some WASP technology installed aboard until 2030, which will require more robust simulation technology to predict the behavior of the sails, and their operation and integration with the ship hull in a broader sense and different phases of the projects. Simulation models using CFD are key to the development of such availability. It precedes real-world tests and is becoming increasingly accurate in terms of computational capacity, model refinement, and optimization in the form of a sail-hull system, as described by Peri et al. [44], producing confident results, able to be applied in real-world conditions in operations under real weather on route. An important limitation that has to be recognized is the validation requirement of such models. Yet essential, the validation of a conceptual technology typically requires expensive experimental data, acquired in test basins and wind tunnels. Once obtained, this data is a valuable resource to be added to the research, as shown by Kwon et al. [43]. On the other hand, empirical evaluations and optimization models are being developed, such as Guzelbulut and Suzuki [75], that created an optimization tool to estimate fuel savings for a tanker ship. However, as pointed out by Lindstad et al. [52], even considering consistent fuel savings confirmed through numerical simulations, it is still necessary to have governmental financial incentives to make the technology economically advantageous, even for cases such as the Supramax ship class with five Rotor Sails installed. Simulations may aid in pushing the technical boundaries of the technology, but the economics still have market links that need to be resolved, as discussed by Shi [5]. This latter text shows how the IMO has been seeking an MBM, like a stable levy over emissions, since the Paris Agreement in 2015, ten years ago. In 2025, however, the European Community started to operate a similar scheme, charging for emissions for the first time in maritime history [76].

Table 2 WASP Installations – Rotor sails

Ship Name	**Ship Type**	**DWT**	**Qtd x Dimens.**	**Refs**
AFROS[3]	Bulk carrier	63,223 t	4 x 16 m	[77,78]
ALCYONE[2]	Tanker	50,000 t	2 x 35 x 5 m	[77,79,80]
ANNIKA BRAREN[3]	General Cargo	5,023 t	1 x 18 x 3 m	[77,81,82]
BERGE NEBLINA[4]	Bulk carrier	392,099 t	4 x 35 x 5 m	[77,83]
BERLIN[5]	Passenger	4,835 t	1 x 30 m	[77,84]
OSTRO[6]	Chemical Tanker	18,500 t	2 x 4 m	[77,85]
BURAN[7]	Chemical Tanker	18,500 t	2 x 4 m	[77,85]
CAMELLIA DREAM[8]	Bulk Carrier	207,317 t	2 x 24 x 4 m	[77,86]
CEM COMMANDER[9]	Cement Carrier	5,876 t	2 x 24 x 4 m	[77,87]
CHANG HANG SHENG HAI[10]	Bulk Carrier	45,542 t	4 x 24 x 3 m	[77,88]
CHINOOK OLDENDORF[11]	Bulk Carrier	100,449 t	3 x 24 m	[77,89]
COPENHAGEN[12]	Passenger	5,000 t	1 x 30 x 5 m	[77,84]
DELPHINE	RoRo	27,687 t	1 x 35 m	[73,77,90,91]
E-SHIP 1[13]	General Cargo	10,020 t	4 x 27 m	[42,77]
ESTRADEN[14]	RoRo	9,740 t	2 x 18 m	[77,92]
GOLDY SEVEN[15]	General Cargo	4,250 t	1 x 18 m	[60,77]
HAI YANG SHI YOU 226[16]	Heavy Lift Vessel	12,752 t	2 x 18 x 4 m	[77,93]
JUN BAI 56[17]	Oil Tanker	4,940 t	2 x 16 x 4 m	[73,77,94]
KORYU[18]	Bulk Carrier	53,762 t	1 x 35 x 5 m	[77,95]
MAERSK PELICAN[19]	Tanker	109,647 t	2 x 30 m	[52,77]
NORTHERN PATHFINDER[20]	Gas Carrier	8,000 t	1 x 28 m	[73,77,96]
NORTHERN PIONEER[21]	Gas Carrier	8,000 t	1 x 28 m	[73,77,96]

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[3] Movable rotor sails, estimated ~20% savings [68]; [2] 4 M€ investment, 8% fuel saved planned; [3] Retroffited with a fixed rotor; [4] Anemoi Rotor Sails; [5] Fixed rotor sail; [6] Second vessel of the 34-unit programme; [7] First vessel of the programme; [8] Chartered by Vale; [9] Norsepower Rotor Sail™, to be delivered; [10] No position on VesselFinder; [11] Ex "DIETRICH OLDENDORF"; [12] Fixed rotor sails; [13] Fixed rotor sails; [14] Ex Fehn Pollux / Adria Kvarner, likely in cold lay-up; [15] Dealfeng Rotor Sails; [16] Dealfeng Rotor Sails, partner HAIYUE; [17] Confirmed savings of 8.2%; [18] Built at DSIC, operator K-Line; [19] Same builder/operator as 18; [20] Hinged rotor sails; [21] Chartered by Vale, hinged sails; [22] Rotors by Anemoi; [23] Ship manager: Zeaborn / Charterer: Cargill; [24] Norsepower Rotor Sail™.

OCEANUS AURORA[22]	Gas Carrier	62,500 t	2 x 20 m	[77,97]
SC CONNECTOR[23]	RoRo	8,843 t	2 x 35 m	[59,77]
SEA ZHOUSHAN[24]	Bulk Carrier	324,268 t	5 x 24 m	[77,98]
SOHAR MAX[25]	General Cargo	400,315 t	5 x 35 x 5 m	[77,86,99]
TR LADY[26]	Bulk Carrier	82,048 t	3 x 24 m	[73,77,100]
YODOHIME[27]	Bulk Carrier	85,022 t	2 x 24 x 4 m	[77,101]

Table 3 WASP Installations – Rigid wing sails

Ship Name	**Ship Type**	**DWT**	**Qtd x Dimens.**	**Refs**
BERGE OLYMPUS[4]	Bulk carrier	211,153 t	4 x 37.5 x 20 m	[77,103]
GNV BRIDGE[2]	Passenger	8,632 t	1 x 12 m	[77,104]
GREEN WINDS[3]	Bulk Carrier	58,000 t	39.5 x 11.4 m	[77,105]
KUROTAKISAN MARU III	Bulk Carrier	89,999 t	1 x 48 m	[77,106]
NEW ADEN[4]	Tanker	306,474 t	4 x 40 m	[77,107]
NEW VITALITY	Tanker	306,752 t	2 x 32 m	[77,102,108]
PACIFIC GREBE[5]	Nuclear Fuel Carrier	4,902 t	1 x 20 m	[73,77,109]
PYXIS OCEAN[6]	Bulk Carrier	80,962 t	2 x 37.5 m	[77,110]
SHOFU MARU[7]	Bulk carrier	100,422 t	1 x 48 m	[77,111]

Table 4 WASP Installations – Kite Sail

Ship Name	**Ship Type**	**DWT**	**Qty x Dimens.**	**Refs**
CAP KERSAINT[5]	Fishing Vessel	942 t	—	[77,110]
FORBIN[2]	LPG Tanker	5,072 t	500 m^2	[77,113]
JASON[3]	AHTS	2,100 t	50 m^2	[77,114]

Table 5 WASP Installations – Suction wing

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[4] Four retractable WindWings™ by BAR Technologies; [2] Wing Sail Module (WSM) by Naos Design; [3] Second ship to receive Wind Challenger Hard Sail; [4] Four rigid sails, ca. 9.8 % fuel economy [104]; [5] FastRig™ retractable sails; [6] Similar configuration to BERGE OLYMPUS; [7] Telescopic height-adjustable sail; up to 17 % fuel reduction [102].

[5] To be installed 2025 Q4; [2] Installed in 2025 Q1; [3] In tests [112].

Ship Name	**Ship Type**	**DWT**	**Qty x Dimens.**	**Refs**
AMADEUS SAFFIER[1]	General Cargo	3,600 t	2 x 16 m	[73,77,115]
ANKIE[2]	General Cargo	3,638 t	2 x 13 m	[77,116]
ANNA[3]	General Cargo	5,097 t	2 x 16 m	[77,117]
ATLANTIC ORCHARD[4]	Fruit Juice Tanker	24,584 t	4 x 26 m	[77,118]
BOW OLYMPUS[5]	Tanker	49,042 t	4 x 22 x 4.5 m	[77,119]
CHEMICAL CHALLENGER	Chemical Tanker	16,111 t	4 x 16 m	[77,120]
CORAL PATULA[6]	LPG Tanker	8,571 t	—	[77,121]
EEMS TRAVELER[7]	General Cargo	2,903 t	2 x 17 m	[77,122]
FRISIAN SEA[8]	General Cargo	6,477 t	2 x 11 m	[77,123]
JUMBO JUBILEE[9]	Heavy Load Carrier	13,017 t	2 x 16 m	[73,77,124]
KALAMAZOO[10]	Container Ship	12,593 t	2 x 12 m	[73,77,125]
MARFRET NIOLON[11]	RoRo	5,282 t	2 x 12 m	[77,126]
NBA MAGRITTE[12]	Bulk Carrier	82,099 t	2 x 10 m	[73,77,127]
ODDA MARIE	General Cargo	5,000 t	2 x 12 m	[73,77,128]
PACIFIC SENTINEL[13]	Chemical/Oil Products Tanker	50,332 t	3 x 22 m	[77,129]
PRIMA VERDE[14]	General Cargo	17,500 t	2 x 12 m	[77,130]
RIJNVLIET	General Cargo	3,800 t	—	[77,131]
SUNNANVIK[15]	Cement Carrier	9,157 t	2 x 16 m	[77,132]
VILLE DE BORDEAUX[16]	RoRo	5,200 t	3 x 22 m	[77,133]
WAALVLIET	General Cargo	3,800 t	—	[77,131]
WILSON EYDE	General Cargo	4,340 t	3 x 22 m	[77,134]
VECTIS PROGRESS[17]	General Cargo	11,183 t	—	[77,135]

[1] 2 × Ventofoil; [2] Retrofit bow-mounted sails; [3] To be installed in 2025; [4] One of the largest installations to date; [5] Near zero-emission vessel (biofuel B100); [6] First suction-wing install in a chemical tanker (Economwind); [7] Stern installation of two

suction sails; [8] Two retrofit Flatrack suction sails; [9] 2 × Ventofoil; [10] Economwind wings in 40’ container, “up to 400 kW power” [125]; [11] Hinged/containerized suction wings (update Q1 2025); [12] Chartered by Cargill, VentoFoil systems; [13] eSAILs®; [14] First ship with green-steel hull + wind propulsion [130]; [15] First cargo ship with sails in Great Lakes [132]; [16] eSAILs® installation; [17] 1 × AirWing®20 from GT Wings.

Table 6 WASP Installations – Soft Sails

Ship Name	Ship Type	DWT	Qty x Dimens.	Refs
ANEMOS	General Cargo	2,050 t	2 masts, 2200 m^2	[77,136]
ARTEMIS[1]	General Cargo	2,050 t	2 masts, 2200 m^2	[77,137]
CANOPEE[2]	RoRo	5,491 t	4 x 30 m	[73,77,138]
CLUB MED 2	Passenger	1,674 t	5 masts, 2400 m^2	[73,77]
GOLDEN HORIZON[3]	Passenger	2,120 t	5 masts, 6345 m^2	[77,139]
LE PONANT[4]	Passenger	1,071 t	3 masts, 300 m^2	[77,140]
ROYAL CLIPPER	Passenger	1,000 t	5 masts, 5202 m^2	[77,141]
SEA CLOUD	Passenger	788 t	4 masts, 2972 m^2	[77,142]
SEA CLOUD II	Passenger	780 t	3 masts, 2694 m^2	[77,142]
SEA CLOUD SPIRIT	Passenger	904 t	3 masts, 4097 m^2	[77,142]
WIND SPIRIT	Passenger	846 t	3 masts, 2200 m^2	[77,143]
WIND STAR	Passenger	922 t	4 masts, 2200 m^2	[77,144]
WIND SURF	Passenger	1,654 t	5 masts, 2600 m^2	[77,145]

[1] Anemos’s sister ship; [2] 4 × Oceanwings, potential savings 15-40 % [77], confirmed at sea[146]; [3] Replica of a 1913 barque; [4] SolidSail tested temporarily on this vessel [77].

3. Simulation Models and Techniques

A variety of simulation techniques have been applied to assess the performance of wind-assisted ship propulsion systems. These approaches range from highly detailed numerical models to simplified empirical formulations, each with specific advantages and limitations. In the following subsections, the main categories of models are presented: first, Computational Fluid Dynamics (CFD); then, empirical and hybrid models, including purely empirical formulations, semi-empirical approaches supported by experimental data, and Velocity Prediction Programs (VPPs) coupled with numerical validation. This structure provides a progressive view, from high fidelity but computationally costly methods to simplified approaches that can be more easily applied in operational contexts.

3.1 Computational Fluid Dynamics (CFD)

CFD models are widely used to simulate the interaction between wind and sail, providing detailed insights into the lift and drag forces generated by various WASP technologies. However, the complexity and computational cost of CFD simulations remain challenging for real-time applications. In general, CFD approaches can be categorized according to the level of turbulence resolution. Direct Numerical Simulation (DNS) resolves all turbulent scales of the flow with high fidelity but requires prohibitive computational resources. Reynolds Averaged Navier Stokes (RANS) models, in contrast, use turbulence-averaging techniques that significantly reduce computational demand, making them more suitable for practical engineering applications, although with less detail in capturing small-scale flow structures. Intermediate approaches, such as Large Eddy Simulation (LES) and hybrid methods like Detached Eddy Simulation (DES), partially resolve turbulent structures and offer improved physical fidelity at the expense of increased computational cost. The paper by Kwon et al. [43] focuses on simulation within a CFD environment. It demonstrates how this powerful tool can help define boundaries for a piece of stand-alone equipment, later to be contextualized for a generic ship. It effectively creates a virtual map of the principal parameters to be adjusted in rotor sails. The validation of the model with experimental data enhances confidence in the presented results and lays the groundwork for future investigations using this data. One of the most significant contributions (including the subsequent optimization) is the set of performance maps derived from the simulation, as presented in Table 7. These results describe the rotor performance as a function of the Spin Ratio, which is the primary input parameter for the target rotor design.

In the context of the present study, CFD-based inputs are considered within large-scale parametric simulations, where computational efficiency is a key requirement. For this reason, RANS-based approaches are adopted as the reference level of modeling, while higher-fidelity methods such as LES and DES are not considered, due to their significantly higher computational demands, which limits their application in extensive parametric analysis.

Table 7 Aerodynamic and Mechanical Parameters at Different Spin Ratios (SR)

SR [-]	C_L / C_D (L/D)[1] [-]	Power [W]	Efficiency [%]
1	1.95 / 0.40 (4.81)	97.1	81.9
2	5.30 / 0.95 (5.57)	495.6	43.8
3	8.48 / 2.26 (3.76)	1379.8	25.1
4	9.38 / 2.86 (3.28)	3112.8	12.3
5	9.66 / 3.17 (3.05)	6126.8	6.45

[1] C_L and C_D are the lift and drag coefficients, while L/D is their ratio. Data adapted from Kwon et al. [43]

In this table, “Efficiency” refers to the effective conversion of wind energy into useful propulsive force contributing to ship thrust, rather than a global propulsion system efficiency. The term is used comparatively to indicate the relative performance of different wind-assisted propulsion modeling approaches. These numbers are certainly helpful and could already lead to significant regressions for new models using this using this reference Flettner rotor geometry. The results correspond to a reference rotor geometry and fixed operating conditions as defined in the study, allowing for a consistent comparison across different spin ratios. Nevertheless, the author also brought conclusions to the results found, creating a link between the data and helping identify critical dependencies, such as the inverse relationship between torque and energy efficiency or the direct relationship between aspect ratio (the ratio between the height and the diameter/width of the sail) and energy efficiency for the Flettner Rotors, despite the apparent increase in lift due to the increase in the diameter. The study also identifies that an increase in the aspect ratio leads to a slight reduction in lift, but greater energy savings. The study further highlighted the relationship between the Thom disk diameter ratio - the ratio between the flow separation device diameter and the diameter of the rotating cylinder itself - and the efficiency of the equipment due to the induced torque. All these findings were presented in the form of graphics by the author, providing an essential visual reference for the behavior of the analyzed Flettner rotor geometry. A key factor governing this work is the lack of interaction between the sail effects and the ship hull behavior. As stated in the title, it evaluates the standalone equipment, without interference on the ship it is supposed to be installed into. This results in a gap where an interaction with the ship’s structure and the other concurrent sails is expected, especially for the application of the technology in real-world scenarios. It is particularly interesting to use the reference for the design phase. Still, a different approach is needed—and consequently, more resources are required for a time-lapse of a whole real-world voyage.

In a more recent study, by Massaro et al. [59], it is clearer how the airflow behavior - and the hydrodynamic model - around the cylinder is fundamental to understanding the basis of such equipment's standalone performance, specifically for marine usage. The author developed a DNS model, also varying the rotation speeds. An important finding is the turbulence wakes behind the cylinder, even in ideal conditions. It clearly represents how each cylinder may affect others installed over the deck in an array of Flettner Rotors, for example, in a typical application seen in recent installations. It is also pointed out that this induced turbulent wake may extend further than 60 times the diameter of the cylinder, and due to that, according to the authors, it may affect other ships. However, the most affected devices are the other sails present on the deck of the same vessel, covering the entire deck, regardless of the ship's size, according to these findings. It is fair to say that Massaro et al. [59] dives even deeper into the aerodynamic effects of the rotor in a simulated environment, in a different approach from previous works. Despite the significant contributions from this latter work, it also lacks a more defined environment, such as the marine shipping conditions created by the conjunction of weather and operational factors - including the multiplicity of sails possible over the deck of a single ship and their interference.

Seo and Park [53] investigated the interactions between multiple Flettner rotors installed on a single ship, distributed along both sides and at the bow and stern. The study confirmed the behavior of standalone windward rotors reported by Kwon et al. [43]. It also highlighted the superior performance of windward units compared to leeward ones, mainly due to the short separation distance between the devices. It is worth noting, however, that the separation range proposed and iterated in the study is limited by both the deck area of the case study vessel and the number of rotors, when considering solely four units. In theory, any number of rotors may be iterated over any type of ship with a variable deck area, in order to produce a variety of comparable results. On the other hand, considering the simulation in the CFD environment, the proposed boundaries are sufficient for the possible computational limitations of the technique, producing valuable results of lift and drag coefficients that can complement further studies with four rotors distributed over the deck of a vessel.

Kume et al. [147] conducted a comprehensive simulation to understand the behavior of rotor sails under various wind conditions by comparing wind tunnel test results with CFD (RANS) simulations. The study highlights the direct relationship between wind speed and Spin Ratio. This approach not only reflects conditions closer to real-world operations but also introduces a reliable form of cross-validation by combining two types of models – numerical (CFD) and empirical (model tests) – which will be further discussed in a later section. The results also account for the interaction with the superstructure above the deck, providing even more adherence to real-world case scenarios. Moreover, the study suggests that almost all angles of Apparent Wind Angle (AWA) are feasible for producing thrust, except those in the range of -20 to +20 degrees in relation to the bow. Within more controlled conditions, Garzón and Figueroa [62] examines the installation and aerodynamic effects of an array of Flettner Rotors through mathematical modeling and scaled experimentation. The authors emphasize the role of induced flow fields in influencing the downstream performance of multiple rotors, exploring the dynamic interactions between them. However, the study lacks full-scale operational data, limiting its applicability to real-world scenarios. As a result, it serves as a strong example of fundamental scientific research conducted in a controlled environment rather than practical implementation. As a numerical approach to the problem, it highlights several models that each solution may include, apart from the discretizations of the mesh in which the environment is modeled and the variables tested using the numerical solution of the Navier-Stokes equations. The author demonstrated how the superposition of the linear effects of each rotor can represent an array, unlike the standalone approach of Kwon et al. [43]. Both studies employed RANS-based commercial solvers with standard turbulence models (e.g., k–ω SST), which confines the results to controlled rather than full-scale conditions.

Park et al. [63] presents a numerical study on the aerodynamic performance of an asymmetric vertical folding rotor sail. Designed to enhance propulsion for smaller vessels, this innovative approach introduces asymmetrical geometry, reducing diameter along the vertical axis and improving lift-to-drag ratios by up to

12% compared to traditional rotor sails, according to the authors. The results, based on CFD analysis, explore variations in spin ratios and aspect ratios, indicating that folding the rotor sail may significantly decrease drag by approximately 48% when not in operation. This feature addresses operational challenges on smaller ships, where deck space and maneuverability are limited. In this sense, numerical simulation plays an important role. Seo and Park [53] focuses on the aerodynamic interaction of multiple rotors at varying distances and spin ratios, while Park et al. [63] emphasises the benefits of adaptive geometry, by contrast. This differs from the approach of Garzón and Figueroa [62], whose reduced-scale experimental modeling of multiple rotors lacks the operational adaptability demonstrated by the rotor sails proposed by Park et al. [63]. Chen et al. [58] provides a valuable summary of the experimental works developed and compares their results, demonstrating how close workbench lab results can be when using proper models and hypotheses for the wind technology. The study examines explicitly velocity ratio regimes, aspect and endplate ratios (Thom disk ratio), and rotor–rotor interference, establishing hypotheses that link laboratory measurements to full-scale applicability. Kume et al. [147] further validates rotor performance through wind tunnel tests and CFD, providing insights into largescale rotor installations. In contrast, Park et al. . [63] shifts the focus towards design flexibility and real-world applicability for smaller vessels. Park et al. . [63] 's contribution lies in addressing the gap between aerodynamic efficiency and practical deployment, offering scalable solutions to enhance wind-assisted propulsion in smaller maritime vessels.

It becomes evident, by the amount of effort setting up the CFD or numerical environment, and the time this process takes to converge, according to the references, that a finite volume method simulation is a very time-consuming process, and will hardly be part of a just-in-time solution for operational procedures. Kramer and Steen [148] propose a simplification in the modeling of such an environment, but even then, report a substantial amount of refinement required to satisfy the boundary conditions, resulting in a confident outcome, more suitable for design and feasibility phases, and also paving the way for more just-in-time operational evaluations. They introduce a simplification in the modeling of the CFD environment, trying to reduce the computational cost of such a solution while maintaining reliable accuracy. The authors focus on essential variables and exclude less relevant parameters, which accelerates the simulation. However, the effort to refine the mesh accordingly and adjust boundary conditions offsets the computational savings, showing the paradox of the numerical simulation. Despite all simplifications, the extensive refinement process needed to satisfy boundary conditions often offsets the anticipated computational savings. Moreover, the simplified model, despite its efficiency, may struggle to capture the non-linear and unstable nature of operational environments, which demand more dynamic and responsive types of simulations.

Beyond the simulation of active aerodynamic devices such as Flettner Rotors, other WASP technologies may also require structural modeling and motion planning due to the adaptive or flexible nature of the structure of the sail itself. For instance, Kater et al. [57] present a finite element model (FEM) of an adaptive elastic wing sail with embedded actuators, currently under development for yacht propulsion, but also analogous to larger merchant vessels. The study proposes a systematic motion planning methodology combining flatness-based feedforward control and Proportional-Integral (PI) state-feedback, starting from a detailed Computer-Aided Design (CAD) model of the geometry. The resulting high-dimensional system of Ordinary Differential Equations (ODEs) is reduced via modal truncation, enabling feasible control of the wing sail's deformation. While still at a simulation stage, this approach exemplifies how coupling structural flexibility with advanced control strategies opens new perspectives for high-performance, responsive wind-assisted propulsion systems. This highlights a different class of simulation demands, also required when evaluating new technology systems, and especially where structural dynamics and control integration play a central role in the overall efficiency. Similarly, when dealing with new or experimental wind-assisted propulsion devices, both structural and fluidic simulations are essential to ensure a robust evaluation of performance. As shown by Li et al. [50], simulation efforts must often span multiple levels of complexity, particularly when structural dynamics and control integration are critical - in that case, to develop a new sail design based on the Magnus effect. While high-fidelity numerical models remain necessary for capturing detailed behaviors, early-stage development may benefit from simplified empirical models that support preliminary design iterations. These empirical approaches, their limitations, and their potential applications in early development stages will be further addressed in the following sections.

3.2 Empirical and Hybrid Models

Empirical models, based on historical or real-world performance data, use simplified mathematical formulations to estimate the aerodynamic and fuel-saving potential of WASP technologies under typical operating conditions. However, they are limited in precision and adaptability. To overcome these limitations, hybrid or semi-empirical models have been developed. They combine empirical data with computational techniques, offering a balanced trade-off between accuracy and computational efficiency. As seen in the previous sections, such models provide greater flexibility, particularly when both accuracy and rapid results are required. They are often used to integrate different levels of evaluation, such as combining CFD with wind tunnel or tank test validation. Most of the discussed literature is based on calibrated models, as these rely on available data to have empirical (or CFD model) studies as accurately as possible. Below, we present not only a summary of the findings from several of the cited contributions to the development of an accurate structure of empirical and hybrid simulations applied for wind-assisted technology, but also an in-depth analysis of the pros and cons of each approach.

3.2.1 Empirical Methods

Tillig and Ringsberg [149] performed a simulation regarding a different aspect of the rotors, more focused on their application over the deck of a ship. The author evaluated four degrees of freedom in his simulation, regarding the movements of the ship. The simulation, however, is regarded as entirely empirical, as it combines several known methods of calculation to obtain the desired results and includes conventional ship models that can be simulated with minimal input information, thereby speeding up the results, according to the authors. In this work, it is possible to verify that the yaw moments in the ship should be monitored when the technology is installed, observing the recommendation to define rudder limit operation to counteract this effect. This model aimed not only to estimate fuel consumption under specific weather conditions but also to evaluate the dynamic response of the ship hull. Such responses include those caused by shallow water effects and current interactions, enabling more accurate adjustments of wind-assistance parameters (e.g., sail-generated forces) and hull behavior in realistic operational scenarios. Owing to its parameterized inputs and computational simplifications, the model also appears suitable for near-real-time adjustments, offering practical advantages for routine ship operations.

Although it does not provide a detailed numerical simulation of aero- and hydrodynamic parameters, the method offers a faster approach with fewer input variables. This makes it suitable for just-in-time hypothetical adjustments. According to the authors, such efficiency is particularly valuable for applying WASP technology to common ship types, where hull geometry and sail integration are already well documented and can be predicted without relying on complex and computationally expensive methods. Naval Engineer, BMT Defence Services Ltd, UK and Pearson [51] presents an early-stage application of Flettner Rotors on a vessel with available deck space, employing a simplified iterative empirical model to evaluate aerodynamic and hydrodynamic performance. The study assumes a fixed rotor configuration—specifically, an aspect ratio of 5 and a Thom disk diameter 1.5 times the rotor length—based on prior experimental results. Despite its simplicity and static nature, the model proves effective for preliminary assessments and conceptual design evaluations of wind-assisted propulsion systems.

3.2.2 Hybrid Empirical and Experimental Models

Ghorbani et al. [150] summarize very well the two types of non-numerical simulation models available: the empirical one, which is available in the scientific literature, and the experimental, more scarcely available, though more robust. Both are possible approaches for the study of marine wind-assisted technology, as the author shows. The model proposed by Ghorbani et al. [150] contributes to the methodology of an optimization that calculates the best rotor fit for a particular hull shape. This approach can be used as a base composition, including a two-level interaction (design and operation), for a model to be proposed and expanded to accommodate possible improvements. The two levels are complementary, being described in the code as two enclosed loops that run one inside another, covering all the possible sail parameters. The loops are organized in order to iterate over each of the environmental scenarios for all the sail design parameters, which means that all the design parameters will be evaluated in conjunction (within) every weather scenario. During simulation, the Spin Ratio of the array of Flettner Rotors is to be continuously optimized to minimize fuel consumption. The objective function - to minimize cost of the equipment and the total energy consumption - described in Guzelbulut and Suzuki [75] is prime to test and varies the combination of the different parameters. The two levels are defined as a bi-level optimization for each ship:

1. **Operational Level:** optimization of the rotor operation under different environmental scenarios (wind and waves), using real-world meteorological data to maximize fuel savings.

2. **Design Level:** adjustment of rotor design parameters (such as dimensions and disk ratios) to identify the most efficient configuration for each ship.

Once the aerodynamic coefficients have been determined, the forces generated by the Flettner rotors are integrated into the ship's dynamics. A correct approach at this stage requires calculating the net power after accounting for the contribution of the rotor array. In addition, the study includes a simplified economic analysis, where equipment cost is approximated as a function of area and volume. The incorporation of direct economic parameters remains a challenge, as it simplifies the broader supply chain addressed by other authors [4,151]. This limitation, however, also highlights an opportunity for future studies, particularly in supporting decision-making by shipowners.

Optimization is performed based on the outcomes of simulations for a given array of parameters. Taking a wing sail as an example of structure to be optimized, an author may parameterize the variables and propose an approach (or method) to iterate in several steps along a proposed flowchart. A possible approach would be a multi-point optimisation, in which two or more parameters are weighted differently to fulfill a design requirement or meet a boundary condition, as shown by Ma et al. [152]. This type of optimization can be applied at both the design (first level) and operational (second level) stages, aiming to identify the most efficient configurations within the geometric and performance parameter space. At the operational level, classical strategies such as sail angle adjustment, trim and heading optimization, or adaptive speed profiling along a given route may be incorporated to enhance the system's responsiveness to real-world conditions. The specific method adopted will depend on the required sensitivity, computational cost, and the degree of integration between aerodynamic and control parameters, as further explored in empirical and hybrid models. In order to contextualize the present works reviewed, Ghorbani et al. [150] proposed a workflow for the optimisation, based on design and operational parameters that converge to an ideal range of coefficients of lift, drag, and power (the latter, consumed by the WASP equipment, including the electric engine demand, responsible for the active rotation).

Some other possible modelling approaches have also been carried on by several other authors, such as AIS follow-up of vessels in different conditions, evaluation of route sailing direction, or the length of the route. Route deviation from the Great Circle and seasonal differences were captured by Chou et al. [17]. On the other hand, Lu and Ringsberg [49] simulates three different scenarios using different wind-assisted technologies (kites, rigid sails, and rotor sails) and performs a simple yet effective empirical calculation to understand which is more suitable for the ship type and mean weather conditions in the particular route. It is comprehensible that the diversification in two long routes and two different types of ships - adequate for each route and cargo type - increases the perception of the usefulness and effectiveness of each technology. It also brings real-world scenarios to focus, comparing fuel data with potential savings, but still keeping the model as simple as possible in terms of optimisation methods, relying on an iterative code to evaluate the results obtained for each step of the simulation on an empirical basis. This more holistic approach provides a comprehensive framework for evaluating the application of different technologies. Comparing two routes over three types of WASP (Dyna Rig - canvas, Rotor, and Rigid sails), the authors utilise the same empirical 4 degrees of freedom algorithm as

Tillig and Ringsberg [149] but put it into the perspective of actual routes performed by two types of ships. While it confirms the findings from more detailed investigations, such as those using CFD or numerical hydrodynamic methods, it shifts the focus towards broader, more practical applications. This balance allows for the modelling of various conditions while ensuring fast convergence towards actionable and applicable results for the parametrised ships.

3.2.3 VPPs and Numerically Validated Methods

Velocity Prediction Programs (VPPs) are often considered important hybrid models because they typically consist of empirical equations and may incorporate experimental results or rely on experimental data to improve accuracy and validity. This was first introduced for fast sailing yachts by MIT in the 1970s [153] but has gained momentum with both racing yachts over the years and the recent development of sailing technologies for merchant vessels. The principle is further explored by Charlou et al. [154] propose a system-based model to predict the performance of wind-assisted vessels. Their approach is one of many ways to structure a VPP and deliver thorough, consistent results. The authors highlight challenges with empirical methods, such as obtaining data for side forces acting on the hull, due to a lack of reliable sources about sailing conditions in ships. It stresses both the rapid outcomes from such models and the natural requirements for validation, using real-world or model testing to overcome them. Other challenges, according to the author, may lie in the variability of operational conditions, which poses a difficulty even for model testing.

Reche-Vilanova et al. [155] presents a VPP model that can be adapted for three sail technologies: Flettner Rotors, Wing Sails, and Canvas Sails. The model's accuracy is validated using real-world data from a ship equipped with Flettner Rotors, showing that the model's predictions closely match the data collected. Both simplicity and robustness of this approach are the strengths of this so-called semi-empirical model. However, as the author herself describes, it lacks a more in-depth definition of the airflow passing through the devices, which only the numerical/CFD simulation could provide, and that might not be relevant if the resolution of the problem involves the ship's ongoing efficiency and a more holistic view of the fuel-saving problem.

The latter author described that the Rotor Flettner model could be calibrated thanks to the installation of this technology in a real-world ship, which provided accurate data for the superposition of the model results. Hence, hybrid models prove useful, resulting in a complete life cycle of models, merging in this case both experimental and empirical methods. Vahs [61] shows the validation of a Flettner Rotor simulation that had the opportunity to be validated in a real-world ship. The authors describe how the force management of the strain gauges was prime for the confirmation of laboratory predictions in such equipment. Besides, it was concluded that sea trials were essential to validate the premises of the CFD experiments, providing confidence to the lab work and paving the path for future, more robust investigations.

Experimental studies, although relatively scarce, provide valuable benchmarks for empirically oriented modeling approaches. Chen et al. [58] and Zhang et al. [156] used experimental data to assess the aerodynamic performance of sail-based propulsion systems, showing consistent results across a range of operating conditions, including variations in angle of attack (AoA). In particular, CFD results were validated against wind-tunnel data reported by Zhang et al. [156], where calibration of the numerical model improved agreement and increased confidence in the predictions. In single-sail validation tests, the extrema of lift and drag coefficients were identified, while a two-sail configuration demonstrated that thrust increases with the apparent wind angle (AWA), a trend also captured by the CFD simulations. Additional studies, such as Zeng et al. [157] and Li et al. [158], explored different sail technologies and geometric variations, contributing to the validation and optimization of empirical models. Furthermore, Ghorbani et al. [150] refined existing CFD data for Flettner rotors by contextualizing it for a representative hull configuration and incorporating environmental parameters, including more severe operating conditions. The reviewed methods are summarized in Table 8, which provides a comparative overview of the main simulation techniques discussed in this work. The table contrasts their key characteristics—such as accuracy, computational and economic cost, operational applicability, and validation requirements—to support the selection of the most suitable modeling approach depending on the project's objectives, available data, and stage of application. Further research may expand this comparison as new modeling strategies continue to emerge.

4. Discussion

While simulation models provide valuable insights, several challenges remain, including high computational costs, the need for extensive data validation, and the scalability of models across different ship types and operational conditions. This comparative review highlights clear trade-offs between model accuracy, computational demand, and operational applicability. While CFD-based simulations offer unmatched fidelity and are valuable in early design phases for detailed analysis of specific configurations, their computational cost and setup time limit their use in early-stage exploratory studies and real-time applications. In contrast, empirical and VPP models are more practical for operational scenarios but often simplify key interactions such as hull-sail coupling or sea state effects.

4.1 Conceptual Taxonomy of Simulation Models for WASP

To improve clarity in the selection and comparison of simulation models for Wind-Assisted Ship Propulsion (WASP), this review proposes a conceptual taxonomy that classifies existing modelling approaches according to three key dimensions: model fidelity, operational applicability, and degree of technological integration. This framework helps bridge the gap between purely technical evaluations and the practical needs of ship designers, operators, and decision-makers. Table 9 presents the proposed taxonomy as a reference for contextualizing the simulation models.

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This taxonomy allows for a clearer positioning of each modelling approach. For example:

- CFD models: high fidelity, suitable for design phase, but low integration due to computational demands.
- Hybrid VPP models: medium fidelity, used in both evaluation and operations, partially integrated when coupled with real-time data sources.
- Empirical models: low fidelity, but high operational applicability, with strong potential for integration using AIS or onboard sensor data.

Table 8 Expanded comparison of modelling methods for wind-assisted ship propulsion (WASP)

Method	Accuracy	Computational / Economic Cost	Operational Applicability	Requires Prior Data	Main Advantages	Main Limitations
CFD (Computational Fluid Dynamics)	Very high	Very high	Low	Yes	Captures detailed flow interactions and geometries; useful for sail design optimization	High setup and runtime; unsuitable for realtime or early-stage studies
Empirical Models	Moderate	Low	High	Yes	Simple, fast, and based on existing operational data	Limited to known conditions; may not generalize to new ship types

Hybrid Models	High	Medium to High	Medium	Yes	Balanced fidelity vs cost; flexible structure	Calibration and validation depend on high-quality datasets
VPP (Velocity Prediction Programs)	Medium to High	Medium	Medium to High	Yes	Fast scenario simulations; widely adopted for comparisons	Simplified hydrodycoupling
Experimental (Wind Tunnel / Sea Trials)	Very high	Very high	Low	No	Direct measurement; important for validation	High cost, complex logistics, limited scalability

For full references, see main text. “Operational Applicability” refers to the method’s suitability in design, validation, or real-time contexts.

Table 9 Conceptual taxonomy for WASP simulation models, based on model fidelity, operational applicability, and integration level

Category	**Subcategories**	**Definition**
Model Fidelity	High / Medium / Low	Level of physical realism. CFD models generally offer high fidelity; empirical models are low-fidelity.
Operational Applicability	Design / Evaluation / Real-Time Ops	Stage in the ship’s lifecycle where the model is most valuable: preliminary design, performance analysis, or onboard decision making.
Integration Level	Isolated / Partial / Full	Degree to which the model is coupled with real-world data (e.g., sensors, AIS, weather), optimization tools, and onboard control systems.

This taxonomy helps clarify model selection for different WASP simulation purposes.

Note: The cost categories presented in this table are qualitative and intended for comparative purposes only. “Computational cost” refers to required processing time and resources, while “economic cost” reflects overall financial implications, including infrastructure, labor, and operational expenses. Although related, these metrics are not directly equivalent and should be interpreted as indicative of relative resource intensity.

Figure 6 presents an illustrative representation of the outcomes. Such classification has not been explicitly systematized in existing literature and is proposed here as an original contribution to help guide researchers and practitioners in selecting modeling approaches aligned with their specific objectives and constraints.

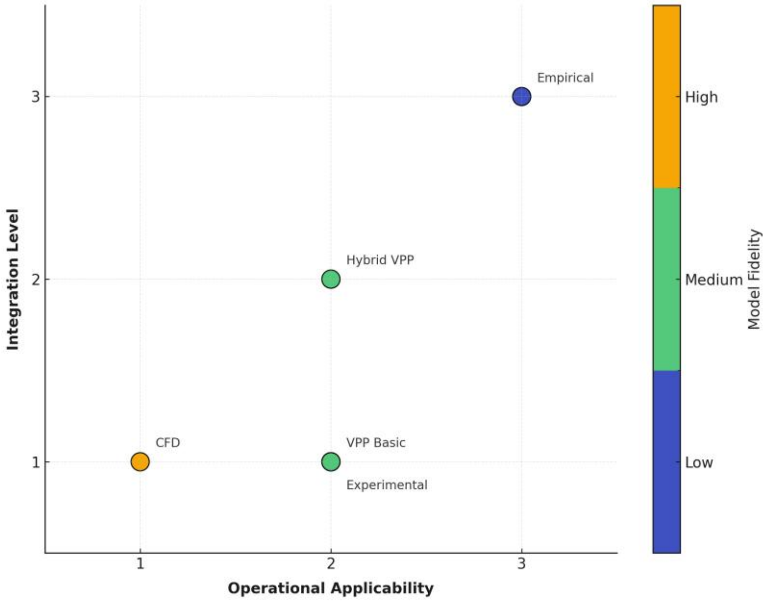

Fig. 6 Taxonomy of simulation models for WASP according to fidelity, operational applicability, and integration level (1 is low, 2 is medium and 3 is high). VPP Basic refers to models based predominantly on empirical or experimental inputs with limited integration, whereas “Hybrid VPP” denotes approaches that combine empirical data with higher-fidelity models, resulting in increased integration and applicability

4.2 Structured Comparative Framework for Model Selection

Building upon the proposed taxonomy, this section introduces a structured comparative framework to support model selection decisions in practical WASP applications (Table 10). The matrix below evaluates key modeling approaches based on weighted performance criteria relevant to ship design and operation.

The comparative evaluation of simulation approaches highlights clear trade-offs between model fidelity, computational requirements, validation robustness, and operational applicability. Rather than identifying a single universally optimal solution, the results reveal distinct performance profiles across modeling families, reflecting their underlying assumptions and intended use cases. The following observations summarize the key trends emerging from the weighted comparative framework and provide guidance for selecting appropriate simulation strategies across different stages of design, assessment, and operation:

- Hybrid modeling approaches exhibit the strongest overall performance, offering a balanced compromise between computational cost, predictive accuracy, validation maturity, and integration potential across the ship lifecycle.
- CFD-based models, while delivering the highest level of physical fidelity, rank lower in overall applicability due to their high computational cost and limited suitability for real-time or operational decision-making.
- Empirical models perform well in terms of computational efficiency and ease of deployment but are constrained by reduced physical fidelity and limited validation when extrapolated beyond their calibration domain.

Experimental approaches demonstrate high accuracy and validation credibility; however, their broader application is restricted by cost, scalability limitations, and challenges in operational integration.

Table 10 Structured comparative matrix for selecting WASP simulation models based on weighted performance criteria

Criterion	**Weight (%)**	**CFD**	**Empirical**	**cVPP**	**Hybrid**	**Experimental**
Result fidelity	30	5	1	3	4	5
Computational cost	15	1	5	4	3	2
Simulation speed	10	1	5	4	3	2
Integration feasibility	15	2	4	3	5	2
Technological maturity	10	3	5	4	4	2
Existing empirical validation	20	3	2	4	5	5
Weighted total score	**100**	**2.9**	**3.25**	**3.6**	**4.25**	**3.15**

Each model is scored from 1 (low) to 5 (high) for each criterion. Weights were assigned based on relevance to ship design and operational decision-making, following typical engineering trade-offs between fidelity, cost, and applicability. The final score is the weighted sum across all criteria.

Note 1: The weight distribution presented in this table reflects the relative importance of each criterion in the context of ship design and operational decision-making. Higher weights are assigned to aspects directly influencing performance prediction and practical applicability (e.g., result fidelity), while lower weights are attributed to supporting or context-dependent factors (e.g., empirical validation). The percentages are intended to provide a structured comparative framework rather than absolute or universally applicable values.

Note 2: For experimental approaches, “computational cost” and “simulation speed” are interpreted in terms of overall resource and time requirements associated with experimental setup, execution, and data processing, rather than numerical computation. These criteria are used comparatively to maintain consistency across different modeling approaches.

4.3 Discussion of Model Applications, Limitations and Future Integration Strategies

As shown in the previous sections, several authors have developed models that differ in their study methodologies, which in turn affect both the objective and, consequently, the results. Plessas and Papanikolaou [159] go beyond the optimization boundaries, proposing an algorithm that iterates different design aspects based on the parameters of sail technologies. However, each of them is limited by the complex applicability of such technology, which must be adapted to the characteristics of each ship type and the specific weather conditions of its operating routes. According to Mannarini et al. [12], weather plays an important role in the efficiency of the installed devices. More robust models are to be developed and integrated with ship operations, possibly in real-time, in order to contribute significantly to the efficiency of the ship and the resulting fuel savings. Adjusting the sails in real-time with the aid of sensors for maximum efficiency is already playing an important role for manufacturers of WASP; therefore, the opportunity may lie in the use of such data in future works to improve empirical models and validate CFD simulations for each type of ship that benefits from this installation. Hybrid models have emerged as a middle ground, combining the adaptability of empirical approaches with selected high-fidelity components. For instance, optimization routines or adaptive control algorithms can be embedded to simulate route-specific conditions. These models, however, depend on quality calibration data that are still under continuous development and are often restricted by limited access to operational measurements. The growing availability of onboard sensors and AIS-derived wind estimates opens the door to real-time tuning of such models, as demonstrated by studies that integrate WASP simulations into weather routing systems, such as Bentin et al. [160] and Smith et al. [161].

Recent efforts to validate simulation models using real operational data remain limited but are beginning to emerge. Reche-Vilanova et al. [155] demonstrated alignment between simplified VPP simulations and onboard data from a commercial vessel equipped with Flettner rotors, highlighting the practical utility of such models in routing strategies. Likewise, Anemoi [162] conducted a full-scale validation of rotor sail performance using onboard strain measurements, providing essential insights to bridge the gap between numerical models and real-world applications. These initiatives are valuable steps, but broader access to standardized datasets and coordinated experimental campaigns are still needed to improve reproducibility and comparability across studies. It is important to stress that an ideal holistic model should capture a wide range of weather conditions and ship types. Its purpose is to serve as an abacus (i.e., a practical decision aid) for selecting the wind-assisted technology and the parameters that best fit a particular ship. Such a model should account for the vessel's operational profile, the ports most frequently attended, and the available deck space for the equipment, among other practical constraints. As discussed in the previous section, several efficiency trials have been conducted for different WASP technologies. However, a route-specific assessment that explores multiple ship types and WASP options is still underdeveloped—beyond the scope of manufacturer-led studies—and would be highly relevant for shipowner decision-making.

Opportunities lie in mapping the several potential routes around the globe that may benefit most from wind-assisted technology. In this sense, modeling and optimization are crucial, as they identify the optimal operational envelope for a ship to follow along that particular route and time. Investigations of how devices behave require additional computational resources and validation, as proposed by Bordogna et al. [163], including experiments simulating different Reynolds numbers in a Flettner Rotor. It shows in detail how the lift coefficient can turn negative over a range of Reynolds numbers, as several other authors have reported for similar effects on the lift and drag coefficients. On the other hand, the validation techniques should be extensively pursued in order to comply with the demands for accurate models that will subsidize the broader adoption of the technology. Besides, in the face of a growing fleet of WASP ships, it will be an opportunity to understand how the several types of vessels behave when refitted with wind-assisted technology. Thies and Ringsberg [164] demonstrates the efficiency of a particular type of vessel with rotor sails installed and simulates the outcomes using an empirical model, illustrating the potential of such predictions for the future fleet.

Future research may also focus on developing standardized models that incorporate both aerodynamic performance and operational efficiency, even relating economic metrics to better evaluate the results. Additionally, integrating real-time data into simulation models can enhance predictive accuracy, particularly for weather-dependent systems like WASP. Hybrid systems, combining both WASP and several possible energy-saving devices, are also a concrete possibility to fulfil IMO milestones. Combining technologies requires a comprehensive understanding of the individual efficiency profiles of each solution, such as the combination between electrification and wind-assistance technology, which is a benefit of such stimulus, as discussed by Arabnejad et al. [165], who analyzed a zero-emission concept ship integrating multiple propulsion and energy management systems—including WASP, or Al-Baity et al. [166], that defined an optimization tool to combine a hybrid system considering both fuel cells and storage systems. Hence, integrated models may be part of future research.

An important asset to be built from experience with different simulation tools, for the WASP technology field of study, would be the creation of a benchmark. Given the persistent challenges of conducting numerical CFD simulations and comparing results with full-scale vessels [167], it's not only practical and convenient to have a holistic empirical model, but also to rely on different simulation technologies to build a repository of knowledge on the integration of WASP with different ships. If a repository of datasets were made publicly available on standard ship types and the results of performance trials of different WASP systems, it would be very important to the growth of the knowledge base on WASP. It could also serve as the foundation for open-source platforms that enable simulations with fast and interoperable modules, which can work together or separately, depending on the application. That scenario of open and broad research is certainly key for future developments and the faster adoption of WASP technology, as well as for evaluating different types of decarbonization technology.

Building on these observations, future research should prioritize: (i) the standardization of validation protocols and shared datasets for merchant vessels equipped with WASP; (ii) the expansion of VPP and hybrid models to incorporate hull-sail interactions beyond traditional sailing yacht assumptions; (iii) the development of route- and vessel-specific simulations to account for variations in wind availability, ship size, and voyage type; and (iv) the integration of simulation models into onboard decision-support systems using sensor data and optimization frameworks. The incorporation of machine learning and artificial intelligence may further enhance model adaptability and responsiveness, though their application in safety-critical maritime contexts will require robust validation and regulatory alignment. Another interdisciplinary opportunity is to integrate policy and regulatory simulations with the outcomes of technical simulations. This could broaden the pathway for WASP to become a fundamental technology in global decarbonization, particularly in decision-making and design phases. It should also encompass the life-cycle assessment of both the equipment and the ship, as well as the human factors associated with WASP operation, since these aspects are closely linked to the adoption of new technologies—especially for WASP, which is often perceived as an antiquated device associated with traditional rope-and-canvas tall ships.

5. Conclusions

This review highlights the significant role of simulation models in predicting the efficiency of wind-assisted propulsion systems (WASP). By comparing various modeling techniques, it identifies the main contributions and limitations of each approach, aligning the discussion with the ever-evolving scenario of simulation strategies and optimization frameworks. The main categories of models—numerical (e.g., CFD), empirical, hybrid, experimental, and VPP-based—are discussed with respect to their applications, trade-offs, and data requirements.

CFD-based simulations stand out for their detailed aerodynamic analysis and are particularly suited to the design phase. However, their high computational cost and lack of standardized operational, real-world, or experimental data still limit broader applicability. Recent contributions in the field are highlighted for their potential to inform future developments in sail geometry and aerodynamic behaviour. Moreover, these high-fidelity results may serve as valuable inputs for empirical and hybrid models, improving accuracy and responsiveness for real-time operational control. Empirical models offer strong flexibility and low computational cost, making them able to comply with real-time executions and being highly appreciated, especially in the operational phase of the implementation of each wind propulsion technology. Despite their lower fidelity, their usefulness increases when coupled with results from CFD or experimental testing, combining precision with flexibility and, consequently, forming hybrid models. These approaches balance precision and adaptability and are frequently used in literature to validate or enhance the respective methods.

Experimental validation—such as wind tunnel tests or full-scale measurements—remains essential but underused, often constrained by cost, logistical complexity, or lack of data-sharing protocols. Similarly, VPP models, while efficient for performance estimation, require further adaptation to the realities of commercial shipping beyond the context of sailing yachts. It is worth stressing that each modeling approach has its strengths and relevance depending on the context. An empirical model is not simply less valuable than a CFD model. An ideal framework balances clear rules for when to use each model with the availability of data for consistent inputs and robust validation.

Given the rapid advances in onboard sensing and computational power for real-time, data-intensive simulations, studies of this kind capture only a snapshot of current WASP practice. This underscores the need to assess the capability to test multiple sail configurations and to improve the accuracy of results. The several findings in each paper reviewed could be of great use for upcoming research in decarbonization, especially with WASP applications, as models play a crucial role in guiding development and significantly contribute to the increase in the readiness level of each system and its proper usage.

References

[1] International Maritime Organization, IMO, 2018. Adoption of the Initial IMO Strategy on Reduction of GHG Emissions from Ships and Existing IMO Activity Related to Reducing GHG Emissions in The Shipping Sector.

[2] International Maritime Organization, IMO, 2023. 2023 IMO Strategy on Reduction of GHG Emissions from Ships. https://www.imo.org/en/OurWork/Environment/Pages/2023-IMO-Strategy-on-Reduction-of-GHGEmissions-from-Ships.aspx (accessed 24th June 2025)

[3] International Maritime Organization, IMO, 2025. Circular Letter No.5005 - Draft Revised Marpol Annex Vi (Secretariat).

[4] Rojon, I., Dieperink, C., 2014. Blowin' in the wind? Drivers and barriers for the uptake of wind propulsion in international shipping. *Energy Policy*, 67, 394-402. https://doi.org/10.1016/j.enpol.2013.12.014

[5] Shi, Y., 2016. Reducing greenhouse gas emissions from international shipping: Is it time to consider market-based measures? *Marine Policy*, 64, 123-134. https://doi.org/10.1016/j.marpol.2015.11.013

[6] Mallouppas, G., Yfantis, E.A., 2021. Decarbonization in Shipping Industry: A Review of Research, Technology Development, and Innovation Proposals. *Journal of Marine Science and Engineering*, 9(4), 415. https://doi.org/10.3390/jmse9040415

[7] Allal, A. A., Mansouri, K., Youssfi, M., Qbadou, M., 2018. Toward a review of innovative solutions in the ship design and performance management for energy-saving and environmental protection. In *2018 19th IEEE Mediterranean Electrotechnical Conference (MELECON)*, pages 115-118, Marrakech; Morocco. https://doi.org/10.1109/MELCON.2018.8379078

[8] Zhao, F., Yang, W., Wan Tan, W., Kiang Chou, S., Yu, W., 2015. An Overall Ship Propulsion Model for Fuel Efficiency Study. *Energy Procedia*, 75, 813-818. https://doi.org/10.1016/j.egypro.2015.07.139

[9] Psaraftis, H. N., Kontovas, C. A., 2009 CO2 emission statistics for the world commercial fleet. *WMU Journal of Maritime Affairs*, 8(1), 1-25. https://doi.org/10.1007/BF03195150

[10] Psaraftis, H. N., Kontovas, C. A., 2013. Speed models for energy-efficient maritime transportation: A taxonomy and survey. *Transportation Research Part C: Emerging Technologies*, 26, 331-351. https://doi.org/10.1016/j.trc.2012.09.012

[11] Psaraftis, H., 2019. Speed optimization vs speed reduction: The choice between speed limits and a Bunker Levy. *Sustainability (Switzerland)*, 11(8), 2019. https://doi.org/10.3390/su11082249

[12] Vidović, T., Šimunović, J., Radica, G., Penga, Željko, 2023. Systematic Overview of Newly Available Technologies in the Green Maritime Sector. *Energies*, 16(2), 641. https://doi.org/10.3390/en16020641

[13] Mannarini, G., Salinas, M. L., Carelli, L., Petacco, N., Orović, J., 2024. VISIR-2: Ship weather routing in Python. *Geoscientific Model Development*, 17(10), 4355-4382. https://doi.org/10.5194/gmd-17-4355-2024

[14] Liang, Q, Tvete, H A, Brinks, H. W., 2019. Prediction of vessel propulsion power using machine learning on AIS data, ship performance measurements and weather data. *Journal of Physics: Conference Series*, 1357(1), 012038. https://doi.org/10.1088/1742-6596/1357/1/012038

[15] Vigna, V., Figari, M., 2023. Wind-Assisted Ship Propulsion: Matching Flettner Rotors with Diesel Engines and Controllable Pitch Propellers. *Journal of Marine Science and Engineering*, 11(5), 1072. https://doi.org/10.3390/jmse11051072

[16] Molland, A.F., Hawksley, G.J., 1985. An investigation of propeller performance and machinery applications in wind assisted ships. *Journal of Wind Engineering and Industrial Aerodynamics*, 20(1-3), 143-168. https://doi.org/10.1016/0167-6105(85)90016-9

[17] Winnes, H, Styhre, L., Fridell, E., 2015. Reducing GHG emissions from ships in port areas. *Research in Transportation Business & Management*, 17, 73-82. https://doi.org/10.1016/j.rtbm.2015.10.008

[18] Chou, T., Kosmas, V., Acciaro, M., Renken, K., A., 2021. Comeback of Wind Power in Shipping: An Economic and Operational Review on the Wind-Assisted Ship Propulsion Technology. *Sustainability*, 13(4), 1880. https://doi.org/10.3390/su13041880

[19] Wang, Y., Zhang, X., Lin, S., Qiang, Z., Hao, J., Qiu, Y., 2022. Analysis on the development of wind-assisted ship propulsion technology and contribution to emission reduction. In *IOP Conference Series: Earth and Environmental Science*, volume 966. https://doi.org/10.1088/1755-1315/966/1/012012

[20] Petković, M., Zubčić, M., Krčum, M., Pavić, I., 2021. Wind assisted ship Propulsion Technologies– can they help in emissions reduction? *NAŠE MORE: znanstveni časopis za more i pomorstvo*, 68(2), 102-109. https://doi.org/10.17818/NM/2021/2.6

[21] Balcombe, P., Brierley, J., Lewis, C., Skatvedt, L., Speirs, J., Hawkes, A., Staffell, I., 2019. How to decarbonise international shipping: Options for fuels, technologies and policies. *Energy Conversion and Management*, 182, 72-88. https://doi.org/10.1016/j.enconman.2018.12.080

[22] Khan, L., Macklin, J., Peck, B., Morton, O., Souppez, J.B.R.G., 2021. A review of wind-assisted ship propulsion for sustainable commercial shipping: Latest developments and future stakes. In *Wind Propulsion Conference*. Royal Institution of Naval Architects. https://doi.org/10.3940/rina.win.2021.05

[23] Li, Z., Wang, K., Ruan, Z., Li, D., Liang, H., Ma, R., et al., 2025. A fuel consumption prediction model for wind-assisted ship based on operational data. *Transportation Research Part D: Transport and Environment*, 149, 105045. https://doi.org/10.1016/j.trd.2025.105045

[24] Liang, H., Wang, K., Liu, X., Xing, H., Li, Z., Jing, Z., et al., 2026. A novel fuel consumption optimization strategy for the wind-assisted hybrid power ship considering sea conditions. *Energy*, 347, 140343. https://doi.org/10.1016/j.energy.2026.140343

[25] Li, Z., Wang, K., Liu, Y., Liang, H., Zhang, D., Wang, Z., et al., 2026. Evaluation of energy-saving effects of a wing-typed sail-assisted ship using wind energy density route analysis. *Ocean Engineering*, 345, 123693. https://doi.org/10.1016/j.oceaneng.2025.123693

[26] Wang, K., Li, Z., Zhang, R., Ma, R., Huang, L., Wang, Z., et al., 2025. Computational fluid dynamics-based ship energy-saving technologies: A comprehensive review. Renewable and Sustainable *Energy Reviews*, 207, 114896. https://doi.org/10.1016/j.rser.2024.114896

[27] Parry, J. H., 1963. *The Age of Reconnaissance: Discovery, Exploration and Settlement, 1450-1650*. Mentor Books, New York.

[28] Chatterton, E. K., 1915. Sailing Ships: The Story of Their Development from the Earliest Times to the Present Day. *J. B. Lippincott Company*, Philadelphia.

[29] Holmes, G. C. V., 1911. Ancient and Modern Ships. Part I: Wooden Sailing-Ships. *Her Majesty's Stationery Office*, London.

[30] Hatton, T., 2021. The resilience of the sailing ship. https://cepr.org/voxeu/columns/resilience-sailing-ship (accessed 24th June 2025)

[31] Cohn, R. L., 2005. The transition from sail to steam in immigration to the United States. *The Journal of Economic History*, 65(2), 469-495. https://doi.org/10.1017/S0022050705000161

[32] Rizzo, F., 1925. The Flettner rotor ship in the light of the Kutta-Joukowski theory and of experimental results. Technical Report NACA-TN-228, National Advisory Committee for Aeronautics (NACA), 1925.

[33] Walker, J. G., 1985. A high performance automatic wingsail auxiliary propulsion system for commercial ships. *Journal of Wind Engineering and Industrial Aerodynamics*, 20(1-3), 83-96. https://doi.org/10.1016/0167-6105(85)90013-3

[34] Ouchi, K., Uzawa, K., Kanai, A., 2011. Huge hard wing sails for the propulsor of next generation sailing vessel. In *The Second International Symposium on Marine Propulsors, Hamburg, Germany*.

[35] Duckworth, R., 1985. The application of elevated sails (kites) for fuel saving auxiliary propulsion of commercial vessels. *Journal of Wind Engineering and Industrial Aerodynamics*, 20(1), 297-315. https://doi.org/10.1016/0167-6105(85)90023-6

[36] Page, M. J., McKenzie, J. E, Bossuyt, P. M., Boutron, I., Hoffmann, T. C, Mulrow, et al. 2021. The PRISMA 2020 statement: An updated guideline for reporting systematic reviews. *BMJ*, 71. https://doi.org/10.1136/bmj.n71

[37] Atkinson, G., Nguyen, H., Binns, J., 2018. Considerations regarding the use of rigid sails on modern powered ships. *Cogent Engineering*, 5(1), 1543564. https://doi.org/10.1080/23311916.2018.1543564

[38] Parlier, Y.,2018. Français: Kite tractant un cargo, https://www.meretmarine.com/fr/marine-marchande/transport-maritime-propulse-par-le-vent-tour-d-horizon-des-concepts-et-projets (accessed 20th December 2025).

[39] Viola, I. M., Sacher, M., Xu, J., Wang, F., 2015. A numerical method for the design of ships with wind-assisted propulsion. *Ocean Engineering*, 105, 33-42. https://doi.org/10.1016/j.oceaneng.2015.06.009

[40] Hussain, M. D., Amin, O. M., 2021. A Comprehensive Analysis of the Stability and Powering Performances of a Hard Sail–Assisted Bulk Carrier. *Journal of Marine Science and Application*, 20(3), 426-445. https://doi.org/10.1007/s11804-021-00219-w

[41] Tillig, F., Ringsberg, J. W., 2020. Design, operation and analysis of wind-assisted cargo ships. *Ocean Engineering*, 211, 107603. https://doi.org/10.1016/j.oceaneng.2020.107603

[42] Bentin, M., Kotzur, S., Schlaak, M., Zastrau, D., Freye, D., 2018. Perspectives For a Wind Assisted Ship Propulsion. *International Journal of Maritime Engineering*, 160(A1). https://doi.org/10.5750/ijme.v160iA1.1043

[43] Offshore Energy, 2019. Norsepower Rotor Sails confirmed savings of 8.2 % fuel and associated CO2 in Maersk Pelican project. https://www.offshore-energy.biz/norsepower-rotor-sails-achieve-8-2-of-fuelsavings-on-maersk-pelican (accessed 24th June 2025)

[44] Kwon, C. S., Yeon, S. M., Kim, Y. C., Kim, Y. G., Kim, Y. H., Kang, H. J., 2022. A parametric study for a Flettner rotor in standalone condition using CFD. *InternationalJournal of Naval Architecture and Ocean Engineering*, 14, 100493. https://doi.org/10.1016/j.ijnaoe.2022.100493

[45] Peri, D., Rossetti, M., Campana, E. F., 2001. Design optimization of ship hulls via CFD techniques. *Journal of Ship Research*, 45, 140-149. https://doi.org/10.5957/jsr.2001.45.2.140

[46] Ammar, N. R. Seddiek, I. S., 2022. Wind assisted propulsion system onboard ships: Case study Flettner rotors. *Ships and Offshore Structures*, 17(7), 1616-1627. https://doi.org/10.1080/17445302.2021.1937797

[47] Searcy, T., 2017. Harnessing the wind: A case study of applying Flettner rotor technology to achieve fuel and cost savings for Fiji's domestic shipping industry. *Marine Policy*, 86, 164-172. https://doi.org/10.1016/j.marpol.2017.09.020

[48] Angelini, G., Muggiasca, S., Belloli, M., 2023. A Techno-Economic Analysis of a Cargo Ship Using Flettner Rotors. *Journal of Marine Science and Engineering*, 11(1), 229. https://doi.org/10.3390/jmse11010229

[49] Talluri, L., Nalianda, D.K., Giuliani, E., 2018. Techno economic and environmental assessment of Flettner rotors for marine propulsion. *Ocean Engineering*, 154, 1-15. https://doi.org/10.1016/j.oceaneng.2018.02.020

[50] Lu, R., Ringsberg, J. W., 2020. Ship energy performance study of three wind-assisted ship propulsion technologies including a parametric study of the Flettner rotor technology. *Ships and Offshore Structures*, 15(3), 249-258. https://doi.org/10.1080/17445302.2019.1612544

[51] Li, B., Zhang, R., Zhang, B., Yang, Q., Guo, C., 2021. An assisted propulsion device of vessel utilizing wind energy based on Magnus effect. *Applied Ocean Research*, 114, 102788. https://doi.org/10.1016/j.apor.2021.102788

[52] BMT Defence Services Ltd, UK, Pearson, D R., 2014. The Use of Flettner Rotors in Efficient Ship Design. In *Influence of EEDI on Ship Design 2014*, 151-158.

[53] Lindstad, E., Stokke, T., Alteskjær, A., Borgen, H., Sandaas, I., 2022. Ship of the future – A slender dry-bulker with wind assisted propulsion. *Maritime Transport Research*, 3, 100055. https://doi.org/10.1016/j.martra.2022.100055

[54] Seo, J., Park, D., 2024. Numerical Study on the Aerodynamic Performance of Four Flettner Rotors by Varying Distance and Spin Ratio. *Journal of Marine Science and Technology*, 32(2). https://doi.org/10.51400/2709-6998.2735

[55] Norsepower. Performance Simulator. https://www.norsepower.com/performance-simulator/ (accessed 21st December 2025).

[56] Maritime Faculty, Marine Engineering Department, Istanbul Technical University, 2024. Decarbonization of shipping: Hydrogen and fuel cells legislation in the maritime industry. *Brodogradnja*, 75(2), 1-13, 75205. https://doi.org/10.21278/brod75205

[57] Traut, M., Gilbert, P., Walsh, C., Bows, A., Filippone, A., Stansby, P., Wood, R., 2014. Propulsive power contribution of a kite and a Flettner rotor on selected shipping routes. *Applied Energy*, 113, 362-372. https://doi.org/10.1016/j.apenergy.2013.07.026

[58] Kater, A., Wriedt, J.P., Meurer, T., 2017. Finite element modeling and motion planning of an adaptive elastic wingsail. *IFAC-PapersOnLine*, 50(1), 6768-6773. https://doi.org/10.1016/j.ifacol.2017.08.1194

[59] Chen, W., Wang, H., Liu, X., 2023. Experimental investigation of the aerodynamic performance of Flettner rotors for marine applications. *Ocean Engineering*, 281, 115006. https://doi.org/10.1016/j.oceaneng.2023.115006

[60] Massaro, D., Karp, M., Jansson, N., Markidis, S., Schlatter, P., 2024. Direct numerical simulation of the turbulent flow around a Flettner rotor. *Scientific Reports*, 14(1), 3004. https://doi.org/10.1038/s41598-024-53194-x

[61] Schuler, M., 2021. First Tilting Rotor Sails Installed on SC Connector. https://gcaptain.com/first-tiltingrotor-sails-installed-on-sc-connector/ (accessed 21st December 2025)

[62] Vahs, M., 2020. Retrofitting of Flettner Rotors – Results From Sea Trials of the General Cargo Ship “Fehn Pollux”. *International Journal of Maritime Engineering*, 162(A4). https://doi.org/10.3940/rina.2020.a4.641

[63] Garzón, F., Figueroa, A., 2017. The Study on the Flow Generated by an Array of Four Flettner Rotors: Theory and Experiment. *Applied Mathematics*, 08(12), 1851-1858. https://doi.org/10.4236/am.2017.812132

[64] Park, J. Y., Seo, J., Park, D.W., 2024. Numerical Study on the Aerodynamic Performance of Asymmetric Vertical Folding Rotor Sail. *Journal of the Society of Naval Architects of Korea*, 61(2), 68-76. https://doi.org/10.3744/SNAK.2024.61.2.68

[65] Leloup, R., Roncin, K., Behrel, M., Bles, G., Leroux, J.-B., Jochum, C., Parlier, Y., 2016. A continuous and analytical modeling for kites as auxiliary propulsion devoted to merchant ships, including fuel saving estimation. *Renewable Energy*, 86, 483-496. https://doi.org/10.1016/j.renene.2015.08.036

[66] Nelissen, D., Traut, M., Köhler, J., 2016. Study on the analysis of market potentials and market barriers for wind propulsion technologies for ships.

[67] Delgado, V. A., 2016. *Skysail: Estudio Del Sistema y Aportacion a La Sostenibilidad En El Transporte Maritimo*. PhD thesis, Universitat Politècnica de La Catalunya, Barcelona.

[68] Bigi, N., Roncin, K., Leroux, J-B., Parlier, Y., 2020. Ship Towed by Kite: Investigation of the Dynamic Coupling. *Journal of Marine Science and Engineering*, 8(7), 486. https://doi.org/10.3390/jmse8070486

[69] Xing, H., Spence, S., Chen, H., 2020. A comprehensive review on countermeasures for CO2 emissions from ships. *Renewable and Sustainable Energy Reviews*, 134, 110222. https://doi.org/10.1016/j.rser.2020.110222

[70] Al-Enazi, A., Okonkwo, E. C., Bicer, Y., Al-Ansari, T., 2021. A review of cleaner alternative fuels for maritime transportation. *Energy Reports*, 7, 1962-1985. https://doi.org/10.1016/j.egyr.2021.03.036

[71] Julià, E., Tillig, F., Ringsberg, J. W., 2020. Concept design and performance evaluation of a fossil-free operated cargo ship with unlimited range. *Sustainability*, 12(6609). https://doi.org/10.3390/su12166609

[72] Comer, B., Chen, C., Stolz, D., Rutherford, D., 2019. Rotors and bubbles: Route-based assessment of innovative technologies to reduce ship fuel consumption and emissions. *J. ICCT working pa per*, 11(6).

[73] Bureau Veritas, 2024. Technology report: Wind propulsion. Technical report, https://marine-offshore.bureauveritas.com/wind-propulsion-report (accessed 24th August 2025)

[74] IWSA, 2024. Vessel List, https://www.wind-ship.org/vessel-list/ (accessed 22nd August 2025)

[75] Grain de Sail, 2025. Our cargo sailboats, https://graindesail.com/en/cargo-sailboat-grain-de-sail-iii/ (accessed 24th August 2025).

[76] Guzelbulut, C., Suzuki, K., 2023. Optimal Design of Rotor Sails Based on Environmental Conditions and Cost. *Journal of Marine Science and Engineering*, 12(1), 31. https://doi.org/10.3390/jmse12010031

[77] Transport EC, 2025. New EU rules aiming to decarbonise the maritime sector take effect - European Commission. https://transport.ec.europa.eu/news-events/news/new-eu-rules-aiming-decarbonise-maritimesector-take-effect-2025-01-10_en (accessed 24th August 2025)

[78] Velic Consulting, 2025. WASP Vessels - Tracking Map: https://velic-consulting.com/?page_id=309 (accessed 20th August 2025)

[79] Anemoi, 2024. M/V Afros - The world's first rotor sail bulk carrier. https://anemoimarine.com/afros-rotorsail-bulk-carrier/, (accessed 20th August 2025)

[80] Socatra. Alcyone - Socatra, https://socatra.com/flotte/alcyone/ (accessed 20th August 2025)

[81] MarineTraffic, 2025. Alcyone Vessel Characteristics: Détails pour: ALCYONE (Oil/Chemical Tanker) - IMO 9929819MMSI 9929819Call Sign FMSF enregistré en France | AIS Marine Traffic. https://www.marinetraffic.com/en/ais/details/ships/shipid:6930996/mmsi:228423800/imo:9929819/vessel:ALC (accessed 20th August 2025)

[82] NorthSeaRegion. 2020. Ship profile MS Annika Braren, Interreg VB North Sea Region Programme. https://northsearegion.eu/wasp/our-technologies/flettner-rotor-eco-flettner/ship-profile-msannika-braren/index.html (accessed 20th August 2025)

[83] Mandra, J. O., 2023. WASP draws to a close with five vessels retrofitted, https://www.offshore-energy.biz/wasp-draws-to-a-close-with-five-vessels-retrofitted/ (accessed 31st October 2025)

[84] Anemoi, 2024. Berge Neblina VLOC installed with 4 folding Anemoi Rotor Sails. https://anemoimarine.com/vloc-rotor-sails-berge-neblina/ (accessed 11th September 2025)

[85] Jufo Peltomaa, 2022. Norsepower installs Rotor Sail on second Scandlines hybrid ferry following successful results achieved on sister vessel, https://www.norsepower.com/post/norsepower-installs-rotor-sail-on-second-scandlines-hybrid-ferry/ (accessed 20th August 2025)

[86] Bureau Veritas, 2025. Bureau Veritas strengthens support for wind propulsion with Union Maritime's Methanol-ready tankers | Marine & Offshore. https://marine-offshore.bureauveritas.com/newsroom/bureau-veritas-strengthens-support-wind-propulsion-unionmaritimes-methanol-ready-tankers (accessed 20th August 2025)

[87] The Maritime Executive, 2020. First Rotor Sails Retrofitted to MOL Capesize Bulker Operating for Vale. https://maritime-executive.com/article/first-rotor-sails-retrofitted-to-mol-capesize-bulkeroperating-for-vale (accessed 21st August 2025)

[88] ShipeOffshore, 2024. German Government funds rotor sail installation on newly delivered cement carrier *Cemcommander*. https://www.shipandoffshore.net/ship-repair/detail/news/german-government-fundsrotor-sail-installation-on-newly-delivered-cement-carrier-cemcommander.html (accessed 22nd August 2025)

[89] World Reports Org., 2023. China makes headway in domestically-developed rotor sails with 1st ship installation, https://www.worldports.org/china-makes-headway-in-domestically-developed-rotor-sails-with-1st-ship-installation/ (accessed 22nd August 2025)

[90] Oldendorff, 2024. Oldendorff Successfully Installs Rotor Sails. https://www.oldendorff.com/news/oldendorffsuccessfully-installs-flettner-rotors (accessed 22nd August 2025)

[91] Mandra, J. O., 2023. World's largest short-sea RO/RO fitted with rotor sails, https://www.offshore-energy.biz/worlds-largest-short-sea-roro-fitted-with-rotor-sails/ (accessed 22nd August 2025)

[92] The Maritime Executive, 2022. Rotor Sails to Be Fitted to Largest Short Sea Ro/Ro. https://maritimeexecutive.com/article/rotor-sails-to-be-fitted-to-largest-short-sea-ro-ro (accessed 22nd August 2025)

[93] Norsepower, 2021. Viking Grace completes Rotor Sail trials, https://www.norsepower.com/post/viking-grace-completes-rotor-sail-trials/ (accessed 23rd August 2025)

[94] ZESTAs. Dealfeng receives CCS approval and signs China's first offshore rotor sail deal, https://zestas.org/dealfeng-receives-ccs-approval-and-signs-chinas-first-offshore-rotor-sail-deal/ (accessed 23rd August 2025)

[95] China daily, 2024. Taizhou shipyard makes breakthrough, https://subsites.chinadaily.com.cn/ezhejiang/etaizhou/202404/29/c_983568.htm (accessed 23rd August 2025)

[96] Naida Prevljak, 2024. Combination carrier Koryu fitted with rotor sails - Offshore Energy. https://www.offshore-energy.biz/combination-carrier-koryu-fitted-with-rotor-sails/ (accessed 23rd August 2025)

[97] Gary Howard, 2025. Second CO2 carrier delivered to Northern Lights. https://www.seatrade-maritime.com/sustainability/second-co2-carrier-delivered-to-northern-lights (accessed 23rd August 2025).

[98] Mfame, 2024. Oceanus Aurora equipado com velas de rotor Norsepower para transporte sustentável, https://mfame.guru/oceanus-aurora-equipped-with-norsepower-rotor-sails-for-sustainable-shipping/ (accessed 23rd August 2025)

[99] Sam Chambers, 2021. 325,000 dwt giant bulker gets the wind rotor treatment, Vale keen on further sail investments, https://splash247.com/325000-dwt-giant-bulker-gets-the-wind-rotor-treatment-vale-keen-on-further-sail-investments/ (accessed 23rd August 2025)

[100] Lloyds Register, 2023. Rotor sails taking off | LR. https://www.lr.org/en/knowledge/horizons/december2023/rotor-sails-taking-off/ (accessed 23rd August 2025)

[101] Anemoi, 2024. TR Lady - Tufton Kamsarmax with 3 Anemoi Rotor Sails. https://anemoimarine.com/kamsarmax-rotor-sails-tr-lady/ (accessed 23rd August 2025)

[102] The Maritime Executive, 2025. Japanese Coal Carrier Completes First Trip with Retrofitted Rotor Sail, https://maritime-executive.com/article/japanese-coal-carrier-completes-first-trip-with-retrofitted-rotor-sail (accessed 24th August 2025)

[103] MarineTraffic, 2024. Vessel Characteristics: Ship NEW VITALITY (Oil Products Tanker) Registered in Hong Kong - Vessel details, Current position and Voyage information - IMO 9799173MMSI 9799173Call Sign VRSF7 | AIS MarineTraffic. https://www.marinetraffic.com/en/ais/details/ships/shipid:5748919/mmsi:477231700/imo:9799173/vessel:NEWVITALITY (accessed 24th August 2025)

[104] BAR Technologies, 2025. Berge Olympus, https://www.bartechnologies.uk/project/berge-olympus/ (accessed 24th August 2025)

[105] Naos Design, 2021. The wind propulsion system by Naos Design and Concrane makes its debut on the new GNV Bridge. https://www.naos-design.com/news/sulla-nuova-gnv-bridge-esordisce-anche-lapropulsione-eolica-di-naos-design-e-concrane/, (accessed 24th August 2025)

[106] Mitsui OSK Lines Ltd, MOL, 2024. MOL Announces Delivery of Bulk Carrier Green Winds, 2nd Vessel Equipped with Wind Challenger Hard Sail Propulsion System | Mitsui O.S.K. Lines. https://www.mol.co.jp/en/pr/2024/24084.html (accessed 24th August 2025)

[107] ShipeOffshore, 2024. MOL to retrofit sail propulsion system on coal carrier *Kurotakisan Maru*, https://www.shipandoffshore.net/ship-repair/detail/news/mol-to-retrofit-sail-propulsion-system-oncoal-carrier-kurotakisan-maru-ii.html (accessed 24th August 2025)

[108] Blain, L., 2022. Giant supertanker uses 9.8% less fuel thanks to 130-foot sails. https://newatlas.com/marine/new-aden-supertanker-sails/ (accessed 24th August 2025)

[109] MarineTraffic, 2024. New Vitality | AIS MarineTraffic. https://www.marinetraffic.com/en/photos/of/ships/shipid:5 (accessed 24th August 2025)

[110] World Nuclear News, 2024. British nuclear transport ship fitted with innovative sail. https://world-nuclear-news.org/articles/british-nuclear-transport-ship-fitted-with-innovative-sail (accessed 24th August 2025)

[111] Beyond the Sea, 2023. The Seakite - Beyond the sea. https://beyond-the-sea.com/en/the-seakite/ (accessed 24th August 2025)

[112] Rosenoegger, J., 2025. MOL's Wind Challenger: Height-Adjustable Rigid Wing Sails for Commercial Shipping. https://maritime-innovations.com/mol-wind-challenger-rigid-wing-sail-technology/ (accessed 25th August 2025)

[113] European Commission, 2023. New wind powered cargo ship sets sail - European Commission. https://cinea.ec.europa.eu/news-events/news/new-wind-powered-cargo-ship-sets-sail-2023-0822_en (accessed 26th August 2025)

[114] Beyond the sea, 2024. Beyond The Sea has begun installing its kite on the Forbin by Geogas. https://beyond-the-sea.com/en/beyond-the-sea-has-begun-installing-its-kite-on-the-forbin-by-geogas/ (accessed 24th August 2025)

[115] ActuNautique Magazine, 2025. UNOC3 - Premiers essais de traction par kite sur le remorqueur de haute-mer Jason au large de Nice. https://www.actunautique.com/2025/06/unoc3-premiers-essais-de-traction-parkite-sur-le-remorqueur-de-haute-mer-jason-au-large-de-nice.html (accessed 24th August 2025)

[116] Prevljak, N. H., 2024. Wind-powered, diesel-electric Amadeus Saffier joins HGK Shipping. https://www.offshore-energy.biz/wind-powered-diesel-electric-amadeus-saffier-joins-hgkshipping/ (accessed 24th August 2025)

[117] NorthSeaRegion, 2025. Ship profile Ankie, Interreg VB North Sea Region Programme https://northsearegion.eu/wasp/our-technologies/suction-wings-retractable-econowind/ship-profileankie/index.html (accessed 24th August 2025)

[118] VesselFinder, 2025. ANNA, General Cargo Ship - Details and current position - IMO 9361110 - VesselFinder. https://www.vesselfinder.com/vessels/details/9361110 (accessed 24th August 2025)

[119] Prevljak, N. H., 2025. Bound4blue: 'World's largest' suction sails installed on LDC juice carrier, https://www.offshore-energy.biz/bound4blue-worlds-largest-suction-sails-installed-on-ldc-juice-carrier/ (accessed 15th July 2025)

[120] Barlett, P., 2025. Bow Olympus nears end of close-to-zero-emission trans-Atlantic voyage. https://www.seatrade-maritime.com/wind-powered-ships/bow-olympus-nears-end-of-close-tozero-emission-trans-atlantic-voyage (accessed 26th August 2025)

[121] Eason, C., 2024. World first for Chemship: Suction sails set to drive down emissions. https://www.tradewindsnews.com/technology/world-first-for-chemship-suction-sails-set-todrive-down-emissions/2-1-1599776 (accessed 26th August 2025)

[122] Bakker, N., 2024. Anthony Veder pioneers wind-assisted propulsion on gas carrier. https://anthonyveder.com/blog/2024/10/11/wind-assisted-propulsion-on-gas-carrier (accessed 26th August 2025)

[123] Marine Insight News Network, 2023. Biggest Suction Sails Ever Built Installed on Dutch Short-Sea Cargo Ship https://www.marineinsight.com/videos/biggest-suction-sails-ever-built-installed-on-dutch-short-sea-cargo-ship-eems-traveler/ (accessed 15th July 2025)

[124] The Maritime Executive, 2024. Dutch Cargo Ship Sails with New Wind-Assisted Technology. https://maritimeexecutive.com/article/dutch-cargo-ship-sails-with-new-wind-assisted-technology (accessed 26th August 2025)

[125] Arinci, M., 2024. Jumbo installs wind assisted propulsion to Jumbo Jubilee in latest decarbonisation move. https://www.jumbomaritime.nl/shipping/jumbo-maritime-installs-wind-assisted-propulsion-tojumbo-jubilee-in-latest-decarbonisation-move (accessed 26th August 2025)

[126] ONE Line, 2023. ONE Embarks on Wind Propulsion Trial for a Sustainable Maritime Future, https://www.one-line.com/en/news/one-embarks-wind-propulsion-trial-sustainable-maritime-future (accessed 26th August 2025)

[127] Guedj, A., 2025. Marfret Niolon equipped with new, more powerful sails, https://www.marfret.com/en/news-nl-en/marfret-niolon-equipped-with-new-more-powerful-sails/ (accessed 26th August 2025)

[128] Marine Insight News Network, 2024. NYK Group Installs Its First Wind-Assisted Ship-Propulsion Units On Bulk Carrier, https://www.marineinsight.com/shipping-news/nyk-group-installs-its-first-wind-assisted-ship-propulsion-units-on-bulk-carrier/ (accessed 15th July 2025)

[129] MarineTraffic, 2025. Vessel Characteristics: Ship ODDA MARIE (General Cargo) Registered in Finland - Vessel details, Current position and Voyage information - IMO 9123570MMSI 9123570Call Sign OJTS | AIS Marine Traffic. https://www.marinetraffic.com/en/ais/details/ships/shipid:378589/mmsi:230691000/imo:9123570/vessel:ODDA MARIE (accessed 15th July 2025)

[130] bound4blue, 2025. Bound4blue completes eSAIL® installation on EPS tanker with three 22-meter-high non-ATEX suction sail. https://www.xindemarinenews.com/en/carrier/2025/0224/58548.html (accessed 15th July 2025)

[131] Martinez, C., 2025. Green steel meets sails: MOL's 'first-of-its-kind' vessel champions clean shipping | World Ports Organization. https://www.worldports.org/green-steel-meets-sails-mols-first-of-its-kindvessel-champions-clean-shipping (accessed 15th July 2025)

[132] Kypriotaki, A., 2025. Dutch yard delivers coasters equipped with wind propulsion. https://safety4sea.com/dutch-yard-delivers-coasters-equipped-with-wind-propulsion/ (accessed 15th July 2025)

[133] CSL Ships, 2024. MV Sunnanvik – First Cargo Ship With Sails on the Great Lakes. https://cslships.com/news/mvsunnanvik-first-cargo-ship-with-sails-on-the-great-lakes/ (accessed 15th July 2025)

[134] Bahtić, F., 2024. Bound4blue installs first fixed suction sails on RoRo ship. https://www.offshoreenergy.biz/bound4blue-installs-first-fixed-suction-sails-on-roro-ship (accessed 15th July 2025)

[135] Boysen, J. C., 2025. Hydro and Wilson launch innovative and energy efficient transport solution. https://www.hydro.com/en/global/media/news/2025/hydro-and-wilson-launch-innovative-andenergy-efficient-transport-solution (accessed 15th July 2025)

[136] Young, A., 2025. Wind-powered cargo ship begins maiden voyage in 'milestone' for sustainable shipping. https://www.thehullstory.com/allarticles/sustainable-shipping-airwing (accessed 15th July 2025)

[137] Peters, A., 2024. The world's largest wind-powered cargo ship just made its first delivery across the Atlantic. https://www.fastcompany.com/91185144/the-worlds-largest-wind-powered-cargo-ship-justmade-its-first-delivery-across-the-atlantic (accessed 17th July 2025)

[138] iMarine News, 2024. Piriou Shipyard Delivers a 1,100 DWT Sail-Powered Cargo Vessel, https://www.imarinenews.com/13284.html (accessed 17th July 2025)

[139] Zéphyr Borée, 2024. Canopée. https://zephyretboree.com/en/projects/canopee/ (accessed 23rd October 2024)

[140] DIV Group, 2025. Golden Horizon - Vessels. https://www.brodosplit.hr/en/vessels/golden-horizon (accessed 17th July 2025)

[141] Kerr, J., 2018. Le Ponant Solid Sail technology, https://www.theluxurycruisereview.com/luxury-ponant-ship-gets-new-solid-sail/ (accessed 17th July 2025)

[142] Star Clipper Cruises, 2025. Royal Clipper. https://www.starclippercruises.co.uk/ships/royal-clipper (accessed 17th July 2025)

[143] Manske, L., 2024. Luxury Escapes For Ocean Lovers: 'Sea Cloud' Tall Ship Cruises. https://www.forbes.com/sites/lauramanske/2023/12/28/2024-luxury-escapes-for-ocean-loverssea-cloud-tall-ship-cruises/ (accessed 17th July 2025)

[144] Windstar, 2025. Wind Spirit | Small Cruise Ship | Windstar Cruise Line. https://www.windstarcruises.com/ships/wind-spirit/ (accessed 17th July 2025)

[145] Windstar, 2025 Wind Star| Small Cruise Ship | Windstar Cruise Line. https://www.windstarcruises.com/ships/wind-star/ (accessed 17th July 2025)

[146] Windstar, 2025 Wind Surf | Small Cruise Ship | Windstar Cruise Line. https://www.windstarcruises.com/ships/wind-surf/ (accessed 17th July 2025)

[147] Hakirevic, N. P., 2025. Canopée proves wind propulsion potential on transatlantic voyage, https://www.offshore-energy.biz/canopee-proves-wind-propulsion-potential-on-transatlantic-voyage/ (accessed 15th August 2025)

[148] Kume, K., Hamada T., Kobayashi H., Yamanaka S., 2022. Evaluation of aerodynamic characteristics of a ship with Flettner rotors by wind tunnel tests and RANS-based CFD. *Ocean Engineering*, 254, 111345. https://doi.org/10.1016/j.oceaneng.2022.111345

[149] Kramer, J. V., Steen, S., 2022. Simplified test program for hydrodynamic CFD simulations of wind-powered cargo ships. *Ocean Engineering*, 244, 110297. https://doi.org/10.1016/j.oceaneng.2021.110297

[150] Tillig, F. Ringsberg, J. W., 2019. A 4 DOF simulation model developed for fuel consumption prediction of ships at sea. *Ships and Offshore Structures*, 14, 112, 120. https://doi.org/10.1080/17445302.2018.1559912

[151] Ghorbani, M., Slaets, P., Lacey, J., 2023. A numerical simulation tool for a wind assisted vessel verified with logged data at sea. *Ocean Engineering*, 290, 116319. https://doi.org/10.1016/j.oceaneng.2023.116319

[152] Rehmatulla, N., Calleya, J., Smith, T., 2017. The implementation of technical energy efficiency and CO2 emission reduction measures in shipping. *Ocean Engineering*, 139, 184-197. https://doi.org/10.1016/j.oceaneng.2017.04.029

[153] Ma, Y., Bi, H., Hu, M., Zheng, Y., Gan, L., 2019. Hard sail optimization and energy efficiency enhancement for sail-assisted vessel. *Ocean Engineering*, 173, 687-699. https://doi.org/10.1016/j.oceaneng.2019.01.026

[154] Kerwin, J. E., Advance Draft, MIT Projectf, Nev' London, 1975. A velocity prediction program for ocean racing yachts. *Technical report*, MIT, Report - Department of Ocean Engineering Massachusetts Institute of Technology.

[155] Charlou, M., Babarit, A., Gentaz, L., 2023. A new validated open-source numerical tool for the evaluation of the performance of wind-assisted ship propulsion systems. *Mechanics & Industry*, 24, 26. https://doi.org/10.1051/meca/2023026

[156] Reche-Vilanova, M., Hansen H., Bingham, H. B., 2021. Performance Prediction Program for Wind-Assisted Cargo Ships. *Journal of Sailing Technology*, 6(01), 91-117. https://doi.org/10.5957/jst/2021.6.1.91

[157] Zhang, R., Huang, L., Peng, G., Ma, R., Wang, K., Tian, F., Song, Q., 2023. A novel method of desynchronized operation of sails for ship wind-assisted propulsion system. *Ocean Engineering*, 288, 115964. https://doi.org/10.1016/j.oceaneng.2023.115964

[158] Zeng, Q., Zhang, X., Cai, W., Zhou, Y., 2023. Wake distortion analysis of a Dynarig and its application in a sail array design. *Ocean Engineering*, 278, 114341. https://doi.org/10.1016/j.oceaneng.2023.114341

[159] Li, Q., Nihei, Y., Nakashima, T., Ikeda, Y., 2015. A study on the performance of cascade hard sails and sail-equipped vessels. *Ocean Engineering*, 98, 23-31. https://doi.org/10.1016/j.oceaneng.2015.02.005

[160] Plessas, T., Papanikolaou, A., 2025. Multi-Objective Optimization of Ship Design for the Effect of Wind Propulsion. *Journal of Marine Science and Engineering*, 13(1), 167. https://doi.org/10.3390/jmse13010167

[161] Bentin, M., Zastrau, D., Schlaak, M., Freye, D., Elsner, R., Kotzur, S., 2016. A New Routing Optimization Tool-influence of Wind and Waves on Fuel Consumption of Ships with and without Wind Assisted Ship Propulsion Systems. *Transportation Research Procedia*, 14, 153-162. https://doi.org/10.1016/j.trpro.2016.05.051

[162] Smith, T., Newton, P., Winn, G., La Rosa, A. G., 2013. Analysis techniques for evaluating the fuel savings associated with wind assistance. In *Low Carbon Shipping Conference*.

[163] Anemoi, 2025. LR Performance Verification Paper, Technical report, https://anemoimarine.com/wp-content/uploads/2025/07/Anemoi-LR-Performance-Verification-Paper.pdf (accessed 18th July 2025)

[164] Bordogna, G., Muggiasca, S., Giappino, S., Belloli, M., Keuning, J. A., Huijsmans, R. H. M., Van 'T Veer, A. P., 2019. Experiments on a Flettner rotor at critical and supercritical Reynolds numbers. *Journal of Wind Engineering and Industrial Aerodynamics*, 188, 19-29. https://doi.org/10.1016/j.jweia.2019.02.006

[165] Thies, F., Ringsberg, Jonas W., 2023. Retrofitting WASP to a RoPax Vessel—Design, Performance and Uncertainties. *Energies*, 16(2), 673. https://doi.org/10.3390/en16020673

[166] Arabnejad, M. H., Thies, F., Yao, H-D., Ringsberg, J. W., 2024. Zero-emission propulsion system featuring, Flettner rotors, batteries and fuel cells, for a merchant ship. *Ocean Engineering*, 310, 118618. https://doi.org/10.1016/j.oceaneng.2024.118618

[167] Al-Baity, O., Ahmed, Y., Elgohary, M., 2026. Hybrid marine power systems: techno-economic and environmental optimisation of alternative fuel pathways. *Brodogradnja*, 77(3), 77304. https://doi.org/10.21278/brod77304

[168] Matija, V., Kalajdžić, M., Ponkratov, D., 2026. CFD approach to full-scale resistance: The Lucy Ashton case. *Brodogradnja,* 77(3), 77307. https://doi.org/10.21278/brod77307