Journal of
Marine Science and Engineering

MDPI

Review

Review of the Decision Support Methods Used in Optimizing Ship Hulls towards Improving Energy Efficiency

Mina Tadros [1,2,*], Manuel Ventura [1] and C. Guedes Soares [1]

[1] Centre for Marine Technology and Ocean Engineering (CENTEC), Instituto Superior Técnico, Universidade de Lisboa, Av. Rovisco Pais 1, 1049-001 Lisboa, Portugal; manuel.ventura@centec.tecnico.ulisboa.pt (M.V.); c.guedes.soares@centec.tecnico.ulisboa.pt (C.G.S.)

[2] Department of Naval Architecture and Marine Engineering, Faculty of Engineering, Alexandria University, Alexandria 21544, Egypt

* Correspondence: mina.tadros@centec.tecnico.ulisboa.pt

Abstract: This paper presents a review of the different methods and techniques used to optimize ship hulls over the last six years (2017–2022). This review shows the different percentages of reduction in ship resistance, and thus in the fuel consumption, to improve ships' energy efficiency, towards achieving the goal of maritime decarbonization. Operational research and machine learning are the common decision support methods and techniques used to find the optimal solution. This paper covers four research areas to improve ship hulls, including hull form, hull structure, hull cleaning and hull lubrication. In each area of research, several computer programs are used, depending on the study's complexity and objective. It has been found that no specific method is considered the optimum, while the combination of several methods can achieve more accurate results. Most of the research work is focused on the concept stage of ship design, while research on operational conditions has recently taken place, achieving an improvement in energy efficiency. The finding of this study contributes to mapping the scientific knowledge of each technology used in ship hulls, identifying relevant topic areas, and recognizing research gaps and opportunities. It also helps to present holistic approaches in future research, supporting more realistic solutions towards sustainability.

Keywords: energy efficiency; IMO; ship hull; decision support methods; regulations

Citation: Tadros, M.; Ventura, M.; Guedes Soares, C. Review of the Decision Support Methods Used in Optimizing Ship Hulls towards Improving Energy Efficiency. *J. Mar. Sci. Eng.* **2023**, *11*, 835. https://doi.org/10.3390/jmse11040835

Academic Editor: Vincenzo Crupi

Received: 27 March 2023
Revised: 11 April 2023
Accepted: 12 April 2023
Published: 15 April 2023

1. Introduction

Increasing energy efficiency in ships has become essential for reducing fuel consumption and exhaust emissions at a reasonable ship speed while increasing the amount of cargo. This topic attracts international organizations' interest in mitigating climate change, especially global warming, and achieving zero emissions by 2050. As the primary organization responsible for maritime activities, the International Maritime Organization (IMO) took the lead through the Marine Environment Protection Committee (MEPC) to apply stringent regulations, starting from 2000 until now, to reduce the level of different emissions from ships along different tiers.

As a result, nitrogen oxides (NO_x) were cut by 80% in 2016 compared with 2000 [1]. Sulphur oxides (SO_x) have been cut by 95% in emission control areas (ECAs) starting from 2015 compared with 2010, and by 90% in non-ECAs starting from 2020 compared with 2012 [2]. Carbon dioxide (CO_2) has been evaluated based on several indices, such as the Energy Efficiency Design Index (EEDI) for design purposes and Energy Efficiency Operational Indicator (EEOI) for operational purposes. Due to some limitations in these indices in presenting accurate estimations, the Energy Efficiency Existing Ship Index (EEXI) for design is under development. It will come into force at the beginning of 2023. Also, the Carbon Intensity Indicator (CII), which is still under development as well, will be used to evaluate a ship's performance along the trip [3,4]. The last indicator will rank the ship from A to E, where a Ship Energy Efficiency Management Plan (SEEMP) will be required to improve ship performance, mainly when the ship's ranking is located in the last two places (D and E). These new indices will be considered short-term solutions to enhance the SEEMP, which will be replaced by alternative fuels to mitigate the CO_2 emissions, as shown in Figure 1.

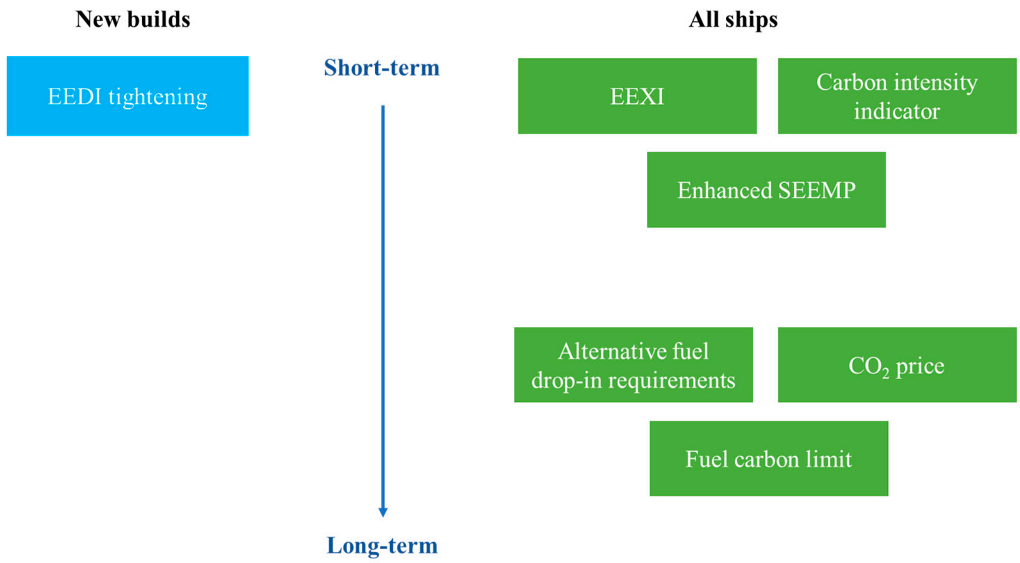

Figure 1. Indicative timeline for developing and implementing possible global policy measures.

Over the years, several techniques have been proposed to ensure ships' sustainability and improve their energy efficiency. These techniques cover the different parts of the ship from design and operational points of view [5].

The main technique to ensure sustainability is to keep upgrading the propulsion system and using alternative and clean fuels to reduce fuel consumption [6–8]. Therefore, optimization procedures are required in order to find the optimal configurations for operating the engine with lower consumption and emissions [9–14], as well as the use of alternative fuels such as natural gas or biofuel [15–19], with methanol and ammonia will to be used in the near future [20]. Figure 2 shows the different technologies and fuels on a pathway to zero-emissions shipping. This will require selecting the best waste heat recovery system (WHRS), the second technique used, to ensure the system's maximum benefit from the exhaust gas [21–24].

The third technique used is to install after-treatment systems such as selective catalytic reduction (SCR) for NO_x emissions reduction [25–27], scrubbers for SO_x emissions reduction [28–31] and carbon capture and storage (CCS) for CO_2 reduction [17,32]. Ship speed reduction is another solution already considered to significantly reduce the amount of fuel consumed [33–35]. Another concept considered during the design stage is selecting an optimum propeller to operate effectively and efficiently [36–42]. Combining all of these techniques in a ship routing code can achieve an accurate overview of the ship's performance and, in particular, the fuel consumption along the ship's routes [43–49].

From all these techniques used, the ship hull is the main part that requires optimization procedures towards energy efficiency by reducing the ship resistance, and thus the required power, and by holding the maximum amount of cargo [50]. More advantages will accrue from comparing computational fluid dynamics (CFD) results with empirical formulas [51].

In the past few years, several review papers have been published concerning an overview of the energy efficiency techniques used to improve ship performance towards the mitigation of greenhouse gas (GHG). These review papers provided the percentage of fuel consumption and exhaust emissions reduction of the different systems installed on board [17,52,53].

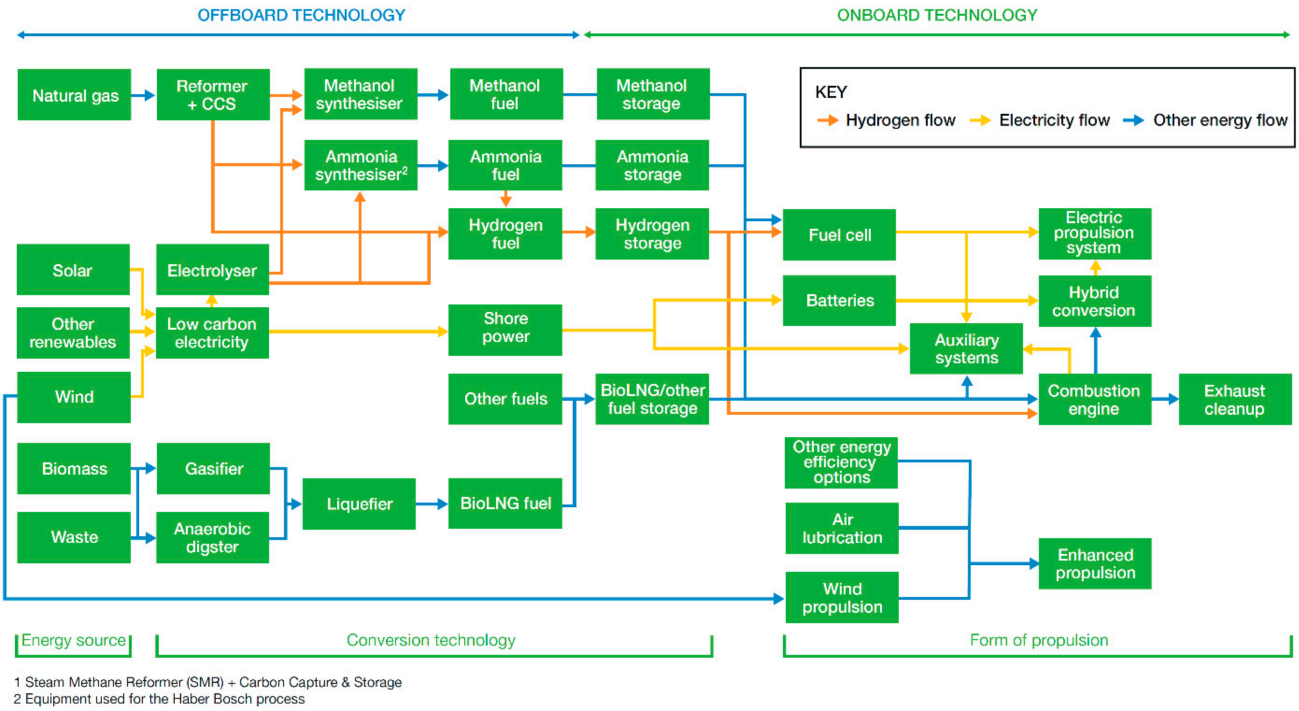

Figure 2. Technologies and fuels on a pathway to zero-emission shipping. Reproduced from [54], with permission from Department for Transport, 2019.

Hence, this paper aims to focus on the improvement performed on the main hull to reduce the resistance and increase the amount of cargo by analyzing the decision support techniques and map future research. This leads to the main question, which is:

What methods and techniques are adopted to improve ship energy efficiency and help the ship designer to achieve the optimal hull form in terms of design and operational conditions?

This paper covers the recent journal papers published over the last six years (2017–2022) based on the Scopus database, since the international regulations to reduce exhaust emissions have become applicable, as well as considering the rapid improvement in software tools and computer performance. This helps to extract the main findings related to energy efficiency and to identify the emerging trends and future research needs.

The remainder of this paper is organized as follows: Section 2 presents an overview of the decision support methods and techniques used in the literature review. Section 3 shows the application of the decision support methods in four research areas to improve hull performance. Finally, Section 4 presents some conclusions and recommendations for further research.

2. Decision Support Methods and Techniques

This section briefly describes the two common methods used in the literature to find the optimal solutions for ship hulls: operational research (OR) and machine learning (ML) techniques.

2.1. Operational Research

The OR techniques are considered one of the effective methods to find the optimal solutions for complex systems, where the machine can achieve more accurate results than manual computation [55]. It is an analytical method to find a system's optimal solution by defining one or more objectives, while complying with the limitations of given constraints. These kinds of methods are applied to achieve the optimal configurations of different complex systems. Usually, several numerical models are coupled to achieve optimal results, where one or more optimizers are implemented to evaluate the system's performance. The optimizers can be local or global according to the chosen problem and software and hardware performance.

In addition to deterministic optimization, stochastic optimization or optimization under uncertainty is a branch of optimization methods where the data or the model is uncertain, and the probability distribution can be estimated. This helps to optimize the expected performance of the system.

2.2. Machine Learning

ML is a data analysis method that automates the building of analytical models. It is an application of artificial intelligence (AI) where the developed systems can learn from data and make decisions without the intervention of humans [56]. ML has a different learning approach according to the type and amount of human supervision during the training and can adapt to new data and be applied to very complex problems where there is no solution with a typical approach, for instance, recognizing the ship type [57].

3. Application of Decision Support Methods and Techniques for Efficient Ship Hulls

In this section, the results from the literature review are presented and discussed, covering the different methods and techniques used to improve the ship hull form, hull structure, hull cleaning and hull lubrication.

3.1. Hull Form

The hull is considered the most notable structural entity of the ship, which holds and protects the ship's cargo, machinery, and accommodation spaces along the ship's trip. This is why it requires more attention during the preliminary stages of ship design, not only to ensure the safety of the ship but also to maximize the amount of cargo with the lowest required power to move the ship. Therefore, several types of hull series, such as series 60, are proposed as reference hulls, based on experimental tests, to assist the ship designers in easily selecting the best hull form for different hull parameters. To ensure high-precision surface finishes, the electro-discharge machining (EDM) technique is applied to highly complex geometries [58].

Uncertainty analysis, OR and ML techniques have become widely used to improve hull performance and can be easily coupled to any kind of software using application programming interfaces (API). Therefore, the study's goals consider single and multiple objectives for the different proposed optimization models.

Considering the energy efficiency indices during the computation becomes essential to evaluate the ship's performance and present a clear overview of the ship's energy efficiency. Therefore, Hou [59] used the uncertainty technique during the hull form optimization without constraints to minimize the EEOI based on the variation of ship speed. Also, Hou et al. [60] coupled different types of uncertainty and optimization techniques to minimize EEDI while finding the optimal hull parameters. These methods of uncertainty showed a great benefit in minimizing the values of the energy efficiency index.

Due to the complexity of the ship hull as a factor in achieving the most reduction in ship resistance, OR and ML effectively achieve highly accurate results. The research mainly focuses on the design conditions while reducing ship hull resistance; however, it has been extended recently to cover the operating conditions while considering the added resistance for different weather conditions, which is more realistic than only considering the concept of design.

In calm water conditions, Pechenyuk [61] applied an optimization technique to minimize ship resistance using CFD models by finding the longitudinal weight distribution and the corresponding hull contours. The results reduced the resistance of the optimized KRISO Container Ship (KCS) hull form by 8.9%. Li et al. [62] focused on optimizing the bow and the stern of the KCS, showing a reduction in total resistance and an improvement in wake fraction. Edalat and Barzandeh [63] used a genetic algorithm (GA) to optimize the hull form using empirical formulas and reduce the resistance, thus achieving lower fuel consumption. Huang et al. [64] focused on optimizing the fore part of the KCS based on the vortex search algorithm with gradient-based approximation. The algorithm is very fast at finding the global solution to reduce the resistance. To reduce problem complexity, Liu et al. [65] used sensitivity analysis to find the optimal hull form, showing the importance of using Sobol and kriging model-based tensor-product basis function (TPBF) methods to achieve the best solution.

After that, Wu et al. [66] developed OPTShip-SJTU as an optimization tool based on a multi-objective genetic algorithm (MOGA). This tool can optimize the hull of a DTMB Model 5415 using the obtained Pareto front at three design speeds. The results showed a reduction in the hull resistance validated by the CFD solver. Also, Liu et al. [67] used the same model to study the hull-propeller interaction, showing an improvement in the hydrodynamics of the ship; however, it takes several months to achieve the results in high fidelity. Goren et al. [68] used the quadratic programming technique to reduce wave resistance by modifying the hull parameters at the design waterline. The results were validated using experimental data, ensuring the accuracy of the developed model. The results proposed an effective model operating between Froude numbers greater than 0.21 and less than 0.4, where the generated wavelength is less than the ship length.

Duy et al. [69] focused on studying the flow around the transom stern using the CFD method based on various transom configurations. They concluded that the transom breadth and depth greatly affect ship resistance and the generated wave along the stern, which require an optimization technique to find the optimal design. Then, Zhang et al. [70] applied the immune quantum-behaved particle swarm optimization (IQPSO) as a global optimization technique to optimize both stem and stern and thus achieve a robust design in the prediction of the ship hull form. Cheng et al. [71] generated new surfaces using an optimization technique to improve the hydrodynamic performance of the ship by changing the bow shape, while keeping the same displacement and center of buoyancy.

Feng et al. [72] used the non-dominated sorting genetic algorithm II (NSGAII) as a multi-objective optimization technique to find the optimal hull form characterized by nine parameters to minimize the resistance and the wake flow. The results show a reduction in ship resistance by 1.59%, while the wake flow is reduced by 17.8%, compared with the original hull. Also, Tezdogan et al. [73] used a developed model coupling CFD and a nonlinear optimizer to find the optimal parameters of a fishing boat while reducing the ship resistance for the same displacement and at a defined speed.

Hou et al. [74] used a reliability-based optimization design (RBOD) to reduce the EEDI by optimizing hull parameters using the Monte Carlo simulation technique. The concept showed effectiveness in reaching a solution, though more reliability constraints could improve the quality of the model. Adaptive Simulated Annealing (ASA) was the considered optimizing algorithm to find the optimal design variables while increasing the moulded volume and decreasing the ship resistance for a given speed and propulsive coefficient.

By considering twin skeg as presented by Lin et al. [75], the resistance is reduced by 5.5% based on CFD computation and a surrogate model, where the optimization technique (NSGA-II) was used to find the optimal design with high accuracy and low time cost. The model could be more effective by considering the hull, propeller and rudder interaction. Furthermore, Lindstad and Bø [76] suggested that the slender hull form was more effective than the conventional hull in reducing ship resistance and thus reducing the required power in the ship, and could reach a reduction in GHG by 7–9%.

Cheng et al. [77] performed multi-velocity simulations. They used a developed model coupling CFD and a multi-objective genetic algorithm to reduce the wave-making resistance by finding the optimal shape of the bow and its parameters. This tool was considered practical for engineering applications. While the model was very effective, it was time-consuming, and it would benefit from considering the maneuvering and seakeeping behaviour of the ship during the optimization. Qiang et al. [78] performed a data mining approach after performing multi-objective optimization procedures to achieve the best design of the bulbous bow and the hull section to reduce the resistance at both low and high speeds. It was shown that a longer bulb and U- shaped body plan could reduce the wave-making resistance.

Guan et al. [79] improved the hull design of a large tanker by developing a method for the parametric design of the hull surface. This method is based on energy optimization procedures and takes into account several design procedures, while it is limited in considering the hydrodynamic performance from model tests.

Seok et al. [80] improved the bow shape of a tanker ship using design of experiment (DoE) and CFD methods. As a result, they reduced the added resistance by 52% compared with the original hull. Jung and Kim [81] optimized the hull form of KVLCC2 using MOGA by minimizing the total resistance of a ship in waves and the speed loss due to the existence of additional resistance. Different hull forms were proposed using a Pareto front and compared to the original hull. Skoupas et al. [82] used the NAPA [83] software environment to find the design variables of a roll-on/roll-off (Ro-Ro) passenger ship, taking into account transport capacity and economic viability, in addition to the propulsive power, while considering the intact and damaged stability as constraints.

Coppedè et al. [84] used trained machine learning techniques based on the Gaussian process-response surface method to generate multi-dimensional surfaces for optimization procedures, which have been validated using high-fidelity CFD simulations. Zhang et al. [85] used a deep belief network (DBN) as a machine learning technique to reduce wave-making resistance by finding the optimal hull parameters of a Wigley ship. As a result, the accuracy of the results was much higher than using the traditional surrogate model presented in the paper. Zhang [86] combined the DBN and research operation to optimize the bow shape as a way to minimize the total resistance. It was concluded that the method was suitable for finding the optimal solution. More parameters would be beneficial to improve the machine learning method. By applying Self-Organizing Maps (SOM) and Model-based Annealing Random Search (MARS) as in [87], the design space could be reduced and the optimization problem could be faster in finding the optimal solution.

Feng et al. [88] optimized the hull of a multi-purpose wind offshore supply vessel to reduce the total resistance. The resistance was computed based on a potential flow boundary element method and a Reynolds-averaged Navier–Stokes equation solver coupled with two multi-objective optimization algorithms. They found that a thinner and longer bulbous bow could greatly reduce resistance between 11 and 14 knots, while a bloated bulbous bow would be more effective for higher speeds. Zhao et al. [89] optimized the hull and the bulbous bow of a trawler separately using a developed model coupling CFD and CAESES software. The results from the optimization model were validated using experimental tests and showed a reduction in ship resistance for different operational conditions. However, optimizing both parts at the same time would achieve more accurate results. Wang et al. [90] developed an optimization model coupling a uniform design (UD), free-form deformation method (FFD), radial basis neural network (RBFNN) and a series of GAs to optimize the hull form based on more than three objectives proposed. The results, which were validated using experimental data, showed an improvement in ship resistance and wake flow in full load and ballast conditions. Feng et al. [91] found the optimal hull form according to the optimized bow thrusters to improve the propulsion efficiency and reduce the pressure along the ship hull.

In terms of seakeeping, Zha et al. [92] optimized ship hull form to reduce calm water resistance and improve the vertical motion performance using CFD solvers. Based on the different proposed cases in the Pareto front, the optimization tool showed effectiveness in helping the ship designer to find the optimal hull form based on given constraints.

In weather conditions, Lee et al. [93] introduced a preliminary study on the effects of motion, incident wave, and green-water allowance around the bow region. They studied the effect of bow shape on ship performance using experimental tests for two modified hull forms from the parent hull of KVLCC2. They concluded that Ax-bow shows lower added resistance among the cases, while the motion responses are unaffected.

Zhang et al. [94] achieved a reduction by up to 4.41% in ship resistance in waves, calculated by the Reynolds Averaged Navier–Stokes (RANS) method when optimizing the bow of two hulls using CFD models coupled with a nonlinear optimizer. This model could lay the foundation for further optimization procedures of full-scale ships. Lee et al. [95] used GA and ML to optimize the bulbous bow and, thus, the corresponding hull parameters to reduce the ship resistance and predict the added resistance due to waves. They proposed an alternative method that saves time and effort to train the data from experimental tests (12 cases) and generate a new prediction function to be further used during the early design process.

Kim et al. [96] found the optimal hull parameter to reduce ship resistance in calm water and weather conditions. Based on GA, the optimal hull is thinner and longer compared with the parent hull. A reduction in ship resistance was achieved by 3.58%, while the speed losses were reduced by 10.2%. The authors confirmed that optimizing the hull in weather conditions could increase the ship's energy efficiency more than in calm water conditions. Feng et al. [97] used a multi-objective optimization algorithm to find the optimal ship parameters of containerships. The computed results were compared to experimental data. Based on several generated designs, the wave-added resistance and the total ship resistance in regular waves were successfully reduced while affecting the ship motions in head waves.

As the slow steaming technique is followed by several ships to cut the level of fuel consumption significantly, it is interesting to optimize the ship hull form under these operational conditions. Yin et al. [98] applied an optimization method to find a container ship's optimal bulbous bow form under various service conditions, especially the slow steaming conditions, providing more practical computations along the ship route than a single specification design.

In addition to finding the optimal hull form, Hou et al. [99] applied the energy-saving device (underwater stern foil) concept to reduce the resistance and improve motion response based on experimental data. As a result, the resistance and the oscillating trim amplitude could be reduced by 6.4% and 26% at high speeds, respectively.

3.2. Hull Structure

During the construction, steel, with different grades, is still the common material used in a ship hull, which is approved by the classification societies according to the ship type and the loads applied to the structure.

In terms of energy efficiency, Gilbert et al. [100] applied a life cycle assessment approach to reuse steel to reduce CO_2 emissions. This approach can also improve the management of the shipbreaking and recycling industry, which requires stringent safety aspects [101], and can reduce CO_2 emissions by 29% with a 100% reusable hull and by 10% with a 50% reusable hull. However, more cooperation between public and private organizations is required to ensure steel quality. Based on the results of the same method [102], renewing steel every ten years in addition to annual hull inspections and re-coating can achieve significant cost reductions and contribute to reducing hull resistance.

These studies have been extended by applying a multi-objective probabilistic optimization process (MOPOP). Continuous long-term structural health monitoring is studied for efficient service life management [103]. This model can assess fatigue damage by minimizing the expected damage detection, the expected maintenance delay and the expected life-cycle cost while maximizing the damage detection time-based reliability index and the expected service life extension. Zareei and Iranmanesh [104] optimized the maintenance planning of the ship structure using a multi-objective optimization problem. This optimization model is based on minimizing the structure's life-cycle maintenance costs, including inspection and repair costs, and minimizing the risk of structural failure during the ship's life.

In terms of ship design, Kim and Paik [105] applied a multi-objective optimization model to minimize the structure's weight and maximize the safety aspects. They achieved a 20% reduction in required man-hours, a 3% reduction in structural weight, and improved safety factors. Yu et al. [106] used the first-order method to find the optimal solution, which showed a reduction in the weight of the superstructure using composite material by 30% compared with a steel superstructure. Garbatov and Huang [107] optimized the ship structural components subjected to stochastic loads to avoid local buckling and minimize the component net-section area, lateral deflection, and fatigue damage. Based on the Pareto frontier, the optimal solution decreased the section area by 9%. Silva-Campillo et al. [108] minimized the structure's weight by finding the geometry of an innovative bracket in the bow and ensuring the buckling strength. The results showed valuable design criteria in achieving the objective of the study. Mancuso et al. [109] combined finite element analysis (FEM) and topology optimization to find the optimal reinforcement places inside the hull and relevant improvements were found in terms of reduction of moments of inertia and local stiffness.

By considering the capacity of cargo, Jafaryeganeh et al. [110] and Jafaryeganeh et al. [111] optimized the internal layout of a shuttle tanker using a multi-objective optimization model. This developed model could minimize the oil outflow parameter, maximize the cargo capacity and minimize the longitudinal bending moment while finding the positions of watertight members in the internal layout. In addition, Jafaryeganeh et al. [112] extended the previous work covering uncertainty analysis for a more realistic robust design.

3.3. Hull Cleaning

Hull cleaning is an essential process that is required frequently to remove the layer of biofilms on the structure below the waterline, to ensure that the ship has lower resistance, consumes less fuel and reduces speed losses, as shown in Figure 3. For instance, increasing the resistance by 30% due to biofouling for a 100,000 DWT tanker can increase the consumption of fuel by 12 tons/day [113] or increase the fuel consumption by 10% after ten years of operation [114,115].

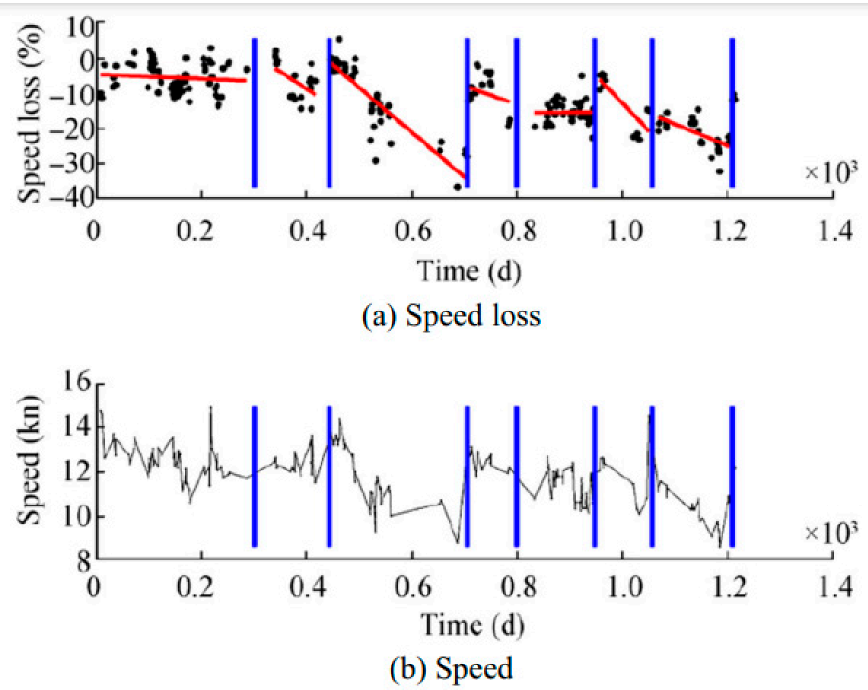

Figure 3. Variation in speed loss and measured speed of a tanker over three years. Vertical blue lines mark the cleaning events. Reproduced from [116], with permission from Chalmers University of Technology, 2017.

The three methods of ship hull cleaning—(1) manual hull cleaning, (2) powered rotary brush cleaning systems and (3) noncontact cleaning technology—were presented by Song and Cui [117]. They found that using unmanned underwater vehicles would be cost-effective and robust in the future. Also, they found a combination of the different methods to achieve the best performance during the cleaning process [118].

Adland et al. [119] investigated the effect of cleaning the ship hull to increase the ship's energy efficiency. They concluded that periodic hull cleaning significantly reduces fuel consumption. Cleaning the hull in dry-dock achieves a 17% reduction in fuel consumption, compared with underwater hull cleaning, which can achieve only a 9% reduction.

Using CFD software, Farkas et al. [120] demonstrated the effect of biofilm on ship propulsion that should not be ignored. They showed that the delivered power could be increased by up to 36.3%, accompanied by a reduction in ship speed of 2 knots. They concluded that studying the time-dependent biofouling growth is related to economic and environmental benefits. Demo et al. [121] developed a complete numerical optimization model for the hull shape design. They coupled FFD to deform the hull surface, CFD to compute the total resistance, a surrogate model to reduce model complexity and an optimization method to find the optimal full form. They found a reduction in the total resistance coefficient by 1.2% compared with the original design. However, there could be improvement in the selection of the active subspace dimension to improve the efficiency of the optimizer while using a fast algorithm for the computation of the control points.

Oliveira and Granhag [122] used an immersed waterjet setup to test wall forces on different fouling-control coatings. By applying minimal cleaning forces on biocidal antifouling (AF) or the biocide-free foul-release (FR) coatings, they reported no significant damage to the hull over one year. Further research could be extended to achieve the same effect on the hull for many years. Erol et al. [123] analyzed the performance of a battery hybrid electric ship for nine months using Curve Fitting and Detrended Fluctuation Analysis (DFA) and found a reduction in ship speed by 6%. The investigation would be extended to cover more than one year to detect and improve ship operation performance.

An automatic system was proposed by Le et al. [124] to save energy and water during ship hull cleaning using a convolutional neural network (CNN) by finding the optimal path of the robot to perform cleaning procedures. The method could reduce the energy and water required by around 10% while ensuring the ship's maintenance standards to avoid hull deformation. Finally, Yusuf et al. [125] showed that creating surfaces using specific materials, such as those with superhydrophobic or superhydrophilic wettability properties, would be effective as self-cleaning surfaces in the marine environment.

3.4. Hull Lubrication

Recently, hull lubrication has been utilized to reduce frictional resistance by creating a layer of air bubbles between the keel and the water, thus reducing the required power to operate the ship and consuming less fuel, as shown in Figure 4. It has the direct effect that the ships can improve energy efficiency and reduce energy losses and it is expected to achieve up to a 10–15% reduction in CO_2 emissions. In addition to the emissions reduction, hull lubrication has an advantage in reducing underwater noise due to the reduction of vibration and engine noises as well as the reduction of the accumulation of aquatic organisms [126]. According to the American Bureau of Shipping (ABS) [127], the number of cruise ships that have a hull lubrication system is the highest compared with other types of ships.

There are different systems; the main idea of all systems is the same, but the technology used and integrated into the hull is different. Air lubrication systems (ALS) [128], Air Cavity Ships (ACS) [129], and Winged Air Inject Pipes (WAIP) [130] are the three systems that exist in the market. These systems are approved by the MEPC.1/Circ.815 17 [131] to reduce the level of EEDI.

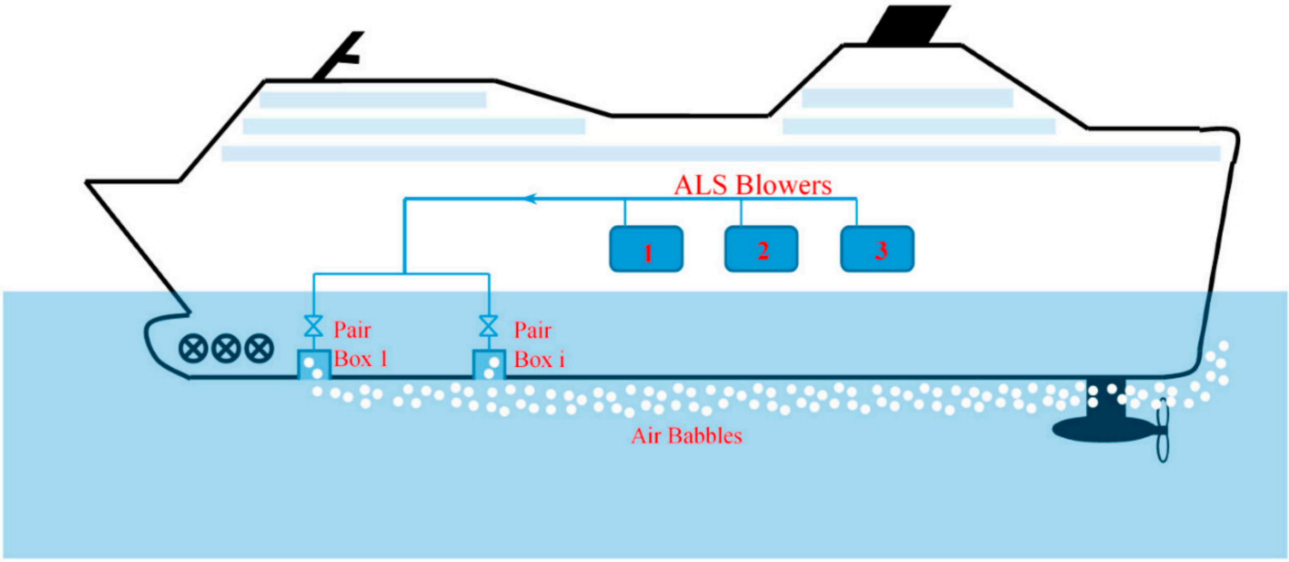

Figure 4. Diagram of ALS system producing air layer under the hull bottom of a passenger vessel. Reproduced from [132], with permission from MDPI, 2021.

Yanuar et al. [133] found that the air layer drag reduction (ALDR) technique is very effective and can apply to a self-propelled barge to reduce the ship drag by 90%, in particular at low speed. Hao et al. [134] found a reduction in the frictional resistance of a bulk carrier ship model at specific conditions of air injection. The bottom air layer was observed and the expected power savings were estimated to reach 15% in a full-scale ship without considering the consumption of air injection. As the simulation was performed in calm water, considering the waves in further research is important to ensure the behaviour of the ship in terms of efficiency and safety aspects.

Matveev [135] provided a simplified potential-flow method of air cavities formed under horizontal walls. They found that increasing the air rate is valuable at low amplitudes of pressure fluctuations in the flow, while a reduction in the air rate can be effective in terms of power-saving at high amplitudes of pressure oscillations.

Kim and Park [136] compared the frictional drag reduction achieved due to air lubrication. Simulation-based CFD was performed for various injected airflow rates and compared with experimental results. They confirmed that the characteristics of the air and water have a great effect on drag reduction. In addition, the authors presented an important conclusion related to the limitations of the solver in CFD models, showing that Coupled Level-Set and Volume of Fluid (CLSVOF) was better able to predict the air layer well in air lubrication systems than only using a volume of fluid (VOF) solver.

Giernalczyk and Kaminski [132] evaluated the effectiveness of the ALS installed on a passenger ship to reduce fuel consumption and improve EEDI. They proposed different operational conditions to compute the different powers required, the fuel consumed, and the ship speed according to the on–off status of the ALS. The study presented a preliminary investigation of the ship performance using ALS, while it was required to be validated using experimental data.

According to Matveev [137] and based on CFD computation, the ACS showed lower vertical accelerations in waves compared to the same solid hull, and it was suggested that the time histories of kinematic parameters and distributions of flow field variables presented in the manuscript could be beneficial for developers of air-cavity hulls.

4. Conclusions and Future Trends

This paper comprehensively reviews the methods and tools used during hull design to improve ships' energy efficiency to reduce resistance and thus fuel consumption during the last six years (2017–2022).

As the hull becomes more complex, normal simulation techniques are insufficient to achieve the optimal goal. Therefore, uncertainty analysis, operation research and machine learning could be coupled to the simulation models to achieve the best performance. Four research areas have been presented in this paper related to hull design: hull form, hull structure, hull cleaning and hull lubrication. Different software and methods were developed, mainly based on CFD computation, to achieve optimal results. No specific method is considered the optimum, while the combination of several methods can achieve more accurate results. It has been concluded that:

Regarding the hull form, several tools have been developed to help the ship designer during the stages of ship design to achieve the best hull form in calm water [138,139]. These tools can minimize the total resistance of the ship and improve the propulsive coefficients. However, it is also important to consider the weather conditions to achieve the optimum design regarding the operational conditions, especially the most frequent ones, particularly with the availability of climate information [140].

Few papers considered the operation concept during the simulation and prediction of hull form. However, a holistic approach is required, combining the reduction in ship resistance, maximization of the amount of cargo and improvement in the seakeeping performance along the ship route to verify the limitations of the new regulations applied, such as EEXI and/or CII [141].

Regarding the hull structure, several papers have been published considering a single objective, such as reducing the hull weight. However, it is also essential for further research to assess the reduction of hull weight using composite materials by finding the optimal division of the inner hull while considering the operation of loading and unloading conditions to achieve a robust design.

Regarding the hull cleaning, more information is required regarding ship operation over the entire life, so it can be easily predicted by surrogate models to estimate the amount of required power and fuel consumption. It is also important to provide more realistic data related to the deformation of the hull from the cleaning process and its effect on the ship resistance [142].

Regarding hull lubrication, the presented techniques show a significant reduction in ship resistance, which can be considered a standard technique for energy savings. Further research needs to include stability calculations in addition to the reduction of ship resistance, mainly in real operational conditions, to achieve an overall point of view along the ship route.

The findings of this study contribute to mapping the scientific knowledge of ship hull technology, identifying relevant topic areas, and recognizing research gaps and opportunities. Furthermore, this review helps to present holistic approaches towards maritime sustainability in further research to provide more realistic solutions.

Author Contributions: Conceptualization, M.T.; methodology, M.T.; formal analysis, M.T.; investigation, M.T.; writing—original draft preparation, M.T., M.V. and C.G.S.; writing—review and editing, M.T., M.V. and C.G.S. All authors have read and agreed to the published version of the manuscript.

Funding: This work was performed within the scope of the Strategic Research Plan of the Centre for Marine Technology and Ocean Engineering (CENTEC), which is financed by the Portuguese Foundation for Science and Technology (Fundação para a Ciência e Tecnologia-FCT) under contract UIDB/UIDP/00134/2020.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

3D	Three dimensional
ABS	American Bureau of Shipping
ACS	Air Cavity Ships
AF	Antifouling
AI	Artificial intelligence
ALDR	Air layer drag reduction
ALS	Air lubrication system
API	Application programming interfaces
ASA	Adaptive Simulated Annealing
CCS	Carbon capture and storage
CFD	Computational fluid dynamics
CII	Carbon Intensity Indicator
CLSVOF	Coupled Level-Set and Volume of Fluid
CNN	Convolutional neural network
CO_2	Carbon dioxide
DBN	Deep belief network
DFA	Detrended Fluctuation Analysis
DoE	Design of experiments
ECAs	Emission Control Areas
EDM	Electro-discharge machining
EEDI	Energy Efficiency Design Index
EEOI	Energy Efficiency Operational Indicator
EEXI	Energy Efficiency Existing Ship Index
FEM	Finite element analysis
FFD	Free-form deformation method
FR	Foul-release
GA	Genetic algorithm
GHG	Greenhouse gas
IMO	International Maritime Organization
IQPSO	Immune quantum-behaved particle swarm optimization
KCS	KRISO Container Ship
MARS	Model-based Annealing Random Search
MEPC	Marine Environment Protection Committee
ML	Machine learning
MOGA	Multi-objective genetic algorithm
MOPOP	Multi-objective probabilistic optimization process
NO_x	Nitrogen oxides
NSGAII	Non-dominated sorting genetic algorithm II
OR	Operation research
RANS	Reynolds Averaged Navier–Stokes
RBFNN	Radial basis neural network
RBOD	Reliability-based optimization design
Ro-Ro	Roll-on/roll-off
SCR	Selective catalytic reduction
SEEMP	Ship Energy Efficiency Management Plan
SOM	Self-Organizing Maps
SO_x	Sulphur oxides
TPBF	Tensor-product basis function
UD	Uniform design
VOF	Volume of Fluid
WAIP	Winged Air Inject Pipe
WHRS	Waste heat recovery system

References

1. IMO. Nitrogen Oxides (NOx)—Regulation 13. IMO. Available online: http://www.imo.org/en/OurWork/Environment/PollutionPrevention/AirPollution/Pages/Nitrogen-oxides-(NOx)-%E2%80%93-Regulation-13.aspx (accessed on 28 September 2017).
2. IMO. Sulphur oxides (SOx)—Regulation 14. IMO. Available online: http://www.imo.org/en/OurWork/environment/pollutionprevention/airpollution/pages/sulphur-oxides-(sox)-%E2%80%93-regulation-14.aspx (accessed on 28 September 2017).
3. DNV. EEXI—Energy Efficiency Existing Ship Index. Available online: https://www.dnvgl.com/maritime/insights/topics/eexi/calculation.html (accessed on 1 December 2020).
4. Psaraftis, H.N. Shipping decarbonization in the aftermath of MEPC 76. *Clean. Logist. Supply Chain.* **2021**, *1*, 100008. [CrossRef]
5. Karatuğ, Ç.; Arslanoğlu, Y.; Guedes Soares, C. Evaluation of decarbonization strategies for existing ships. In *Trends in Maritime Technology and Engineering*; Guedes Soares, C., Santos, T.A., Eds.; Taylor & Francis Group: London, UK, 2022; pp. 45–54.
6. Trivyza, N.L.; Rentizelas, A.; Theotokatos, G.; Boulougouris, E. Decision support methods for sustainable ship energy systems: A state-of-the-art review. *Energy* **2022**, *239*, 122288. [CrossRef]
7. Stark, C.; Shi, W.; Troll, M. Cavitation funnel effect: Bio-inspired leading-edge tubercle application on ducted marine propeller blades. *Appl. Ocean Res.* **2021**, *116*, 102864. [CrossRef]
8. Stark, C.; Xu, Y.; Zhang, M.; Yuan, Z.; Tao, L.; Shi, W. Study on Applicability of Energy-Saving Devices to Hydrogen Fuel Cell-Powered Ships. *J. Mar. Sci. Eng.* **2022**, *10*, 388. [CrossRef]
9. Tadros, M.; Ventura, M.; Guedes Soares, C. Optimization procedure to minimize fuel consumption of a four-stroke marine turbocharged diesel engine. *Energy* **2019**, *168*, 897–908. [CrossRef]
10. Tadros, M.; Ventura, M.; Guedes Soares, C. A nonlinear optimization tool to simulate a marine propulsion system for ship conceptual design. *Ocean Eng.* **2020**, *210*, 107417. [CrossRef]
11. Tadros, M.; Ventura, M.; Guedes Soares, C. Optimization of the performance of marine diesel engines to minimize the formation of SOx emissions. *J. Mar. Sci. Appl.* **2020**, *19*, 473–484. [CrossRef]
12. Zhou, S.; Gao, R.; Feng, Y.; Zhu, Y. Evaluation of Miller cycle and fuel injection direction strategies for low NOx emission in marine two-stroke engine. *Int. J. Hydrogen Energy* **2017**, *42*, 20351–20360. [CrossRef]
13. Liu, J.; Zhao, H.; Wang, J.; Zhang, N. Optimization of the injection parameters of a diesel/natural gas dual fuel engine with multi-objective evolutionary algorithms. *Appl. Therm. Eng.* **2019**, *150*, 70–79. [CrossRef]
14. Tadros, M.; Ventura, M.; Guedes Soares, C. Optimization procedures for a twin controllable pitch propeller of a ROPAX ship at minimum fuel consumption. *J. Mar. Eng. Technol.* **2022**. [CrossRef]
15. El-Gohary, M.M. Overview of past, present and future marine power plants. *J. Mar. Sci. Appl.* **2013**, *12*, 219–227. [CrossRef]
16. Elkafas, A.G.; Elgohary, M.M.; Shouman, M.R. Numerical analysis of economic and environmental benefits of marine fuel conversion from diesel oil to natural gas for container ships. *Environ. Sci. Pollut. Res.* **2021**, *28*, 15210–15222. [CrossRef] [PubMed]
17. Balcombe, P.; Brierley, J.; Lewis, C.; Skatvedt, L.; Speirs, J.; Hawkes, A.; Staffell, I. How to decarbonise international shipping: Options for fuels, technologies and policies. *Energy Convers. Manag.* **2019**, *182*, 72–88. [CrossRef]
18. Tadros, M.; Ventura, M.; Guedes Soares, C. A review of the use of Biodiesel as a green fuel for diesel engines. In *Developments in Maritime Technology and Engineering*; Guedes Soares, C., Santos, T., Eds.; Taylor & Francis Group: London, UK, 2021; pp. 481–490.
19. Tadros, M.; Ventura, M.; Guedes Soares, C. Assessment of marine Genset performance with biodiesel fuel using the double-Wiebe function. In *Trends in Maritime Technology and Engineering*; Guedes Soares, C., Santos, T.A., Eds.; Taylor & Francis Group: London, UK, 2022; pp. 545–551.
20. DNV. *Maritime Forecast to 2050: Energy Transition Outlook 2020*; DNV: Bærum, Norway, 2020.
21. Altosole, M.; Benvenuto, G.; Zaccone, R.; Campora, U. Comparison of Saturated and Superheated Steam Plants for Waste-Heat Recovery of Dual-Fuel Marine Engines. *Energies* **2020**, *13*, 985. [CrossRef]
22. Ng, C.; Tam, I.C.K.; Wu, D. Thermo-Economic Performance of an Organic Rankine Cycle System Recovering Waste Heat Onboard an Offshore Service Vessel. *J. Mar. Sci. Eng.* **2020**, *8*, 351. [CrossRef]
23. Ouyang, T.; Huang, G.; Lu, Y.; Liu, B.; Hu, X. Multi-criteria assessment and optimization of waste heat recovery for large marine diesel engines. *J. Clean. Prod.* **2021**, *309*, 127307. [CrossRef]
24. Tadros, M.; Ventura, M.; Guedes Soares, C. Sensitivity analysis of the steam Rankine cycle in marine applications. In *Developments in Maritime Technology and Engineering*; Guedes Soares, C., Santos, T., Eds.; Taylor & Francis Group: London, UK, 2021; pp. 491–500.
25. Liang, X.; Zhao, B.; Zhang, F.; Liu, Q. Compact research for maritime selective catalytic reduction reactor based on response surface methodology. *Appl. Energy* **2019**, *254*, 113702. [CrossRef]
26. Sung, Y.; Choi, M.; Park, T.; Choi, C.; Park, Y.; Choi, G. Synergistic effect of mixer and mixing chamber on flow mixing and NOx reduction in a marine urea-SCR system. *Chem. Eng. Process.* **2020**, *150*, 107888. [CrossRef]
27. Ni, P.; Wang, X.; Li, H. A review on regulations, current status, effects and reduction strategies of emissions for marine diesel engines. *Fuel* **2020**, *279*, 118477. [CrossRef]
28. Guo, H.; Zhou, S.; Shreka, M.; Feng, Y. A Numerical Investigation on the Optimization of Uneven Flow in a Marine De-SOx Scrubber. *Processes* **2020**, *8*, 862. [CrossRef]
29. Bui, K.Q.; Ölçer, A.I.; Kitada, M.; Ballini, F. Selecting technological alternatives for regulatory compliance towards emissions reduction from shipping: An integrated fuzzy multi-criteria decision-making approach under vague environment. *Proc. Inst. Mech. Eng. M* **2021**, *235*, 272–287. [CrossRef]

30. Wilailak, S.; Yoo, B.-H.; Kim, Y.; Lee, C.-J. Parametric analysis and design optimization of wet SOx scrubber system in marine industry. *Fuel* **2021**, *304*, 121369. [CrossRef]
31. Karatuğ, Ç.; Arslanoğlu, Y.; Guedes Soares, C. Feasibility Analysis of the Effects of Scrubber Installation on Ships. *J. Mar. Sci. Eng.* **2022**, *10*, 1838. [CrossRef]
32. Buirma, M.; Vleugel, J.; Pruyn, J.; Doedée, V.; Schott, D. Ship-Based Carbon Capture and Storage: A Supply Chain Feasibility Study. *Energies* **2022**, *15*, 813. [CrossRef]
33. Ammar, N.R. Energy- and cost-efficiency analysis of greenhouse gas emission reduction using slow steaming of ships: Case study RO-RO cargo vessel. *Ships Offshore Struct.* **2018**, *13*, 868–876. [CrossRef]
34. Dere, C.; Deniz, C. Load optimization of central cooling system pumps of a container ship for the slow steaming conditions to enhance the energy efficiency. *J. Clean. Prod.* **2019**, *222*, 206–217. [CrossRef]
35. Tadros, M.; Vettor, R.; Ventura, M.; Guedes Soares, C. Effect of different speed reduction strategies on ship fuel consumption in realistic weather conditions. In *Trends in Maritime Technology and Engineering*; Guedes Soares, C., Santos, T.A., Eds.; Taylor & Francis Group: London, UK, 2022; pp. 553–561.
36. Tadros, M.; Vettor, R.; Ventura, M.; Guedes Soares, C. Coupled Engine-Propeller Selection Procedure to Minimize Fuel Consumption at a Specified Speed. *J. Mar. Sci. Eng.* **2021**, *9*, 59. [CrossRef]
37. Tadros, M.; Ventura, M.; Guedes Soares, C. Design of Propeller Series Optimizing Fuel Consumption and Propeller Efficiency. *J. Mar. Sci. Eng.* **2021**, *9*, 1226. [CrossRef]
38. Lungu, A. Energy-Saving Devices in Ship Propulsion: Effects of Nozzles Placed in Front of Propellers. *J. Mar. Sci. Eng.* **2021**, *9*, 125. [CrossRef]
39. Saettone, S.; Taskar, B.; Steen, S.; Andersen, P. Experimental measurements of propulsive factors in following and head waves. *Appl. Ocean Res.* **2021**, *111*, 102639. [CrossRef]
40. Samsul, M.B. Blade Cup Method for Cavitation Reduction in Marine Propellers. *Pol. Marit. Res.* **2021**, *28*, 54–62. [CrossRef]
41. Tadros, M.; Ventura, M.; Guedes Soares, C. An optimisation procedure for propeller selection for different shaft inclinations. *Int. J. Marit. Eng.* **2022**, *164*, 295–315. [CrossRef]
42. Tadros, M.; Ventura, M.; Guedes Soares, C. Towards Fuel Consumption Reduction Based on the Optimum Contra-Rotating Propeller. *J. Mar. Sci. Eng.* **2022**, *10*, 1657. [CrossRef]
43. Vettor, R.; Guedes Soares, C. Development of a ship weather routing system. *Ocean Eng.* **2016**, *123*, 1–14. [CrossRef]
44. Vettor, R.; Tadros, M.; Ventura, M.; Guedes Soares, C. Route planning of a fishing vessel in coastal waters with fuel consumption restraint. In *Maritime Technology and Engineering 3*; Guedes Soares, C., Santos, T.A., Eds.; Taylor & Francis Group: London, UK, 2016; pp. 167–173.
45. Vettor, R.; Tadros, M.; Ventura, M.; Guedes Soares, C. Influence of main engine control strategies on fuel consumption and emissions. In *Progress in Maritime Technology and Engineering*; Guedes Soares, C., Santos, T.A., Eds.; Taylor & Francis Group: London, UK, 2018; pp. 157–163.
46. Moreira, L.; Vettor, R.; Guedes Soares, C. Neural Network Approach for Predicting Ship Speed and Fuel Consumption. *J. Mar. Sci. Eng.* **2021**, *9*, 119. [CrossRef]
47. Zaccone, R.; Ottaviani, E.; Figari, M.; Altosole, M. Ship voyage optimization for safe and energy-efficient navigation: Adynamic programming approach. *Ocean Eng.* **2018**, *153*, 215–224. [CrossRef]
48. Zaccone, R.; Figari, M.; Martelli, M. An optimization tool for ship route planning in real weather scenarios. In Proceedings of the International Offshore and Polar Engineering Conference, Sapporo, Japan, 10−15 June 2018.
49. Tadros, M.; Vettor, R.; Ventura, M.; Guedes Soares, C. Effect of propeller cup on the reduction of fuel consumption in realistic weather conditions. *J. Mar. Sci. Eng.* **2022**, *10*, 1039. [CrossRef]
50. Lloyd's Register. *Implementing the Energy Efficiency Design Index*; Lloyd's Register: London, UK, 2012.
51. Islam, H.; Ventura, M.; Guedes Soares, C.; Tadros, M.; Abdelwahab, H.S. Comparison between empirical and CFD based methods for ship resistance and power prediction. In *Trends in Maritime Technology and Engineering*; Guedes Soares, C., Santos, T.A., Eds.; Taylor & Francis Group: London, UK, 2022; pp. 347–357.
52. Mallouppas, G.; Yfantis, E.A. Decarbonization in Shipping Industry: A Review of Research, Technology Development, and Innovation Proposals. *J. Mar. Sci. Eng.* **2021**, *9*, 415. [CrossRef]
53. Bouman, E.A.; Lindstad, E.; Rialland, A.I.; Strømman, A.H. State-of-the-art technologies, measures, and potential for reducing GHG emissions from shipping—A review. *Transp. Res. D Transp. Environ.* **2017**, *52*, 408–421. [CrossRef]
54. Department for Transport. *Clean Maritime Plan*; Department for Transport: London, UK, 2019.
55. Hillier, F.S.; Lieberman, G.J. *Introduction to Operations Research*; McGraw-Hill: New York, NY, USA, 1980.
56. Russell, R. *Machine Learning: Step-by-Step Guide To Implement Machine Learning Algorithms with Python*; Create Space Independent Publishing Platform: Scotts Valley, CA, USA, 2018.
57. Wang, F.; Liang, H.; Zhang, Y.; Xu, Q.; Zong, R. Recognition and Classification of Ship Images Based on SMS-PCNN Model. *Front. Neurorobot.* **2022**, *16*, 889308. [CrossRef]
58. Mascaraque-Ramírez, C.; Franco, P. High-precision machining in the shipbuilding industry. Applicability and advantages of electro discharge machining technology. *Ships Offshore Struct.* **2018**, *13*, 750–758. [CrossRef]
59. Hou, Y.H. Hull form uncertainty optimization design for minimum EEOI with influence of different speed perturbation types. *Ocean Eng.* **2017**, *140*, 66–72. [CrossRef]

60. Hou, Y.h.; Li, Y.j.; Liang, X. Mixed aleatory/epistemic uncertainty analysis and optimization for minimum EEDI hull form design. *Ocean Eng.* **2019**, *172*, 308–315. [CrossRef]
61. Pechenyuk, A.V. Optimization of a hull form for decrease ship resistance to movement. *Comput. Res. Model* **2017**, *9*, 57–65. [CrossRef]
62. Li, Y.; Gu, X.; Ma, N.; Zhang, Y. A Ship Hull Optimization for Low Resistance and Uniform Wake Based on the Simulation of Hydrodynamics Performance. In Proceedings of the 32nd International Ocean and Polar Engineering Conference, Shanghai, China, 5–10 June 2022.
63. Edalat, P.; Barzandeh, A. Fuel efficiency optimization of tanker with focus on hull parameters. *J. Ocean Eng. Sci.* **2017**, *2*, 76–82. [CrossRef]
64. Huang, Y.; Hou, G.; Cheng, X.; Feng, B.; Gao, L.; Xiao, M. A new vortex search algorithm with gradient-based approximation for optimization of the fore part of KCS container ship. *J. Mar. Sci. Technol.* **2017**, *22*, 403–413. [CrossRef]
65. Liu, Q.; Feng, B.; Liu, Z.; Zhang, H. The improvement of a variance-based sensitivity analysis method and its application to a ship hull optimization model. *J. Mar. Sci. Technol.* **2017**, *22*, 694–709. [CrossRef]
66. Wu, J.; Liu, X.; Zhao, M.; Wan, D. Neumann-Michell theory-based multi-objective optimization of hull form for a naval surface combatant. *Appl. Ocean Res.* **2017**, *63*, 129–141. [CrossRef]
67. Liu, Z.; Zhao, W.; Wan, D. Resistance and wake distortion optimization of JBC considering ship-propeller interaction. *Ocean Eng.* **2022**, *244*, 110376. [CrossRef]
68. Goren, O.; Calisal, S.M.; Bulent Danisman, D. Mathematical programming basis for ship resistance reduction through the optimization of design waterline. *J. Mar. Sci. Technol.* **2017**, *22*, 772–783. [CrossRef]
69. Duy, T.-N.; Hino, T.; Suzuki, K. Numerical study on stern flow fields of ship hulls with different transom configurations. *Ocean Eng.* **2017**, *129*, 401–414. [CrossRef]
70. Zhang, Y.; Lin, Y.; Lu, C. A universal prototype design framework of the stem and stern contours of hull surface and the self-adaptive solving strategy. *J. Mar. Sci. Technol.* **2018**, *23*, 399–411. [CrossRef]
71. Cheng, X.; Feng, B.; Liu, Z.; Chang, H. Hull surface modification for ship resistance performance optimization based on Delaunay triangulation. *Ocean Eng.* **2018**, *153*, 333–344. [CrossRef]
72. Feng, Y.; Chen, Z.; Dai, Y.; Wang, F.; Cai, J.; Shen, Z. Multidisciplinary optimization of an offshore aquaculture vessel hull form based on the support vector regression surrogate model. *Ocean Eng.* **2018**, *166*, 145–158. [CrossRef]
73. Tezdogan, T.; Shenglong, Z.; Demirel, Y.K.; Liu, W.; Leping, X.; Yuyang, L.; Kurt, R.E.; Djatmiko, E.B.; Incecik, A. An investigation into fishing boat optimisation using a hybrid algorithm. *Ocean Eng.* **2018**, *167*, 204–220. [CrossRef]
74. Hou, Y.H.; Liang, X.I.; Mu, X.Y. Hull lines reliability-based optimisation design for minimum eedi. *Brodogradnja* **2018**, *69*, 17–33. [CrossRef]
75. Lin, Y.; He, J.; Li, K. Hull form design optimization of twin-skeg fishing vessel for minimum resistance based on surrogate model. *Adv. Eng. Softw.* **2018**, *123*, 38–50. [CrossRef]
76. Lindstad, E.; Bø, T.I. Potential power setups, fuels and hull designs capable of satisfying future EEDI requirements. *Transp. Res. D Transp. Environ.* **2018**, *63*, 276–290. [CrossRef]
77. Cheng, X.; Feng, B.; Chang, H.; Liu, Z.; Zhan, C. Multi-objective optimisation of ship resistance performance based on CFD. *J. Mar. Sci. Technol.* **2019**, *24*, 152–165. [CrossRef]
78. Qiang, Z.; Hai-Chao, C.; Bai-Wei, F.; Zu-Yuan, L.; Cheng-Sheng, Z. Research on knowledge-extraction technology in optimisation of ship-resistance performance. *Ocean Eng.* **2019**, *179*, 325–336. [CrossRef]
79. Guan, G.; Yang, Q.; Yang, X.; Wang, Y. A new method for parametric design of hull surface based on energy optimization. *J. Mar. Sci. Technol.* **2019**, *24*, 424–436. [CrossRef]
80. Seok, W.; Kim, G.H.; Seo, J.; Rhee, S.H. Application of the Design of Experiments and Computational Fluid Dynamics to Bow Design Improvement. *J. Mar. Sci. Eng.* **2019**, *7*, 226. [CrossRef]
81. Jung, Y.-W.; Kim, Y. Hull form optimization in the conceptual design stage considering operational efficiency in waves. *Proc. Inst. Mech. Eng. M* **2019**, *233*, 745–759. [CrossRef]
82. Skoupas, S.; Zaraphonitis, G.; Papanikolaou, A. Parametric design and optimisation of high-speed Ro-Ro Passenger ships. *Ocean Eng.* **2019**, *189*, 106346. [CrossRef]
83. NAPA. Intelligent Solutions for Maritime Industry. Available online: https://www.napa.fi/?gclid=Cj0KCQjwzLCVBhD3ARIsAPKYTcRGdJMri-H3az-Vekalwqdl2YlC8b8FY_DfFbsPmvHiD3Xqs5Pl5mEaAkWEEALw_wcB (accessed on 5 May 2022).
84. Coppedè, A.; Gaggero, S.; Vernengo, G.; Villa, D. Hydrodynamic shape optimization by high fidelity CFD solver and Gaussian process based response surface method. *Appl. Ocean Res.* **2019**, *90*, 101841. [CrossRef]
85. Zhang, S.; Tezdogan, T.; Zhang, B.; Lin, L. Research on the hull form optimization using the surrogate models. *Eng. Appl. Comput. Fluid Mech.* **2021**, *15*, 747–761. [CrossRef]
86. Zhang, S. Research on the Deep Learning Technology in the Hull Form Optimization Problem. *J. Mar. Sci. Eng* **2022**, *10*, 1735. [CrossRef]
87. Qiang, Z.; Bai-Wei, F.; Zu-Yuan, L.; Hai-Chao, C.; Xiao, W. Optimization method for hierarchical space reduction method and its application in hull form optimization. *Ocean Eng.* **2022**, *262*, 112108. [CrossRef]
88. Feng, Y.; Moctar, O.e.; Schellin, T.E. Hydrodynamic optimisation of a multi-purpose wind offshore supply vessel. *Ship Technol. Res.* **2020**, *67*, 69–83. [CrossRef]

89. Zhao, C.; Wang, W.; Jia, P.; Xie, Y. Optimisation of hull form of ocean-going trawler. *Brodogradnja* **2021**, *72*, 33–46. [CrossRef]
90. Wang, P.; Chen, Z.; Feng, Y. Many-objective optimization for a deep-sea aquaculture vessel based on an improved RBF neural network surrogate model. *J. Mar. Sci. Technol.* **2021**, *26*, 582–605. [CrossRef]
91. Feng, Y.; Chen, Z.; Dai, Y.; Cui, L.; Zhang, Z.; Wang, P. Multi-objective optimization of a bow thruster based on URANS numerical simulations. *Ocean Eng.* **2022**, *247*, 110784. [CrossRef]
92. Zha, L.; Zhu, R.; Hong, L.; Huang, S. Hull form optimization for reduced calm-water resistance and improved vertical motion performance in irregular head waves. *Ocean Eng.* **2021**, *233*, 109208. [CrossRef]
93. Lee, J.; Park, D.-M.; Kim, Y. Experimental investigation on the added resistance of modified KVLCC2 hull forms with different bow shapes. *Proc. Inst. Mech. Eng. M* **2017**, *231*, 395–410. [CrossRef]
94. Zhang, S.; Tezdogan, T.; Zhang, B.; Xu, L.; Lai, Y. Hull form optimisation in waves based on CFD technique. *Ships Offshore Struct.* **2018**, *13*, 149–164. [CrossRef]
95. Lee, J.-H.; Kim, S.-S.; Lee, S.-S.; Kang, D.; Lee, J.-C. Prediction of added resistance using genetic programming. *Ocean Eng.* **2018**, *153*, 104–111. [CrossRef]
96. Kim, B.-S.; Oh, M.-J.; Lee, J.-H.; Kim, Y.-H.; Roh, M.-I. Study on Hull Optimization Process Considering Operational Efficiency in Waves. *Processes* **2021**, *9*, 898. [CrossRef]
97. Feng, Y.; el Moctar, O.; Schellin, T.E. Parametric Hull Form Optimization of Containerships for Minimum Resistance in Calm Water and in Waves. *J. Mar. Sci. Appl.* **2021**, *20*, 670–693. [CrossRef]
98. Yin, X.-B.; Lu, Y.; Zou, J.; Wan, L. Numerical and experimental study on hydrodynamic bulbous bow hull-form optimization for various service conditions due to slow steaming of container vessel. *Proc. Inst. Mech. Eng. M* **2019**, *233*, 1103–1122. [CrossRef]
99. Hou, H.; Krajewski, M.; Ilter, Y.K.; Day, S.; Atlar, M.; Shi, W. An experimental investigation of the impact of retrofitting an underwater stern foil on the resistance and motion. *Ocean Eng.* **2020**, *205*, 107290. [CrossRef]
100. Gilbert, P.; Wilson, P.; Walsh, C.; Hodgson, P. The role of material efficiency to reduce CO2 emissions during ship manufacture: A life cycle approach. *Mar. Policy* **2017**, *75*, 227–237. [CrossRef]
101. Welaya, Y.M.A.; Naby, M.M.A.; Tadros, M.Y. Technological and economic study of ship recycling in Egypt. *Int. J. Nav. Archit. Ocean Eng.* **2012**, *4*, 362–373. [CrossRef]
102. Wang, H.; Oguz, E.; Jeong, B.; Zhou, P. Life cycle cost and environmental impact analysis of ship hull maintenance strategies for a short route hybrid ferry. *Ocean Eng.* **2018**, *161*, 20–28. [CrossRef]
103. Kim, S.; Frangopol, D.M. Multi-objective probabilistic optimum monitoring planning considering fatigue damage detection, maintenance, reliability, service life and cost. *Struct. Multidiscip. Optim.* **2018**, *57*, 39–54. [CrossRef]
104. Zareei, M.R.; Iranmanesh, M. Optimal Risk-Based Maintenance Planning of Ship Hull Structure. *J. Mar. Sci. Appl.* **2018**, *17*, 603–624. [CrossRef]
105. Kim, D.H.; Paik, J.K. Ultimate limit state-based multi-objective optimum design technology for hull structural scantlings of merchant cargo ships. *Ocean Eng.* **2017**, *129*, 318–334. [CrossRef]
106. Yu, H.; Chen, Z.; Zhou, Y.; Guo, Z. Optimal Design of Integrative Superstructure in Composite Materials. *Ship Build. China* **2017**, *58*, 30–37.
107. Garbatov, Y.; Huang, Y.C. Multiobjective Reliability-Based Design of Ship Structures Subjected to Fatigue Damage and Compressive Collapse. *J. Offshore Mech. Arct. Eng.* **2020**, *142*, 051701. [CrossRef]
108. Silva-Campillo, A.; Ulla-Campos, L.; Suárez-Bermejo, J.C.; Herreros-Sierra, M.A. Effect of bow hull form on the buckling strength assessment of the corner bracket connection. *Ocean Eng.* **2022**, *265*, 112562. [CrossRef]
109. Mancuso, A.; Saporito, A.; Tumino, D. Designing the internal reinforcements of a sailing boat using a topology optimization approach. *Appl. Ocean Res.* **2022**, *129*, 103384. [CrossRef]
110. Jafaryeganeh, H.; Ventura, M.; Guedes Soares, C. Multi-Objective Optimization of Internal Compartment Layout of Oil Tankers. *J. Ship Prod. Des.* **2019**, *35*, 374–385. [CrossRef]
111. Jafaryeganeh, H.; Ventura, M.; Guedes Soares, C. Effect of normalization techniques in multi-criteria decision making methods for the design of ship internal layout from a Pareto optimal set. *Struct. Multidiscip. Optim.* **2020**, *62*, 1849–1863. [CrossRef]
112. Jafaryeganeh, H.; Ventura, M.; Guedes Soares, C. Robust-based optimization of the hull internal layout of oil tanker. *Ocean Eng.* **2020**, *216*, 107846. [CrossRef]
113. Smith, F.; Colvin, G. Magnetic Track. U.S. Patent US20140077587A1, 20 March 2014.
114. Tadros, M.; Vettor, R.; Ventura, M.; Guedes Soares, C. Assessment of Ship Fuel Consumption for Different Hull Roughness in Realistic Weather Conditions. *J. Mar. Sci. Eng.* **2022**, *10*, 1891. [CrossRef]
115. Tadros, M.; Ventura, M.; Guedes Soares, C. Effect of Hull and Propeller Roughness during the Assessment of Ship Fuel Consumption. *J. Mar. Sci. Eng.* **2023**, *11*, 784. [CrossRef]
116. Oliveira, D. The Enemy Below-Adhesion and Friction of Ship Hull Fouling. Master's Thesis, Chalmers University of Technology, Gothenburg, Sweden, 2017.
117. Song, C.; Cui, W. Review of Underwater Ship Hull Cleaning Technologies. *J. Mar. Sci. Appl.* **2020**, *19*, 415–429. [CrossRef]
118. Swain, G.; Erdogan, C.; Foy, L.; Gardner, H.; Harper, M.; Hearin, J.; Hunsucker, K.Z.; Hunsucker, J.T.; Lieberman, K.; Nanney, M.; et al. Proactive In-Water Ship Hull Grooming as a Method to Reduce the Environmental Footprint of Ships. *Front. Mar. Sci.* **2022**, *8*, 808549. [CrossRef]

119. Adland, R.; Cariou, P.; Jia, H.; Wolff, F.-C. The energy efficiency effects of periodic ship hull cleaning. *J. Clean. Prod.* **2018**, *178*, 1–13. [CrossRef]
120. Farkas, A.; Song, S.; Degiuli, N.; Martić, I.; Demirel, Y.K. Impact of biofilm on the ship propulsion characteristics and the speed reduction. *Ocean Eng.* **2020**, *199*, 107033. [CrossRef]
121. Demo, N.; Tezzele, M.; Mola, A.; Rozza, G. Hull Shape Design Optimization with Parameter Space and Model Reductions, and Self-Learning Mesh Morphing. *J. Mar. Sci. Eng.* **2021**, *9*, 185. [CrossRef]
122. Oliveira, D.R.; Granhag, L. Ship hull in-water cleaning and its effects on fouling-control coatings. *Biofouling* **2020**, *36*, 332–350. [CrossRef]
123. Erol, E.; Cansoy, C.E.; Aybar, O.Ö. Assessment of the impact of fouling on vessel energy efficiency by analyzing ship automation data. *Appl. Ocean Res.* **2020**, *105*, 102418. [CrossRef]
124. Le, A.V.; Kyaw, P.T.; Veerajagadheswar, P.; Muthugala, M.A.V.J.; Elara, M.R.; Kumar, M.; Khanh Nhan, N.H. Reinforcement learning-based optimal complete water-blasting for autonomous ship hull corrosion cleaning system. *Ocean Eng.* **2021**, *220*, 108477. [CrossRef]
125. Yusuf, Y.; Ghazali, M.J.; Taha, M.M.; Omar, N.I. A brief overview of the marine environmentally friendly anti-fouling surface strategy. *Proc. Inst. Mech. Eng. Part J J. Eng. Tribol.* **2022**. [CrossRef]
126. Safety4Sea. Air Lubrication: How Blowing Bubbles under Ships Can Reduce Emissions. Available online: https://safety4sea.com/cm-how-blowing-bubbles-under-ships-can-reduce-emissions/?utm_medium=DNV%20-%20Maritime&utm_campaign=MARANDE%2CBA-Maritime&utm_source=linkedin&utm_content=90d3105014b744b7b4fde5c867252628-5011444&utm_term=social&fbclid=IwAR1DLxJyO2IinhsRqoTAPcvh_OmCrKLWmRWnxhCAhYOK-61TQuKkVg2hzPQ (accessed on 5 March 2023).
127. ABS. *Air Lubrication Technology*; ABS: Spring, TX, USA, 2019.
128. Sindagi, S.; Vijayakumar, R.; Saxena, B.K. Parametric CFD investigation of ALS technique on reduction in drag of bulk carrier. *Ships Offshore Struct.* **2020**, *15*, 417–430. [CrossRef]
129. Slyozkin, A.; Atlar, M.; Sampson, R.; Seo, K.C. An experimental investigation into the hydrodynamic drag reduction of a flat plate using air-fed cavities. *Ocean Eng.* **2014**, *76*, 105–120. [CrossRef]
130. Yanuar; Putra, M.S.G.; Akbar, M.; Alief, M.; Fatimatuzzahra. Numerical Study on Influence of Hydrofoil Clearance Towards Total Drag Reduction on Winged Air Induction Pipe for Air Lubrication. *Int. J. Technol.* **2020**, *11*, 91–99. [CrossRef]
131. MEPC.1/Circ.815 17. In *Guidance on Treatment of Innovative Energy Efficiency Technologies for Calculation and Verification of the Attained EEDI*; IMO: London, UK, 2013.
132. Giernalczyk, M.; Kaminski, P. Assessment of the Propulsion System Operation of the Ships Equipped with the Air Lubrication System. *Sensors* **2021**, *21*, 1357. [CrossRef] [PubMed]
133. Yanuar; Waskito, K.T.; Pratama, S.Y.; Candra, B.D.; Rahmat, B.A. Comparison of Microbubble and Air Layer Injection with Porous Media for Drag Reduction on a Self-propelled Barge Ship Model. *J. Mar. Sci. Appl.* **2018**, *17*, 165–172. [CrossRef]
134. Hao, W.U.; Yongpeng, O.; Qing, Y.E. Experimental study of air layer drag reduction on a flat plate and bottom hull of a ship with cavity. *Ocean Eng.* **2019**, *183*, 236–248. [CrossRef]
135. Matveev, K.I. Simplified model for unsteady air cavities under ship hulls. *Proc. Inst. Mech. Eng. M* **2020**, *234*, 100–107. [CrossRef]
136. Kim, H.; Park, S. Coupled Level-Set and Volume of Fluid (CLSVOF) Solver for Air Lubrication Method of a Flat Plate. *J. Mar. Sci. Eng.* **2021**, *9*, 231. [CrossRef]
137. Matveev, K.I. Computational Simulations of Wide-Beam Air-Cavity Hull in Waves. *J. Ship Prod. Des.* **2022**, *38*, 183–192. [CrossRef]
138. Chang, H.; Wang, C.; Liu, Z.; Feng, B.; Zhan, C.; Cheng, X. Research on the Karhunen–Loève Transform Method and Its Application to Hull Form Optimization. *J. Mar. Sci. Eng.* **2023**, *11*, 230. [CrossRef]
139. Liu, X.; Wan, D.; Lei, L. Multi-fidelity model and reduced-order method for comprehensive hydrodynamic performance optimization and prediction of JBC ship. *Ocean Eng.* **2023**, *267*, 113321. [CrossRef]
140. Bernardino, M.; Gonçalves, M.; Campos, R.M.; Guedes Soares, C. Extremes and variability of wind and waves across the oceans until the end of the 21st century. *Ocean Eng.* **2023**, *275*, 114081. [CrossRef]
141. Gaidai, O.; Wang, K.; Wang, F.; Xing, Y.; Yan, P. Cargo ship aft panel stresses prediction by deconvolution. *Mar. Struct.* **2023**, *88*, 103359. [CrossRef]
142. Zhao, W.; Han, F.; Qiu, X.; Peng, X.; Zhao, Y.; Zhang, J. Research on the identification and distribution of biofouling using underwater cleaning robot based on deep learning. *Ocean Eng.* **2023**, *273*, 113909. [CrossRef]