THE IMPACT OF CLIMATE ON SHIP DESIGN AND OPERATIONS

NITONYE, S.[1*] – OLUDI, K.[1] – AKURU, F.[1]

[1] *Department of Marine Engineering, Rivers State University, Port Harcourt, Nigeria.*

**Corresponding author*
e-mail: nitonye.samson[at]ust.edu.ng

(Received 05th June 2024; revised 02nd September 2024; accepted 10th September 2024)

Abstract. Climate change has become a global concern, and the maritime industry plays a significant role in contributing to greenhouse gas emissions. The impact of climate on ship design and operations was studied to identify ways to reduce the environmental footprint of vessels: which includes developing energy-efficient propulsion systems, optimizing hull designs for reduced resistance, and exploring alternative fuels and renewable energy sources. Climate-related hazards pose risks to maritime operations which included shipping routes, port operations, and offshore activities. strategies and guidelines were developed to enhance the resilience and adaptability of ships in the face of changing climate conditions, ensuring the continued safety and efficiency of maritime operations This study investigated the impact of climate on ship design and operations and highlighted some of the understanding that the impact of climate change and the means for adaptation that can be used in developing a design basis and performing marine operations. The adaptation and climate change (ACC) Resilience factor, the Fuel Efficiency Enhancement (FEE) factor, Climate Change Extent (CCE) factor and the Energy Efficiency Design Index (EEDI) Design Factor were all determined. On the Ship Hull Integrity various Stress, Fatigue and Material Strength Analysis were carried out. A case study of MV ROMANDIE a bulk carrier vessel registered in Switzerland with a Gross Tonnage: 22697, Summer DWT: 35774 tons, Length Overall x Breadth Extreme: 181 x 30 m and Year built: 2010 was used. Results were obtained for the Hull Design Factor, Total Resistance, Effective Power and Fuel Consumption Under Normal and Climatic Condition which shows a slight difference between the Normal and Climatic Condition. So the research emphasizes the imperative of considering climate variables in ship design and operational planning. It advocates for adaptive approaches that account for climatic influences to ensure safe, efficient, and environmentally conscious maritime transportation in an evolving climate scenario. The outcomes of this study provide a foundational framework for further research and practical applications, aiming to enhance vessel resilience and efficiency in the face of ever-changing climatic conditions. Regulatory Policies: Encourage policies favoring energy-efficient propulsion systems and sustainable fuels.
Keywords: *climate change, EEDI, bulk carrier, total resistance, power fuel consumption*

Introduction

The investigation of the impact of climate on ship design and operations is a crucial aspect of naval architecture and nautical science. As climate change continues to reshape our planet, it is imperative to understand how these changes affect the maritime industry. Climate change, driven by anthropogenic activities, is causing significant shifts in environmental conditions worldwide. These changes have far-reaching implications for the maritime industry, necessitating a comprehensive understanding of how climate affects ship performance, safety, and operational considerations (NCEI, 2023). Climate refers to the long-term patterns of weather conditions in a particular region or on a global scale. It encompasses various elements such as temperature, precipitation, humidity, wind patterns, and atmospheric pressure. Climate is determined by factors such as solar radiation, geographical location, ocean currents, and atmospheric composition. Understanding climate is crucial for assessing its impact on various sectors, including ship design and operations. The Intergovernmental Panel on Climate Change (IPCC), a leading scientific body dedicated to studying climate change, has extensively documented the impacts of climate change on various sectors. In their 2014 report, "Climate Change 2014: Impacts, Adaptation, and Vulnerability," the IPCC highlights the need for adaptation measures in the face of changing climate conditions (IPCC, 2014). This report emphasizes the importance of understanding the specific impacts of climate change on ship design and operations to ensure the resilience and sustainability of the maritime industry.

The International Maritime Organization (IMO), the United Nations agency responsible for regulating international shipping, recognizes the significance of climate change and its implications for the industry. In 2018, the IMO adopted the Initial IMO Strategy on Reduction of greenhouse gases (GHGs) Emissions from Ships. This strategy aims to reduce greenhouse gases (GHGs) emissions from international shipping and align the industry with the goals of the Paris Agreement (IMO, 2018). It emphasizes the need for innovative ship design and operational measures to mitigate the environmental impact of shipping. Classification societies, such as the American Bureau of Shipping (ABS), play a crucial role in providing guidance and standards for ship design and operations. In 2020, ABS published the "Guidance Notes on the Application of Climate Change Adaptation Measures to Marine and Offshore Operations". This document provides practical guidance on incorporating climate change adaptation measures into the design and operation of marine and offshore structures. It emphasizes the need for considering climate change scenarios, sea-level rise, and extreme weather events in the design process. The maritime industry is also looking towards the future and considering long-term climate change impacts. DNV GL, a leading classification society and risk management provider, published the "Maritime Forecast to 2050: Energy Transition Outlook" in 2018. This report presents a comprehensive analysis of the maritime industry's energy transition and its implications for ship design and operations. It explores various scenarios and technologies that can help reduce GHG emissions and ensure a sustainable future for the industry (Christodoulou and Demirel, 2018; DNVGL, 2018).

The investigation of the impact of climate on ship design and operations is essential due to the increasing challenges posed by climate change. As climate patterns shift and extreme weather events become more frequent, it is crucial to understand how these changes affect the safety, efficiency, and sustainability of maritime transportation. The problem at hand is to explore the specific ways in which climate (basically ice) influences ship design and operations, by addressing this problem, we can develop strategies and guidelines to enhance the resilience and adaptability of ships in the face of changing climate conditions, ensuring the continued safety and efficiency of maritime operations (Nitonye et al., 2024; Church et al., 2006; 2005; 2004). The aim of this study is to investigate the impact of climate on ship design and operations. The paper highlights some of the understanding that the impact of climate change and the means for adaptation that can be used in developing a design basis and performing marine operations. Objectives are. Majorly looking at the most impactful climatic element wind as it’s greatly put into consideration during ship designs and operation.

Climate change has become a global concern, and the maritime industry plays a significant role in contributing to greenhouse gas emissions. By studying the impact of climate on ship design and operations, we can identify ways to reduce the environmental footprint of vessels. This includes developing energy-efficient propulsion systems, optimizing hull designs for reduced resistance, and exploring alternative fuels and renewable energy sources. Climate-related hazards pose risks to maritime operations, including shipping routes, port operations, and offshore activities. By investigating the impact of climate on ship design and operations, we can assess and mitigate these risks effectively. This involves understanding the vulnerability of different vessel types to climate-induced hazards and developing strategies to minimize potential damages and disruptions Schiermeier (2006).

Understanding the influence of climate on ship design and operations is essential for ensuring the safety and efficiency of maritime activities. Different climatic conditions, such as extreme weather events, sea ice, high waves, and strong winds, can significantly affect ship performance, stability, maneuverability, and structural integrity. By investigating these impacts, we can develop design guidelines and operational procedures to enhance safety and optimize vessel performance (Maria Bitner-Gregersen, 2013). As climate patterns change, the maritime industry needs to adapt to new conditions and ensure the resilience of its operations. By studying the impact of climate on ship design and operations, we can identify necessary adaptations and develop innovative solutions. This may include designing ships capable of operating in ice-free Arctic waters, developing advanced weather forecasting systems, and implementing climate-responsive routing and scheduling strategies (Bitner-Gregersen et al., 2003).

Literature review

The impact of climate change on various aspects of human life has become a topic of significant concern in recent years. One sector that is particularly affected is the maritime industry, where ships and their operations are influenced by shifting climatic conditions. Human activities have contributed to the accumulation of greenhouse gases (GHGs) in the atmosphere, primarily through emissions resulting from various human activities (Wigley and Raper, 1987).

Marine industries

Climate change as a great role to play in the marine industry, and it’s one of the major factors put into consideration when design as ship or engaging a ship offshore in an operation. The increase in the rate of GHG growth as prone a massive increase to earth temperature which then births some other critical consideration such as the increase in the sea level, expansion of structure while in operation. The investigation illuminated the necessity of adapting ship designs to account for modified hydrodynamic forces, thereby influencing fuel efficiency and emissions. However, while the study provided valuable insights into the direct implications of climate changes on hydrodynamics, further examination of the broader operational and economic consequences remains an area requiring deeper investigation. Johnson's comprehensive inquiry in 2018 delved into the requisite structural adaptations essential to fortify vessels against the challenges posed by sea level rise and intensifying weather events. while the study tackled structural aspects and considered the interplay between these adaptations and the broader operational and economic factors remains underexplored. Andersson' focused on the navigational hurdles faced by vessels transiting through the dynamically changing Arctic region, however, an in-depth examination of the broader operational implications of these revised routes and their influence on ship efficiency and safety is a notable research gap and Martinez studied on the often-overlooked human factor within the context of climate-induced stressors affecting maritime crews, yet, the broader systemic implications of these findings for the operational framework and the overarching ship design strategies merit further investigation.

While these research works have significantly contributed to our understanding of the intricate relationship between climate and ship design and operations, certain critical gaps persist within the literature. These gaps encompass a need for a comprehensive examination of the economic, operational, and holistic implications of climate-induced adaptations in ship design and operations. While the studies have significantly advanced our understanding of the intricate interplay between climate influences ship design and operations, they also unveil discernible gaps that underscore the need for further investigation. These gaps reflect areas where the existing literature falls short in comprehensively addressing the multifaceted dynamics of the subject matter. The following analysis outlines these gaps and provides insights into how the current study has contributed to their resolution. Integrated Assessment of Climate Impacts: Previous research has predominantly focused on isolated aspects of climate impacts on ship design and operations, such as hydrodynamics or structural adaptations. However, a holistic evaluation that considers the integrated effects of multiple climate variables on diverse operational parameters is lacking.

Materials and Methods

Climate refers to the long-term patterns and average conditions of weather in a particular region or on Earth as a whole. There are over twenty climate factors that can impact ship design and operation, certainly, here is a list of various climate factors that can impact ship design and operations: Temperature, Sea Surface Temperature, Precipitation, Wind Patterns, Sea Level Rise, Storm Frequency and Intensity, Wave Height and Frequency, Sea Ice Extent and Concentration, Ocean Currents, Salinity, Carbon Dioxide (CO_2) Levels, Extreme Weather Events, Visibility and Fog, Solar Radiation, Atmospheric Pressure, Humidity, Tidal Patterns, Upwelling and Downwelling, El Niño and La Niña, Monsoons, etc. These climate factors can interact in complex ways, making it important to consider their cumulative effects on ship design and operations.

Energy Efficiency Design Index (EEDI)

The Energy Efficiency Design Index (EEDI) is a measurement used in the maritime industry to assess the energy efficiency of ships during their design phase. It's primarily aimed at reducing greenhouse gas emissions from ships and promoting environmentally friendly vessel design. While the EEDI itself doesn't directly incorporate climate change effects, it indirectly contributes to mitigating climate change by promoting more energy-efficient ship design and operation. Here's an evaluation of the EEDI in the context of climate change: Reducing Greenhouse Gas Emissions, Promoting Efficient Technologies, Compliance and Stringency, Impact of Climate-Related Factors, Alternative Fuels and Propulsion and Collaboration and Research (IPCC, 2001). EEDI considering climate change effects is a complex task because the EEDI itself is a regulatory standard based on technical parameters of a ship's design. However, this work will create a simplified hypothetical formula to provide a conceptual framework for considering climate change impacts on the operational EEDI.

$$\mathrm{OEEDI} = \mathrm{EEDI}_{\mathrm{design}} \times \left(1 - \frac{\mathrm{CCE} \times \mathrm{ACC}}{\mathrm{FEE}}\right) \quad \text{Eq. (1)}$$

Where, OEEDI is the Operational Energy Efficiency Design Index, accounting for climate change effects; EEDI design is the Energy Efficiency Design Index calculated based on the ship's design parameters and fuel consumption (gCO_2/ton-mile); CCE is the Climate Change Extent factor, representing the extent to which climate change has impacted the ship's operational environment. This could be derived from historical climate data analysis; ACC is the Adaptation and Climate Change Resilience factor, indicating the ship's readiness to adapt to changing climate conditions. It considers design features that enhance operational efficiency in variable climates, such as advanced weather forecasting systems or ice-class hulls; FEE is the Fuel Efficiency Enhancement factor, reflecting the ship's improved fuel efficiency due to climate change-related design adaptations. This could account for measures like optimized routing to avoid adverse weather or improved hull designs for ice-covered routes. This simplified formula aims to illustrate how climate change factors can be incorporated into the operational EEDI assessment.

Adaptation and Climate Change (ACC) resilience factor

ACC Resilience factor would require a detailed analysis of various ship design features and adaptations that enhance operational efficiency in variable climate conditions. The ACC factor should consider aspects such as hull design, propulsion systems, navigation equipment, and crew training that contribute to a ship's resilience to climate change. Here's a conceptual formula for the ACC factor (Eq. (2) and HDF (Eq. (3):

$$\mathrm{ACC} = \left(\frac{\mathrm{HDF}+\mathrm{PEF}+\mathrm{NEF}+\mathrm{CEF}+\mathrm{SEF}+\mathrm{LEF}}{6}\right) \quad \text{Eq. (2)}$$

$$\mathrm{HDF} = \left(\frac{A_h \times D_h \times R_h \times T_h \times S_h}{P_h \times L_h}\right) \quad \text{Eq. (3)}$$

Where, ACC is the Adaptation and Climate Change Resilience factor; HDF is the Hull Design Factor, representing the impact of specialized hull designs on operational efficiency in specific climate conditions; A_h represents the area of specialized hull features designed for climate resilience (e.g., ice-class hull, wave-piercing hull) relative to the total hull area; D_h represents the depth of specialized hull features relative to the total draft of the vessel; R_h represents the roughness of specialized hull coatings or materials designed to reduce resistance in specific climate conditions; T_h represents the thickness of ice-strengthened materials for ice-class vessels; S_h represents the shape factor, considering how the hull's shape optimizes performance in specific climates (e.g., bulbous bow for icebreaking); P_h represents the power required to overcome resistance due to specialized hull features; L_h represents the length of the vessel.

PEF is the Propulsion Efficiency Factor, reflecting how advanced propulsion systems enhance performance under varying climate conditions (Eq. (4).

$$\mathrm{PEF} = \frac{P_r - P_c}{P_r} \times 100\% \quad \text{Eq. (4)}$$

PEF is the Propulsion Efficiency Factor, expressed as a percentage; P_r is the power required for propulsion under normal or reference conditions (kW); P_c is the power required for propulsion under climate-affected conditions (kW). This formula calculates the improvement in propulsion efficiency under climate-affected conditions compared to reference conditions. A higher PEF percentage indicates greater efficiency when the ship is operating in challenging climates. Actual values for P_r and P_c would be determined through performance measurements or simulations, considering various climate scenarios. P_r and P_c are both effective power P_e of a vessel at different conditions (Eq. (5).

$$P_e = \frac{R \times V}{\eta_p} \qquad \text{Eq. (5)}$$

Pe is the effective power required for propulsion (kW); R is the total resistance (N) that the ship encounters; V is the velocity of the ship (m/s); ηp is the propulsion efficiency, which is expressed as a decimal. NEF is the Navigation Equipment Factor, accounting for the contribution of advanced navigation and communication equipment to climate resilience. While NEF is a qualitative measure and doesn't have a specific mathematical formula, it can be expressed as a rating or score. Here's a conceptual representation of NEF (Eq. (6):

$$\text{NEF} = \text{Qualitative Rating or Score} \qquad \text{Eq. (6)}$$

NEF is typically assessed based on the effectiveness and reliability of a ship's navigation and communication systems in varying climate conditions. The rating or score can be determined through expert evaluation, considering factors such as: precision and accuracy, reliability, adaptability, safety features, integration. The NEF score can be used to qualitatively assess the contribution of navigation equipment to a ship's climate resilience. A higher NEF score indicates more advanced and reliable equipment, enhancing a ship's ability to navigate safely and efficiently in diverse climate conditions. CEF is the Crew Training and Expertise Factor, measuring the impact of well-trained crews in adapting to changing climate conditions. As a qualitative measure, CEF doesn't have a specific mathematical formula. Instead, it is typically expressed as a rating or score based on expert evaluation. Here's a conceptual representation of CEF (Eq. 7):

$$\text{CEF} = \text{Qualitative Rating or Score} \qquad \text{Eq. (7)}$$

The CEF score considers factors related to crew training and expertise in the context of climate resilience, such as: Training Programs, Experience, Adaptability, Communication Skills, Safety Awareness. The CEF score provides a qualitative assessment of the role of crew training and expertise in a ship's ability to operate safely and efficiently under varying climate conditions. A higher CEF score indicates a well-prepared and adaptable crew that contributes to climate resilience. SEF is The Safety and Emergency Preparedness Factor (SEF), it is a qualitative measure that evaluates how safety features and emergency response protocols contribute to a ship's climate resilience. Like other qualitative factors, SEF doesn't have a specific mathematical formula but is often expressed as a rating or score based on expert evaluation. Here's a conceptual representation of SEF (Eq. (8):

$$\text{SEF} = \text{Quantitative Rating or Score} \qquad \text{Eq. (8)}$$

The SEF score considers factors related to safety and emergency preparedness in the context of climate resilience, such as: Safety Equipment, Emergency Response Plans, Drills and Training, Risk Assessment, Communication Protocols. The SEF score provides a qualitative assessment of the safety and emergency preparedness features on a ship and their role in enhancing climate resilience. A higher SEF score indicates that a ship is better equipped to respond to climate-related challenges and ensure the safety of its crew and passengers. LEF is the Logistics and Supply Chain Resilience Factor (LEF) is a qualitative measure that assesses a ship's ability to adapt its logistics and supply chain management in response to climate-related disruptions. As a qualitative measure, LEF doesn't have a specific mathematical formula but is often expressed as a rating or score based on expert evaluation. Here's a conceptual representation of LEF (Eq. (9):

$$\text{LEF} = \text{Qualitative Rating or Score} \qquad \text{Eq. (9)}$$

The LEF score considers various factors related to logistics and supply chain resilience in the context of climate challenges, including: Inventory Management, Supply Chain Flexibility, Redundancy and Contingency Plans, Weather Monitoring and Forecasting, Communication and Coordination. The LEF score provides a qualitative assessment of a ship's resilience in managing logistics and supply chains amid climate-related challenges. A higher LEF score indicates that the ship is better prepared to respond to supply chain disruptions caused by changing weather patterns and other environmental factors.

Fuel Efficiency Enhancement (FEE) factor

The Fuel Efficiency Enhancement (FEE) factor represents the ship's improved fuel efficiency due to climate change-related design adaptations. While this factor is typically qualitative and context-dependent, you can conceptualize it in terms of a hypothetical empirical formula. However, it's essential to note that such a formula would need to be established based on specific research and data. Here's a conceptual representation of the FEE factor (Eq. (10):

$$\text{FEE} = \frac{F_c - F_d}{F_d} \times 100\ \% \qquad \text{Eq. (10)}$$

Where; FEE is the Fuel Efficiency Enhancement factor, expressed as a percentage; F_c is the fuel consumption under climate-affected conditions; F_d is the reference or normal fuel consumption under standard conditions. This formula calculates the improvement in fuel efficiency under climate-affected conditions compared to standard conditions. A higher FEE percentage indicates a more efficient fuel consumption when the ship is operating in challenging climates. It's important to recognize that calculating the actual values for F_c and F_d would require empirical data and a thorough analysis of a specific ship's performance. The F_c and F_d both have the same formula referring to two different conditions. Below is the formula for Fuel Consumption of a Ship (Eq. (11):

$$\text{Fuel Consumption (FC)} = \frac{\text{P}}{\eta_f \times \text{LHV}} \qquad \text{Eq. (11)}$$

Where, FC is the fuel consumption in metric tons or any suitable unit (MT); P is the effective power required for propulsion (kW) as calculated based on the ship's resistance and speed; ηf is the thermal efficiency of the ship's propulsion system, expressed as a decimal; LHV is the Lower Heating Value of the fuel (MJ/kg or GJ/MT), representing the energy content of the fuel being used. This formula calculates the amount of fuel consumed by the ship in a specific unit (e.g., metric tons) to produce the effective power required for propulsion. It accounts for the ship's efficiency and the energy content of the fuel being used.

Climate Change Extent (CCE) factor

The Climate Change Extent (CCE) factor represents the extent to which climate change has impacted a ship's operational environment. It's typically a qualitative measure rather than a mathematical formula, and it's expressed as a rating or score based on expert evaluation. Here's a conceptual representation of CCE (Eq. (12):

$$\text{CCE} = \text{Qualitative Rating or Score} \qquad \text{Eq. (12)}$$

The CCE score is determined through the assessment of several factors, which may include: (1) Climate Trends: An evaluation of long-term climate data and trends for the specific region or route where the ship operates; (2) Frequency of Extreme Weather Events: The assessment of how frequently extreme weather events, such as storms, hurricanes, or ice conditions, occur in the operational area; (3) Environmental Changes: An examination of environmental changes, such as sea-level rise, changing ice cover, or altered wind patterns, that can impact the ship's operation; (4) Historical Data: The analysis of historical data related to climate-related disruptions or incidents that have affected the ship's operations ; as well as (5) Scientific Climate Assessments: Inputs from climate scientists and experts on the extent to which climate change is influencing the ship's operational environment. The CCE score provides a qualitative assessment of how much and how significantly climate change has affected the ship's operating conditions. A higher CCE score indicates a greater impact from climate change, potentially requiring more significant adaptations in ship design and operational strategies.

Energy Efficiency Design Index (EEDI) design factor

The Energy Efficiency Design Index (EEDI) for a ship's design is calculated using a formula that considers the ship's deadweight tonnage (DWT) and the ship's energy efficiency design standards. The formula for EEDI design is as follows (Eq. (13):

$$\text{EEDI}_{\text{design}} = \frac{\text{CO}_2\ \text{Emissions}}{\text{DWT} \times \text{EEDI Reference Value}} \qquad \text{Eq. (13)}$$

Where, $\text{EEDI}_{\text{design}}$ is the Energy Efficiency Design Index for the ship's design; CO_2 Emissions represents the estimated carbon dioxide emissions associated with the ship's design and construction (in metric tons of CO2); DWT is the ship's deadweight tonnage, which is a measure of it carrying capacity (in metric tons); EEDI Reference Value is the reference EEDI value specific to the ship type and size, as determined by international regulations. The $EEDI_{design}$ is used to assess the energy efficiency of a ship's design, with lower values indicating more energy-efficient designs. The EEDI design must meet or be lower than the reference value for a given ship type and size to comply with international energy efficiency standards. Please note that the reference values may vary depending on the ship type, size, and specific regulations in place at the time of design assessment.

Ship hull integrity

Ship hull integrity is a critical aspect of ship design, particularly when considering the impact of climate on ship operations. While there isn't a single formula for ship hull integrity, it involves assessing a combination of factors related to the ship's structural design, materials, maintenance, and operational conditions. Below are some of the key factors and considerations that play a role in assessing ship hull integrity.

Stress analysis

Structural engineers use stress analysis to determine how various loads, including those induced by waves, ice, and other environmental factors, affect the ship's hull. Stress analysis can be complex and typically relies on finite element analysis.

Hull stress analysis (for simple case)

The formula for stress (σ) due to an applied force (F) on a material's cross-sectional area (A) is given by (Eq. (14):

$$\sigma = \frac{F}{A} \qquad \text{Eq. (14)}$$

Buckling analysis (for evaluating stability against buckling)

The critical buckling load (Pcr) for a plate can be determined using the Euler's buckling formula (Eq. (15):

$$P_{cr} = \frac{\pi^2.E.I}{(K.L)^2} \qquad \text{Eq. (15)}$$

Where, E is the material's Young's modulus; I is the plate's moment of inertia; K is the effective length factor; L is the effective length.

Stress due to bending (simple Beam theory)

For a simple beam with a uniform load (q), the maximum stress (σ max) at a distance (y) from the neutral axis can be calculated using the formula (Eq. (16):

$$\sigma_{max} = \frac{M}{S}.y \qquad \text{Eq. (16)}$$

Where, M is the bending moment; S is the section modulus of the beam.

Stress due to torsion (circular cross-section)

For a circular cross-section subjected to torsion, the maximum shear stress (τ max) can be calculated using the formula (Eq. (17):

$$\tau_{max} = \frac{T}{J} \quad \text{Eq. (17)}$$

Where, T is the applied torque; J is the polar moment of inertia; r is the radial distance from the center to the point of interest.

Stress due to pressure (Thin-Walled pressure vessel)

For a thin-walled pressure vessel, the stress (σ) due to internal pressure (P) can be calculated using Lame's formula (Eq. (18):

$$\sigma = \frac{P.R}{t} \quad \text{Eq. (18)}$$

Where, P is the internal pressure; R is the radius of the vessel; t is the thickness of the vessel wall.

Von Mises Stress (for combined loads)

The von Mises stress (σ_{VM}) is used to assess the combined effect of different stresses (e.g., bending, shear, and pressure) and is calculated as (Eq. (19):

$$\sigma_{VM} = \sqrt{\sigma^2 + 3.\tau^2} \quad \text{Eq. (19)}$$

Where, σ is the normal stress; τ is the shear stress. These are simplified stress analysis formulas, and ship hulls are complex structures with varying shapes and loads. In practice, finite element analysis (FEA) and advanced software are often used to conduct stress analysis on ship hulls. The specific formulas used depend on the ship's geometry and loading conditions. For a comprehensive stress analysis of a ship hull, it's essential to consider the entire structure, including the keel, frames, bulkheads, and other components, and to use specialized naval architecture and structural engineering software. Additionally, classification societies and industry standards provide guidance for conducting stress analysis and ensuring the structural integrity of ship hulls.

Fatigue analysis

Fatigue analysis for ship structures involves assessing how repeated loads or cyclic stresses may lead to material fatigue and potential failure over time. The specific formula used in fatigue analysis can vary depending on the type of loading and the material properties. One commonly used method is the Miner's Rule for cumulative damage, which is applicable to various loadings. Here's the formula for Miner's Rule (Eq. (20):

$$\frac{1}{N} = \frac{n_1}{N_1} + \frac{n_2}{N_2} + \frac{n_3}{N_3} + \cdots \quad \text{Eq. (20)}$$

Where, N is the total number of cycles to failure; n1, n2, n3… are the number of cycles at different stress levels or loadings; N1, N2, N3, … are the corresponding fatigue life or endurance limit for each loading condition. The formula considers the cumulative damage due to different stress levels and loadings. The inverse of the total number of cycles to failure (1/N) is the measure of cumulative damage. If 1/N exceeds 1, it indicates that the structure is expected to fail. It's essential to consider stress concentrations, load spectra, and stress-life (S-N) curves specific to the material and loading conditions for a more accurate fatigue analysis. Fatigue analysis for ship structures is typically a complex process that may involve finite element analysis (FEA) and the use of industry standards and guidelines to ensure the structural integrity of the hull and other components over the ship's operational life.

Material strength

The material strength of a material is typically described by two key properties: the ultimate tensile strength (UTS) and the yield strength (YS). These properties are critical in understanding how a material responds to loads and stresses.

Ultimate Tensile Strength (UTS)

The ultimate tensile strength (σ UTS) is the maximum stress that a material can withstand when subjected to a tensile (pulling) load. It is typically measured in Pascals (Pa), Mega-Pascals (MPa), or other pressure units. The formula for UTS is (Eq. (21):

$$\sigma_{UTS} = \frac{F_{max}}{A} \qquad \text{Eq. (21)}$$

Where, σ_{UTS} is the ultimate tensile strength; F_{max} is the maximum force applied to the material; A is the original cross-sectional area of the material.

Yield Strength (YS)

The yield strength (σ_{YS}) is the stress at which a material undergoes plastic deformation. In other words, it's the stress at which the material no longer returns to its original shape after the load is removed. The formula for YS is (Eq. (22):

$$\sigma_{YS} = \frac{F_{yield}}{A} \qquad \text{Eq. (22)}$$

Where, σ_{YS} is the yield strength; F_{yield} is the force at which plastic deformation begins; A is the original cross-sectional area of the material. These strength properties are critical for designing and assessing the integrity of ship hulls and other structural components. When conducting stress analysis or designing ship structures, it's essential to ensure that the applied stresses (e.g., from waves, loads, or other factors) remain below these material strengths to prevent structural failure. Additionally, industry standards and regulations often specify allowable stress limits for different materials and structural components. Other ship hull integrity criteria are, corrosion rate, maintenance and inspection, operational condition, etc.

Results and Discussion

Hull design factor

The actual parameters put into consideration is that of MV ROMANDIE a bulk carrier vessel registered in Switzerland with a Gross Tonnage: 22697, Summer DWT: 35774 tons, Length Overall X Breadth Extreme: 181 X 30m and Year built: 2010 (VesselFinder Web Portal, 2024). The hull design factor under normal conditions unveils a distinct trend as vessel speed varies. It demonstrates a significant alteration in values corresponding to different speed intervals. As the speed escalates from 4 to 20 knots, there's a substantial reduction in the hull design factor. At lower speeds (4-8 knots), the hull design factor notably decreases, indicating a considerable shift in the vessel's design effectiveness concerning speed. Beyond 8 knots, the trend continues with a more pronounced decrease in the factor. This illustrates a nonlinear relationship, showcasing a substantial change in the hull's efficiency relative to the vessel's velocity. This observation underscores the dynamic nature of hull design efficiency concerning speed variations. The decreasing trend suggests a potential enhancement in the hull's hydrodynamic characteristics at higher speeds, contributing to reduced resistance and improved performance. Such alterations in the hull design factor signify the vessel's adaptability to different speed regimes and its improved capacity to navigate efficiently across various speed ranges. Understanding these alterations in hull design efficiency concerning vessel speed is pivotal for optimizing maritime operations. It highlights the need for adaptive hull designs capable of efficiently maneuvering through diverse speed conditions. These findings prompt further exploration into hull design modifications, aiming to enhance performance and reduce resistance across varying speed intervals, thereby contributing to more efficient and adaptable vessel operations.

The hull design factor under climatic conditions showcases a discernible pattern across varying vessel speeds (*Figure 1*). As the vessel accelerates from 4 to 20 knots, there's a marked reduction in the hull design factor, signifying a notable alteration in the hull's effectiveness under diverse climatic scenarios. At lower speeds (4-8 knots), the hull design factor exhibits a substantial decline, indicating a pronounced shift in the vessel's design efficiency relative to speed in climatically challenging conditions. Beyond 8 knots, this decline persists, emphasizing an evident nonlinear relationship between speed and the hull design factor, accentuating the hull's adaptability to varying climatic challenges. These observations underline the dynamic nature of hull performance concerning different climatic conditions. The decreasing trend in the hull design factor suggests potential modifications in the hull's hydrodynamic capabilities in adverse climates, contributing to improved performance and reduced resistance. This indicates the vessel's potential to navigate more efficiently under diverse climatic circumstances. Understanding the alterations in hull design efficiency under climatic conditions is crucial for enhancing maritime operations. It underscores the importance of adaptive hull designs capable of maneuvering efficiently through varying climatic challenges. These findings encourage further exploration into optimizing hull designs, aiming to bolster vessel performance and reduce resistance, particularly in climates that impose additional navigational hurdles.

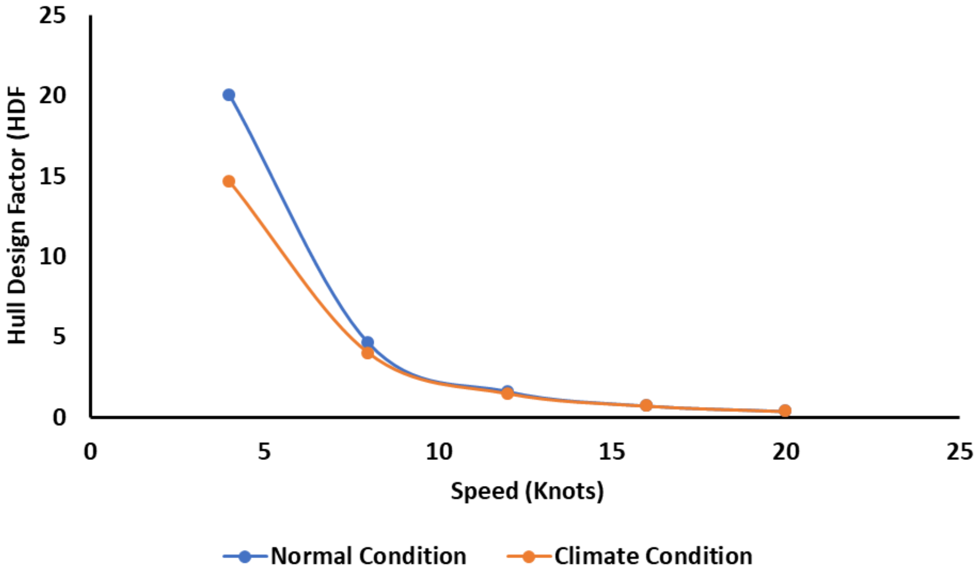

Figure 1. *Hull Design Factor under normal and climatic condition.*

Propulsion efficiency factor

The data illustrates a distinctive trend showcasing the relationship between vessel speed and effective power under normal conditions (*Figure 2*). As the vessel speed escalates from 4 to 20 knots, there's a substantial and consistent rise in the effective power required for propulsion. At the lower speed range (4-8 knots), the effective power demonstrates a gradual increment. However, the curve steepens notably beyond 8 knots, indicating a more pronounced surge in power demand with each subsequent increase in speed. This exponential rise suggests a nonlinear relationship between vessel speed and the energy required for propulsion. This observation aligns with maritime engineering principles, highlighting the substantial increase in power needed to propel a vessel as it accelerates. The escalating effective power with higher speeds reflects the augmented resistance encountered by the vessel due to greater hydrodynamic forces and water resistance, demanding a substantial boost in engine power for sustained propulsion. Also, this trend emphasizes the considerable energy requirements associated with higher speeds in maritime transport. It underscores the imperative for ship operators and designers to carefully consider the trade-off between vessel speed and energy efficiency. While higher speeds might offer shorter transit times, they significantly elevate the energy demands, impacting fuel consumption, operational costs, and environmental footprints.

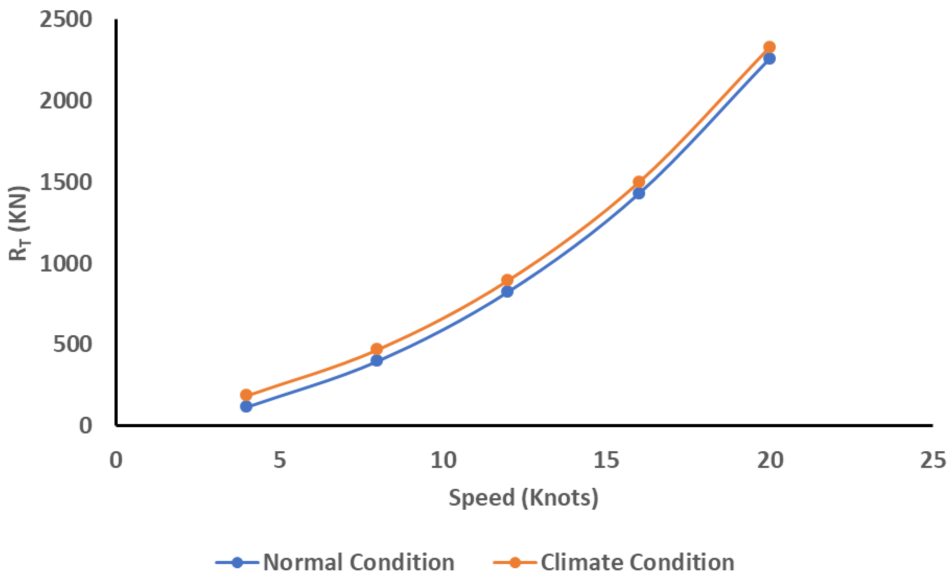

Figure 2. *Total Resistance under normal and climatic conditions.*

The escalating effective power underscores the significance of optimizing vessel speed based on the economic and operational requirements. It accentuates the need for innovative propulsion technologies, streamlined designs, and efficient operational practices to balance speed requirements with energy-efficient propulsion, ensuring optimal performance while minimizing energy consumption and operational costs. The effective power under climatic conditions reveals a similar trend to that observed under normal conditions, demonstrating a consistent increase with escalating vessel speed (*Figure 3*). As the speed rises from 4 to 20 knots, there's a notable and consistent surge in the effective power required for propulsion. The data portrays a proportional relationship between speed and the power demanded for sustained propulsion. It's evident that higher speeds necessitate a substantial increase in effective power to overcome heightened resistance and propel the vessel through climatically affected conditions. This pattern aligns with fundamental principles of maritime engineering, emphasizing the elevated power requirements associated with faster speeds. The steep rise in effective power at higher velocities highlights the increased resistance encountered by the vessel due to various climatic factors, including wave forces, wind resistance, and potentially altered hydrodynamic conditions.

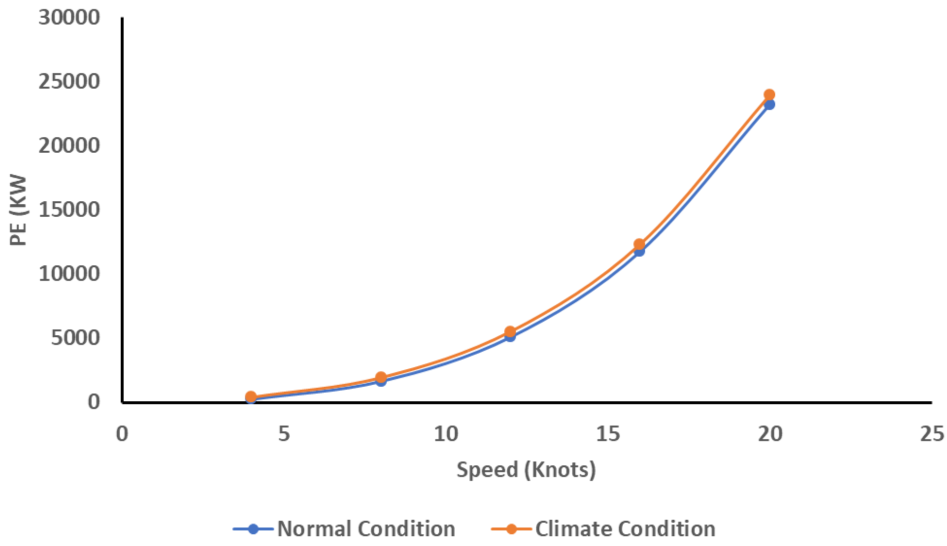

Figure 3. *Effective Power under normal and climatic condition.*

Understanding this relationship between speed and effective power under climatic conditions is crucial for maritime operations. It underscores the necessity for strategic considerations when navigating through challenging climatic conditions. Operators must weigh the benefits of increased speed against the considerable rise in energy demands, impacting fuel consumption, operational costs, and environmental sustainability. Also, this data emphasizes the significance of developing and adopting efficient propulsion systems and operational strategies to optimize vessel speed while conserving energy under varying climatic scenarios. Balancing speed requirements with energy-efficient propulsion becomes imperative to ensure cost-effective and sustainable maritime operations in adverse climate conditions. The propulsion efficiency factor (*Figure 4*), as evidenced by the data across different vessel speeds, reveals a substantial decline as speed increases from 4 to 20 knots. This decline in the propulsion efficiency factor is consistent under both normal and climatic conditions, emphasizing a direct correlation between vessel speed and propulsion efficiency. At lower speeds (4-8 knots), the propulsion efficiency factor experiences a notable reduction, indicating a decrease in the effectiveness of the propulsion system in converting the effective power into useful thrust. This reduction becomes more pronounced as the vessel accelerates beyond 8 knots, highlighting a nonlinear relationship between speed and propulsion efficiency.

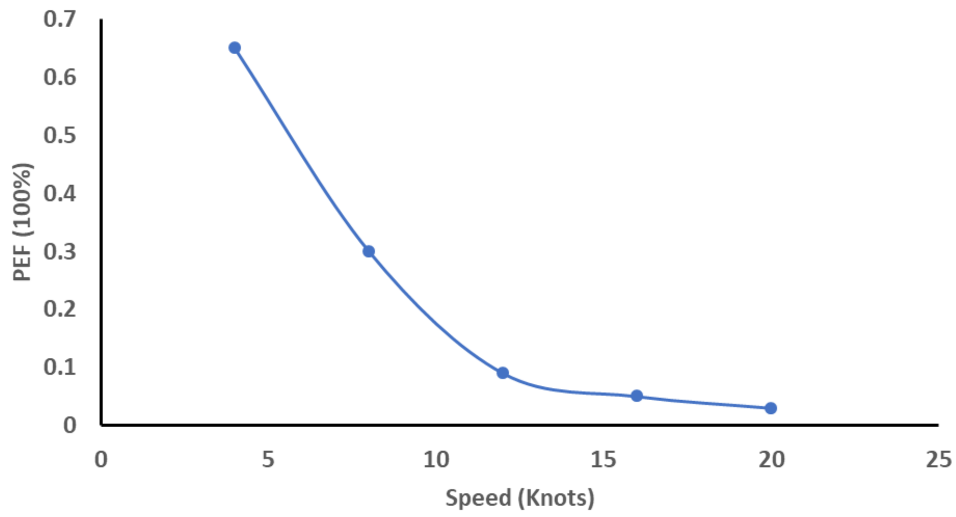

Figure 4. *Propulsion Efficiency Factor.*

The observed trend in the propulsion efficiency factor aligns with the principles of maritime engineering, where higher speeds incur higher hydrodynamic resistance, necessitating increased power for propulsion. The diminishing propulsion efficiency factor underscores the challenges associated with maintaining efficient propulsion systems as speeds elevate, particularly in climatic conditions that may introduce additional resistance factors. Considering the effective power under both normal and climatic conditions, it is evident that the declining propulsion efficiency factor corresponds to an increasing demand for effective power at higher speeds. This interrelation emphasizes the intricate balance required in optimizing vessel performance, considering both the propulsion efficiency factor and the effective power under varying conditions.

Fuel efficiency enhancement

The fuel consumption trends at different vessel speeds under normal conditions exhibit a distinct pattern, highlighting the relationship between speed and fuel usage (*Figure 5*). As the vessel's speed escalates from 4 to 20 knots, there is a conspicuous escalation in fuel consumption. At lower speeds (4-8 knots), the fuel consumption demonstrates a gradual rise, which significantly amplifies as the speed surpasses 8 knots. This observed trend showcases a nonlinear relationship between vessel speed and the amount of fuel consumed, accentuating the escalating fuel demands associated with increased speed. This trend underscores the direct correlation between vessel speed and fuel consumption in normal operational conditions. It emphasizes the substantial impact of speed on the amount of fuel required for propulsion. The notable increase in fuel consumption at higher speeds highlights the challenges in maintaining fuel efficiency while achieving faster transit times. Understanding these fuel consumption patterns is crucial for maritime operators in optimizing operational strategies. It emphasizes the necessity of evaluating the trade-off between speed and fuel efficiency, especially considering the economic and environmental implications associated with increased fuel consumption at higher speeds. This prompts a careful reassessment of optimal cruising speeds to strike a balance between operational efficiency and fuel conservation in maritime transport.

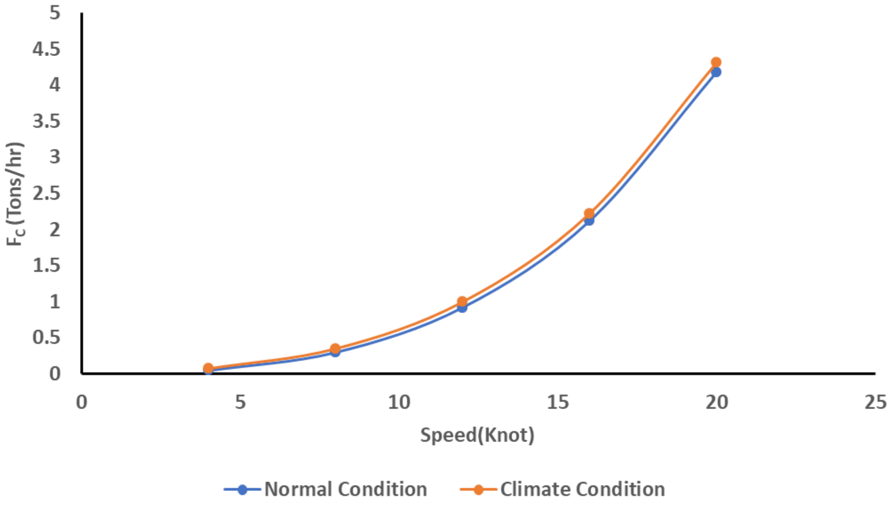

Figure 5. *Fuel consumption under normal and climatic condition.*

The fuel consumption data under climatic conditions reveals a similar trend to the previously observed fuel consumption under normal conditions. As the vessel's speed increases from 4 to 20 knots, there's a consistent and substantial escalation in fuel consumption, indicating a direct correlation between speed and the amount of fuel consumed. Comparatively, the fuel consumption rates under climatic conditions are noticeably higher across all speed intervals when juxtaposed with the fuel consumption observed under normal conditions. This disparity accentuates the amplified impact of climatic variables on fuel consumption, resulting in increased energy demands for propulsion. The higher fuel consumption rates under climatic conditions signify the additional challenges posed by adverse weather conditions, such as increased resistance due to waves, wind, or altered hydrodynamic forces. These factors collectively contribute to greater energy requirements, elevating fuel consumption rates compared to normal operational conditions. This comparison underscores the critical influence of climatic conditions on fuel efficiency in maritime operations. It emphasizes the necessity for adaptive operational strategies and vessel designs capable of mitigating the amplified fuel consumption associated with adverse climates. Balancing operational speed with fuel efficiency becomes paramount, particularly in challenging climatic scenarios, to ensure cost-effective and sustainable maritime transportation.

The data on fuel efficiency enhancements at different vessel speeds presents a compelling narrative of progressive improvements in fuel economy as the speed increases (*Figure 6*). This demonstrates a commendable effort towards optimizing fuel utilization across various operational conditions. At lower speeds (4-8 knots), there's a substantial enhancement in fuel efficiency, notably at 4 knots, where a significant 63% improvement is observed. This underscores the effectiveness of certain modifications or technological interventions aimed at conserving fuel without compromising on vessel performance. The trend continues as the vessel accelerates, showing a consistent but diminishing pattern in fuel efficiency enhancements. While the improvements taper off as speed increases, they remain noteworthy. This signifies the adaptability of the vessel's systems or operational strategies in maintaining better fuel economy across diverse speed ranges. These results signify the positive impact of initiatives geared towards enhancing fuel efficiency in maritime operations. The substantial improvements, particularly at lower speeds, highlight the potential for innovative technologies or procedural adjustments to significantly reduce fuel consumption. This data encourages further exploration and implementation of strategies aimed at sustaining or even improving fuel efficiency across a broader spectrum of speeds. It emphasizes the importance of continued efforts to mitigate fuel consumption without compromising operational efficacy, supporting cost-effective and environmentally conscious maritime transport. The digitalization of the Bulk carrier will do a lot in environmental situations (Nitonye et al., 2024).

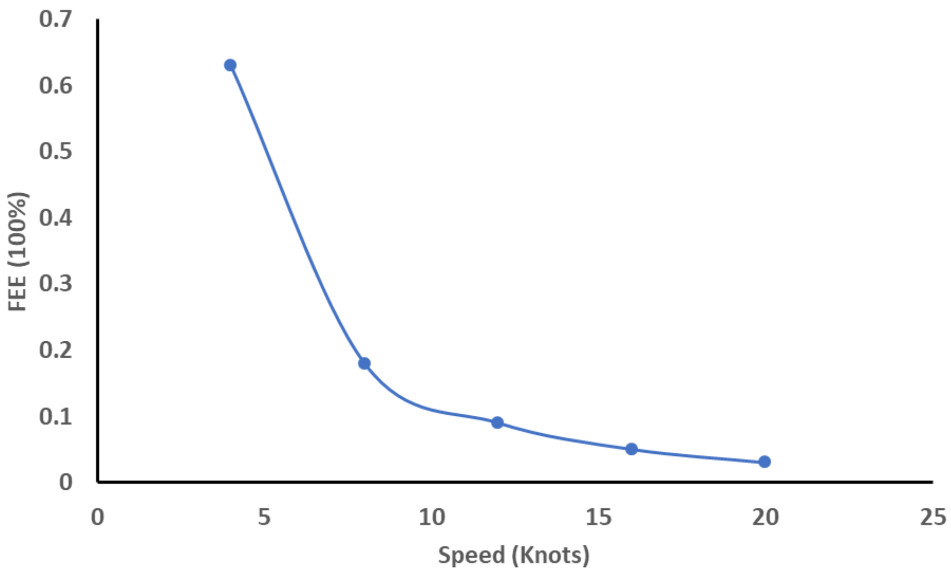

Figure 6. *Fuel efficiency enhancement.*

Conclusion

This research rigorously explored the multifaceted impact of climate on ship design and operations. Through an extensive analysis of various climatic factors, including ice, wind, and wave conditions, along with their influence on vessel performance, several crucial insights were unearthed. The review of past works illuminated the advancements in understanding climate-induced challenges in maritime settings while identifying gaps that necessitated further investigation. By addressing these gaps, this study contributed to elucidating the intricate relationships between climatic variables and ship functionalities. The investigation into hull design factors, propulsion efficiency, and fuel consumption under diverse climatic conditions highlighted the significant influence of weather phenomena on vessel performance. The findings underscored the necessity for adaptive ship designs, technological innovations, and operational strategies to mitigate the amplified challenges posed by adverse climates. Moreover, the fuel efficiency enhancements demonstrated the feasibility of optimizing fuel consumption across different speed intervals, showcasing the potential for sustainable and cost-effective maritime operations. Overall, this research emphasizes the imperative of considering climate variables in ship design and operational planning. It advocates for adaptive approaches that account for climatic influences to ensure safe, efficient, and environmentally conscious maritime transportation in an evolving climate scenario. The outcomes of this study provide a foundational framework for further research and practical applications, aiming to enhance vessel resilience and efficiency in the face of ever-changing climatic conditions. Regulatory Policies: Encourage policies favoring energy-efficient propulsion systems and sustainable fuels.

Acknowledgement

This research is self-funded.

Conflict of interest

The authors confirm that there is no conflict of interest involve with any parties in this research study.

REFERENCES

[1] Bitner-Gregersen, E.M., Hovem, L., Hørte, T. (2003): Impact of freak waves on ship design practice. – In Proc. MaxWave Final Meeting 76p.
[2] Christodoulou, A., Demirel, H. (2018): Impacts of climate change on transport: A Focus on Airports, Seaports and Inland Waterways. – JRC Science For Policy Report 55p.
[3] Church, J.A., White, N.J., Arblaster, J.M. (2005): Significant decadal-scale impact of volcanic eruptions on sea level and ocean heat content. – Nature 438(7064): 74-77.
[4] Church, J.A., White, N.J., Coleman, R., Lambeck, K., Mitrovica, J.X. (2004): Estimates of the regional distribution of sea level rise over the 1950–2000 period. – Journal of Climate 17(13): 2609-2625.
[5] Church, J.A., White, N.J., Hunter, J.R. (2006): Communicating key indicators for sea level. – In Poster presented at the workshop Understanding Sea-level Rise and Variability 4p.
[6] Det Norske Veritas Germanischer Lloyd (DNVGL) (2018): Maritime Forecast to 2050: Energy Transition Outlook. – DNVGL Web Portal 9p.
[7] International Maritime Organization (IMO) (2018): Initial IMO Strategy on Education of GHG Emissions from Ships. – IMO Web Portal 12p.
[8] Intergovernmental Panel on Climate Change (IPCC) (2014): Climate Change 2014: Impacts, Adaptation, and Vulnerability. – Cambridge University Press 30p.
[9] Maria Bitner-Gregersen, E., Ingolf Eide, L., Hørte, T., Skjong, R., Bitner-Gregersen, E.M., Eide, L.I. (2013): Ship and offshore structure design in climate change perspective. – Springer Nature 76p.
[10] National Centers for Environmental Information (NCEI) (2023): State of the Climate: Global Climate Report for 2022. – NCEI Web Portal 20p.
[11] Nitonye, S., Ahiakwo, O.V. Oludi, K. (2024): Digitalization of bulk carries: Revolutionizing efficiency, safety and environmental responsibility. – Quantum Journal of Engineering, Science and Technology 5(1): 30-44.
[12] Schiermeier, Q. (2006): The costs of global warming. – Nature 439(7075): 374-376.
[13] VesselFinder Web Portal (2024): ROMANDIE: Bulk carrier, IMO 9542829. – VesselFinder Web Portal 4p.
[14] Wigley, T.M., Raper, S.C. (1987): Thermal expansion of sea water associated with global warming. – Nature 330(6144): 127-131.