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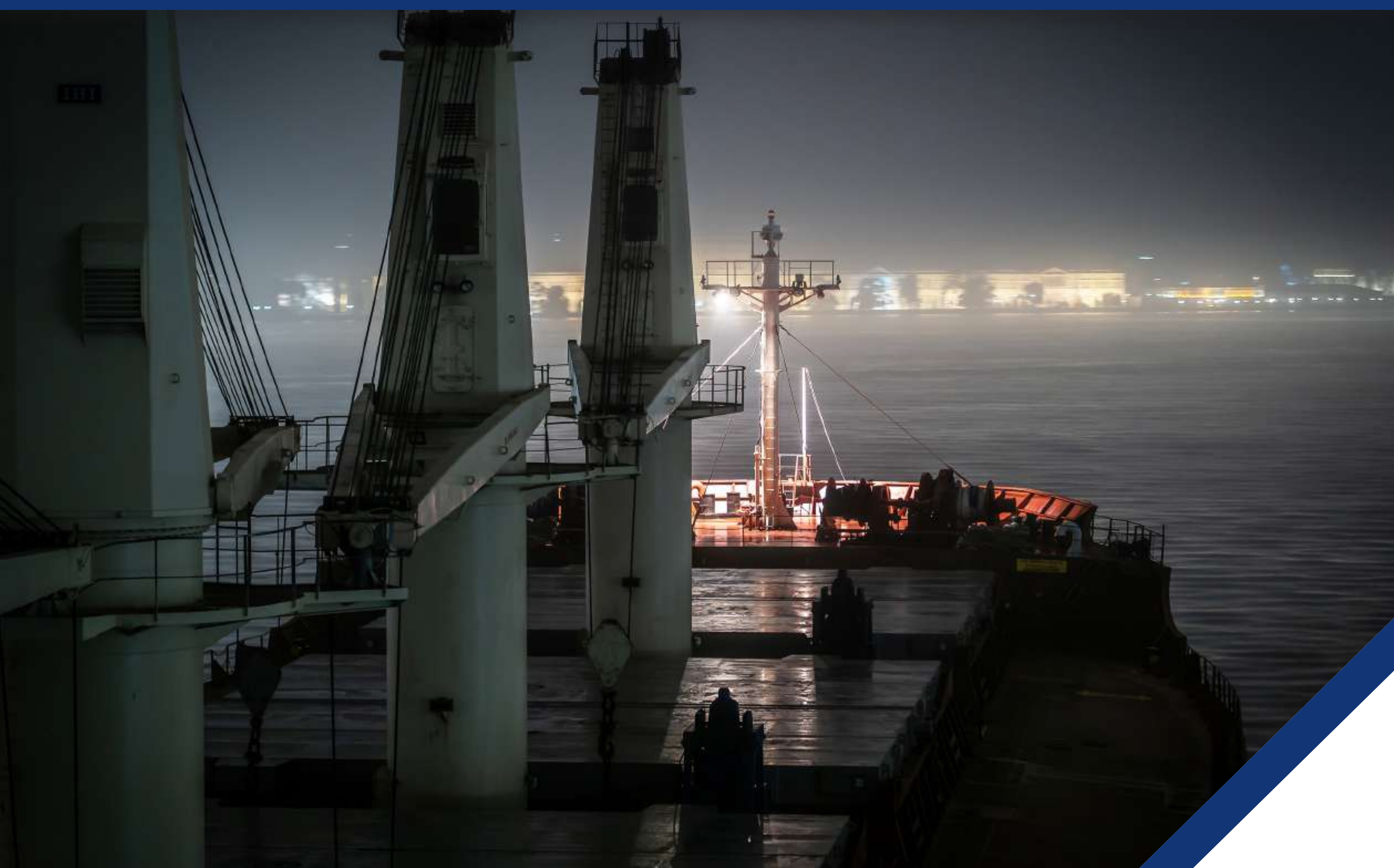
JOURNAL OF ETA MARITIME SCIENCE



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About the JEMS

Aim:

Journal of Eta Maritime Science (JEMS) aims to encourage and publish research studies about the challenges and opportunities associated with considerable numbers of understandings in the maritime sector. Besides, JEMS also aims to reach out to relevant audiences by publishing the latest scientific and technological developments. JEMS journal, which is published periodically and regularly in March, June, September, December, may also publish special issues related to the selected topics.

Scope:

Scope of the journal covers national, international and local studies regarding Marine Engineering, Marine Transportation Engineering, Naval Architecture Engineering, Marine Operations, Logistics, Logistics Engineering, Maritime History, Coastal Engineering, Marine Pollution and Environment, Fishing and Fisheries Technology, Shipbuilding and Ocean Engineering.

JEMS is indexed in **Web of Science Emerging Sources Citation Index (ESCI), TRID, Tubitak Ulakbim Science Database, Index Copernicus International, Directory of Open Access Journals (DOAJ)**, **EBSCO** and **J-Gate**.

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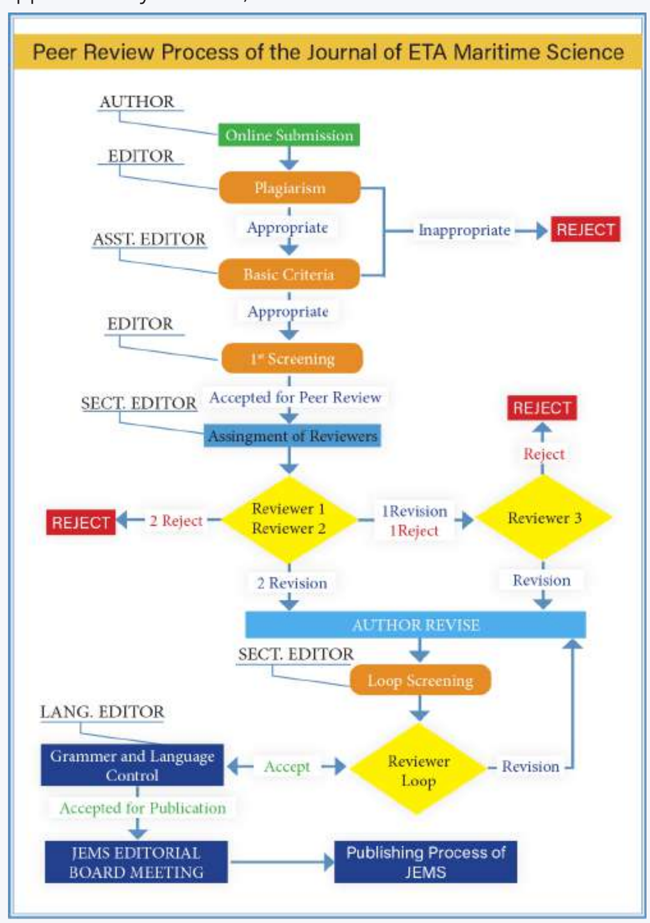

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Abstract

This sample includes the manuscript preparation guideline of Journal of ETA Maritime Science (JEMS). In the abstract section, a brief indicating the novelty and main findings of the study should be written. The text of the abstract should be written fully justified, in italics and 10 pt. The section should be no more than 200 words. The number of keywords should be between 3-5.

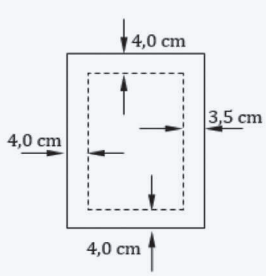
Keywords: JEMS, Author, Manuscript, Guide

1. Introduction

Journal of Eta Maritime Science (JEMS) aims to encourage and publish research studies about the challenges and opportunities associated with considerable numbers of understandings in the maritime sector. Besides, JEMS also aims to reach out to relevant audiences by publishing the latest scientific and technological developments. JEMS journal, which is published periodically and regularly, may also publish special issues related to the selected topics. Scope of the journal covers national, international and local studies regarding Marine Engineering, Maritime Transportation Engineering, Naval Architecture Engineering, Marine Operations, Logistics, Logistics Engineering, Maritime History, Coastal Engineering, Marine Pollution and Environment, Fishing and Fisheries Technology, Shipbuilding and Ocean Engineering

2. Page Layout and Format

JEMS publishes studies conducted in **English**. Text is to be prepared with justified alignment, without indentation in the paragraph beginning, in **"Cambria"** format with **10-point** font size and **1,0** line- spacing. There must be **initially 6nk and then 3nk** line spacing between the new launching paragraph and the previous paragraph. Worksheets must be on **A4** paper size, and margins should b**e 4 cm from the top, 4 cm from the bottom, 4 cm from left** and **3.5 cm from right**.



Studies must be submitted online from the journal's web address (http://www.jemsjournal.org). Articles printed or within CD, articles submitted by mail, fax etc., is not acceptable.

The main title of the article must be written in English and should be **set centered** in **12 point-size. Initially, 6nk and after 6nk** space should be left before the main title.

The first letter of the primary headings in the article should be capital letters. All headings and sub-headings should be designed **10 pt, bold** and **located to the left** with **numbering**, and also navy blue color should be used for sub-headings.

The use of tables and figures should be kept to a **minimum**. For readability purposes, the total number of tables and figures should be no more than **10** per article.

1 OrcaFlex Program

1.1 Axis Team

The table heading should be placed above the table. The figure heading should be placed below the figure. **2 nk** spaces should be added **before** the table heading and figure heading, and also **3 nk** spaces should be added next. The "table" and the "figure" should be written in bold and left-aligned. The first letters of the table, figure and equation headings should be written with capital letters. The heading and the content should be written with **"Cambria"** font and **10-point size**. Suppose tables, figures and equations in the study are cited. In that case, their references should be stated. **2 nk spaces** should be added **before** references, and **3 nk spaces** should be added **after**. If tables and figures don't fit into a single column, they should be designed to include two columns. Tables and figures which include two columns should be stated at the top or bottom of the page.

Table 1. Sample Table

Turkish Male Seafarers (n = 131,152)	BMI < 25.0	BMI 25-30	BMI > 30	Number of Participants
16-24 Ages Group	74.1%	22.5%	3.4%	34,421
25-44 Ages Group	44.1%	43.3%	12.6%	68,038
45-66 Ages Group	25.6%	51.1%	23.4%	28,693
All Turkish Male Seafarers	47.9 %	39.6 %	12.5%	131,152
Turkish Male Population	47.3 %	39.0 %	13.7 %	-

In the article, decimal fractions should be separated with dots and numbers should be separated with commas.

Average age: 28.624

Number of participants: 1,044 people

Page numbers, headers and footers should not be added to the study. The journal administration will make these adjustments.

Authors are deemed to have accepted that they have transferred the copyright of their studies to the journal by submitting their studies to our journal. Submitting a study to two different journals simultaneously is not suitable within the frame of academic ethics.

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This is an article which the editor prepares for determining journal policies in guiding research strategies and in making announcements to researchers and authors.

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This is a short article grounding upon the objectivity criteria, which the editor addresses to make comments, criticism, and contribution on a previously written and published article. Letter to the editor is used to allow sharing of feedback on the articles published in JEMS. Title, Author, Letter, References (Maximum 6000 words, 15 pages).

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Review (RE)

This is an article pertaining to the research compiled by summarizing researches and data which other authors and/or institutions previously carried out. (It cannot be accepted as an original research article) Title, Author, Abstract, Introduction, Literature Review, Conclusion, References (Maximum 6000 words, 15 pages).

Report (RP) Interview (RP)

This is an article pertaining to the short research using structured interview methods with a veteran, recognized with knowledge and expertise in a specific subject, to seek his/her advice in a predetermined topic concerning the maritime industry (Organized by the editor). Title, Author, Abstract, Short biography of the interviewee, Methodology, Questions and Comments, Results, Interview Permit Certificate (Maximum 3000 words).

Case Investigation (RP)

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This is an article pertaining to the short research containing the conclusions of analysis on relevant obtained data in matters concerning the maritime industry referenced upon a limited number of literature material. It covers conclusive reports of industrial research, particularly research reports carried out during the period of academic education, etc. Title, Author, Abstract, Introduction, Methodology, Results, References(Maximum 2000 words).

Book Review (BK)

This is an article where an invited reviewer evaluates a newly published book concerning the maritime industry in conformance with a specific methodology. (Maximum 1000 words).

Academic Perspective

This is an article in characteristics of a compilation or a plain text where veteran academicians who are recognized with their academic knowledge and expertise would share their contributions in maritime science, guide young academicians and researchers, and offer solutions for the demands of the maritime industry. (Invited by the editor).

Industrial Perspective

An article in conformance with a specified text format prepared by an expert as an invitee whose knowledge and experience related to their area of expertise is recognized as beneficial by the industry (Invited by the editor). Title, Author, Abstract, Foresight about the subject, Results (Maximum 6000 words, 15 pages).

After the Meeting

This article is written to convey the impressions, congress conclusion reports, and information gathered during scientific conventions following a congress, conference, and symposium organized on such matters concerning the maritime industry. (Maximum 500 words).

5. References

The citation style used by our journal is Institute of Electrical and Electronics Engineers (IEEE) Reference Style.

The IEEE Style is used for publications in engineering, electronics, telecommunications, computer science and information technology.

IEEE Style uses a notational method of referencing when referring to a source of information within the text of a document.

You can achieve the IEEE reference style and all reference examples used in our journal at https://jemsjournal.org/guide-for-authors.

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Duties of the Publisher

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A submitted manuscript should be original, and the authors ensure that the manuscript has never been published previously in any journal. Data of the research ought to be represented literally in the article. A manuscript ought to include adequate detail and references to allow others to replicate the study.

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Disclosure and Conflicts of Interest

All sources of financial support should be disclosed. All authors ought to disclose a meaningful conflict of interest in the process of forming their study.

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Contents

DOI: 10.4274/jems.2022.24119

Selçuk Nas

Dokuz Eylül University Maritime Faculty, Department of Maritime Education and Training, İzmir/Türkiye

Dear Readers,

IMO Model Courses are a guide for the training of future officers. However, it falls short of keeping up with the industry's dynamic needs and technological developments. "IMO Model Course 1.22. Bridge Resource Management," which has been prepared and finalized, can respond to developments and needs with its dynamic structure. The proposal of IMO Model Course 1.22. Bridge Resource Management prepared by the Republic of Turkey and Dokuz Eylul University Maritime Faculty was finalized in the meeting of "The Intersessional Drafting Group 2 on Model Course" by the end of September 2022. The IMO Model Course Bridge Resource Management was first drafted in 2019. It is expected to be approved at the HTW 9 meeting of IMO's "Sub-Committee on Human Element, Training, and Watchkeeping," which will be held in 2023 with a four-year delay due to pandemic restrictions.

We are pleased to introduce JEMS 10 (3) to our valuable followers. There are valuable and intriguing studies in this issue of the journal. We observed that the studies in this issue of the journal are generally on fuel, emissions, and efficiency. We hope that these studies will contribute to the maritime industry. Thus, we would like to express our gratitude to the authors who sent their valuable articles for publication in this issue. We also want to thank our reviewers, editorial board, section editors, and the publisher, who provided quality publications by diligently following our publication policies.

Yours Sincerely

Prof. Dr. Selçuk NAS

Editor in Chief

Address for Correspondence: Selçuk Nas, Dokuz Eylül University Maritime Faculty, Department of Maritime Education and Training, İzmir/Türkiye
E-mail: snas@deu.edu.tr
ORCID ID: orcid.org/0000-0001-5053-4594

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Investigation of the Effect of CeO_2 Nanoparticle Addition in Diesel Fuel on Engine Performance and Emissions

Abdullah Burak Arslan, Mehmet Çelik

Karabük University Faculty of Engineering, Department of Mechanical Engineering, Karabük, Türkiye

Abstract

In this study, the effects of the additive on engine performance and emissions were investigated by adding cerium oxide (CeO_2) nanoparticles (NPs) into diesel fuel. The use of CeO_2 NPs as an additive increased the lower calorific value (LHV) of the fuel while decreasing its viscosity and density. As a result of the experiments, an increase of 8.99% in engine torque was obtained in DCe100 fuel which 100 ppm CeO_2 NPs were added compared to diesel (D0) fuel. The increase in the LHV had a positive effect on the specific fuel consumption. The use of CeO_2 NPs resulted in an increase in brake thermal efficiency (BTE) due to the increased ending temperature of combustion. A 5.44% increase was obtained in DCe100 fuel compared to D0 fuel in terms of BTE. With an increase in the amount of CeO_2, carbon dioxide (CO), hydrocarbon (HC), and smoke emissions were reduced. Compared to D0 fuel, the lowest values were obtained with the DCe100 fuel. CO emissions were reduced by 18.27%, HC emissions by 30.12%, and soot emissions by 21.63%. However, nitrogen oxides (NO_x) emissions increased with rising CeO_2 amount and in-cylinder temperature. The highest NO_x value in DCe100 fuel was obtained with an increase of 6.65% compared to D0 fuel.

Keywords: CeO_2, Engine performance, Exhaust gas emissions, Nanoparticle additives

1. Introduction

The importance of energy is increasing with the increase in population growth and the acceleration of urban and industrial transformation. The world economy is fragile due to the finite and diminishing fossil fuel reserves, which play a crucial role in meeting the demand for energy [1]. Approximately 95% of the transportation sector uses fossil fuels, which corresponds to half of the global oil consumption [2]. Diesel engines are mostly preferred in transportation due to their high brake thermal efficiency (BTE), long life, and high engine power (EP). But the use of fossil fuels causes the formation of harmful emissions. Many countries and organizations are putting pressure on companies to reduce emissions and design more environmentally friendly engines to limit these emissions [3,4]. Previous studies aimed to provide suitable combustion conditions in diesel engines to raise engine performance and reduce harmful exhaust emissions. It is difficult to achieve through only engine design studies [5]. The quality of the combustion process determines the performance of internal combustion engines, including torque, fuel economy, and toxic emissions. Fuel cannot be fully utilized under lean combustion, resulting in reduced output power, and increased specific fuel consumption (SFC) and toxic emissions. Enhancing the spray evaporation properties of liquid fuels is the major key to improving engine combustion [6]. Emissions are directly related to the quality, properties, and combustion characteristics of the fuel. The most crucial fuel property which affects the combustion of diesel fuel is the cetane number (CN) of fuels. Furthermore, physical peculiarities of the fuel, such as viscosity and density, also affect combustion. There are numerous applications for improving the chemical and physical properties of fuel [7]. NPs additive is one of them [8], which can be directly mixed with the fuel and used without making any changes in the engine, increasing the quality of diesel fuel and improving combustion. With the improved combustion, there are decreases in exhaust emissions [9].

Address for Correspondence: Abdullah Burak Arslan, Karabük University Faculty of Engineering, Department of Mechanical Engineering, Karabük, Türkiye
E-mail: a.burakarslan@hotmail.com
ORCID ID: orcid.org/0000-0002-0897-3507

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Adding NPs to diesel fuel enhances the thermo-physical characteristic of the fuel, including catalytic activity, thermal conductivity, surface-to-volume ratio, mass distribution, self-ignition temperature, CN, and LHV [8,10,11]. Because of the very small size of the NPs fuel additives, it is simple to manipulate the chemical and physical properties of the fuel. NPs additives containing iron, boron, and aluminum atoms show effects such as longer flame duration and reducing ID time during combustion [12]. CeO_2 NPs have unique properties such as high thermal stability, absorbing UV rays, electrical conductivity, high hardness, specific chemical reactivity, high oxygen retention, and carrying capacity. Due to these features, it has a wide range of applications, including glass polishing, automotive, corrosion inhibitor for metals, light-sensitive material protective additive, oxidation catalyst, and solar panels, as well as its low production cost [13,14].

CeO_2 NPs added to the fuel affect viscosity and ignition temperature [15]. Saraee et al. [16] conducted experiments by mixing the CeO_2 NPs additive into diesel fuel at 10, 20, and 40 ppm ratios. As a result of the experiments, the lowest level of 20 ppm in SFC was 0.27 kg/kWh. The lowest hydrocarbon (HC) emission was obtained at the rate of 40 ppm [16]. Selvan et al. [17] used 25 ppm CeO_2 NPs additive and 10% biodiesel and 20% ethanol additives in a water-cooled diesel engine. The lowest SFC was obtained in the mixture of CeO_2 and diesel at 0.3586 kg/kWh due to improved combustion by CeO_2. The addition of CeO_2 reduced CO emissions compared to diesel. The oxygen contribution of cerium causes a decrease in HC emissions after better completion of combustion. Adding NPs additives causes a slight increase in nitrogen oxide (NOx) emissions, increasing the combustion temperature [17]. Sajeevan and Sajith [18] added 5, 15, 25, 35, and 40 ppm CeO_2 NPs additives to diesel fuel and used it in a 4-stroke water-cooled engine. They obtained an increase in the flash point when the CeO_2 concentration was increased. It was stated that the BTE increased by 6% with the addition of 35 ppm CeO_2 in fuel. The efficiency started decreasing when the additive ratio was more than 35 ppm due to the oxygen support provided by CeO_2, leading to improved combustion. A decrease was obtained in HC emissions as the CeO_2 concentration was increased [18]. In his experiments, Aalam [19] used 25 and 50 ppm CeO_2 NPs additives in a single cylinder diesel engine. It was detected that the mixture gives better results than diesel in BTE. The highest BTE was obtained in 50 ppm additive ratio as 25.9% at full load. SFC decreased by 9% when the additive ratio was 50 ppm. The addition of the additive caused an increase in NOx emissions. Smoke and CO emissions were reduced by 36% and 26%, respectively, at full load and 50 ppm CeO_2 [19]. Dinesha et al. [20] used 10, 30, and 80 nm CeO_2 NPs on a mixture of 20% biodiesel and 80% diesel. The highest in-cylinder pressure value was obtained at 30 nm. It was stated that the mixed NPs improved the combustion while reducing the ID and SFC. There was a 35% reduction in HC emissions when 30 nm NPs were added to the mixture. They observed that adding CeO_2 to the mixture acts as a catalyst, lowering the temperature of the carbon activity and CO emissions. Thus, the oxidation of CO produces CO_2 when the temperature drops [20]. Muruganantham et al. [21] added 25, 50, and 75 ppm CeO_2 NPs into corn oil methyl ester-diesel fuel mixture (B10). They stated that the physicochemical features of the fuel were enhanced with the addition of CeO_2 NPs. Thus, the authors determined the optimum NPs ratio as 50 ppm during the experiment. BTE was 34.42% in B10 fuel and 34.7% after 50 ppm nanoparticle addition. The SFC obtained decreased by 3.96% with 50 ppm CeO_2 NPs additive compared to B10 fuel. At 50 ppm CeO_2, hydrocarbon emissions decreased by 13.63%, carbon monoxide (CO) emissions by 16.6%, while NOx emissions increased by 6.15% when compared to B10 fuel [21]. Nayak et al. [22] added aluminum oxide, zinc oxide, and graphene NPs in waste cooking oil biodiesel to improve engine performance. After determining the optimum biodiesel ratio, they mixed diesel fuel with a 20% biodiesel ratio and added NPs. According to the authors, all NPs reduced HC and CO emissions. Furthermore, they stated that an increase in BTE was observed with the addition of NPs. The authors stated that due to the higher surface volume ratio of NPs, the BTE increased as they provided higher EP resulting in a higher heat transfer rate in biodiesel blends. Conversely, compared to diesel, biodiesel and NPs mixtures reduce HC and CO emissions because they provide better combustion due to the higher oxygen content [22]. Mohan and Dinesha [23] found in their study that hydrogen peroxide (H_2O_2) concentrations at different rates (0.5%, 1%, and 1.5%) and amounts (40 and 80 ppm) of CeO_2 NPs with a 20% biodiesel-80% diesel content. They aimed to evaluate the combined effect of adding a fuel mixture on diesel engine performance and exhaust emissions [23]. Ağbulut et al. [24] synthesized graphene oxide (GO) NPs and added different amounts (100, 500, and 1000 ppm) to waste cooking oil (WCO)/diesel fuel mixtures containing edible oil methyl ester (WCO) at different rates (0 and 15%). They assessed these mixtures in diesel engines and investigated their effects on combustion, performance, and emission. The experiments were carried out at a constant speed of 2400 rpm and different engine loads (3, 6, 9, and 12 Nm). The authors stated that GO NPs increase the oxygen ratio in the cylinder and accelerate the chemical reactions until the combustion process, thus providing complete combustion. For this reason, they stated that CO emissions decreased by 22.5% and HC emissions by 30.23%. Furthermore, NOx emissions decreased by 15,17% due to the superior surface/volume ratio and thermal features of GO NPs. The authors reported that the energy content of the test fuels improved, and therefore BTE increased by 7.90%, while brake SFC (BSFC) decreased by 9.72% with the addition of GO NPs. Thus, GO NPs could offer a satisfactory solution to improve the deteriorating properties caused by biodiesel and diesel mixtures in diesel engines [24]. Vedagiri et al. [25] investigated the performance, combustion, and emission parameters of a DI engine powered by grape seed oil biodiesel besides the addition of nano-cerium oxide and zinc oxide NPs. There was a 3.3% decrease in BTE of grape seed oil biodiesel than diesel because of the high viscosity of grape seed oil biodiesel fuel. Conversely, adding NPs improves the combustion process due to the oxygen content, reducing the fuel evaporation time and ID; thus increasing from 28.8% to 30.2% with the CeO_2 mixture and from 28.8% to 30.51% with the zinc oxide mixture. The authors reported that CO and HC emissions were reduced because CeO_2 and zinc oxide NPs act as oxidation catalysts, accelerating and improving combustion. They stated that CeO_2 and zinc oxide NPs significantly reduce NOx emissions and that grape seed oil biodiesel is an effective alternative fuel for diesel engines without any engine modification [25]. In general, the development and different uses of nanotechnology cause inevitable interactions between the environment and nanomaterials. According to the outcomes of previous studies, NPs have a positive impact on the performance of different chemical systems, but the release of metallic oxide NPs into the environment has raised many concerns [26].

This study presents the experimental results of the effect of CeO_2 NPs additive in diesel fuel to improve engine parameters without modifying the engine. Our additive ratios were higher when compared to similar studies. We hope this experimental study will be useful in determining different additive ratios. Furthermore, the study can be improved by using different fluid fuels with the same NPs.

2. Materials and Methods

In the experimental studies, the 4-stroke single cylinder Antor 3LD510 diesel engine, the technical specifications of which are given in Table 1, and the Net Brake engine dynamometer were used as the engine loading equipment. During the experiments, a load cell was used with a precision of 1 g and a measuring range of 0-50 kg for the motor loading. Calibration settings were made according to the instructions received from the manufacturer. The measuring range of the dynamometer used in the experiments is 0-5000 rpm, and the torque of the engine measurement range is 0-350 Nm. During this experimental test process, Bosch-BEA 350 model device (Table 2) was used for measuring exhaust emissions, and the Bosch-BEA 070 model device (Table 3) was used for smoke emission measurement. CeO_2 additive, which has a purity level of 99.98%, was provided by Ege NanoTek for this study. Figure 1 shows the ultrasonic mixer. CeO_2 additive was incorporated into the diesel fuel using an ultrasonic mixer in the amounts of 25 ppm, 50 ppm, 75 ppm, and 100 ppm for 45 min at 50 °C. The test setup consists of two basic measurement systems. The engine test system measures engine torque, SFC, exhaust gas temperature (EGT), and engine oil temperature, and the emission measurement system analyzes exhaust gas. Figure 2 depicts the prepared test setup schematically, and Table 4 presents the features of test fuels [27]. The accuracy and uncertainty values of the parameters obtained as a result of the experiments are given in Table 5. The properties of the CeO_2 additive used in the experiments are shown in Table 6.

Table 1. *Technical specifications of the test engine*

Specifications	
Brand	Antor 3LD510
Engine Type	CI
Number of cylinders	1
Cylinder diameter (mm)	85
Stroke (mm)	90
Stroke volume (cm^3)	510
Compression ratio	17.5:1
Maximum engine speed (rpm)	3000
Maximum power (kW)	12 (3000 rpm)
Maximum torque (Nm)	32.8 (1800 rpm)

Table 2. *Technical specifications of Bosch-BEA 350*

	Measuring Range	Sensibility
CO	0-10% vol	0.001% vol
HC	0-9999 ppm	1 ppm
NO	0-5000 ppm	<=1 ppm
CO_2	0-18% vol	0.01% vol
O_2	0-22% vol	0.01% vol

Table 3. *Technical specifications of Bosch-BEA 70*

	Opacity	k value
Measurement range	0-%100	0.1%
Absorption coefficient (k)	0-9.99 m^{-1}	0.01 m^{-1}
Designation	Worth	
Measuring chamber length	215 mm	
Area of application	+5 °C–+40 °C	
Relative humidity of the ambient air	<%90	

2.1. CeO_2 Nanoparticles

The addition of NPs as an additive to fuel has proven to be a promising technology to improve diesel performance and reduce exhaust emissions. Due to its proven thermo-physical properties, researchers are interested in NPs to analyze properties such as BTE, engine performance, fuel efficiency, carbon emission, and smoke emissions [28]. The thermal conductivity of the fuel can be improved due to the large surface-to-volume ratio and micro-size of the CeO_2 NPs. The boiling point of the fuels is decreased after

Figure 1. *Ultrasonic mixer*

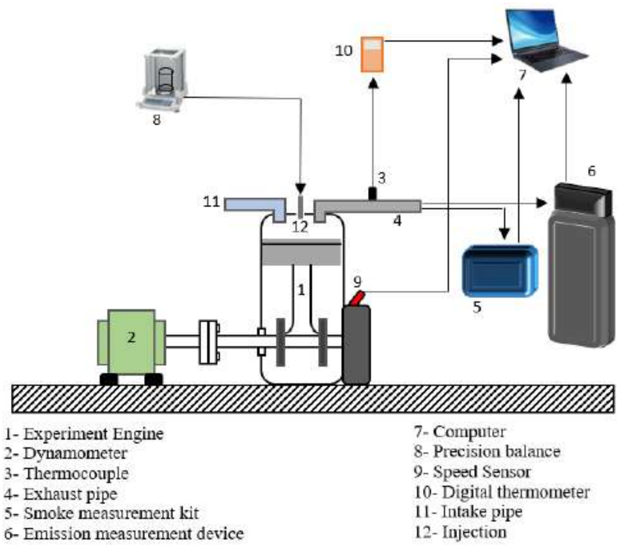

Figure 2. *Schematic view of the experimental system*

Table 6. *Features of the nanoparticle*

Powder size	20 nm
Purity	99.995%
Surface area	20-50 m^2/g
Density (Bulk)	0.8-1.1 g/cm^3
Density (True)	7.132 g/cm^3

Table 4. *Features of the test fuels*

Fuels	Kinematic viscosity (mm^2/s 40 °C)	Flash point (°C)	Density (kg/m^3 15 °C)	Calorific value (MJ/kg)
	ASTM D 445	ASTM D 93	ASTM D 4052	ASTM D 2015
D0	2.60	67	0.860	39.81
DCe25	2.52	64	0.846	40.02
DCe50	2.44	62	0.838	40.10
DCe75	2.39	59	0.834	40.14
DCe100	2.32	57	0.829	40.22

Table 5. *Features of the test fuels*

Parameters	Accuracy (±)	Uncertainty (%)
Temperature (°C)	±1 (°C)	±0.1
Time (s)	±0.1 s	±0.4
Load (N)	±1 N	±0.25
Engine speed (rpm)	±10 rpm	±0.2
Fuel (g)	±0.1 g	±0.1
Exhaust gas temperature (°C)	±1 (°C)	±0.1
Encoder (°CA)	±1°	±0.3
Cylinder pressure transducer (bar)	±0.1 bar	±0.1
Specific fuel consumption (g/kWh)	---	±0.94
Brake thermal efficiency (%)	---	±0.76

adding the NPs. At the high temperature inside the cylinder, NPs form layers when the fuel droplets overheat and swell. After all, a severe vaporizing event named micro explosions occurs (Figure 3).

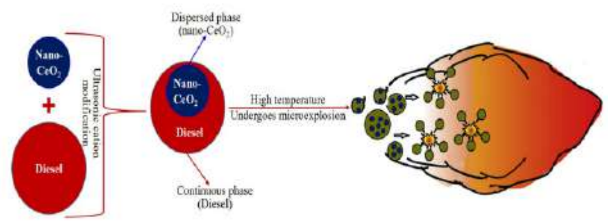

Figure 3. *Micro explosions and secondary atomization of NPs added fuels [29]*

NPs: Nanoparticles

CeO_2 NPs can store oxygen molecules in oxygen-rich conditions. It can form an oxygen buffer by releasing this stored oxygen when they reach the oxygen-poor region. The improvement of oxidation ensures more oxygen reaches fuel molecules, improves combustion, and provides a decrease, especially in PM emissions. Furthermore, the presence of Ce molecules in combustion can reduce the energy required for the combination of H and C atoms, affecting the emission changes positively. Researchers showed that the size of CeO_2 NPs affects the in-cylinder temperature during combustion. NPs can be a heat sink source during fuel combustion, trapping heat and lowering temperatures inside the combustion chamber (Figure 4).

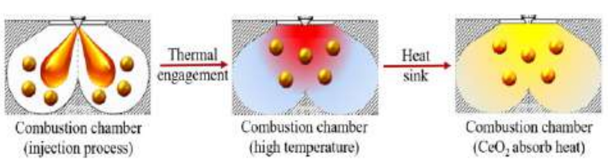

Figure 4. *Thermal activity of NPs [29]*

NPs: Nanoparticles

The evaporation process of nanofluid droplets is too complex for interactions between the surfaces of NPs. Furthermore, collisions accelerate the formation of nucleation sites for random movement of NPs [30]. Since the ambient temperature is much higher than the boiling point of diesel, the CeO_2 NPs are heated faster by thermal radiation than the fuel droplet. When the nanofluid droplet gets heated by the temperature of ambience, it moves and collides with NPs by generating the heat surrounding oil and forming small bubbles on the surface. A few heterogeneous nucleation sites are also formed inside droplets. Droplets burst into large bubbles, the large droplet shrinks, and most droplets are evaporated directly by microburst (Figure 5) [31]. It can also extend droplet life by preventing strong micro-explosion events that can occur during evaporation. The intensity of secondary atomization is affected by the thermo-physical properties of the base fuel and the stability of NPs, as well as the density, porosity, and structure of the nanofluid [32].

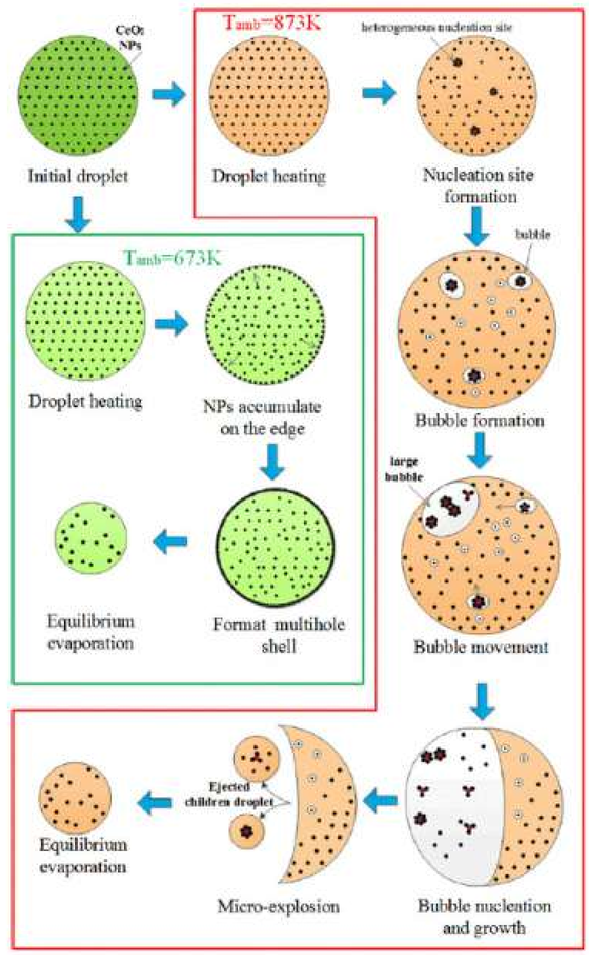

Figure 5. *Evaporation mechanism of nanofluid fuel droplets [31]*

3. Results

3.1. Engine Torque

Figure 6 presents the effect of CeO_2 NPs mixed with diesel fuel on engine torque. Maximum engine torque was achieved at 1800 rpm. While 25.68 Nm torque was obtained in D0 fuel, it was observed that the engine torque increased as CeO_2 concentration increased. Torque increase was 3.89%, 4.67%, 6.81, and 8.99% for DCe25, DCe50, DCe75 and DCe100 fuel mixtures, respectively at 1800 rpm. The increase in maximum engine torque was 13.91% for the DCe100 mixture at 2000 rpm. Using of CeO_2 additive

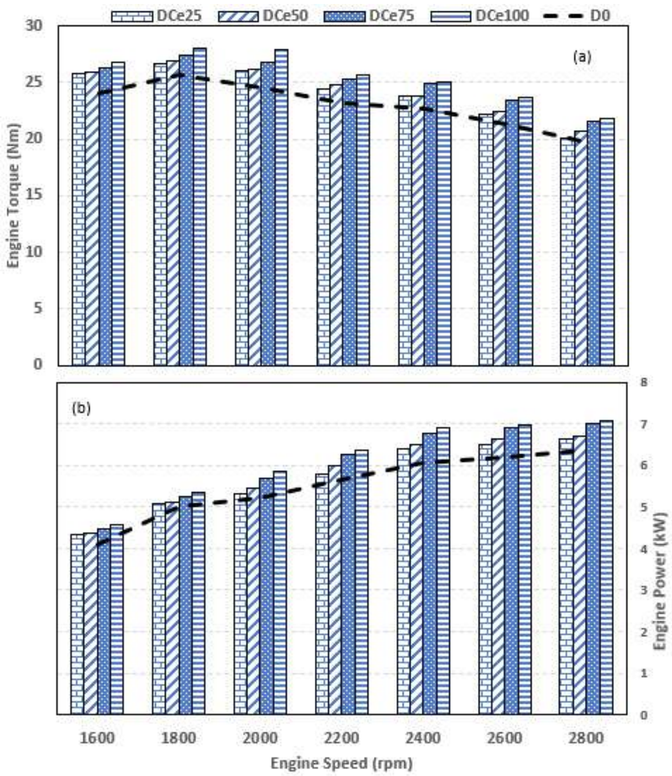

Figure 6. *Alteration of engine torque (a) and EP (b) with respect to engine speed*

EP: Engine power

provides better combustion by enhancing the air/fuel mixture in the cylinder, resulting in better torque. Due to the presence of oxygens in the additive, fuel molecules could access more oxygen, completing combustion and resulting in higher engine torque [12,18,33].

3.2. Engine Power

Figure 6 shows the effect of CeO_2 NPs addition into diesel fuel on EP. The power increases as the CeO_2 concentration rise and maximum power was achieved at 2800 rpm. While the EP was 6.35 kW in diesel fuel, the maximum increment in EP was 11.58% with the addition of 100 ppm CeO_2 compared to diesel fuel. According to diesel fuel, the increase in EP was 4.27, 5.45, and 10.16% in DCe25, DCe50, and DCe75 fuel mixtures, respectively. The highest power increase was obtained as 13.57% in addition to 100 ppm CeO_2 at 2400 rpm fuel. The lower viscosity of the fuel resulted in a higher microburst rate [31]. Adding CeO_2 to diesel fuel reduced the viscosity and density of fuels while increasing LHV. This allows the fuel to have better air/fuel mixtures and better atomization properties in the cylinder. Increased quality of the combustion affects power directly [34-37]. A high surface volume ratio provides better oxidation of fuel mixtures. Thus, high combustion enthalpy and energy density can be released to increase the maximum power [38].

3.3. Specific Fuel Consumption

BSFC is a vital parameter for engine performance because it gives information about how efficiently the amount of fuel supplied to the engine is converted into work [39]. Figure 7 depicts the effect of CeO_2 NPs addition to diesel fuel on the SFC. The lowest SFC was obtained at 1800 rpm, where the maximum torque was obtained. While diesel fuel yielded 330.68 g/kWh, it was 322.64, 316.87, 313.49, and 310.50 g/kWh for DCe25, DCe50, DCe75, and DCe100 fuels with CeO_2 added, respectively. The maximum reduction rate in SFC was obtained at 2000 rpm with 7.69% in DCe100 fuel compared to D0 fuel. Adding CeO_2 NPs additive to diesel fuel increases the LHV and thus provides a reduction in SFC. Adding CeO_2 to the fuel increases the surface/volume ratio [37,40]. The microburst properties of CeO_2 addition positively affected the SFC [41], which depends on density, viscosity, and LHV of the fuel used. Fuels with higher "lower calorific value" are known to have lower consumption [42].

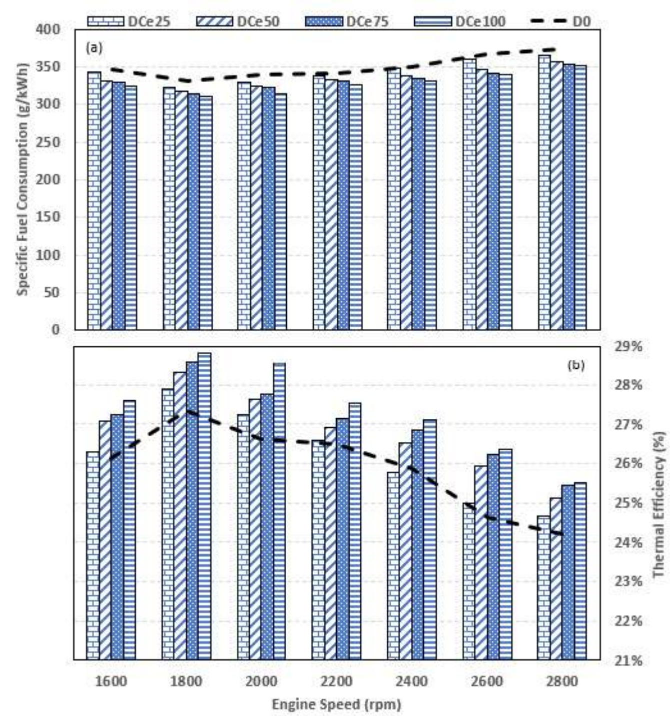

Figure 7. *Alteration of SFC (a) and BTE (b) with engine speed*

SFC: Specific fuel consumption, BTE: Brake thermal efficiency

3.4. Brake Thermal Efficiency

The addition of NPs to diesel fuel increases LHV, improving combustion by increasing the evaporation rate of the fuel

[37,43]. Figure 7 depicts the effect of CeO_2 NPs additive on BTE. The highest BTE was obtained as 28.83% in DCe100 fuel at 1800 rpm. While it was 27.34% in D0 fuel, with the increase in CeO_2 concentration, an increase of 1.97%, 3.63%, 4.64%, and 5.44% was obtained in DCe25, DCe50, DCe75, and DCe100 fuels, respectively. The highest increase rate was 7.25% in DCe100 fuel at 2000 rpm. The decrease in viscosity with the addition of NPs improves the chemical reaction and minor fuel droplets, providing a more extensive active surface and contact area. The chemical reactivity of the fuel increases with the presence of reactive surfaces, which may result in better combustion, and thus BTE goes higher [9,37,44,45]. Considering the effects of fuel properties, lower viscosity and density facilitate evaporation of the fuel in the cylinder. However, mixing fuel droplets with ambient air positively affects the evaporation properties of fuel mixtures. The sprayed fuel droplet is smaller due to the lower viscosity and consequent lower surface tension. Better atomization quality can promote the mixing of fuel and air and provide a full combustion environment to reduce emissions by increasing the BTE of a diesel engine [46].

3.5. Exhaust Gas Temperature

EGT is affected by engine load, amount of fuel taken into combustion chambers, and ID. The LHV of the burned fuel is also effective on the EGT [47]. While the EGT temperature was 575 °C in D0 fuel at 1800 rpm, where the maximum torque was obtained. It was 593 °C in DCe100 fuel. EGT goes up with increasing engine speed and CeO_2 concentration. The highest EGT was obtained as 741 °C at 2800 rpm in DCe100 fuel, and it was 710 °C in DCe0. The addition of CeO_2 NPs to the fuel increases the LHV and the temperature of the EGT by rising the heat produced in each unit mass. Also, the oxygen content of NPs additive enhances combustion in cylinders and increases EGT [48].

3.6. Carbon Dioxide Emissions

Figure 8 presents the effects of CeO_2 addition to diesel fuel on CO emissions. CO emissions indicate insufficient combustion of the fuel. The main factors for the formation of CO emission are a heterogeneous mixture, insufficient O_2 availability, and fewer residence time for combustion [49]. The causes of CO emissions are a lack of oxygen in the fuel and incomplete combustion. CO emissions are primarily controlled by the air/fuel ratio in engines. The concentration of CO emissions in the exhaust increase in the case of a rich mixture of air/fuel ratio in cylinders [7,12]. The lowest CO was obtained in DCe100 fuel at 2800 rpm. Compared to D0 fuel at 2800 rpm, reductions in CO emissions of DCe25, DCe50, DCe75, and DCe100 fuels were respectively 5.12, 10.25, 15.70, and 18.27%. CeO_2 added to the fuel showed a

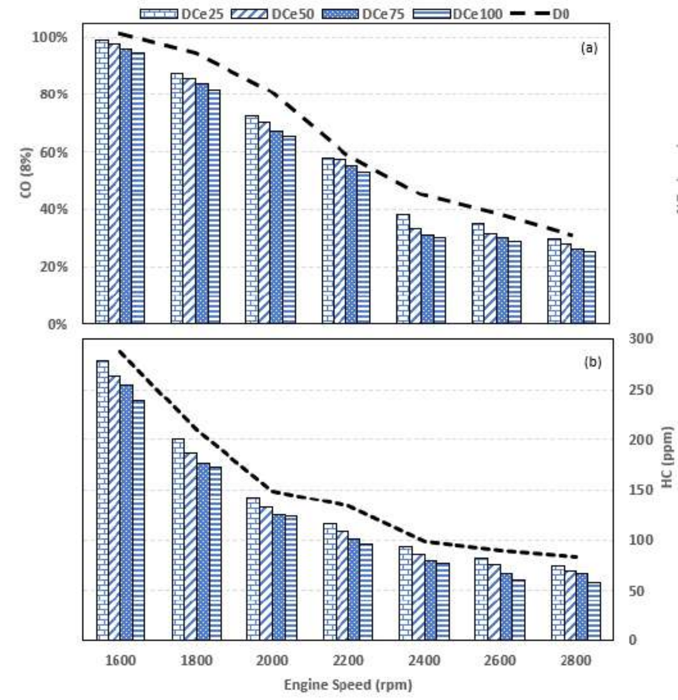

Figure 8. Alteration of CO emissions (a) and HC emissions (b) according to engine speed

CO: Carbon dioxide, H: Hydrocarbon, NOx: Nitrogen oxides

catalyst effect, improved combustion, and provided oxygen support. This way, CO molecules react more with oxygen and turn into CO_2 molecules. Boost oxygen concentrations in combustion chambers ensure that CO emission is more dispersed and meets with more oxygen [9,50]. Increases in temperature in the cylinder with the addition of NPs additives provide better fuel burning, leading to reductions in CO emissions [51].

3.7. Hydrocarbon Emissions

Figure 8 presents the effects of incorporating CeO_2 NPs into diesel fuel on HC emissions. While HC emission was 209 ppm in D0 fuel at 1800 rpm, where the engine torque was maximum, it was 200, 187, 177, and 173 ppm in DCe25, DCe50, DCe75, and DCe100 fuels, respectively. HC emission decreased with increasing CeO_2 concentration and engine speed. Minimum HC emission was obtained at 2800 rpm. At 2800 rpm, DCe25, DCe50, DCe75 and DCe100 fuels with CeO_2 NPs additive reduced HC emissions by 9.64%, 16.87%, 19.27%, and 30.12%, respectively when compared to D0 fuel. The highest reduction rate in HC emissions was 33.3% in DCe100 fuel at 2600 rpm. The addition of CeO_2 provided better combustion, increased the oxygen content, and improved combustion quality. As a result, the combustion was completed, and HC emissions were reduced [52].

3.8. NOx Emissions

Figure 9 shows the effect of adding CeO_2 NPs to diesel fuel on NOx emissions. The lowest NOx amount was obtained as 977 ppm in D0 fuel at 1600 rpm. At low engine speeds, NOx emissions are lower due to the low temperature of inside cylinders. As engine speed and CeO_2 concentration increase, NOx emissions increase. Compared to diesel fuel NOx emissions increased in DCe25, DCe50, DCe75, and DCe100 fuels 1.23%, 5.43%, 9.21%, and 12.28%, respectively at 1600 rpm. The NOx emission increase in DCe100 fuel was 8.19% at 1800 rpm. Maximum engine torque was obtained as 6.65% at 2800 rpm for the maximum EP. The main reason for NOx formation is the increased combustion temperature in the cylinder. It mostly consists of nitrogen molecules in the intake air into the cylinder. If the temperature in the combustion chamber exceeds 1800 °C, oxygen and nitrogen molecules decompose and form NO emissions depending on temperatures [47,53,54]. Mixing NPs with diesel raises the flame temperature, causing more N_2 to oxidize to NOx in the atmospheric air during combustion. Therefore, NOx emissions for NPs blended fuels are higher than pure diesel under all test conditions [55]. One of the reasons for the increase in NOx emissions is the rapid combustion process affects combustion temperature. Since the addition of CeO_2 NPs to diesel fuel increase the LHV of the fuel, the combustion end temperature increase. The oxygen in CeO_2 and the high reaction rate cause an increase in the temperature of inside cylinders and NOx formation [48,56]. Also, the rising of BTE triggers NOx emissions [57].

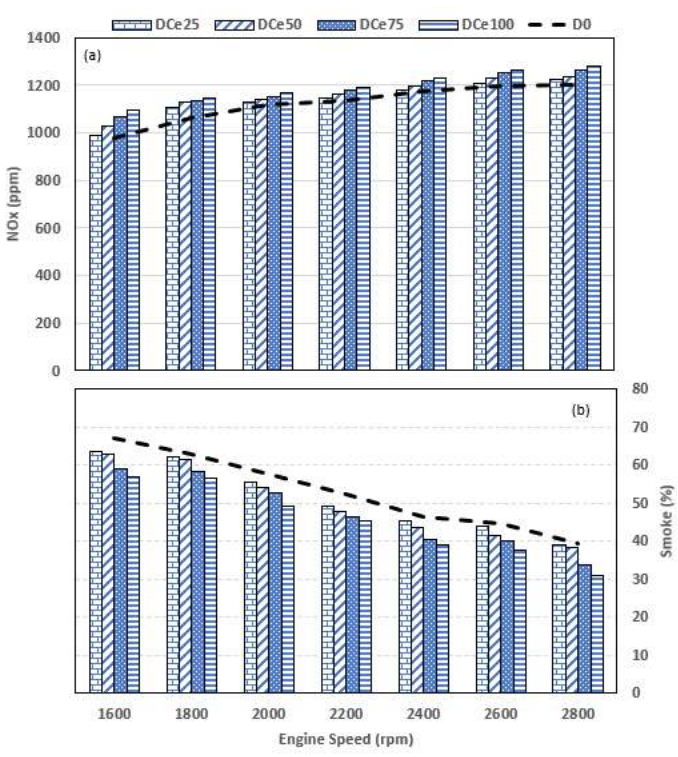

Figure 9. *Alteration of NOX emissions (a) and smoke emissions (b) according to engine speed*

NOx: Nitrogen oxides

3.9. Smoke Emissions

Smoke emission occurs in the rich fuel zones in the cylinders during combustions. The particles of the emission are solid carbon molecules. These molecules are formed when they cannot reach oxygen in the fuel-rich regions in the combustion chamber [47,58]. The effect of CeO_2 addition to diesel fuel on smoke emissions is shown in Figure 9. As the amount of CeO_2 increases, the amount of smoke emission decreases. While it was 62.7% in D0 fuel at 1800 rpm, the reduction in smoke emission was 9.88% in DCe100 fuel compared to D0 fuel. The minimum amount of smoke emissions was measured using DCe100 fuel at 2800 rpm. The reduction in smoke emissions in DCe25, DCe50, DCe75, and DCe100 fuels was 1.27%, 3.05%, 13.99%, and 21.63%, respectively. Smoke emissions can be reduced using the oxygen provided by CeO_2. Furthermore, lowering viscosity and density improves fuel and air mixture recovery and lowers smoke emissions [59,60].

4. Conclusion

The density and viscosity of diesel fuels were decreased by CeO_2 NPs additives. This study improved LHV, resulting in a better air/fuel mixture. The inclusion of CeO_2 NPs additive in diesel fuel provided more oxygen to reach the fuel particles in combustion. Thus, more efficient combustion was formed by nano additive. The CeO_2 NPs created a higher contact area with the fuel droplets. It was observed that the increased active surface area provided an improvement in combustion reactions.

The addition of CeO_2 NPs additive to diesel fuel positively affected emissions. A better combustion occurred due to the oxygen provided by CeO_2, and the rate of unburned fuel was reduced. As an outcome, combustion temperatures in the cylinders increased, and the nitrogen molecules taken from the air reacted more with the oxygen. As a result, while CO, HC, and smoke emissions decreased, NOx emissions increased.

According to the results, the present research positively impacts the fuel industry. However, the long-term impact on the environment and human health due to adding NPs to liquid fuel and subsequent combustion is unknown. Because of their high chemical activity, NPs can pass through cell walls and skin. As a result of combustion, particles coming out from the exhaust mix with water and soil and eventually cause poisoning [61-63]. However, strict laws regarding exhaust emissions exist in Europe to prevent them from contributing to global warming. Due to the negative effects of NPs on human health and the environment, new laws and rules regarding exhaust NPs from exhaust pipes are required before commercialization.

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Authorship Contributions

Concept design: A.B. Arslan, M. Çelik, Data Collection or Processing: A.B. Arslan, M. Çelik, Analysis or Interpretation: A.B. Arslan, M. Çelik, Literature Review: A.B. Arslan, Writing, Reviewing and Editing: A.B. Arslan, M. Çelik.

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Factors Affecting Container Shipping Through Inland Waterways

Bangar Raju Totakura[1], Nilakantan Narasinganallur[2], Syed Aqib Jalil[3], Ajith PJ[1]

[1]University of Petroleum and Energy Studies, School of Business, Dehradun, India
[2]K J Somaiya Institute of Management, Mumbai, India
[3]Sohar University Faculty of Business, Sohar, Oman

Abstract

Inland waterways in India have shown positive growth over the last 10 years. The mode of transport is very promising, yet desired volumes are yet to be achieved. In 2018, India started its first domestic container shipping and the first export of container shipping through inland waterways in 2020. This research work expedites the identification of various prominent factors using the fuzzy analytic hierarchy process method. Four major factors were considered based on feedback from experts, and using the said method, factors and subfactors were ranked globally. Among the four factors we considered, infrastructure factors were found as the most critical factor, followed by economic factors, geographical factors, and, lastly, regulatory factors. Moreover, as per the weights obtained for the subfactors, inadequate river depth of rivers, container inventory, and repositioning emerged as significant factors that need to be addressed. Finally, this research paper puts forward steps necessary for boosting the growth of container shipping through inland waterways.

Keywords: Inland waterways, Container shipping, Fuzzy AHP, MCDM

1. Introduction

Inland waterways provide a viable alternative to road and rail transport and are very desirable, especially from the perspectives of cost and sustainability. Various studies have established that inland water transport (IWT) is economical, fuel efficient, and environmentally friendly. India's previous history indicates that river transport was used extensively by the Mughals and later by the East India Company. After independence, the development of waterways was neglected. Apart from technical and geographical issues, to improve the situation, the Inland Waterways Authority of India (IWAI) was established in 1986 to develop and regulate inland waterways. In this process, the IWAI was mandated to develop shipping and navigation.

However, an insignificant focus was given to IWT [1]. With the National Waterways (NWs) Act of 2016, India has taken forward the development of NWs. Currently, various developmental works are being implemented in different waterways. However, its adoption by users, manufacturers, and shippers is yet to crystallize in a large way. The country has an ambitious plan to develop inland waterways with a target to achieve 100 MT by 2022 from the current traffic of 72 million tons in 2019 and 130 million tons by 2025. Inland container traffic commenced in 2018. The export of steel scrap through containers to Bangladesh in the year 2020 by the Adani group has been a landmark of container movement in India's inland waterways. The government has initiated landmark schemes, such as SagarMala, to develop coastal shipping and link various inland waterways with the coastal shipping network. Due to the growing containerization of the cargo world, which reduces pilferage, flexibility in unitization, and convenience of handling, there is a need to develop a strategic plan and framework to increase container use in inland waterways in India. Recent trends in reducing carbon footprint and innovation in low-carbon emission fuels make inland waterways viable.

Address for Correspondence: Bangar Raju Totakura, University of Petroleum and Energy Studies, School of Business, Dehradun, India
E-mail: bangarraju@gmail.com
ORCID ID: orcid.org/0000-0003-4395-8967

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The last two decades have seen significant growth in the domestic traffic of bulk cargo in these waterways. However, there is a need to study the factors and efforts required for the considerable growth of container traffic. A substantial body of research has been conducted in exploring various studies related to the domain in the literature review in Section 2. The section also explores the development of IWT over a certain period in the country, previous studies related to IWT, and factors affecting IWT. The research methodology and analysis are discussed in Sections 3 and 4, respectively. A detailed conclusion of the study is brought forward in Section 5.

2. Literature Review

Water transport forms a part of the entire transportation system in a country and is invariably not door-to-door by its very nature. While waterways are naturally formed in many countries, they are not fully utilized to their potential because manmade infrastructure are still needed and are not made available. The water transport does not cover the first mile and last mile, so we consider it a part of multimodal operations. We need funds to be identified to create the necessary infrastructure, and tradeoffs are assessed to match with benefits. Tradeoffs normally involve increased time and cost associated with mode switching via ports and jetties, among others. National governments play a significant role in these arrangements. National IWT is defined as "the movement of goods or people on 'inland waters' between two places located in the same country even if transiting through a second country" [2]. IWT explicitly excludes "sea" and coastal shipping [3].

Inland waterways are more suitable for bulk cargoes than unitized/breakbulk cargoes because the speed, consolidation, and intermodal dependence for the first and last miles are higher [4].

Inland waterways provide an alternative to road and rail transportation, especially for containerized transport. It also offers an emergency alternative to natural and manmade disasters. IWT reduces the emphasis on land-based facilities and provides increased transportation capacity and redundancy without further land demands. The IWAI has been testing the commercial viability of container transport by IWT for some time now in India. Pepsico's 16 TEU consignment of foods and snacks was moved from Kolkata to Varanasi in October 2018. In November 2019, the Indian government, 53 TEUS of petrochemicals, edible oil, and beverages were moved from the Haldia Dock Complex to the Guwahati Pandu Port as a mark of a good connectivity to the northeastern region of India. In July 2019, Adani Logistics carried 52 containers on NW-1 from Haldia to Patna, and container cargoes were also sent earlier from Kolkata to Varanasi. In July 2020, Adani Logistics completed its first-ever containerized cargo export (45 TEUs) from India to Bangladesh utilizing inland waterways. Thus, the Indian government is committed to improving the features of IWT and making it attractive and reliable, and customers are also ready to explore the possibilities.

However, we need supporting infrastructure, communication, and navigation technology to integrate IWT into a multimodal transport system [5]. China has 110,000 km of navigable waterways, whereas India has approximately 14,500 km. The World Bank (WB) estimates that 8.7% of the total freights transported are goods transported over inland waterways in China. The corresponding figures for the United States and European Union (EU) are 8.3% and 7%, respectively. India logs in at a 0.5% freight. In the context of containerized transportation and the possible use of IWT for the same in India, we provide a brief literature review of relevant papers leading to our research study. Some of these papers trace developments in the developed and other parts of the world because they are relevant to similar contexts in India. For example, discusses some failures due to the lack of stakeholder support in the USA [6]. According to this report, key issues were labor charges, resistance to new modes, and the harbor maintenance tax, i.e., selective application fee of 0.125% to water-borne cargoes only. Other barriers have been identified in various studies.

Ro-ro transportation is a viable practice and part of multimodal transportation as it helps to reduce costs. A study in China by Yu et al. [7] opines that customers consider many transportation choices, but the four primary elements are safety issues, convenience, lead time, and cost reduction. Developments in the Chinese economy indicate the importance of waterways. China's entry into the World Trade Organization has also introduced high levels of competition in manufacturing within the country. These and other factors have propelled many firms to move their logistics and manufacturing facilities inland to achieve low production costs. In this context, ro-ro and inland waterway transportation is an alternate way out of the difficulties faced by companies located away from coastal ports [8].

Inland waterways require navigable water to operate. Hence, the lack of availability of this resource is the most important challenge or limitation. The distances and weights moved were affected by the length and size (width, depth, and height). Importantly, it is navigable throughout the year. Thus, the performance of IWT is affected by the quality and quantity of features. For example, the USA can operate some of the world's largest inland water vessels (push barges) despite having a less extensive network than China or

Europe [9]. The maintenance of inland waterways requires funding and has implications for stakeholders. We have also observed various developments in the Indian economy. With the Make in India movement, which is expected to give impetus to manufacturing in India-India as a manufacturing hub-and IWT is a viable alternative to road/rail transport, specifically with multimodal transportation connecting to ports of export.

2.1. IWT in India

The Indian government declared NWs through the NWs Act of 2016 [10] and initiated the development process of 111, in which five are old and 106 are new waterways. The details of all the 111 NWs and the latitude-longitude coordinates of the start and endpoints are given in the above Act. These waterways pass through 24 states and two union territories, and the total length of all these NWs is approximately 20274 km. These inland waterways encounter 138 river systems, related canal systems, estuaries, and creek [11]. The IWAI was set up by the Indian government in 1986 to coordinate and manage the development of NWs (initially five). The scope of control of the IWAI was expanded to cover 111 NWs. Since then, the IWAI conducted feasibility and project studies through consultants who enquired into the potential of each NW. According to reference [12], these studies have mostly been completed. The major findings of these studies are as follows:

a. NWs, having tidal influence connected to sea and traditional waterways, are found to be feasible for navigation.

b. Due to the lack of passenger traffic/cargo, some of the NWs are not feasible despite having navigation potential.

c. Through the study, many barriers are encountered, such as navigational locks, rail and road bridge clearances, and power line passage through the waterways.

d. The projects become unviable financially because of the costs imposed by alterations/modifications to these hurdles.

e. There is an inadequate water depth for navigation due to current water diversions and usage from the rivers.

f. Excessive siltation is a major hurdle for navigational channels in summer due to low discharges.

g. Last- and first-mile connectivity require handling of multiple cargoes as most of them originate in special economic zones and industrial hubs away from inland waterways, which in turn increases the transportation cost.

Based on the recommendations of the above studies, 106 new waterways were categorized into three categories, i.e., A, B, and C, based on specific parameters. Category A represents feasible NWs with cargoes, i.e., 18. Category B includes new waterways with tourism potential, i.e., ferry/cruise, which are 25, and the 63 waterways that are not beneficial either for cruises or cargoes have been categorized in Category C. The development of new waterways through action plans has been developed, where rapid ready cargo, navigational potential, and infrastructure are in place. Finally, a total of 17 channels, including five that existed prior to 2016, were taken up for development. The works on 13 of the new waterways are being carried out under various financial and technical assistance from agencies, such as the WB and national agencies. In addition, through new waterways, no. 73, 100, 83, 85, 91, and 94 significant cargo volumes have been moved through river mouths and tidal waters under the Maharashtra, Gujarat, and Goa Maritime Boards, respectively. Limited government support is required as they are run and developed by private entities. Logistics costs in India are estimated to be approximately 14% of GDP, which is quite high compared to the range of 8-10% in developed countries. If India has to compete with other countries, such as China, logistics costs need to be lowered. As per a report by Aritua [13], the cost per ton-kilometer of different modes of transport is meager and more economical compared to worldwide costs. Manufacturers and shippers can choose lower-cost alternatives while simultaneously reducing the overall logistics cost and improving the competitive strategy. Intending to develop NWs as a key transport intervention and lower logistics costs, the IWAI has implemented many measures to improve the utilization of waterways by manufacturers and shippers.

According to a report by reference [11], the IWAI launched a portal Forum of Cargo-Owners and Logistics-Operators in 2018. This portal provides manufacturers and shippers with access to real-time data on vessel availability. In addition, the IWAI signed a project agreement with the WB for the Jal Marg Vikas Project on the Ganges to augment NW-1 from Varanasi to Haldia. To improve the operability and utilization of waterways, the IWAI has also launched a real-time information system called LADIS. LADIS will disseminate real-time data to manufacturers and shippers at the least available depths. This process will facilitate the day-to-day operations of inland vessels on NWs, thereby avoiding hindrance in service and operation. Apart from preempting problems that may occur during vessel movements, this will improve information sharing and achieve seamless operations on NWs. While the reports indicate that the IWAI has made efforts to overcome the challenges and hindrances by engaging with all stakeholders, including state governments/union territories and concerned central ministries, the most important stakeholder who has been left out is possibly the user/company, which finds the option of IWT as beneficial but is unable to use it to the best advantage due to various factors. For example, the information provided by LADIS may not help in the decision making of customers if the least available depths are not improved to make navigation easy. However, the least available depth in many rivers in India may be sufficient for container movements. The issue of depth is usually less critical because containers are of low density and seldom sink the vessel deep enough in the water for it to be fully loaded without ballast [5].

2.2. Container Transport Through Inland Waterways

Container cargo transport has several inherent advantages. While it reduces the handling cost, it also reduces damage and pilferages and allows an easy modal shift. Cargo owners can also reduce their carbon footprints. In the USA, Europe, and China, the growth in container traffic through IWT is quite impressive. In the USA, inland waterway traffic is substantially high, but there is limited traffic in mainland waterways. On the Mississippi River, this situation is mainly due to the north-south orientation of the river, which does not match with the east-west container movements. Container traffic has stabilized in the Columbia-Snake Waterway from east to west to the sea in Portland. The intermodal transport of containers was more than 60% of the total transport in Portland [5]. Meanwhile, Europe has seen considerable growth in multimodal container transport. There has been a considerable double-digit growth in traffic over the last two decades owing to infrastructure adaption and facilitation of traffic. During the early 1980s, the advantages of cost savings through fully dedicated river container ships were recognized, and new container terminals were built by local interests. An increase in container traffic by IWT has also been facilitated by several features, such as no tonnage limitation, free rates, ICD status, expeditious customs clearance, legislation favoring intermodal transport, and financial measures. In China, shippers have been moving containers on the Yangtze and Pearl River Delta since the 1980s. In the 1970s, the Kowloon wharf was a major container-handling terminal, but Kwai Chung became a dedicated container terminal. In 2002, 2.4 million TEUs of containers were handled in the river trade [5].

2.3. Relevant Factors for Choosing IWT

Freight transportation choices have always been based on many factors. These factors could be objective (e.g., cost and frequency) or subjective (e.g., reliability and service quality), as postulated by D'Este and S. Meyrick [14]. Different authors have identified various factors in their studies, with a commonly occurring set of decision criteria emerging in selecting the mode of transport. These factors include safety, speed, price, lead time, convenience, services, and cargo characteristics [15,16]. Murphy and Hall [17] identified key factors in carrier selection based on an extensive review of research papers published in the 1970s and 1980s. These key factors include freight rates, transit time, reliability, carrier characteristics, cargo requirements, and service during emergencies. Similar factors were reported in Cullinane and Toy [18]. Although these studies did not cover relevant factors, they depend on practical considerations. The actual business and logistics environment and factors for one transportation option may not be the same for the other. In addition, innovations in new modes of transport, digital evolution of logistics and supply chains, and increased outsourcing in manufacturing have increased the choices for shippers; thus, changing the context [19]. From the standpoint of sustainability, IWT is more sustainable than road and rail transport, which are highly congested and polluting. However, IWT has many challenges and limitations. Considering that cargo transportation over inland waterways is substantially cost effective, it is worthwhile to study why India, which has the potential to be a regional superpower and a significant manufacturing and logistics hub, is not making optimum use of IWT.

2.4. Inland Waterways in Europe

One of the early papers [20] brought forward the technical description of inland waterways, the shipping fleet for the same at Europe, volume of cargo and business, legal framework, and inland shipping trends across Europe. The paper also attempted a break-even analysis to explain the need for a sufficient volume of cargoes to make the transport viable. Rohács and Simongáti [21] brought forward the need for sustainable transport development, and the role of inland waterways was envisaged. The study focused on the EU, and the need for inland waterways development for efficient sustainable development was discussed. In another attempt to develop sustainable freight transport, Rogerson et al. [22] proposed a feasible study on waterways along Axios-Morava near the Danube River. Considering the energy efficiency and air quality, inland waterways were better than land and rail alternatives. Rogerson et al. [22] critically analyzed barriers toward the shift to inland waterways in Sweden. The need for policymakers to understand various stakeholders' issues and their concerns to promote inland waterways was brought forward in the findings.

2.5. Research Gap

This study explores possible factors for such failures and non-adoption of the IWT facility in the country, especially within container transportation. Shippers and manufacturers face difficult choices in a complex decision-making environment, and IWT as a preferred method of transport, either as an only alternative or as part of multimodal arrangements, is tricky. Various researchers have proposed different methods for studying decision-making features in such a complex environment. Yu et al. [7] studied the adoption of ro-ro transportation in China using a survey method to obtain views from 338 firms/individuals comprising members from three different stakeholders-manufacturers, shippers, and long-haul drivers. Trivedi et al. [23] studied the barriers to IWT adoption in India by employing the Decision Making Trial and Evaluation Laboratory (DEMATEL) and interpretive structural modeling methods. While the study did not cover containerized cargo, we intend to analyze the adoption of IWT for containerized transport.

Based on the literature review, we identified similar factors and grouped them into a few categories. Then, we processed them through discussions with a few experts through interviews and identified the following factors as relevant for our study.

As mentioned earlier, a study using fuzzy analytic hierarchy process (AHP) has not been attempted till now as per our understanding, and ours will be the first such study of assessment of ports and other related infrastructure. The factors and subfactors were shortlisted based on feedback from experts who were also stakeholders. Experts with a minimum of five years of experience were considered. The shortlisted subfactors are listed in Table 1.

Table 1. *List of factors and subfactors*

Code	Factors	Description
	Economics factors	
EF1	Cost competitiveness	Competitive advantage of inland waterways over other modes of transport in terms of cost
EF2	Transportation lead time	Time taken to prepare the cargo for movement
EF3	Convenience and reliability	availability trustworthy of the transport service
EF4	Capital investment	Investment required to develop the infrastructure
EF5	Pilferage	Loss of cargo or fuel in transit
	Infrastructure factors	
IF1	Safety issues	Accident or losses to vessels and personnel working during the transport operation
IF2	MRO facility shortage	Facility or a location for conducting maintenance of repair works of vessels which is maintenance, repair and overhaul
IF3	Modal integration	Connectivity between Inland waterways and other modes of transport
IF4	Navigational infrastructure	Consists of support for easy navigation such as Digital Geographic information systems and River information systems
IF5	Capacity and efficiency of terminals	Equipment to handle containers with good speed and low costs
IF6	Shortage of vessels	Number of vessels available in the inland waterways for containers
IF7	Infrastructure facilities at shippers' premises for handling containers	Equipment and facilities available to handle container operations like loading, unloading, stuffing, lashing etc.
IF8	Container inventory	Number of empty containers available for domestic and export cargoes
IF9	Container repositioning	Movement of empty containers from the place of unloading to place of loading
	Regulatory factors	
RF1	Government control and jurisdiction	Degree of government restrictions imposed in moving cargoes
RF2	Policy parity	Priority given to inland waterways in comparison to other modes of transport, such as railways and roadways
RF3	Legal issues	Uniform legal rules across all states as the inland waterways move across more than one state
RF4	Customs clearance facilities at loading terminals for exports	Facility to customs clearance at loading terminal and thereby containers are sealed by the customs after stuffing them
	Geographical factors	
GF1	Lack of interlinking	Integration of river basins for the smooth flow of waterways and cargoes
GF2	Inadequate depth in waterways	Constant maintenance of water levels for a good navigation
GF3	Terminal location	Location of terminals across the river basin to load the containers

3. Research Methodology

Multi-criteria decision-making (MCDM) is a widely used tool for ranking (prioritizing) the alternatives based on some conflicting criteria [24]. In the domain of maritime logistics, MCDM techniques are applied by researchers to identify and rank various barriers or factors that influence decision-making processes. Özdemir [25] analyzed the empty container accumulation problem of container ports. In their study, they have provided ranks to various factors identified relating to the empty container accumulation problem using fuzzy DEMATEL and fuzzy TOPSIS tools of MCDM. A decision-making approach for selecting the best solution for the selection of ballast water treatment systems for ships was developed in Özdemir [26]. In their study, the authors used the integrated DEMATEL and ANP methods. In our study, we applied the fuzzy AHP method to provide the weights and rank the factors that influence IWT for container transport. The weights are provided at two levels, factors at one level and subfactors at another level. Fuzzy AHP was used for this study, as making comparisons through linguistic terms is relatively easy for respondents. As the network decision-making considered in this study is not very complex (it involves two levels) and does not include several criteria, fuzzy AHP is the most appropriate MCDM tool for this study. Our study is based on a sample of nine respondents from different stakeholder groups and uses a fuzzy AHP methodology.

3.1. Fuzzy AHP Methodology

Among the many MCDM tools, the AHP method developed Saaty [27] is widely used by researchers to provide the weights to criteria and rank alternatives. The AHP analysis is based on preference scores provided by decision-makers (or experts) and, hence, often involves time vagueness. To deal with such vagueness due to human judgments, a fuzzy AHP was proposed by Buckley [28]. Fuzzy AHP involves the concept of fuzzy logic with the pairwise comparison-based MCDM tool AHP. The weights for factors and subfactors in this study are calculated using the FuzzyAHP package in R software [29]. The "FuzzyAHP" package follows the methodology provided by Krejčí et al. [30] for calculating the weights of factors. The inputs from decision-makers for the preference matrix are collected in linguistic terms), which makes the data collection process practical. The fuzzy numbers corresponding to each linguistic term are used for the computation of weights, as given in Table 1. Fuzzy triangular numbers are used to denote linguistic preferences.

The general fuzzy triangular number is denoted by $\widetilde{A}(x) = (l, m, u)$, with the membership function

$$\mu_{\widetilde{A}(x)} = \begin{cases} 0, & x < l \\ \dfrac{x-l}{m-l}, & l \le x \le m \\ \dfrac{u-x}{u-m}, & m \le x \le u \\ 0, & x > u \end{cases} \tag{1}$$

The membership function $\mu_{\widetilde{A}(x)}$ can graphically be presented as Figure 1.

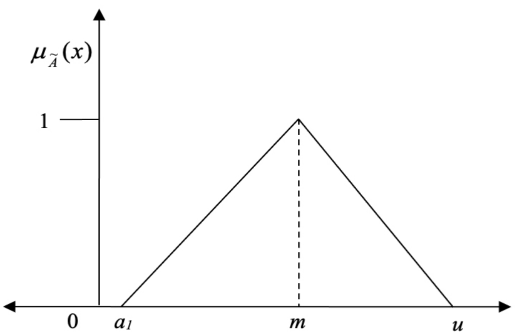

Figure 1. *Membership function for triangular fuzzy numbers*

The stepwise procedure for applying fuzzy AHP is as follows:

Step 1: Construct a fuzzy pairwise comparison matrix:

Based on the responses collected from the experts, fuzzy pairwise comparison matrices were constructed as follows:

$$\widetilde{D} = \begin{bmatrix} \widetilde{a}_{11} & \widetilde{a}_{12} & \cdots & \widetilde{a}_{1n} \\ \widetilde{a}_{21} & \widetilde{a}_{22} & \cdots & \widetilde{a}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \widetilde{a}_{n1} & \widetilde{a}_{n2} & \cdots & \widetilde{a}_{nn} \end{bmatrix} \tag{2}$$

where $\widetilde{a}_{ij}$ represents the preference of the i^{th} criteria over the criteria provided by the decision-maker.

If the triangular fuzzy number for j^{th} is $\widetilde{a}_{ij}$ is (a^l, a^m, a^u), then for $\widetilde{a}_{ji}$, the triangular fuzzy number will be $\left(\frac{1}{a^u}, \frac{1}{a^m}, \frac{1}{a^l}\right)$.

Step 2: Compute the fuzzy geometric mean for the criteria:

Using Equation (3), the geometric mean of the fuzzy pairwise preference matrix was calculated for each criterion.

$$\tilde{r}_i = \left(\prod_{j=1}^{n} \tilde{a}_{ij}\right)^{\frac{1}{n}}, \quad \forall i = 1,2,\ldots,n \tag{3}$$

Step 3: Compute fuzzy weights for the criteria:

The fuzzy weights $\tilde{w}_i$ for each criterion i were calculated using Equation (4).

$$\tilde{w}_i = \tilde{r}_i \times \left(\sum_{i=1}^{n} \tilde{r}_i\right)^{-1} \tag{4}$$

Step 4: Defuzzification of fuzzy weights:

Using the center of area approach represented by Equation (5), we obtain the equivalent crisp weights (w_i) for each of the fuzzy weights, i.e., $\tilde{w}_i = (w_i^l, w_i^m, w_i^u)$.

$$w_i = \left[(w_i^u - w_i^l) + (w_i^m - w_i^l)\right]/3 + w_i^l \tag{5}$$

Step 5: Normalization of crisp weights:

Using Equation (6), the normalized weight (N_i) for each criterion is obtained:

$$N_i = \frac{w_i}{\sum_i w_i} \tag{6}$$

3.2. Data Collection

A well-structured questionnaire was circulated to the group of nine experts in inland waterways in India, who are shippers, operators, and personnel from India's inland waterways' authority. Nine members agreed to respond to a questionnaire based on telephonic requests. The respondents consisted of personnel working with three members working with shippers, four working with inland waterway operators, and two working with the inland waterway's authority. All the respondents worked at the managerial level with a minimum work experience of five years in the inland waterway's domain. The responses were limited due to the pandemic situation in the country, and based on the domain knowledge of the respondents, nine were assumed to be adequate. Brief details of the respondents are given in Table 2. In addition, the scale of importance for the fuzzy AHP analysis are detailed in Table 3.

The responses were used for further analyses. The shortlisted factors and subfactors used for the analysis are shown in Figure 2.

Table 2. *Details of the respondents*

Number of respondents	Respondent category	Experience and role
3	Shippers-Customers using inland waterway services for transportation	Five to 9 years of experience in export/import of cargoes
4	Inland waterway operators-Personnel working at the managerial level with operators in inland waterways	Five to seven years of experience in operating vessels in inland waterways
2	Inland Waterways Authority of India-Personnel working as a consultant or expert in the traffic and logistics department of IWAI	Five to 8 years of experience in the domain
IWAI: Inland Waterways Authority of India		

Table 3. *Scale of importance for the fuzzy AHP analysis*

Linguistic scale	Equivalent crisp score	Equivalent triangular fuzzy scale
Equally important	1	(1, 1, 1)
Weakly important	3	(2, 3, 4)
Fairly important	5	(4, 5, 6)
Strongly important	7	(6, 7, 8)
Absolutely important	9	(9, 9, 9)
Intermittent values	2	(1, 2, 3)
	4	(3, 4, 5)
	6	(5, 6, 7)

4. Results and Analysis

Table 4 and Figure 3 show that infrastructure factors are the highest ranked, followed by economic factors (EFs), geographical factors, and regulatory factors (RFs). This result brings forth the prominence of infrastructure as a major element affecting container shipping. EFs are the second most significant factor affecting waterways. The fuzzy ranking of the subfactors is discussed below, and their importance is discussed.

Among the subfactors of EFs, transportation lead time EF2, capital investment EF4, and convenience and reliability EF3 have emerged as the top three, respectively, as shown in Table 5 and Figure 4.

The container inventory IF8 remains a major concern among IFs. The container repositioning IF9, capacity, and efficiency of terminals IF5 follow, as shown in Table 6 and Figure 5.

The need for customs clearance facilities at loading terminals for exports RF4 is a major subfactor, followed by legal issues RF3 among the RFs, as shown in Table 7 and Figure 6.

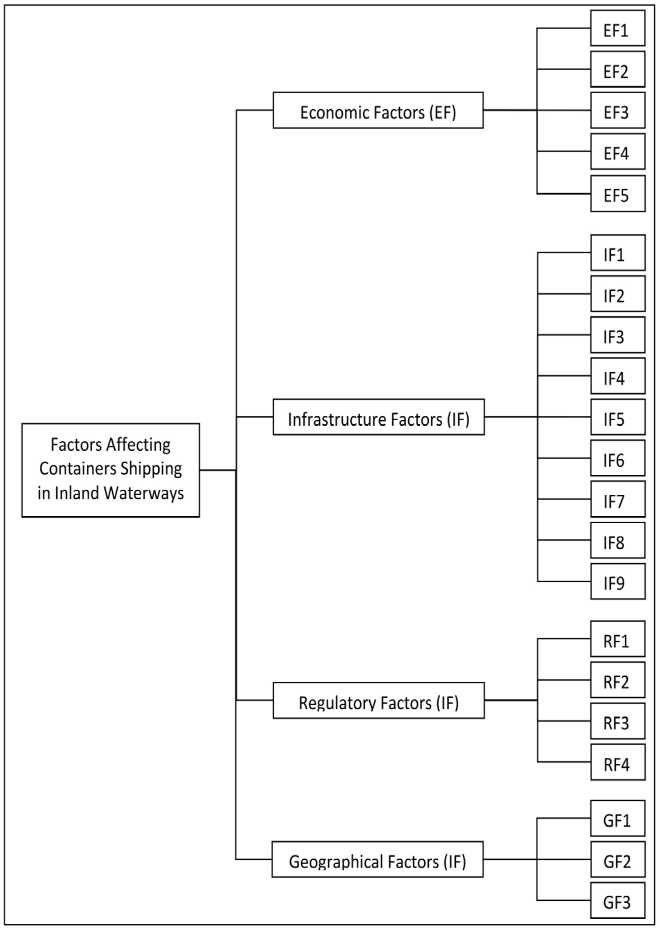

Figure 2. *Hierarchy of factors affecting inland waterway shipment*

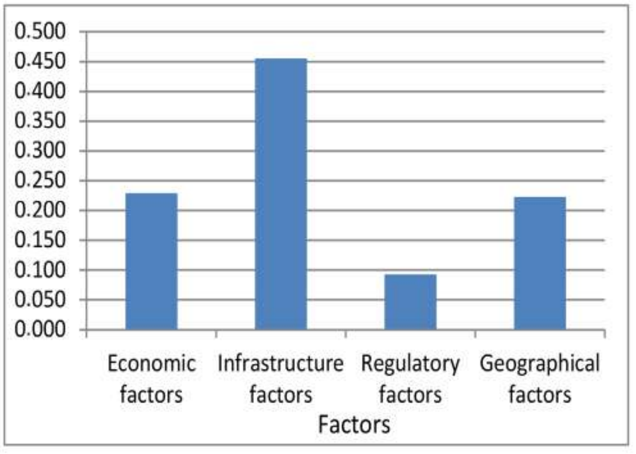

Figure 3. *Relative importance of factors*

Table 4. *Fuzzy and equivalent crisp weights of factors*

Factors	Fuzzy weight for factors	Crisp weight for factors	Normalized weight	Rank
Economic factors	(0.204, 0.238, 0.261)	0.234	0.229	2
Infrastructure factors	(0.426, 0.462, 0.503)	0.464	0.455	1
Regulatory factors	(0.066, 0.097, 0.123)	0.095	0.093	4
Geographical factors	(0.183, 0.227, 0.272)	0.227	0.223	3

Table 5. *Weights and rank of the subfactors of economic factors*

Subfactors	Fuzzy weight (local) for subfactors	Crisp weight (local) for subfactors	Normalized weight	Rank
EF1	(0.089, 0.127, 0.166)	0.127	0.127	4
EF2	(0.354, 0.410, 0.465)	0.41	0.409	1
EF3	(0.113, 0.169, 0.222)	0.168	0.167	3
EF4	(0.223, 0.253, 0.286)	0.254	0.253	2
EF5	(0.033, 0.042, 0.058)	0.044	0.044	5

Inadequate depth in waterways GF2 due to constant silting, rains, and irrigation is a significant subfactor among the GFs, followed by a lack of interlinking of waterways, as shown in Table 8 and Figure 7.

As shown in Table 9 and Figure 8, the inadequate depth in waterways GF2 remains a major subfactor from the global ranking. The next two subfactors are container inventory IF8 and container repositioning IF9, which are related to each other and are due to a shortage of empty containers for export and domestic cargo movements. Finally, transportation lead time EF2 and the capacity and efficiency of terminals IF5 remain globally ranked at 4 and 5, respectively.

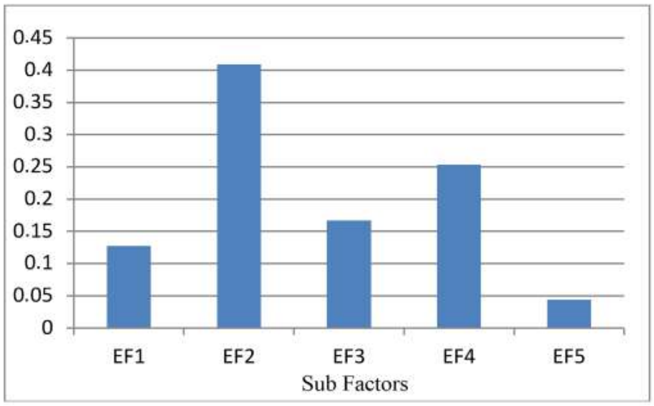

Figure 4. *Relative importance of subfactors of economic factors*

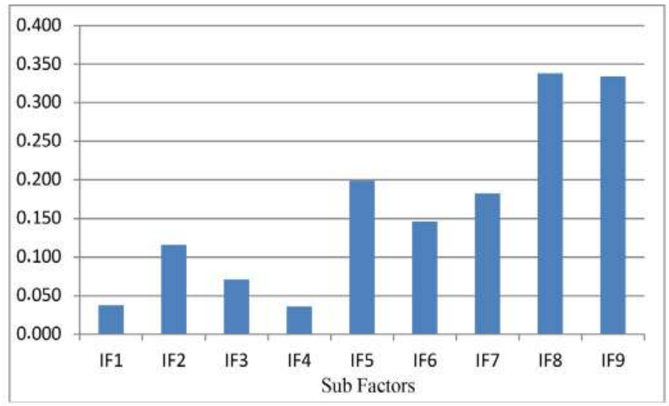

Figure 5. *Relative importance of subfactors of infrastructure factors*

Table 6. *Weights and rank of the subfactors of infrastructure factors*

Subfactors	Fuzzy weight (Local) for subfactors	Crisp weight (local) for subfactors	Normalized weight	Rank
IF1	(0.020, 0.027, 0.038)	0.028	0.038	8
IF2	(0.061, 0.087, 0.109)	0.086	0.116	6
IF3	(0.042, 0.053, 0.066)	0.053	0.071	7
IF4	(0.016, 0.027, 0.038)	0.027	0.036	9
IF5	(0.122, 0.150, 0.172)	0.148	0.199	3
IF6	(0.071, 0.109, 0.146)	0.108	0.146	5
IF7	(0.098, 0.135, 0.172)	0.135	0.182	4
IF8	(0.198, 0.254, 0.301)	0.251	0.338	1
IF9	(0.209, 0.246, 0.288)	0.248	0.334	2

Table 7. *Weights and rank of the subfactors of regulatory factors*

Subfactors	Fuzzy weight (local) for subfactors	Crisp weight (local) for subfactors	Normalized weight	Rank
RF1	(0.165, 0.211, 0.252)	0.209	0.202	3
RF2	(0.076, 0.115, 0.157)	0.116	0.112	4
RF3	(0.228, 0.301, 0.384)	0.304	0.294	2
RF4	(0.316, 0.402, 0.495)	0.404	0.391	1

Table 8. *Weights and ranks of the subfactors of geographical factors*

Subfactors	Fuzzy weight (local) for subfactors	Crisp weight (local) for subfactors	Normalized weight	Rank
GF1	(0.095, 0.163, 0.220)	0.159	0.158	2
GF2	(0.582, 0.693, 0.816)	0.697	0.693	1
GF3	(0.101, 0.151, 0.196)	0.149	0.148	3

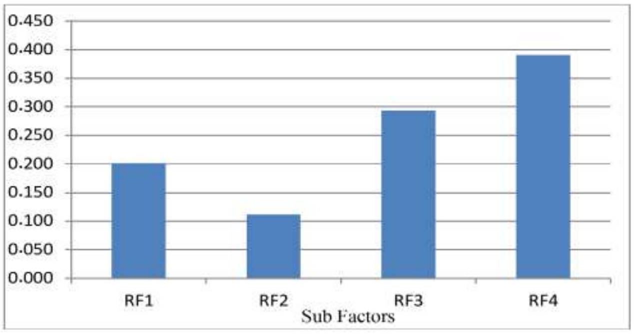

Figure 6. *Relative importance of subfactors of regulatory factors*

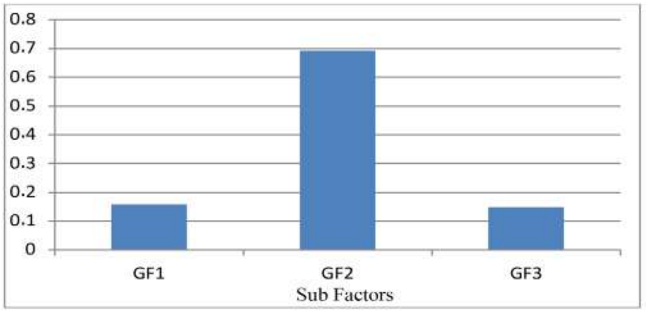

Figure 7. *Relative importance of subfactors of geographical factors*

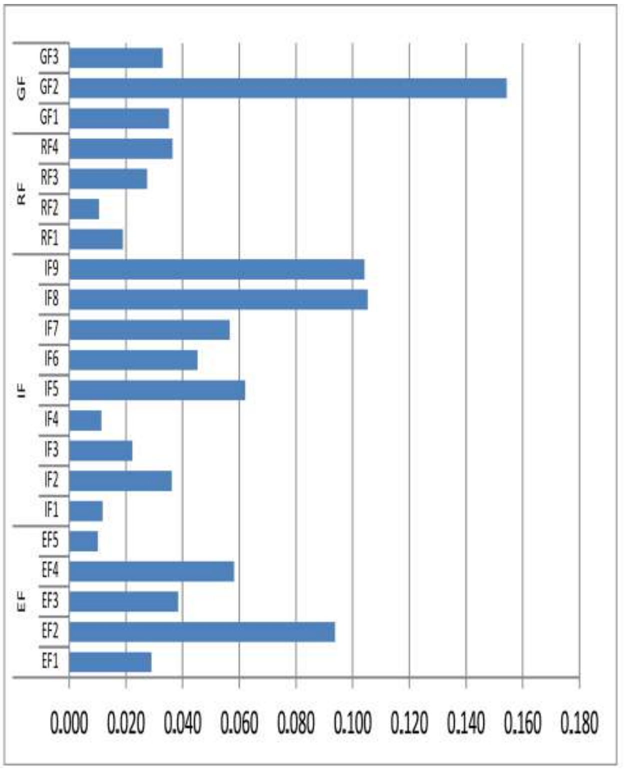

Figure 8. *Relative importance of all subfactors*

Table 9. *Global weights and ranking of subfactors*

Factors	Subfactors	Global weight	Rank
Economic factors (EFs)	EF1	0.029	14
	EF2	0.094	4
	EF3	0.038	9
	EF4	0.058	6
	EF5	0.010	21
Infrastructure factors (IFs)	IF1	0.012	18
	IF2	0.036	11
	IF3	0.022	16
	IF4	0.011	19
	IF5	0.062	5
	IF6	0.045	8
	IF7	0.057	7
	IF8	0.105	2
	IF9	0.104	3
Regulatory factors (RFs)	RF1	0.019	17
	RF2	0.010	20
	RF3	0.027	15
	RF4	0.036	10
Geographical factors (GFs)	GF1	0.035	12
	GF2	0.154	1
	GF3	0.033	13

5. Conclusion

Our study, which uses the AHP method, indicates the lacunae in India's ports and other waterway infrastructure. The indications reinforce our general or specific perception about the shortcomings. To this extent, the study is useful as a reinforcer element in our understanding. The findings from this study suggest that an inadequate depth of rivers is a major factor hindering container shipping. In previous studies, this situation was also evident for general bulk cargo movements across inland waterways. Hence, there is a need for dredging and other related measures to maintain sufficient water levels. Moreover, container inventory and repositioning of containers are major subfactors that need to be addressed. There is a need for two types of containers, first for domestic movements and second for cargo export. Therefore, comprehensive support and policy-driven incentives are required to drive the domestic manufacturing of containers, rather than relying on overseas manufacturers. Imported containers have a constraint of exporting within six months of entry into the country. They must also be stimulated to use inland waterways for inward movements. The capacity and efficiency of terminals need to be improved with good capital investment through the public-private partnership mode, providing better utilization of capital and efficient waterway management. The central government has tried to bring inland waterways and coastal shipping at par with railways and roadways through the SagarMala Project. This project has attempted to integrate coastal shipping, inland waterways, roadways, and railways through an investment of approximately 7 billion USD. Inland waterways also need to be considered an option to reduce the carbon footprint in India. Roadways are more flexible owing to the last-mile connectivity advantage, while inland waterways are the best option to reduce carbon emissions. The reduction of road accidents by high traffic volumes on highways and low pollution levels can be reduced by providing subsidies in freight, directly or indirectly, until the country reaches sustainable traffic in waterways. Although the Indian government has identified the challenges, we need to understand whether sufficient policy initiatives are being made to tackle them. In this context, a study of the major port initiatives and their review is needed to understand how far we can achieve the orchestrated vision. Moreover, as identified in the port sector, the dual-institution structure has led to the development of major and nonmajor ports as separate, unconnected entities. Further policy studies need to be undertaken if this drawback can be removed by bringing all ports under one governmental jurisdiction. Bilateral agreements with neighboring countries, such as Nepal, Bangladesh, Bhutan, and Myanmar, with joint investments in infrastructure are needed to promote low-carbon emission and economical IWT could boost the GDP and economy across the region. The adoption of key performance indicators in inland waterways and linking them through various incentives could help us monitor and achieve good milestones in terms of traffic and profits. The adoption of low-cost and effective dredging from European experiences, maintenance of a minimum depth of water levels by installing effective lock system for good navigation, and accommodation of wide ships and multiple vessels could be useful.

Authorship Contributions

Concept design: B.R. Totakura, Data Collection or Processing: B.R. Totakura, A. PJ, Analysis or Interpretation: S.A. Jalil, Literature Review: N. Narasinganallur, Writing, Reviewing and Editing: B.R. Totakura, N. Narasinganallur, S.A. Jalil, A. PJ.

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An Energy and Fuel-effective Solution for School Exploration of a Fishing Vessel Through Swarm Intelligence Approach

Erhan Sesli

Karadeniz Technical University, Sürmene Abdullah Kanca Vocational School, Trabzon, Türkiye

Abstract

In recent years, energy and fuel efficiencies have been considered in scientific studies. These parameters become extremely important in maritime, especially for fishing vessel activities. In this study, an innovative approach is proposed to reduce the fuel consumed by fishing vessels and carbon emissions to the environment during the fish exploration process. Key elements of the proposed approach are autonomous underwater vehicles (AUVs) and the application of swarm intelligence. With this approach, which can be considered a pioneer in maritime, the AUVs released from the fishing vessel find the school through the swarm intelligence behavior of Grey Wolves. In this article, the method is modeled as a simulation, and its applicability in the future is also discussed. In the present studies, the conventional fish search method and the proposed method were modeled, and the results were examined. When the obtained results are examined, it is seen that the proposed method increases the successful voyage rate by 2.94 times compared to the conventional method, while the distance covered in the exploration activity decreases by 8.61 times. The results demonstrated that the proposed innovative approach is an energy-efficient, cost-effective, and environmentally friendly solution that is also applicable and usable in the future.

Keywords: Energy efficient, Carbon emission, AUVs, Grey Wolf Algorithm, Swarm intelligence

1. Introduction

The EU Marine Strategy Framework Directive states that the economy and energy efficiency in fisheries are critical components of the ecosystem-based approach to fisheries management [1]. It should be emphasized that energy efficiency, approaches, and studies that will protect the ecosystem have become of great importance [1-3]. Scientific awareness has also manifested itself in the institutional field; for example, International Maritime Organization (IMO) has enacted a new law that includes reducing carbon emissions from ships and providing energy efficiency technically and operationally [4].

This scientific study in this context examines the problem of fuel consumption, energy efficiency, and carbon emissions in the scope of fishing vessels. Researchers have significantly contributed to the fuel consumption and efficiency of fishing vessels. Individual voyage planning was studied by creating a decision tree model with the data obtained from fishing vessels [1], and statistical studies based on the product costs of fishing vessels were performed between specific dates [2]. The use of magnetic devices has been tried to provide energy efficiency [3], low-friction mesh technology is recommended [5], and fuel consumption is reduced by using a DC electric propulsion system [6]. As can be seen, studies are primarily focused on statistical approaches to improving existing equipment or approaches to reducing fuel consumption and increasing energy efficiency through weight reduction. In this study, the approach to solving the problem from a novel angle examines a different strategy for lowering fuel consumption and raising energy efficiency in fishing vessels.

For example, the search process of fishing vessels to find fish mass is one of the most important factors that increase fuel consumption and thus product cost [7,8]. Fishing vessels may need to scan fish for long periods to find the fish

Address for Correspondence: Erhan Sesli, Karadeniz Technical University, Sürmene Abdullah Kanca Vocational School, Trabzon, Türkiye
E-mail: erhansesli@ktu.edu.tr
ORCID ID: orcid.org/0000-0002-0039-2927

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mass. One of the most important reasons is that the Sound Navigation and Ranging (SONAR) on board can observe a limited area. In scientific studies, effective SONAR distances are accepted between 100 and 1200 m bands [9-13]. Furthermore, it is necessary to consider that the SONAR device is positioned under the vessel and creates resistance during the vessel [14,15]. The resistance created has an additional direct effect on the increase in fuel consumption.

This scientific study, which includes a completely innovative method for reducing fuel consumption, presents unmanned vehicle technologies, which have become increasingly popular in recent years as an innovative solution for energy efficiency. The development of AUVs dates back to the 1960s. Over the years, hardware developments in this field (energy management, sensing technologies, etc.) have continued [16]. In recent years, studies and applications of autonomous underwater vehicles have become remarkable. Its use in polar regions, where obtaining data in ocean science and traveling with manned vehicles is extremely dangerous, is just one of the AUV applications [17,18]. Other applications include marine environment mapping applications [19,20], evaluation applications of dangerous situations that may arise at submarine oil and gas connection points [18], and military applications [20].

It is clear that the perspectives on the solution to the problem discussed in this study are limited. For this reason, it is exciting that the study fills the gap in this field and contributes to the literature. The proposed method aims to detect the fish mass of a group of AUVs that the fishing vessel will release into the sea in a particular area in a short time, with a collaborative approach focused on swarm intelligence that mimics the hunting behavior of the grey wolf pack. Sharing the detected location information with the fishing vessel via AUVs enables the fishing vessel to achieve less fuel consumption, carbon emissions, and energy efficiency.

The flow order of the article is planned as follows. Section 2 discusses the contributions of the article to the literature. Section 3 explains the method, Section 4 evaluates the studies and findings, and the results are discussed in Section 5.

2. Contributions to the Literature

It is possible to list the contributions of this scientific study to the literature as follows:

• A system model has been proposed that will make fishing vessels cost-effectively and emit less carbon in a shorter time.

• In the proposed system model, one of the maritime applications is integrated through autonomous vehicle technologies, one of the popular technologies of recent years.

• The application of school detecting through a collaborative approach with AUVs, current technology in the maritime field, is proposed for the first time.

• It was achieved that the AUV group reached a solution using a model inspired by nature. It has been a pioneer study in this area.

3. Material and Methodology

The school search process is analyzed with a focus on swarm intelligence, which proposes a solution that will provide cost-effective and less carbon emission. A simulation model was developed for the solution. The swarm is made up of AUVs, and each AUV is a member of the swarm. Swarm intelligence was created by mimicking the natural herd behavior and hunting methods of grey wolves. Mirjalili et al. [21] proposed and used grey wolf pack hunting behavior for the first time to solve an optimization problem. An objective function is needed in conventional optimization problems to reach the solution. In this approach, the objective function is nothing more than the instantaneous distance of the AUVs, defined as the wolf pack, to the school. In the simulation studies, the wolf pack leadership hierarchy and hunting behavior were modeled and integrated into each individual, and an artificial wolf pack consisting of underwater AUVs was obtained. AUVs released from the fishing vessel have been enabled to find the fish school in a cost-effective and eco-friendly way. Figure 1 depicts the applied scenario.

In this section, the method of the scientific study is explained. Figure 1 shows the main elements used in the study: AUVs representing swarm individuals, the grey wolf algorithm used for swarm intelligence, evaluations in terms of applicability, assumptions for simulations, constraints, and conditions.

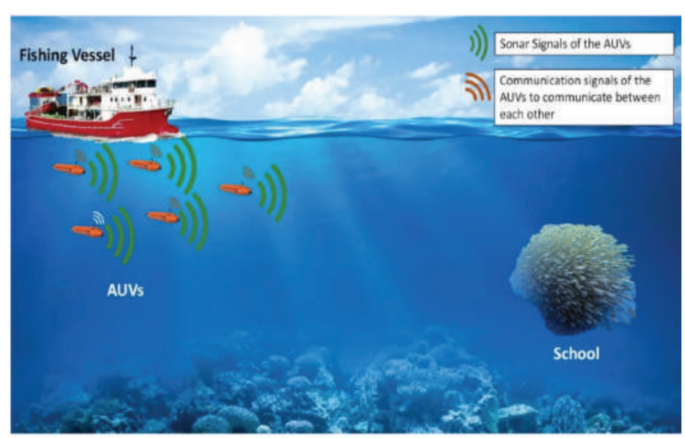

Figure 1. *Applied scenario for the study*

3.1. Autonomous Underwater Vehicles

AUVs have started to be used in most maritime applications as developing technology in recent years. AUVs are equipped with high-resolution cameras, pressure, temperature, proximity, and chemical sensors to collect data while performing tasks [17-20]. They obtain the necessary information using the sensor fusion they have. The figure below shows an AUV used in these studies (Figure 2).

Figure 2. *ABE autonomous vehicle [19]*

Designs for AUVs in scientific studies and applications are being developed and made available in various mobility, size, and speed configurations. Designed and developed AUVs used in scientific studies can have length values between 0.92-10.44 m and speed values in the range of 0.2-41.67 m/s. The length of AUV designs, similar to biological creatures, ranges from 0.09-2.5 m and the maximum rotation angle per second varies in the range of 6.84-670 deg/s [22]. Considering the designs, developments, and scientific studies, it appears that AUV applications resemble biological creatures and can move like them in the near future. This circumstance suggests that the proposed method and the simulated studies will be applicable soon. Another aspect to investigate is the communication between AUVs with swarm intelligence and the management of detection processes for fish school detection. Thus, the feasibility of this simulated study should be discussed.

When the detection and verification of fish swarms are examined, conventionally utilized SONAR can be seen as a natural solution. Image recognition can also be accomplished by equipping AUVs with high-resolution cameras and using image processing and deep learning applications [23]. Another issue is the communication of AUVs with each other. In detecting a school of fish, AUVs must constantly communicate with each other and determine their distance from each other. There are three different methods used for AUV communication in the literature. These are radio frequency (RF), acoustic, and optical wireless communication [24,25]. The channel model in water is unlike the channel model in the air for RF signals. In water, the signal becomes weaker, so the communication distance decreases. The distance can be increased by extending the wavelength, but then the communication speed will decrease [24]. Studies have been conducted on Underwater Wireless Sensor Networks using RF signals [26,27]. Conversely, acoustic communication provides a low data rate (around kbps) over long distances (around 20 km), and they have a high cost and bulky transceiver [25]. Furthermore, optical wireless communication offers the advantages of low cost, a small volume of transceiver hardware, a fast communication speed, and the ability to establish a medium distance connection (at the level of 10 m).

Working with RF signals for the proposed scenario can be an obstacle. In contrast, factors such as the cost-effectiveness of acoustic communication and the need for bulky transceivers may create disadvantages. But optical wireless communication has a cost-effective structure, small volume of transceiver equipment that can reduce energy consumption, fast communication speed, and ability to establish a medium-distance connection. Thus, it can be considered a viable solution for AUV to AUV and AUV to vessel communication.

This analysis showed that the simulated work is applicable in the future.

3.2. Grey Wolf Algorithm for Swarm Intelligence

In the applied scenario, each of the AUVs released from the fishing vessel is considered an individual with swarm intelligence. Grey wolf pack hunting behavior was chosen as swarm behavior. This is because it converges easier and faster in optimization problems [28]. It is assumed that the AUVs have the necessary sensor hardware to mimic the wolf pack hunting behavior.

Grey wolves are predators at the top of the food chain in nature. They live in groups of 5-12 wolves and have a strict leadership hierarchy among themselves, as shown in Figure 3 below. The first layer is the α layer, which is formed by male and female wolves with the highest leadership degree; they are responsible for decisions such as deciding to hunt, sleep, and get up. In the second layer, the β layer, individuals are responsible for helping other wolf pack members and other tasks. The third layer is the δ layer. Members of this layer are responsible for protecting the packing area, warning the wolf pack of any danger, and caring for injured pack members. The last layer of hierarchy is ω, whose members must submit to all other wolf pack members [21,29].

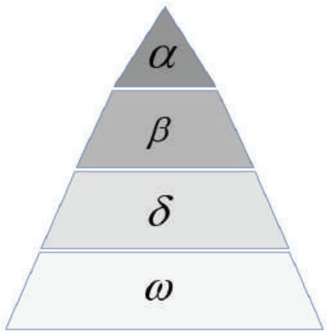

Figure 3. *Hierarchy of the grey wolves*

The hierarchical model mentioned acts a crucial role in the hunting behavior of the grey wolf pack. Primarily, grey wolves seek and track their prey. Then the α wolves direct the other wolves to surround the prey. After that, α wolves order the β and δ wolves to attack. When prey tends to flee, wolves that feed from the rear of the prey continue to attack and capture their prey. The behavior of grey wolves in this hunt has been mathematically modeled [21,29].

If the number of members of the grey wolf pack is K, the search area is d, and i^{th} wolf's position can be defined as: $P_i = (P_{i1}, P_{i2}, P_{i3}, \ldots, P_{id})$. According to the mathematical model, the best solution is considered the solution of the α wolves. The second and third best solutions are β and δ wolves, respectively. The remaining candidate solutions are the solution of ω wolves.

The mathematical model of grey wolves' siege behavior of prey is as follows (equations 1 and 2 as below):

$$\vec{D}=\left|\vec{C}.\vec{P}_p(t)-\vec{P}(t)\right| \tag{1}$$

$$\vec{P}_p(t+1) = \vec{P}_p(t) - \vec{A}.\vec{D} \tag{2}$$

Where t refers to the current iteration; $\vec{A}$ and $\vec{C}$ are the coefficient vectors; $\vec{P}_p$ is the position vector of the prey; $\vec{P}$ denotes the position vector of the wolf pack. The c oefficient vectors $\vec{A}$ and $\vec{C}$ can be calculated as follows (equations 3 and 4 as below):

$$\vec{A} = 2\vec{a}.\vec{r}_1 - \vec{a} \tag{3}$$

$$\vec{C} = 2.\vec{r}_2 \tag{4}$$

Where $\vec{r}_1$ and $\vec{r}_2$ are random vectors $\in [0,1]$; $\vec{a}$ is a linearly decreasing value from 2 to 0 depending on the iteration number and is calculated as follows (equation 5 as below):

$$\vec{a} = 2\left(1 - \frac{t}{T_{\max}}\right) \tag{5}$$

Where $T_{\max}$ denotes the determined maximum iteration number. After the wolf pack has caught the prey, the other wolves surround the prey at the command of the α wolf. Then the α, β, and δ wolves start to approach the prey, and their position with the prey is calculated. The mathematical model of this situation is defined in the equations below:

$$\vec{D}_\alpha = \left|\vec{C}_1.\vec{P}_\alpha - \vec{P}\right| \tag{6}$$

$$\vec{D}_\beta = \left|\vec{C}_2.\vec{P}_\beta - \vec{P}\right| \tag{7}$$

$$\vec{D}_\delta = \left|\vec{C}_3.\vec{P}_\delta - \vec{P}\right| \tag{8}$$

$$\vec{P}_1 = \vec{P}_\alpha - \vec{A}_1.(\vec{D}_\alpha) \tag{9}$$

$$\vec{P}_2 = \vec{P}_\beta - \vec{A}_2.(\vec{D}_\beta) \tag{10}$$

$$\vec{P}_3 = \vec{P}_\delta - \vec{A}_3.(\vec{D}_\delta) \tag{11}$$

$$\vec{P}(t+1) = \frac{\vec{P}_1 + \vec{P}_2 + \vec{P}_3}{3} \tag{12}$$

$\vec{P}_1, \vec{P}_2, \vec{P}_3$ positions of the α, β, and δ wolves can be calculated using equations (6-11). Then next position of the wolf pack $\vec{P}(t+1)$ is obtained by averaging, as shown in equation (12). Pseudo codes of the grey wolf algorithm can be seen in Algorithm 1.

In terms of applicability, to transfer swarm intelligence to individuals, each individual must be able to determine the distance between itself and the other individuals as well as the distance between itself and the school of fish. For the distance detection process between individuals, Underwater Optical Wireless Communication can be used for AUV2AUV communication, considering the underwater optical channel model [25,30]. Conversely, SONAR, image processing, and deep learning techniques can detect the fish school, including the distance between the fish school and AUVs. After these hardware features are equipped for individuals, the relevant algorithms with swarm intelligence are transferred to the individuals, and an artificial grey wolf pack that acts with swarm intelligence is obtained. In optimization problems, the best result is searched until a maximum number of iterations is reached. In the applied scenario, the best result is to provide the desired and predetermined distance of individuals to the school of fish. Therefore, the best distance is constantly updated during the search process to reach the desired value.

Algorithm 1. Grey Wolf Algorithm [21]

Initialize: TheP i (i = 1 ,2, ...,K)grey wolf population P i (i = 1 ,2, ...,K)
Initialize: a, A, t=0, and C
Calculate the fitness of each search agent
X_α=the best search agent
X_β=the second best search agent
X_δ=the third best search agent
While (t<MaxIteration) do
For each search agent
Calculate the position of the current search agent by using Equation (12)
end for
Update the a, A, and C
Calculate the fitness of all search agents
Update the Xα , Xβ and Xδ
t= t+1
end while
Return Xα

3.3. Assumptions, Constraints, and Conditions for Simulation Domain

While various parameter values were selected in the simulation studies, other scientific studies were referenced, and some assumptions, rules, and constraints were created for the applied scenarios.

The simulation environment created for the scenarios assumes that the search and scanning activity is carried out in an area of 20x20 NM^2. The movement of the fish school and the fishing vessel within this area is allowed in the applied scenarios. The speed of fishing vessel was determined as 14.2 knots [31], and horse mackerel was taken into account for the speed of the school. The maximum speed of a horse mackerel is about 6 m/s [22]. In the simulation studies, the school speed was accepted as 6 m/s. Two scenarios were used in simulations. The first scenario is the fishing vessel surveying the school of fish in the designated area, and the second is the proposed approach. However, in the simulations, a search upper limit has been set for the fishing vessel; if the fishing vessel cannot find a school of fish within 100 NM, the search for fish for that voyage is terminated. This was referred to as a failed voyage because any search activity beyond the specified limit would be illogical and inefficient.

4. Simulation Studies and Results

Simulation studies are performed using MATLAB® and a computer with Intel® Core™ i7-6500U CPU @ 2.5 GHz and 8 GB RAM. In the study for the first scenario, the effective SONAR distance of the fishing vessel was determined as 800 m [10]. The fishing vessel is assumed to maneuver by randomly changing one direction at 0.5, 1, 2, and 5 NM, and the fish shoal is assumed to maneuver by randomly changing one direction at 0.15, 0.3, 0.6, and 1.5 NM, respectively. Running the scenario 5000 times yielded the average distance values of the fishing vessel until it found the fish school, including the histograms it produced. Figure 4 depicts the simulations run.

The Figure 4 shows the random displacement behavior of the fishing vessel and the school of fish and the point at which the vessel detects the school of fish. Some movements change direction randomly at 5 NM intervals of the fishing vessel and 1.5 NM intervals of the school. It is seen that the two elements encounter each other under the radar distance determined as 0.43 NM within the defined area.

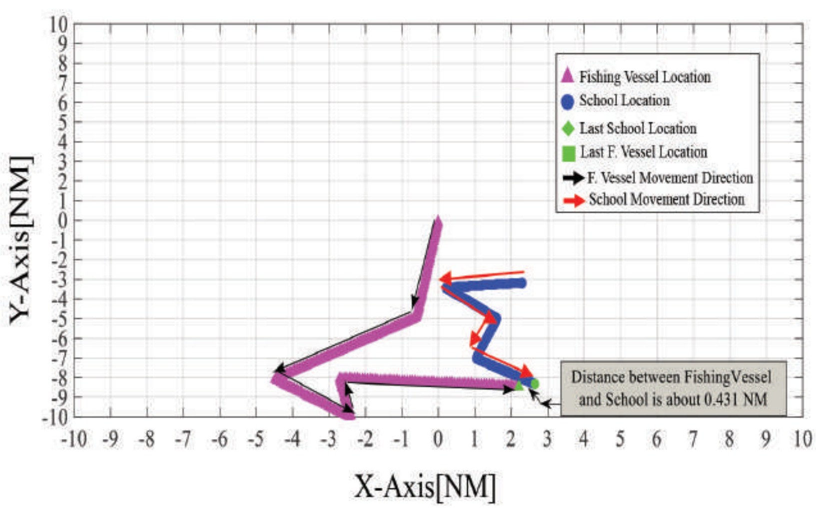

***Figure 4.** One of the performed simulations belongs to 1st scenario*

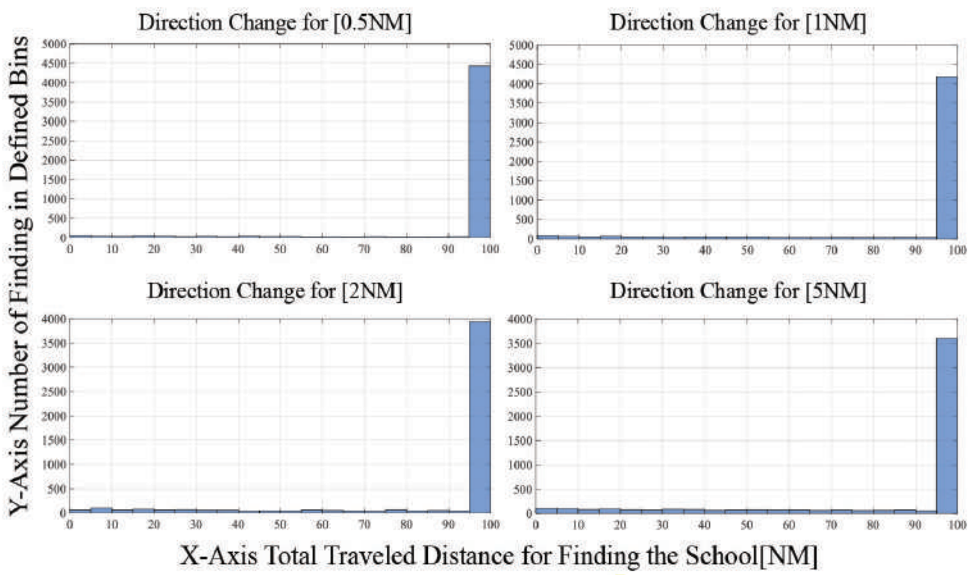

Figure 5. *Histograms for different direction change range in the 1st scenario*

Figure 5 depicts the histograms of the results obtained from 5000 runs for the case where the fishing vessel maneuvers at 0.5, 1, 2, and 5 NM and the school at 0.15, 0.3, 0.6, and 1.5 NM, respectively, by changing direction. When the histograms are examined, there is clear clustering in the 80-100 NM range for each random change of direction distance, indicating that similar results were obtained in most of the simulations run on each graph. The main reason for clustering 80-100 NM is that a certain NM constraint is given to the simulation. The search has been called off if a school of fish is not found after 100 NM of exploration. Table 1 presents the number of the successful voyage and giving up of the school within the determined distance constraint (100 NM) as a result of 5000 runs for each random change of direction distance.

Table 1. *School finding distances under different change of direction range for 1st scenario*

Direction changing range of fishing vessel (FV) and school	Average finding distance [NM]	Number of giving up	Number of successful voyages	Success rate [%]
FV (5NM), School (1.5NM)	84.62	3542	1458	29.16
FV (2NM), School (0.6NM)	88.08	3899	1101	22.02
FV (1NM), School (0.3NM)	90.21	4156	844	16.88
FV (0.5NM), School (0.15NM)	93.16	4410	580	11.60

According to Table 1, as the distance to change direction decreases, the number of successful voyages decreases, and the average distance traveled increases. While evaluating the conventional method, the best result obtained with this method was considered, i.e., it was assumed that the fishing vessel traveled an average of 84.62 NM at a time. Therefore, under the determined constraint, the success rate of the conventional method is 29.16%.

The second scenario, i.e., the primary proposed method in this study, is detecting school through AUVs. Like the first scenario, this scenario is modeled in the MATLAB® environment. The number of individuals is selected between 5 and 12 in the Grey Wolf Algorithm. In this simulation, the number of individuals was kept to a minimum in terms of cost-effectiveness and was determined as 5. The search space boundaries, school speed, and the number of simulation runs remain unchanged from the first scenario.

In the second scenario, in any running process, the voyage is considered unsuccessful if any of the AUV individuals perform a search activity over 100 NM. After the unsuccessful voyage number is obtained, it is subtracted from the total number of runs, and the successful voyage number is calculated. Figure 6 presents the results of four different successful sample search activities based on simulation studies. It was initially assumed that an average school of fish moves at a speed of 6 m/s. The swarm intelligence approach designed for AUV individuals was revised under this condition, $\vec{a}$ expressed in equation (5). In optimization problems, $\vec{a}$ value is a number decreasing from 2 to 0 as the number of iterations increases. But in a real application, the iteration number makes no sense. Therefore, the fitness

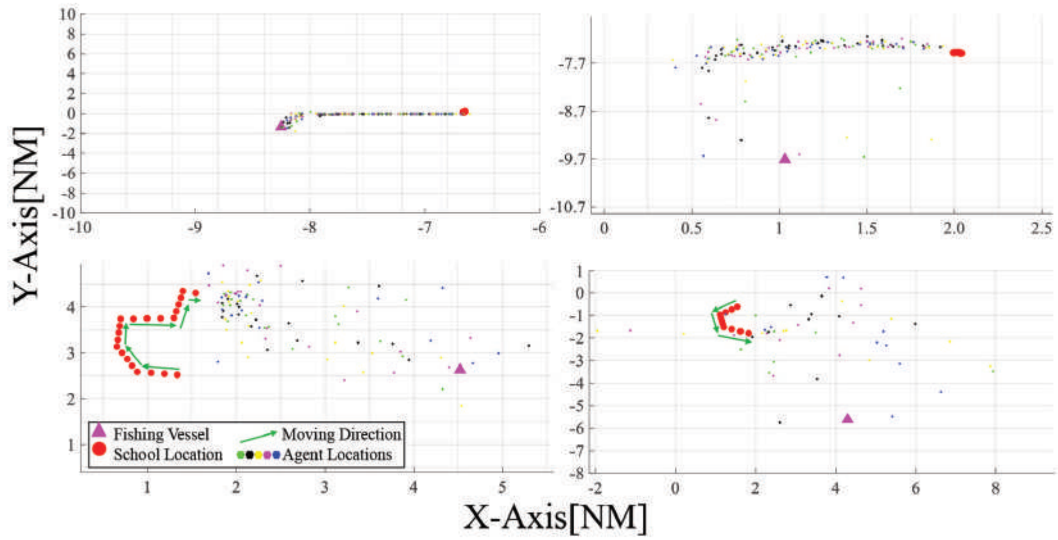

Figure 6. *Some of the performed simulations belong to 2nd scenario*

value should be related to a real parameter. In the applied scenario, fitness value is associated with the distance value of all AUVs to the target (school) and distances with each other in a cyclical process. Distances between AUVs are estimated through communication, whereas SONAR estimates distances to the school. In this study the $\vec{a}$ value was obtained, as shown in equation (13). As seen from the equation, the $\vec{a}$ value decreases as it gets closer to target.

$$\vec{a} = |\text{fitness} - \psi| \quad (13)$$

The fitness value mentioned in the above equation is the distance of the i^{th} individual from the target. ψ is a coefficient, which was determined as 3750. Modeling experience and search space dimensions are important factors when determining this coefficient. The performances obtained in the experiments while determining the ψ coefficient are shown in the graphic below (Figure 7).

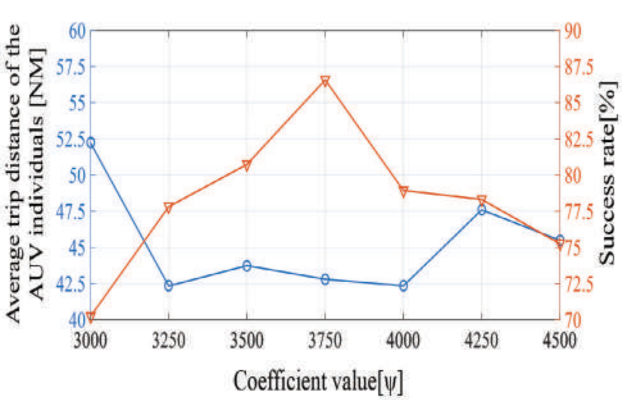

Figure 7. *Success rates and average trip distances under different* ψ *values*

In this study, a success rate of 86.58% and an average distance of 42.81 NM AUV per individual were found at ψ = 3750, as performed to determine the optimal value. This obtained value was used in the simulation studies. Figure 8 depicts the distance-number of success histograms for 5 AUV individuals resulting from 5000 runs for the determined ψ value. The density at 100 NM bin in the obtained histograms is due to the 100 NM maximum search constraint determined in the studies.

From the histograms, AUVs find the school of fish in the 25-50 NM band with a considerable rate. The simulation results are obtained by accepting the school speed as 6 m/s. Table 2 shows the performances obtained at different school speeds due to 5000 runs.

Table 2. *Performances in different school fish speeds*

School speed [m/s]	Average AUV distance [NM]	Successful voyages	Unsuccessful voyages	Success rate [%]
2	49.28	3554	1446	71.08
3	43.95	3894	1106	77.88
4	47.68	3897	1103	77.94
5	47.81	3817	1183	76.34
6	42.81	4329	671	86.58
7	44.9	4272	728	85.44
8	49.92	3940	1060	78.8
9	47.52	3917	1083	78.34
10	46.88	4088	912	81.67

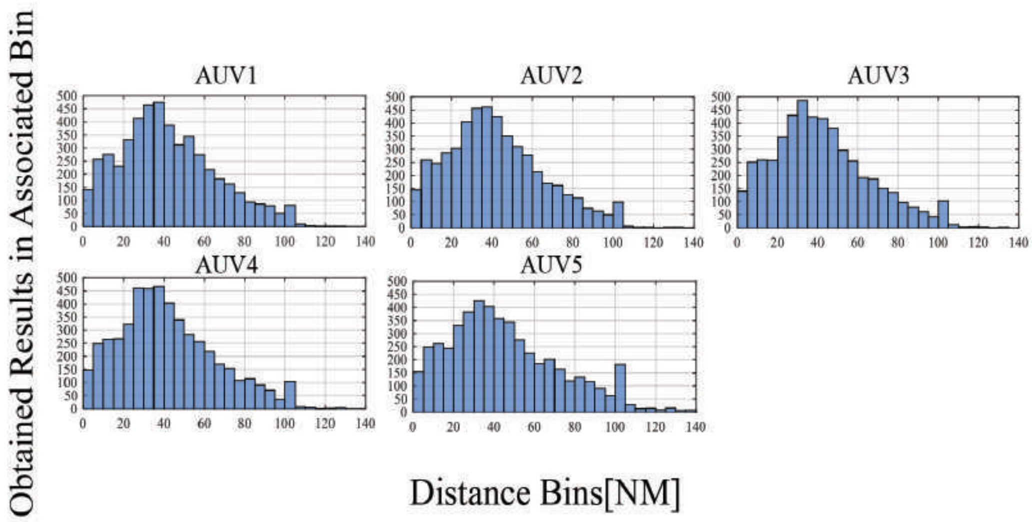

Figure 8. *Distance-number of success histograms of each AUV individual (for 5000 runs)*

AUV: Autonomous underwater vehicle

When the table is examined, the success rate at 2-10 m/s school speeds is between 71.08 and 86.58%. AUVs travel the average distance varied between 42.81 and 49.92 NM. These results show that it can be used for school at speeds of 2-10 m/s. Furthermore, as technology advances, the speed and maneuverability of AUVs will undoubtedly increase, enhancing their success rates.

5. Conclusions and Recommendations

When the simulation studies and results are examined, it is found that a fishing vessel that performs fish exploration activities using the conventional method has a success rate of 29.4% in 5000 voyages and has covered an average of 84.62 NM. This means that the conventional method has a low success rate. Conversely, the fishing vessel traveled 423,100 NM in 5000 voyages. Since this situation increases fuel consumption, product prices will rise. And, long-distance travel will naturally increase carbon emissions and cause environmental pollution.

In the proposed method, 86.58% success was achieved in 5000 voyages in the simulations, and AUV individuals traveled an average of 42.81 NM. In these simulation results, the average covered distance is 9.82 NM since the fishing vessel moves only from the point where its initial position to the school point that the AUVs have found. Therefore, considering 5000 voyages, the total covered distance is about 49,100 NM. As can be seen, the success rate increases 2.94 times, while the distance traveled decreases by 8.61 times. Also, the distances covered by AUVs appear to be within the range they can travel with a full charge. Considering that these distances and AUV speeds will increase with the advancing technology, the proposed approach is a suitable solution. AUVs can meet their energy needs through energy harvesting methods such as PV panels, small wind turbines mounted on the fishing vessel, or fusions, allowing AUVs to be charged on a fishing vessel. Consequently, the results of the simulation studies and the applicability of the proposed method clearly show that this approach can be used in the future. Moreover, the proposed approach can be used in applications such as military infiltration and submarine operations, with minor modifications and the destruction of enemy units.

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A Multi-objective Optimization Model for Determining the Performance of a Sailboat

Mustafa Kafalı[1], Erhan Aksu[2]

[1]İzmir Katip Çelebi University, Department of Naval Architecture and Marine Engineering, İzmir, Türkiye
[2]Karadeniz Technical University, Department of Naval Architecture and Marine Engineering, Trabzon, Türkiye

Abstract

The current research is focused on determining the optimum true wind angle (TWA or β_{TW}). A model is developed to calculate the wind angle at which a sailboat's optimum performance can be achieved. First, the equations for the hull speed, velocity made good (VMG), and the heel angle are determined through the regression analysis by using the data produced by the velocity prediction program analysis. The equations are written for true wind velocities (V_{TW}), with the independent variable being TWA. Later, a multiobjective optimization model is developed, and the wind angles providing the maximum benefit at the respective wind velocities are determined. The goal of the model is to maximize the hull speed and VMG while minimizing the heel angle. The simulated annealing algorithm is employed. Consequently, TWAs providing the optimum performance of a specific sailboat at various wind velocities are calculated.

Keywords: Sailboat, VPP, Performance determination, Optimization, Simulated annealing

1. Introduction

Throughout history, societies have given importance to maritime transport to increase their commercial activities and become richer and more powerful. In this context, freight and passenger transportation between long distances using sailing ships has gained much importance. Owing to technological developments, the uses of sailing ships have turned more toward marine tourism and sporting activities. Motorized or nonmotorized sailboats are used in sports activities to determine the performance of athletes and sailboat. Consequent to economic developments, sailboats with a comfortable interior and a high performance, which can be safe and fast in all weather conditions, are produced.

As in other naval vessels, many scientific studies are conducted on the optimization of the sailboats. These studies are mainly concerned with finding the best route by maximizing the boat speed while minimizing voyage time, as well as determining the optimal shapes and sizes of the boat and the rig.

In this context, if we look at the route optimization problems on sailboats, Wiersma [1] optimized the thrust force contributing to the yacht speed under certain constraints on the lateral force and heeling moment. Day [2] used the computational aerodynamic and hydrodynamic efficiency prediction synthesis to develop methods for estimating the lifting distribution for maximal hull speed. Sugimoto [3] suggested a method for optimum sail strategy, which also performed sail optimization for the maximum yacht speed, was useful in improving the optimum sail design and controlling the optimal sail strategy. Philpott and Mason [4] devised a technique for estimating the minimum-time routes in an uncertain weather. Mairs [5] investigated the flow regimes of two sails experimentally and numerically at different wind angles in his study in which he created an aerodynamic-structural model of windless yacht sails to predict the sail forces. In a separate article, Philpott [6] addressed the use of stochastic optimization methodologies in high-performance yacht racing. Ferguson and Elinas [7] conducted studies on how to reliably determine the best

Address for Correspondence: Mustafa Kafalı, İzmir Katip Çelebi University, Department of Naval Architecture and Marine Engineering, İzmir, Türkiye
E-mail: mustafa.kafali@ikcu.edu.tr
ORCID ID: orcid.org/0000-0002-8077-1686

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routes for gaining an advantage in coastal sailing races. Xiao et al. [8] reported that despite the changing wind conditions, the extreme seeker, which maximizes hull speed by changing the sail angle, can pursue the optimum speed of the sailboat on different routes. Tagliaferri et al. [9] stated that they could calculate the minimum estimated time required to reach the opposite direction of the wind by presenting a method for solving the stochastic shortest path problem in races. Dalang et al. [10] proposed mathematical sailboat racing methods that used the statistical analysis of wind disturbance and were useful for the stochastic optimization methods. Tagliaferri and Viola [11] presented an optimal strategy in sailboat racing to complete the race in the minimum expected time. Ferretti and Festa [12] showed that the hybrid control method can be used to plan sailboat routes in the shortest possible time. Sarı and Aydın [13] investigations on the sailing yachts aimed to establish the ideal sailing parameter dimensions and forecast performance values for the given sail and boat. Kemali et al. [14] utilized computational fluid dynamics to examine the impact of the leading-edge tubercles of the wing-type sails used in the 2013 America's Cup.

In this study, a multiobjective optimization problem is defined to maximize the speed of a boat over ground and the VMG, and to minimize the angle of inclination. The true wind angles (TWAs) exhibiting the best performance at different wind velocities have been determined.

2. Materials and Methods

A hierarchic model combining VPP and multi objective optimization is built in this study (Figure 1).

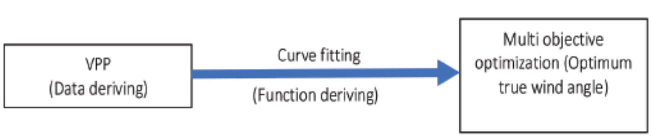

Figure 1. *The model used to determine optimum TWAs*

Sailing boat speed can be estimated using VPP, based on the balance of forces and moments acting on a sailboat. In the first step, a sailboat is analyzed to generate data using the Bentley Systems' VPP software (www.bentley.com). In the second step, a regression analysis is performed to find the fitted equation for each function based on the data generated in the previous step. The third step involves obtaining optimum TWAs according to the defined objective functions. Information on all steps is given in the following subsections.

2.1. Description of the Sailboat

In various sizes and sail configurations, sailboats that move by using wind power are produced. The sailboat in the application is a Bentley Systems VPP software sample design. The sailboat (Figure 2) consists of a mainsail that catches a large part of the wind and provides the required propulsion, a headsail that increases the air flow by steering the wind to the front of the mainsail, a spinnaker, which is a downwind sail that balloons to increase the boat's efficiency, and a keel for hydrostatic resistance that allows the sailboat to navigate upwind and provides some stability by lowering the center of the gravity of the boat. The dimensions and the sailing equipment of the sailboat are listed in Table 1.

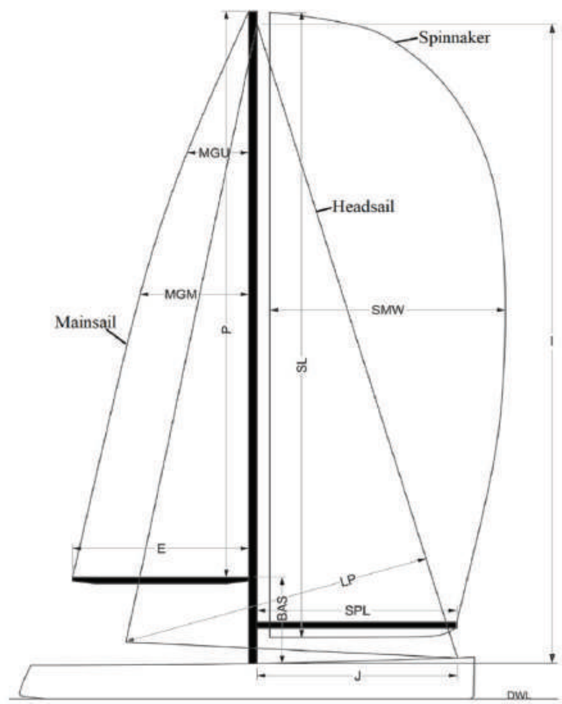

Figure 2. *Sailboat with three sails [15]*

2.2. Deriving Data for Optimization

To obtain equations for hull speed, heel angle, and VMG, data generated by using Bentley Systems VPP software. MAXSURF VPP is a widely used software for predicting the sailboat's performance. By resolving the lift and drag equations for the hull and the rig, it determines the equilibrium velocity and the heel angle. The sample design and measurement data in its library is used. This study deals with true wind velocity and angle as the input, and with hull speed, heel angle, and VMG as the output. In this regard, six true wind velocities are determined to reflect low, medium, and high wind force. The parameters used in the optimization are shown in Figure 3.

Table 1. *Dimensions of hull and the sail [15]*

HULL				MAINSAIL	
Length W.L.	10.36 m			The luff length of the mainsail (P)	14.783 m
Beam W.L.	2.508 m			The foot length of the mainsail (E)	4.203 m
Draft	2.44 m			The upper girth length of the mainsail (MGU)	1.554 m
Displaced volume	4.013 m^3			The middle girth length of the mainsail (MGM)	2.743 m
Block coeff.	0.059			Length of the lower mainsail luff band (BAS)	2.102 m
Prismatic coeff.	0.484			**HEADSAIL**	
Max. sec. area coeff.	0.129			The distance measured between the sheer line and the top of the foretriangle (I)	16.605 m
Waterplane area coeff.	0.702			Distance between the headstay base and front of the mast (J)	4.849 m
KEEL DIMENSIONS				Perpendicular distance from the headsail clue to the luff (LP)	7.602 m
	Length	Beam	Depth	**SPINNAKER**	
Bulb: NACA 65-015	1.6 m	0.286 m	0.25 m	Pole length of the spinnaker (SPL)	4.871 m
Bulb keel: NACA 64-010	0.746 m	0.068 m	2.2 m	Luff length of the spinnaker (SL)	16.002 m
Ballast ratio: 0.45				Maximum width of the spinnaker (SMW)	8.778 m

For each true wind velocity, upwind and downwind situations are calculated at certain TWAs (Table 2). As an example, the calculated data in the upwind sail for a 6-knot (kn) true wind velocity is given in Table 3. Here, VMG represents the speed component in the reverse wind direction. When the wind is blowing at an angle of over 90 degrees and is coming from behind the rig, VPP yields negative VMG values. The Reef factor is constantly set to 1 in the calculations. Figure 4 shows the polar plots for the VPP results.

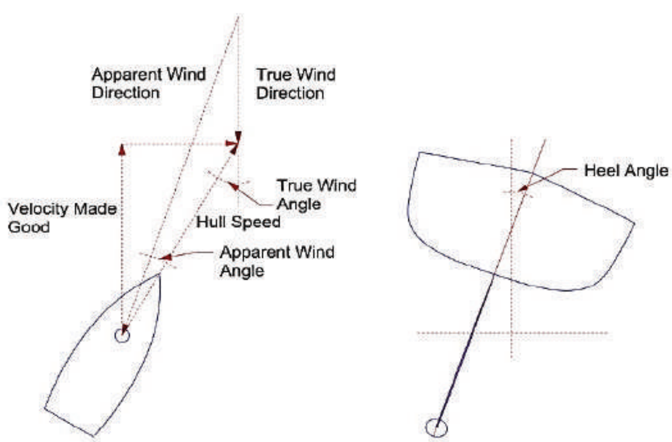

Figure 3. *Concepts employed in the optimization model*

2.3. Optimization Model

The optimization model is concentrating to determine the optimum TWAs. In this regard, two main scenarios are considered: downwind and upwind. Two functions are included in the downwind case, i.e., the "hull speed" and "heel angle." Both depend on TWA at a certain true wind velocity. Conversely, in the upwind case, one more function is added, i.e., VMG. Thus, there are three functions in the upwind situation: "hull speed," "heel angle," and "VMG." These functions vary with TWA at a given true wind velocity, as in a downwind situation.

Regression analysis is used to derive the hull speed, heel angle, and VMG functions. These functions are used in the multi objective optimization. In both cases, six different true wind velocities are considered. VMG is not included in the

Table 2. *The input, output, true wind velocity, and TWA values in both situations*

Sail course	Input		Output
Upwind	True wind velocity (V_{TW}) (kn)	6, 10, 14, 18, 22, 26	Hull speed Heel angle VMG
	TWA (β_{TW}) (deg)	35, 38, 41, 44, 47, 50, 53, 56, 59, 62, 65, 68, 71, 74, 77, 80, 83, 86, 89, 92, 95, 98, 101, 104, 107, 110	
Downwind	True wind velocity (V_{TW}) (kn)	6, 10, 14, 18, 22, 26	Hull speed Heel angle
	TWA (β_{TW}) (deg)	80, 83, 86, 89, 92, 95, 98, 101, 104, 107, 110, 113, 116, 120, 123, 126, 129, 132, 135, 138, 141, 144, 147, 150, 153, 156, 159, 162, 165, 168, 171, 174, 177, 180	

Table 3. *VPP results for a 6-kn true wind velocity in the upwind sail*

β_{TW} deg	35	38	41	44	47	50	53	56	59	62	65	68	71
Hull speed kn	4.6	4.93	5.23	5.51	5.76	6	6.21	6.39	6.54	6.68	6.79	6.89	6.98
VMG kn	3.76	3.89	3.95	3.96	3.93	3.86	3.74	3.57	3.37	3.13	2.87	2.58	2.27
Heel angle deg	13.26	14.85	16.08	17.01	17.74	18.31	18.76	19.12	19.43	19.69	19.9	20.06	20.18
β_{TW}deg	**74**	**77**	**80**	**83**	**86**	**89**	**92**	**95**	**98**	**101**	**104**	**107**	**110**
Hull speed kn	7.05	7.12	7.18	7.22	7.24	7.24	7.23	7.2	7.16	7.1	7.03	6.93	6.81
VMG kn	1.94	1.6	1.25	0.88	0.5	0.13	−0.25	−0.63	−1	−1.36	−1.7	−2.03	−2.33
Heel angle deg	20.27	20.33	19.34	17.36	15.51	13.77	12.12	10.54	9.02	7.55	6.12	5.13	4.49

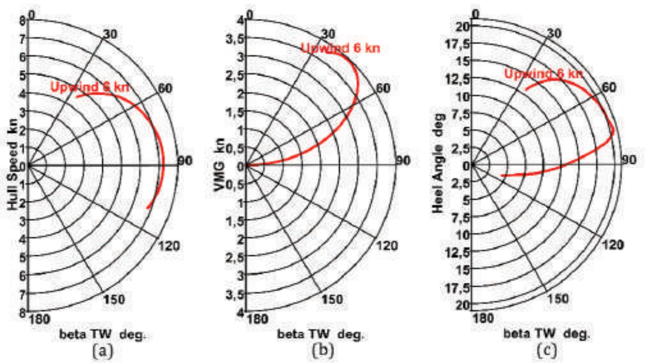

Figure 4. *Polar plots for the VPP results (a) Hull speed; (b) VMG; (c) Heel angle*

downwind situation as it takes negative values for multiple TWAs and is therefore, not included in the optimization model (Table 4).

Table 4. *Parameters for the upwind and downwind cases*

Upwind situation		Downwind situation	
Function	Independent variable	Function	Independent variable
Hull speed Heel angle VMG	TWA (β_{TW})	Hull speed Heel angle	TWA (β_{TW})

Following the formulation of functions, a multi objective optimization model is constructed for both situations. There are two objective functions in the downwind situation and three objective functions in the upwind situation. By using the weighted-sum method, both models are converted into a single objective optimization, and the simulated annealing (SA) algorithm is used to determine the optimal solutions. SA has been introduced by Kirkpatrick et al. [16] and Černý [17]. This algorithm is a probabilistic search technique and was developed inspired by the annealing process in metalworking. A heuristic mechanism is specified in the SA algorithm to avoid sticking to the local optimum. This heuristic mechanism works by performing a random search that accepts the neighboring solutions improving the objective function, but also some of those not improving the objective function [18].

Probability of acceptance is calculated using equation 1 where ΔE is the difference between the calculated value of the objective function according to the neighbor solution and its current value [19].

$$P(\Delta E, T) = e^{-\frac{f(s')-f(s)}{T}} \tag{1}$$

The acceptance probability is compared to a random number generated between 0 and 1. If $P(\Delta E, T)$ is greater than the generated random number, the neighboring solution that does not improve the objective function is accepted [20]. The occasional acceptance of the neighboring solutions, worsening the objective function value, frees the SA algorithm from being stuck with the local optimum. Bad solutions are more likely to be accepted at higher temperatures, i.e., early in the search [19].

2.3.1. Multi Objective Optimization

In the weighted sum method, objective functions are weighted and aggregated. For the downwind (2) and upwind (3) situations, optimization models are given below:

$$\begin{aligned} min\left(\bar{F}_{dw}\right) &= w_1\bar{f}_1(x) + w_2\bar{f}_2(x) \\ w_1 + w_2 &= 1 \end{aligned} \tag{2}$$

$$\begin{aligned} min\left(\bar{F}_{uw}\right) &= w_1\bar{f}_1(x) + w_2\bar{f}_2(x) + w_3\bar{f}_3(x) \\ w_1 + w_2 + w_3 &= 1 \end{aligned} \tag{3}$$

where, the subscripts *dw* and *uw* stand for the downwind and upwind situations, respectively. $\bar{f}_i$ denotes the normalized function. $\bar{f}_i(x)$ is calculated by equation 4 [21]. w_i represents the weight of the objective function. Since w_i is so important in the weighted sum method, several w_i combinations are considered in this study. More information on the w_i values can be gathered from the findings and discussions section. Functions depend on the TWA and velocity. However, as mentioned before, six true wind velocities are examined separately so that at a certain true wind velocity, each function depends on TWA only. Hence, *x* in the equations above stands for TWA.

$$\bar{f}_i(x) = \frac{f_i(x) - f_{i,min}(x)}{f_{i,max}(x) - f_{i,min}(x)} \quad (4)$$

In the equations (2), (3), and (4), the indices stand for a function mentioned in Table 5.

***Table 5.** Subscripts and their meanings*

Subscript (i)	Meaning
1	Hull speed
2	Heel angle
3	VMG

As seen in the optimization model, the aggregated function is minimized. However, the hull speed and VMG must be maximized. To accomplish that goal, the hull speed function is converted to its inverse form. Let us assume that the hull speed function is $f'_1(x)$, then $f_1(x) = \frac{1}{f'_1(x)}$. In the upwind case, VMG takes a negative value for certain TWAs; thus, the same principle does not apply here. To address this issue, a value greater than the maximum of VMG data is identified, and the difference between the two is computed. Say, VMG function is $f'_3(x)$, then $f_3(x) = M - f'_3(x)$. Here M stands for the big value.

3. Findings and Discussions

Determination of the weights (w_i) of the objective functions is quite crucial in the weighted sum method. Therefore, in this study, the model is analyzed for several weight combinations. The weights are raised or reduced at the intervals of 0.25 for convenience. The optimization model gives a different solution for each weight combination. These results represent a variety of cases that could be optimal for various scenarios. The detailed findings for both the upwind and downwind sails are given and discussed in the following subsections.

3.1. Downwind Course

It is possible to show all weight combinations in a single graph for this condition. The results obtained for the downwind condition are reflected in Figure 5. w_1 and w_2 represent the weight of the optimization parameters. $w_1 = 1$ and $w_2 = 0$ mean the importance of the hull speed equals 1, and that of the heel angle equals 0 in the optimization. The term "importance" refers to the impact of the related factor on the optimization. Accordingly, the "$w_1 = 1$; $w_2 = 0$" and

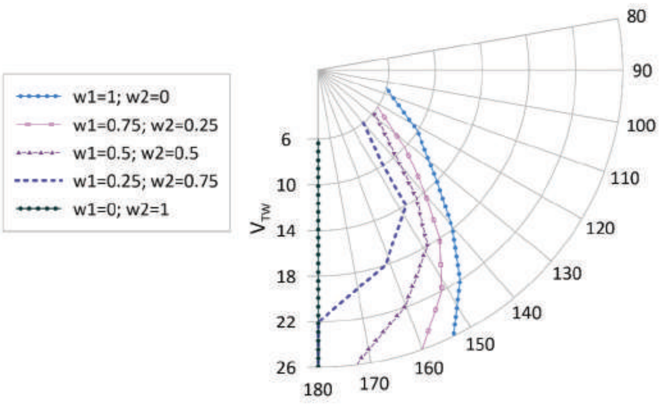

***Figure 5.** Optimization results for optimum β_{TW} at the downwind course*

"$w_1 = 0$; $w_2 = 1$" weight combinations represent the single objective cases for the maximum hull speed and the minimum heel angle, respectively. As expected, the optimal β_{TW} (TWA) for the minimum heel angle is high and equal to 180 degrees. Meanwhile, the optimal β_{TW} varies according to the V_{TW} (true wind velocity) for the maximum hull speed. The optimum angle is also relatively low at low V_{TW}s and stays below 135 degrees. The optimal β_{TW} shifts toward 150 degrees as the V_{TW} increases.

Other weight combinations depict the multiobjective scenarios. When we look closely, we see that when the importance of the heel angle rises, so does the value of optimum β_{TW}. This increase is more restricted at lower V_{TW} s and more apparent at higher V_{TW}s such that when V_{TW} is over 22 knots, β_{TW} equals 180 degrees. Generally, from low to medium V_{TW}s, the optimum β_{TW} ranges from 120 to 150 degrees. Conversely, from medium to high V_{TW}s, the optimum β_{TW} ranges from 140 to over 170 degrees. Apparently, a set of intersection angles exists for both states. In addition, at the extreme ends of V_{TW}, optimum β_{TW} comes closer to single objective optimum solutions. Notably, no optimum β_{TW} between 110 and over 140 degrees has been determined from medium to high V_{TW}s. Similarly, no optimum β_{TW} between 150 and 180 degrees has been detected from low to medium V_{TW}s, except the single objective condition of the heel angle. Generally, it can be claimed that if the heel angle is much more important, β_{TW} should be high. Conversely, if the hull speed is much more important, β_{TW} should be relatively low.

3.2. Upwind Course

In this case, three objective functions are considered. The results of multiple weight combinations are presented in separate graphics. w_1, w_2, and w_3 are the parameter weights. Accordingly, w_1 stands for the weight of the hull speed, w_2 stands for the weight of the heel angle, and w_3 stands for the weight of the VMG in the optimization. In Figure 6, the curve belongs to the "w_1 = 0; w_2 = 1; w_3 = 0" combination, intersects the 10-knot radius at the two points because of a sudden change in the optimum β_{TW} and the structure of the polar graph. However, the first intersection must be considered since only one optimum β_{TW} value has been calculated for each V_{TW}. The same issue exists in some subsequent cases, and the same explanation applies to them.

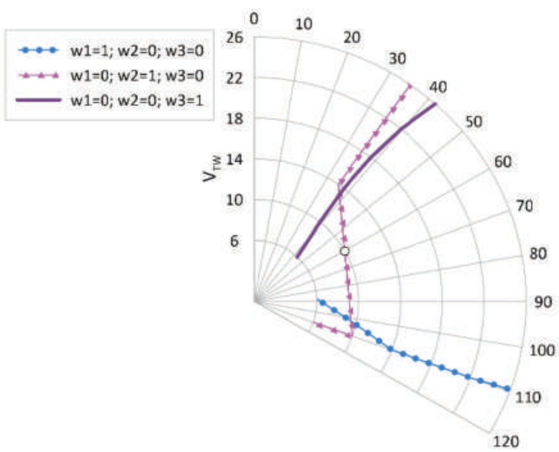

Figure 6. *Single objective optimization results for optimum β_{TW} at the upwind course*

A close examination of Figure 6 reveals that the optimum β_{TW} changes between 90 and 110 degrees only for the maximum hull speed. At the lower V_{TW}s, it is close to 90 degrees, while being close to 110 degrees at medium and high V_{TW}s. When only the heel angle is considered, optimum β_{TW} varies in an interesting way. While the optimum β_{TW} is 110 degrees at lower V_{TW}s, it suddenly changes to 35 degrees at the medium and high V_{TW}s. Because of the sudden change, the curve in Figure 6 intersects the 10-knot radius at the two points. However, only the first intersection is valid. The other intersection occurs because of the polar graph's structure. When VMG is considered solely, the optimum β_{TW} has a consistent behavior and varies around 40 degrees at all V_{TW}s.

Figure 7 represents the biobjective cases. The first graph (Figure 7a) exhibits the case where the weight of the hull speed is zero. Therefore, it reflects the change in the optimum β_{TW} for different weight combinations of the heel angle and VMG. Accordingly, when the importance of the heel angle is high, optimum β_{TW} exhibits similar attitude with a single objective case that only the heel angle has been considered. Hence, at lower V_{TW}s, the optimum β_{TW} is 110 degrees. At the medium and high V_{TW}s, the optimum β_{TW} is 35 degrees. When the importance of the heel angle and VMG is equal, the behavior of the change of the optimum β_{TW} is similar (except 6 knots) to that in the single objective case where only the heel angle is considered. When the case wherein the weight of the VMG is much more important than the heel angle is considered, the optimum β_{TW} displays stability and varies around 35 degrees at all V_{TW}s.

The second graph (Figure 7b) exhibits the case where the weight of the heel angle is zero. Therefore, it reflects the change in the optimum β_{TW} for different weight combinations of the hull speed and VMG. Accordingly, when the importance of the hull speed is high, the optimum β_{TW} changes between 70 and 100 degrees at lower V_{TW}s. At the medium and high V_{TW}s, the optimum β_{TW} exhibits a more stable character, and the optimum β_{TW} changes between 85 and 90 degrees approximately. When the importance of the hull speed and VMG is equal, the optimum β_{TW} displays a stable form and varies around 60 degrees at all V_{TW}s. Considering that VMG is significantly more important than the hull speed, the optimum β_{TW} displays a stable character and varies around 50 degrees at all V_{TW}s.

The third graph (Figure 7c) signifies that the weight of VMG is zero. Therefore, it reflects the change in the optimum β_{TW} for different weight combinations of the hull speed and the heel angle. Accordingly, if the importance of the hull speed is higher than the heel angle, optimum β_{TW} changes between 100 and 110 degrees. At medium V_{TW}s, the optimum β_{TW} is close to 100 degrees, while it changes around 110 degrees at low and high V_{TW}s. When the importance of the hull speed and the heel angle is equal, the optimum β_{TW} changes a lot according to the V_{TW}. Hence, at low V_{TW}s, the optimum β_{TW} is steady and changes around 110 degrees. Meanwhile, at medium V_{TW}s, it changes between 40 and 85 degrees approximately. Therefore, under these circumstances, it exhibits a more unstable character. At higher V_{TW}s, it differs and draws a more stable character and changes around 80 degrees. When the weight of the heel angle is considerably more than the hull speed, the optimum β_{TW} displays a similar character with a single objective case that only heel angle has considered. Thus, while the optimum β_{TW} is 110 degrees at lower V_{TW}s, it suddenly changes to 35 degrees at medium and high V_{TW}s.

Figure 8 illustrates the triobjective cases. The conditions seen in this figure include all the objective functions. The red dotted curve indicates the condition in which the weight of the hull speed is slightly more than other factors of equal importance. Accordingly, at lower V_{TW}s, the optimum β_{TW} changes between 100 and 110 degrees. At medium V_{TW}s, it differs and draws a more unstable character and changes between 50 and 75 degrees. At high V_{TW}s, the optimum β_{TW} is

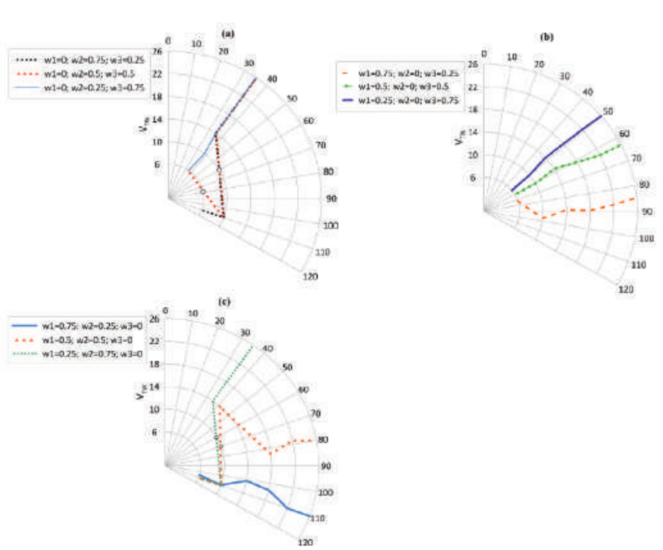

Figure 7. *Biobjective optimization results for optimum β_{TW} at the upwind course*

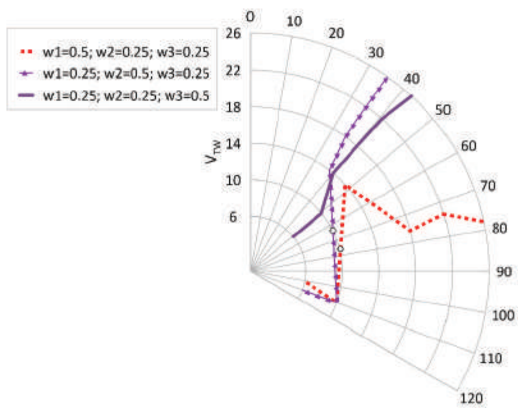

Figure 8. *Triobjective optimization results for optimum β_{TW} at the upwind course*

again more stable and changes around 75 degrees.

The purple triangle curve indicates the condition in which the weight of the heel angle is slightly more than other factors of equal importance. In this condition, the optimum β_{TW} exhibits a similar attitude with the single objective case where only the heel angle is considered. Hence, at lower V_{TW}s the optimum β_{TW} is 110 degrees. At medium and high V_{TW}s, the optimum β_{TW} is around 35 degrees.

The continuous curve indicates the condition in which VMG's weight is slightly more than other factors of equal importance. Accordingly, at lower V_{TW}s, the optimum β_{TW} is 50 degrees. At medium and high V_{TW}s, the optimum β_{TW} exhibits close resemblance with the single objective case where only VMG is considered. Consequently, it fluctuates around 40 degrees.

4. Conclusion

Sailboats are watercrafts that sail the oceans by using wind power. They come in a range of sizes and sail configurations. For sailboats to perform well, the optimum wind angle must be identified. Consequently, a model is constructed to calculate the TWAs at which a sailboat can achieve the best performance. A multiobjective optimization problem is also included in this model. At respective wind velocities, the TWAs that give the greatest benefit are calculated. In this research study, a particular sailboat is investigated. The model considers a variety of different weight combinations. The model's output represents a set of situations that may be suitable for different scenarios. The findings in the downwind and upwind scenarios are different. While the significance of the hull speed increases in the downwind case, the optimum β_{TW} moves from 180 degrees to lower values. Since three objective functions exist in the upwind case, it is a little more complicated. However, in the general terms, when the importance of the hull speed is high, optimum β_{TW} approaches higher values, i.e., toward 110 degrees. When the importance of VMG is high, optimum β_{TW} shifts to lower values, i.e., toward 40 degrees. When the importance of the heel angle is high, optimum β_{TW} varies according to the wind velocity. Thus, it shifts toward higher values, i.e., toward 110 degrees at the higher true wind velocities. In contrast, it shifts toward lower values, i.e., toward 35 degrees at lower true wind velocities.

In the future research, various types of sailboat hulls can be studied and compared. Moreover, different mainsails and jibs can be investigated for sailboat performance in optimization studies. Meanwhile, objective functions can be changed according to the desired goals. Additionally, the objective functions can be modified to meet specific targets. In this case, new outcomes could be appropriate to accomplish the expectations.

Authorship Contributions

Concept design: M. Kafalı, E. Aksu, Data Collection or Processing: M. Kafalı, E. Aksu, Analysis or Interpretation: M. Kafalı, E. Aksu, Literature Review: E. Aksu, Writing, Reviewing and Editing: M. Kafalı.

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Analytic Evaluation of Intellectual Capital for Ship Management Companies Under a Fuzzy Environment

Gizem Çevik, Özcan Arslan

İstanbul Technical University, Department of Maritime Transportation and Management Engineering, İstanbul, Türkiye

Abstract

To determine the market value of a ship management company, apart from its book value, it is necessary to also know its intellectual capital. The impact of this type of capital is evident, especially for ship management companies that are service-based. If these businesses follow the intellectual capital level and managers determine the necessary strategies based on this, these companies, which compete internationally beyond ensuring the continuity of their businesses, can stay one step ahead of their competitors. The purpose of this article is to provide an analytical perspective for ship management companies to evaluate their intellectual capital. In this context, the study adopts the analytical hierarchy process in the environment of fuzzy sets to increase sensitivity. Based on the analysis results, the most important intellectual capital elements for ship management companies are "human capital" as compared to "structural capital" and "relational capital" elements. As the key performance indicators applied for evaluation may differ according to enterprises, group performance indicators to be evaluated in the measurement of the elements were determined. The indicators related to human capital were more weighted than the others. This study guides not only the evaluation of the intellectual capital of ship management companies but also the determination of new strategies by managers for the development and valuation of companies.

Keywords: Intellectual capital, Valuation, Performance measurement, Fuzzy AHP, Ship management

1. Introduction

For the first time in 1969, John Kenneth Galbraith defended a thesis stating that intellectual capital is the entirety of intellectual activities [1]. Then, in 1975, Michael Kalecki used this term in a statement: "I wonder if you realize how much those of us the world around have owed to the intellectual capital you have provided over these past decades." "I wonder how many of us are conscious of the intellectual capital we have acquired over the past few decades?" The first scientific study on the concept is the book "Mobilizing Invisible Assets," written by Japanese scientist Hiroyuki Itami [2] in 1980 and translated into English in 1987.

The concept was used for the first time in an organizational sense in the article "Brainpower," written by Fortune Magazine Editor Thomas A. Stewart in 1991, with the expression "a hidden treasure to be discovered" and "the sum of everything that employees know, giving the business a competitive advantage in the market" [3]. Stewart [4] explained the concept of intellectual capital as "obtained useful knowledge" in his work titled "Intellectual Capital: The New Wealth of Organizations" published in 1997. He stated that intellectual capital includes data on customers and suppliers, organizational processes, information technologies, brands, patents, and employee knowledge-skills.

Thomas Stewart defines it more broadly than others: "Intellectual capital is all the intellectual materials that the business puts to use to create wealth, such as knowledge, information, intellectual property, skills, and experience of employees. Intellectual capital is the sum of all the assets in a company that are known to people and that gives the company a competitive advantage" [4].

Intellectual capital is generally the difference between a company's book value and what it is willing to pay for that value. It is a phenomenon that includes assets that are

Address for Correspondence: Gizem Çevik, İstanbul Technical University, Department of Maritime Transportation and Management Engineering, İstanbul, Türkiye
E-mail: cevikg@itu.edu.tr
ORCID ID: orcid.org/0000-0001-8736-8497

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not seen in balance sheets. To measure the unmeasured, knowledge draws attention as a concept used to determine the relationships between people and ideas with all its dimensions.

In sum, intellectual capital is the sum of invisible assets that cannot be fully obtained from a business balance sheet and is the main source of ensuring the permanence of the competitive advantage of enterprises. The management of the intellectual capital of an enterprise is an important managerial responsibility. The increase or decrease in intellectual capital can be called intellectual performance and can be measured and made visible. A systematic approach to measuring and making visible intellectual capital is becoming increasingly valuable regardless of the type, size, structure, owners, and geographic location of businesses [5].

While information-based economy measures strengthen their place in the world, the importance of intangible assets is increasing every day. The capitals related to these assets are examined under three main headings in the literature as human capital, investment (organizational) capital, and customer capital, and the resultant is intellectual capital [1,4,6,7]. Human capital includes employee competence, skills, brainpower, and tacit knowledge. Customer capital includes inputs on customer relationships, feedback, product/service, recommendation, experience, and tacit knowledge. A customer is broadly defined to include suppliers, distributors, and other players that can contribute to the value chain. Structural capital is organizational knowledge contained in databases, practices, know-hows, and cultures. It represents all organizational capabilities that enable it to respond and meet market needs and challenges.

This type of capital plays a more dominant role in the service sectors compared to enterprises operating in the production field. Maritime businesses are among service-intensive businesses when their fields of activities are taken into account, and they are in a sector where all national and international social, economic, and political variables play an active role [8].

A close relationship exists between the performance of businesses and their intellectual capital [9]. Generally, the value of intellectual capital will increase as the business performance of companies increases [10]. In the maritime industry, which is within the scope of this study, only two studies draw attention. First, Del Giudice and De Paola [11] made a performance measurement on a maritime company with the intangible assets monitor method and concluded the findings as a result of this evaluation, which has many predictive data, with a financial formulation. The company, which is under branding, has been followed up by keeping it dependent on the general/restricted variables for three periods, and some suggestions have been made to decision-makers. Second, a sectoral report on Intellectual Capital Services Ltd. was published, and a performance measurement using the "the conjoint value hierarchy" method was performed, adhering to a much more comprehensive list of variables with key performance variables compared to the work of Del Giudice and De Paola [11]. This performance measurement can be considered a preliminary study for the evaluation of the intellectual capital of the ship operating company.

The key indicators used in performance evaluations constitute the building blocks of this capital. However, key performance indicators (KPIs) may differ as a result of the companies' operating areas and the depth of their assessments. For this reason, the focus of this study is to distinguish the importance levels of intellectual capital elements in a ship operating company and to determine the group performance indicators that should be examined to measure these elements and prioritize them among themselves. Thus, the KPIs have been integrated, which differ at the enterprise level, in a certain structure. To achieve this goal, the analytical hierarchy process (AHP) was used under a fuzzy environment [12-14]. Accordingly, this paper is organized as follows: Chapter 1 reviews the motivation behind the study and the key literature on the assessment of intellectual capital of ship management companies. Chapter 2 describes the theoretical framework of Fuzzy AHP. Chapter 3 further discusses intellectual capital in shipbuilding and how the proposed approach has been applied. Chapter 4 presents a conclusion and future works.

2. Methodology

In this section, the Fuzzy AHP method is explained step by step to evaluate the intellectual capital of ship management companies.

2.1. Fuzzy AHP

As one of the best-known techniques for decision making, multicriteria decision making (MCDM) offers a systematic method for solving decision problems on the basis of multiple criteria. This method, which often focuses on simultaneously dealing with multiple and contradictory criteria, often depends on quantitative and qualitative approaches. Although it varies depending on the approaches, MCDM can increase decision quality with more effective and rational methods than traditional processes [15].

The AHP is a powerful method for solving complex decision problems. Any complex problem can be decomposed into several subproblems using the AHP in terms of hierarchical levels, where each level represents a set of criteria or attributes relative to each subproblem. The AHP method is a multicriteria analysis method based on the additive weighting process, in which many relevant features are represented by their relative importance. The AHP has been extensively applied by academics and professionals in engineering practices, which includes financial decisions predominantly associated with non-financial qualifications [16]. Through the AHP, the importance of several attributes is derived from a pairwise comparison process in a hierarchical structure of the relevance of categories of attributes or drivers of intangibles. With the potential to speed up the MOP analysis, the AHP offers a convenient technique to derive an initial linear approximation of this unexpressed utility function. Another advantage of using the consistency metric is that it improves decision-maker learning.

However, the pure AHP model has some shortcomings [17]. The AHP method is mainly used in decision applications with almost clear information. Moreover, it creates and deals with a very unbalanced judgment scale. The AHP method does not take into account the uncertainty associated with mapping human judgments to several natural languages, and the ordering of the AHP method is rather uncertain.

Subjective judgments through perception, evaluation, improvement, and choice based on decision-makers' preferences have a great influence on AHP results. To overcome these problems, several researchers have integrated fuzzy theory with the AHP to improve uncertainty. To determine the fuzzy weights of objects from fuzzy pairwise comparison matrices, Buckley added trapezoidal fuzzy numbers to the fuzzy AHP theory and fuzzified the geometric mean approach in 1985 [18]. Cheng and Mon [19] estimated the fuzzy eigenvectors of a fuzzy pairwise comparison matrix using interval arithmetic and α-cuts. To obtain fuzzy weights from a fuzzy pairwise comparison matrix, Xu [20] proposed a fuzzy extension of the least-square priority method. Considering all the information available in a decision-making problem, Enea and Piazza [21] proposed techniques depending on the constrained fuzzy arithmetic for deriving fuzzy weights. These formulas were further developed by Krejˇcí et al. [22], who also used the restricted fuzzy arithmetic to the aggregated fuzzy priority of possible alternatives. In this study, Buckley's Fuzzy AHP method has been utilized, which has key benefits, including offering a distinct solution to the reciprocal comparison matrix and a reasonably simple calculation using the algorithm to calculate weights with trapezoidal fuzzy numbers and the criterion. The fuzzy AHP relies on the fuzzy interval arithmetic with triangular fuzzy numbers and confidence index to determine the weights of evaluation elements.

It has become necessary to weigh the group performance indicators that combine elements in a way that will facilitate the measurement and management of the intellectual capital of ship management companies. For this purpose, it would be appropriate to use the AHP method. While constructing the hierarchical structure, a weighting study was performed for the group performance indicators and intellectual capital elements. In this way, while effective indicators are compared with the indicators in their clusters, the group performance indicators are weighted according to the capital types. Nodes in each cluster are compared in pairs based on linguistic terms in Table 1.

Thirteen mariner experts, with a minimum of 11 years of experience and an average of 15 years of experience, evaluated group performance indicators and supporting elements from sources as discussed in Section 2.1. Using the answers from the experts, the following steps were followed, and the importance levels of the elements and group performance indicators were determined.

Step 1: Generate pairwise comparison matrices between all elements/criteria in the dimensions of the hierarchy system.

Assign language terms to pairwise comparisons by asking which of the two dimensions is more important, as in matrix $\widetilde{A}$ below:

$$\mu\left(\frac{x}{\widetilde{M}}\right) = \begin{cases} 0, x < l \\ \frac{(x-l)}{(m-l)}, l \le x \le m \\ \frac{(u-x)}{(u-m)}, m \le x \le u \\ 0, x > u \end{cases}, \tag{1}$$

$$\widetilde{M} = \begin{pmatrix} 1 & \widetilde{a}_{12} & \cdots & \widetilde{a}_{1n} \\ \widetilde{a}_{21} & 1 & \cdots & \widetilde{a}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \widetilde{a}_{n1} & \widetilde{a}_{n2} & \cdots & 1 \end{pmatrix} = \begin{pmatrix} 1 & \widetilde{a}_{12} & \cdots & \widetilde{a}_{1n} \\ 1/\widetilde{a}_{12} & 1 & \cdots & \widetilde{a}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ 1/\widetilde{a}_{1n} & 1/\widetilde{a}_{2n} & \cdots & 1 \end{pmatrix}, \tag{2}$$

where

$$\tilde{a}_{ij} = \begin{cases} \tilde{1}, \tilde{3}, \tilde{5}, \tilde{7}, \tilde{9} \text{ criterion } i \text{ has relative} \\ \text{importance to criterion } j \\ 1.\, i = j \\ \tilde{1}^{-1}, \tilde{3}^{-1}, \tilde{5}^{-1}, \tilde{7}^{-1}, \tilde{9}^{-1} \text{ criterion } i \text{ hasless} \\ \text{importance to criterion j} \end{cases} \tag{3}$$

Step 2: Use the geometric means method to integrate the opinions of respondents [18].

$$\widetilde{a}_{ij} = \left(\widetilde{a}_{ij}^{1} \otimes \widetilde{a}_{ij}^{2} \otimes \ldots \otimes \widetilde{a}_{ij}^{n}\right)^{\frac{1}{n}}, \tag{4}$$

where $\widetilde{a}_{ij}$ is the triangular fuzzy number in the *i*th column and *j*th row of the fuzzy positive reciprocal matrix and $\widetilde{a}_{ij}^{n}$ is the assessment value of respondent *N*.

Step 3: Perform the column geometric mean method

In this step, the fuzzy weights of each criterion are determined using the following equation, where i^{th} denotes the fuzzy weight of the criterion $\widetilde{w}_i$ and is denoted by $\widetilde{w}_i = (lw_i, mw_i, uw_i)$ [23].

$$\widetilde{w}_i = r_i \otimes [r_1 \oplus ... \oplus r_i \oplus ... \oplus r_n]^{-1}, \quad (5)$$

$$r_i = \left(\tilde{a}_{i1} \otimes ... \otimes \tilde{a}_{ij} \otimes ... \otimes \tilde{a}_{in}\right)^{\frac{1}{n}}, \quad (6)$$

where $\widetilde{w}_i$ is the fuzzy weight value of each column in the fuzzy positive reciprocal matrix and r_i is the geometric mean of the triangular fuzzy number.

Step 4: Obtain data consistency using Equations (7, 8, and 9). If the consistency ratio (CR) is less than or equal to 0.10, the expert opinion is considered reasonable and consistent. The CR is calculated to evaluate the consistency of the comparison matrix in the classical AHP. However, the results of the fuzzy AHP are a fuzzy number of linguistic judgments. Therefore, it is necessary to apply a defuzzification technique.

$$CI = \frac{\lambda_{max.} - n}{n - 1} \quad (7)$$

$$\sum_{j=1}^{n} a_{ij} w_j = \lambda_{max} w_i \quad (8)$$

$$CR = CI / RI \quad (9)$$

Step 5: In the final step, the center of area method is utilized to determine the best non-fuzzy performance (net weight) of each criterion. For each w_i fuzzy number, defuzzified values are obtained as follows:

$$BNP\, \widetilde{w}_i = \frac{l + m + u}{3} \quad (10)$$

After the completion of these steps, eventually, the sum of the weights of the group performance indicators is equalized to the element to which they depend. Weightings are recalculated using the simple proportionality method.

3. Analytic Evaluation of Intellectual Capital for Ship Management Companies Under A Fuzzy Environment

In this section, the fuzzy AHP method is applied among the group performance indicators determined to evaluate the intellectual capital of ship management companies.

3.1.1. Intellectual capital assessment for ship management companies

Considering the fields of activities of ship management companies, they are considered part of service-intensive businesses, and they are in a sector where all national and international social, economic, and political variables play an active role. Regardless of where they are located geographically, these companies are fighting to get a share from the world market due to their international structure. Meanwhile, many variables, such as knowledge, experience, organizational culture, organizational structure, relations with national and international stakeholders, education level of employees, safety level of operations, inspection and follow-up procedures, and number and tonnage of ships in their operations, affect these enterprises positively or negatively.

These and many more factors should be evaluated to increase the intellectual assets and capital of ship management companies. Considering the literature and sectoral applications, many of these factors are used in the performance measurements of companies. For an accurate analysis to be made, the rules, regulations, and systems on which these companies have built their correct and safety management systems should be explained. For this reason, the International Safety Management Code prepared by the International Maritime Organization, which is thought to be affected by operational factors, International Ship and Port Facility Security Code, Maritime Labor Convention 2006 prepared by the International Labor Organization, Ship Inspection Report Program, and Internal Evaluation Program in Tanker and Dry Cargo Management [Tanker Management Self Assessment (TMSA)/Bulk Management Self Assessment (BMSA)] published by the International Maritime Forum of Oil Companies were examined. In addition, the Quality Management System (ISO: 9001) and Environmental Management System (ISO: 14001) offered by the International Standards Organization, which we encounter in other sectors, are included in the content, considering businesses that implement these systems, although they are not mandatory for maritime operators. The evaluation of the KPIs (shipping KPI system) designed by the Baltic and International Maritime Council (BIMCO) to examine the performance of ship operators in terminological harmony has been prioritized as it will provide ease of perception, application, and follow-up to the companies. It cannot be claimed that the performance standards of BIMCO used in the research can be accepted as an absolute performance indicator for ship owners. Companies should not only use the performance standards of the BIMCO or any other organization but also have the opportunity to analyze, manage their ships, and increase their performance by developing and using their own KPI standards and having the opportunity to measure, evaluate, and monitor their performance [24]. However, these sectorally determined performance factors will not be sufficient for the evaluation and management of intellectual capital.

In a pilot study report published by the Intellectual Capital Services Ltd. in 2005, 28 KPIs for ship management companies were agreed upon as a result of workshops held with the participation of ship managers, ship owners, port control authorities, and major oil companies, and these KPIs were gathered in five groups. In this report, the aforementioned 28 indicators were prioritized using the "conjoint value hierarchy" method.

This study aimed to determine the other factors that play a role in the ability of ship management companies to evaluate their own intellectual capital and determine the importance of all these factors on a sectoral basis.

3.1.2. Problem definition

For calculating the full value of ship management companies, the values of ships and other immovable or material resources are not sufficient for these institutions, which are service-based businesses. While valuing a firm, its intellectual capital, which is outside of the book value, should also be measured. Again, if these companies want to increase their value, they should understand the intellectual capital indicators well, monitor their performance in this field, and create development strategies. As mentioned in the section above, the management performances of ship management companies are measured and followed up with the recommendation of the BIMCO and the benchmarking method of companies. However, to understand intellectual capital and monitoring and managing company performance in this context, the indicators that the BIMCO recommends to follow are insufficient. To measure intellectual capital and increase it with the integration of innovative strategies, the above-mentioned element and group performance indicators should be evaluated, taking into account the critical influencing factors.

3.1.3. Evaluation of intellectual capital for ship management companies under a fuzzy environment

A survey was conducted with 13 experts, including employees of a prestigious ship management company or academics compatible with their field of expertise, to measure the intellectual capital of ship management companies, identify critical performance indicators, and evaluate their management. The average experience of specialists in this field is about 15 years. These group performance indicators were then grouped (Figure 1), and each expert was asked to compare each element and the indicators according to Saaty's 1-9 scale given in Table 1.

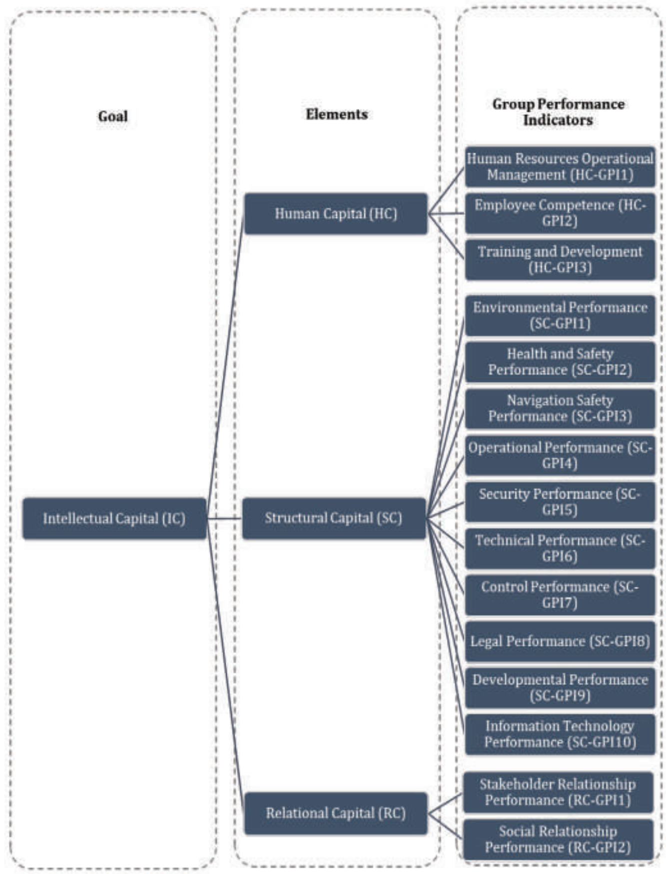

Figure 1. *Hierarchical structure of elements and group performance indicators of intellectual capital for ship management companies*

Table 1. *Triangular fuzzy scale and linguistic terms [15]*

Saaty's scale	Description	Triangular fuzzy scale	Triangle fuzzy reciprocal scale
1	Equal importance (E)	(1, 1, 1)	(1, 1, 1)
3	Moderate importance (MI)	(2, 3, 4)	(0.25, 0.333, 0.5)
5	Strong importance (SI)	(4, 5, 6)	(0.167, 0.2, 0.25)
7	Demonstrated importance (DI)	(6, 7, 8)	(0.125, 0.143, 0.167)
9	Extreme importance (EI)	(9, 9, 9)	(0.111, 0.111, 0.111)
2	Intermediate values between two adjacent judgments	(1, 2, 3)	(0.333, 0.5, 1)
4		(3, 4, 5)	(0.2, 0.25, 0.333)
6		(5, 6, 7)	(0.143, 0.167, 0.2)
8		(7, 8, 9)	(0.111, 0.125, 0.143)

According to Saaty's scale, the fuzzy and standardized matrices were obtained as a result of the evaluation of 13 experts. First, whether judgments of each expert are consistent (CR<0, 1) were examined, and the results are shown in Table 2. Group performance indicators represent the elements of intellectual capital and the weightings of the group performance indicators that should be used in the measurements of these elements (Tables 3.1, Table 3.2, Table 3.3, and Table 3.4).

After the evaluation by the 13 experts, Equations (1-9) were used to calculate the priority weight for each element and group performance indicator. In the final step, defuzzification was performed by using Equation (5) to get the exact value of each indicator. The CR was 0.0121 for the elements, 0.0246 for the human capital group performance indicators, 0.0285 for the structural capital group performance indicators, and 0.0000 for the relational capital group performance indicators, each within acceptable limits. Therefore, the maritime expert judgments included in the comparison matrices were reasonable. Accordingly, Table 4 shows the defuzzified and normalized importance weights of the intellectual capital elements and group performance indicators constituting the elements.

Table 2. *Consistency control of the judgments of each expert*

	Intellectual capital			Human capital			Structural capital			Relational capital		
	λmax	CI	CR	λmax	CI	CR	λmax	CI	CR	λmax	CI	CR
E1	3.040	0.020	0.035	3.040	0.020	0.034	10.707	0.079	0.053	2.00	0.00	0.00
E2	3.110	0.055	0.095	3.089	0.045	0.077	10.948	0.105	0.071	2.00	0.00	0.00
E3	3.078	0.039	0.067	3.111	0.055	0.096	10.932	0.104	0.069	2.00	0.00	0.00
E4	3.078	0.039	0.067	3.087	0.044	0.075	10.712	0.079	0.053	2.00	0.00	0.00
E5	3.077	0.039	0.067	3.007	0.004	0.006	11.119	0.124	0.083	2.00	0.00	0.00
E6	3.000	0.000	0.000	3.095	0.048	0.082	11.167	0.130	0.087	2.00	0.00	0.00
E7	3.037	0.018	0.032	3.070	0.035	0.061	11.245	0.138	0.093	2.00	0.00	0.00
E8	3.072	0.036	0.062	3.059	0.029	0.051	11.275	0.142	0.095	2.00	0.00	0.00
E9	3.038	0.019	0.033	3.098	0.049	0.085	10.578	0.064	0.043	2.00	0.00	0.00
E10	3.047	0.023	0.040	3.054	0.027	0.046	10.902	0.100	0.067	2.00	0.00	0.00
E11	3.021	0.011	0.018	3.105	0.053	0.091	10.421	0.047	0.031	2.00	0.00	0.00
E12	3.104	0.052	0.090	3.078	0.039	0.067	11.244	0.138	0.093	2.00	0.00	0.00
E13	3.091	0.045	0.078	3.050	0.025	0.043	11.168	0.130	0.087	2.00	0.00	0.00

Table 3. *Fuzzy and standardized matrices*

Table 3.1. *Intellectual capital*

Fuzzy geometric mean			Fuzzy weights			BNP	Normalization	Criterion weights	
1.614	1.805	1.997	0.429	0.538	0.673	0.547	0.537	0.537	HC
0.854	0.985	1.106	0.227	0.294	0.373	0.298	0.292	0.292	SC
0.499	0.563	0.658	0.133	0.168	0.222	0.174	0.171	0.171	RC
Consistency index (CI)			0.0064						
Consistency ratio (CR)			0.0110						

Table 3.2. *Human capital*

Fuzzy geometric mean			Fuzzy weights			BNP	Normalization	Criterion weights	
0.959	1.103	1.285	0.275	0.365	0.491	0.377	0.367	0.367	HC-GPI1
0.743	0.850	0.967	0.213	0.282	0.370	0.288	0.280	0.280	HC-GPI2
0.914	1.066	1.236	0.262	0.353	0.472	0.363	0.353	0.353	HC-GPI3
Consistency index (CI)			0.0118						
Consistency ratio (CR)			0.0203						

Table 3.3. *Structural capital*

Fuzzy geometric mean			Fuzzy weights			BNP	Normalization	Criterion weights	
0.875	1.042	1.235	0.065	0.093	0.133	0.065	0.092	0.092	SC-GPI1
1.760	2.173	2.568	0.130	0.193	0.277	0.130	0.191	0.191	SC-GPI2
1.785	2.158	2.542	0.132	0.192	0.274	0.132	0.190	0.190	SC-GPI3
0.820	0.998	1.222	0.061	0.089	0.132	0.061	0.089	0.089	SC-GPI4
0.869	1.049	1.262	0.064	0.093	0.136	0.064	0.093	0.093	SC-GPI5
1.003	1.222	1.492	0.074	0.109	0.161	0.074	0.109	0.109	SC-GPI6
0.702	0.843	1.012	0.052	0.075	0.109	0.052	0.075	0.075	SC-GPI7
0.474	0.567	0.693	0.035	0.050	0.075	0.035	0.051	0.051	SC-GPI8
0.421	0.512	0.639	0.031	0.046	0.069	0.031	0.046	0.046	SC-GPI9
0.576	0.683	0.829	0.043	0.061	0.089	0.043	0.061	0.061	SC-GPI10
Consistency index (CI)			0.0382						
Consistency ratio (CR)			0.0256						

Table 3.4. *Relational capital*

Fuzzy geometric mean			Fuzzy weights			BNP	Normalization	Criterion weights	
1.49	1.70	1.91	0.579	0.743	0.946	0.756	0.741	0.741	RC-GPI1
0.52	0.59	0.67	0.203	0.257	0.332	0.264	0.259	0.259	RC-GPI2
Consistency index (CI)			0.000						
Consistency ratio (CR)			0.000						

Table 4. *Weights of elements and group performance indicators*

Elements	w	GPI	w
HC	**0.54**	HC-GPI1	0.20
		HC-GPI2	0.15
		HC-GPI3	0.19
SC	**0.29**	SC-GPI1	0.03
		SC-GPI2	0.06
		SC-GPI3	0.06
		SC-GPI4	0.03
		SC-GPI5	0.03
		SC-GPI6	0.03
		SC-GPI7	0.02
		SC-GPI8	0.01
		SC-GPI9	0.01
		SC-GPI10	0.02
RC	**0.17**	RC-GPI1	0.13
		RC-GPI2	0.04

Considering the importance weights of the elements, the human capital element is quite important compared to the structural capital and relational capital. Although the human capital group performance indicators, human resources operational management (0.20), employee competence (0.15), and training and development (0.19) indicators are interpreted with approximately similar importance levels, when all group performance indicators are examined, they become the leading criteria.

While evaluating the relational capital element, which can be described as another leading criterion, the group performance indicator stakeholder relationship performance also comes after the group performance indicators of the human capital element with 0.13. Ten groups of performance indicators (environmental performance, health, and safety performance, navigational safety performance, operational performance, safety performance, technical performance, control performance, legal performance, developmental performance, and information technology) used when measuring the structural capital element, which has a 0.29 degree of importance in factor weighting. Hence, the weights of the indicators examined in this section and the social relationship performance indicator, which is the second of the indicators that make up the relational capital element, have a low degree of importance.

4. Findings and Discussion

The intellectual capital elements that are considered critical in the measurement and management of the intellectual capital of ship management companies and the group performance indicators that provide the analysis of these elements and the priorities examined by applying the fuzzy AHP model are given in percentages by the 13 maritime experts.

Based on this, as presented in Figure 2.1, when evaluating the intellectual capital of ship enterprises, which is a service-based sector, the most important element is human capital with a weight of 54%, followed by structural capital with 29% and relational capital with 17%.

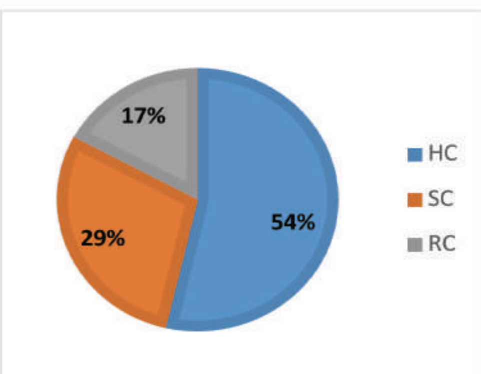

Figure 2.1. *Weights of the elements of intellectual capital*

As shown in Figure 2.2, three group performance indicators need to be considered while evaluating the human capital aspect. Accordingly, we can list them according to their importance as follows: 1. human resources operational management (37%), 2. training and development (35%), and 3. employee competence (28%). In addition, this ranking is valid for all group performance indicators, and the three indicators lead to the general situation.

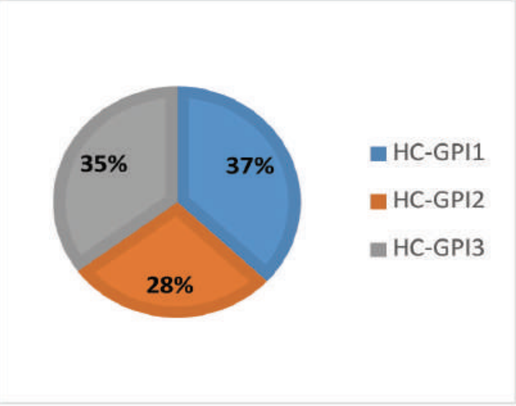

Figure 2.2. *Weights of the group performance indicators of human capital*

As shown in Figure 2.3, 10 group performance indicators make up the structural capital aspect, and when ranked according to their importance, health and safety performance and navigational safety performance (19%) share the first place. Technical performance comes in third place with 13% importance, but other groups remained below 10%. Nonetheless, evaluating intellectual capital requires a holistic perspective. The total of structural capital group performance indicators, which are divided into more groups and therefore have a little effect, constitutes 29% of intellectual capital.

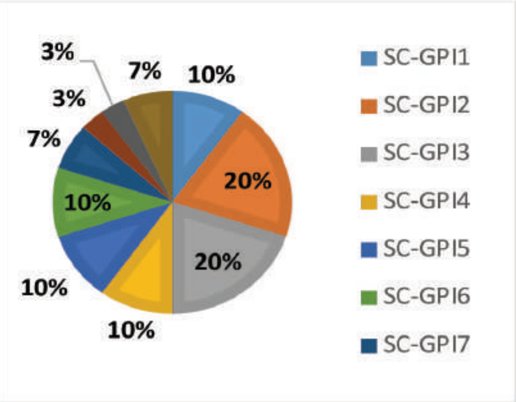

Figure 2.3. *Weights of the group performance indicators of structural capital*

Finally, from the group performance indicators that make up the relational capital element are examined closely, the stakeholder relationship performance for ship management companies dominates this element with an impact of 74%, as shown in Figure 2.4. Again, we measure 26% of relational capital, which makes up 17% of intellectual capital, with the social relationship performance.

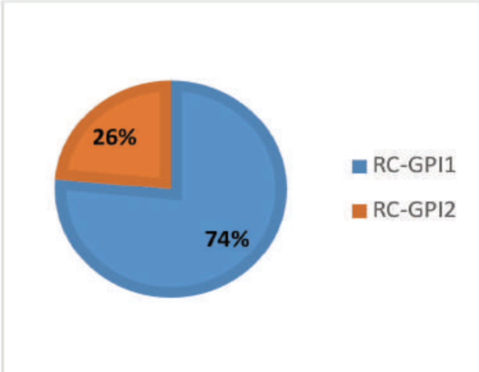

Figure 2.4. *Weights of the group performance indicators of relational capital*

To summarize the findings, 15 group performance indicators created by experts for a closer analysis of the elements of the intellectual capital of a ship management company were put forward within the scope of this study, and the importance levels of these indicators were determined. The order of these indicators is clearly shown in Figure 3, and the indicators with the highest importance are as follows: 1. human resources operational management (HC-GPI1), 2. training and development (HC-GPI3), 3. employee competence (HC-GPI2), and 4. stakeholder relationship performance (RC-GPI1).

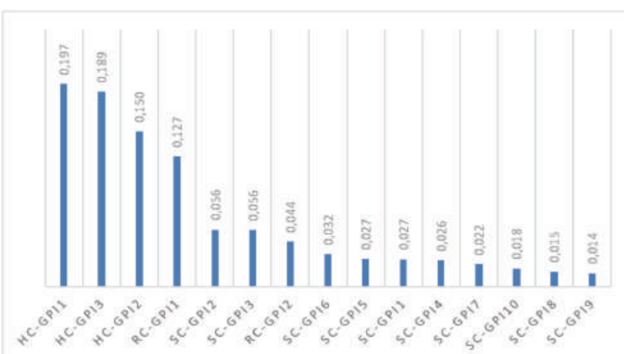

Figure 3. *Ranking of the group performance indicators of relational capital*

5. Conclusions

Measuring intellectual capital gains is important in revealing the real values of ship management companies, which are considered service-based businesses. In addition, the evaluation and management of intellectual capital will contribute to the determination of sustainable development strategies of these companies. For this reason, it is necessary to determine the elements that make up the intellectual capital for ship management companies and the important indicators that play a role in the analysis of these elements. In this study, three elements of intellectual capital, namely, human capital, structural capital, and relational capital, and group performance indicators that will enable them to follow these elements have been prioritized using the fuzzy AHP method.

Based on the analysis results, the importance of the human capital and the determined human resources operational management, employee competence, training, and development group performance indicators will play in the value acquisition strategies of a ship management company due to the nature of the business. Although the structural capital element is the second priority element, the group performance indicators lose their priority when examined individually due to the difference in the indicators that make up the element. However, the correct point of view on this issue is that, undoubtedly, none of them should be neglected about its effect on the whole. While relational capital comes as the third element, the stakeholder relationship performance, one of the related group performance indicators, is three times more important than the social relationship performance.

The results of this study will encourage ship owners and managers to focus on intellectual capital management and identify priority strategies to increase firm value. With the entry into force of the BMSA program, which is similar to the TMSA program, where tanker companies are currently subjected, companies can more effectively plan their further steps toward their targets by collecting their data to monitor their management and interpreting them periodically. The procedures and checklists that can be created in the light of this study will support these enterprises in making their own evaluations and will also be useful in increasing the company values while measuring and managing their performance.

As with most studies, the design of the present study is subject to limitations, in this case two, which could be addressed in future research. First, there are very limited resources in the literature on the evaluation of the intellectual capital of the ship management companies, which are the focus of the study, and it shows terminology differences due to the nature of the application area. Second, the parameters used to measure maritime intellectual capital were kept at the level of group performance indicators. Components to measure performance indicators in these groups were excluded due to time constraints. In further studies, KPIs compatible with sectoral terminology and their measurement methods can be determined for the measurement of this group of performance indicators.

Authorship Contributions

Concept design: G. Çevik, Ö. Arslan, Data Collection or Processing: G. Çevik, Ö. Arslan, Analysis or Interpretation: G. Çevik, Ö. Arslan, Literature Review: G. Çevik, Ö. Arslan, Writing, Reviewing and Editing: G. Çevik, Ö. Arslan.

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Marine Engine Oil Diagnostics by Means of NMR Spectroscopy and Relaxometry of Protons

Nikolay Sinyavsky[1], Ivan Mershiev[2]

[1]Kaliningrad State Technical University, Kaliningrad, Russia
[2]Immanuel Kant Baltic Federal University, Kaliningrad, Russia

Abstract

The goal of this work is to investigate fresh and used marine engine oil by high-resolution ^1H nuclear magnetic resonance (NMR) as well as by NMR relaxometry with Laplace transform inversion. The largest decrease in the molar content of CH_3 groups was observed in used 10W40 oil, from 37.7% to 27.3%, and the largest increase in the content of CH groups was observed in 15W40 engine oil, from 8.8% to 11.5%. The inversion method based on standard deviation minimization and regularization (RILT) was used to obtain the distribution of relaxation times. It is demonstrated that the bimodal distributions of the longitudinal relaxation times practically differ very little between fresh and used oils. T_2 relaxation times for the used 10W40 oil (21 ms and 63 ms) shift to shorter values in the bimodal distribution when compared to fresh oil (25 ms and 89 ms). The T_2 relaxation times for the used M-4015 oil increased from 14 ms and 42 ms to 19 ms and 60 ms, respectively. This indicates a change in the mobility of the functional groups of macromolecules caused by a change in the viscosity of the used oil. It is proposed to use the NMR method of proton relaxometry and the distributions of relaxation times to diagnose marine engines using used motor oil.

Keywords: Marine motor oils, Diagnostics, NMR

1. Introduction

One of the primary tasks of the maritime industry is to improve the reliability, durability, and efficiency of machines and units. The global experience of operating marine diesel power plants demonstrates that, in addition to engine design and manufacturing technology advancements, the most important factor determining engine technical life is the quality of the fuels and oils used. Under normal operating conditions, the quality of the oil used for lubrication is one of the few ways to achieve a noticeable increase in engine durability and economy without incurring any tangible costs.

Typically, information on the aging of marine engine oils is usually obtained through a comprehensive laboratory analysis that determines the change in the main indicators typically used to assess the quality of the oil. The main physical and chemical properties determined in the laboratory are: flash point in an open crucible; density; water-soluble acids and alkalis; acidity; acid and alkaline numbers; water content, kinematic viscosity; conditional viscosity; coking capacity; the presence of mechanical impurities and their composition; and ash content.

Motor oils provide lubricating, thermal control, detergent, sealing, and anti-corrosion properties. These are all provided by motor oil. Many factors act on the lubricating oil while the engine is running, including high temperatures, fuel entering. The study of the processes of oil aging and mechanical impurity dispersion is critical for extending the engine's service life. lubrication temperature, the lubrication system, oxygen contained in the air, and foreign impurities. The oil's properties change as a result of the numerous physical and chemical processes that it goes through: the oil "ages" [1]. It darkens during operation, changes in viscosity, flash point, acidity change, molecular

Address for Correspondence: Nikolay Sinyavsky, Kaliningrad State Technical University, Kaliningrad, Russia
E-mail: n_sinyavsky@mail.ru
ORCID ID: orcid.org/0000-0003-1285-206X

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weight increases, and mechanical impurities of organic and inorganic origin appear. Oil oxidation products reduce reliability and increase engine wear. The engine ages much more rapidly in the engine than it does in the laboratory under artificial oxidation conditions. Studies of the group chemical composition of the oil depending on the duration of the engine operation showed that the contribution of aromatic hydrocarbons remains practically unchanged, but the contribution of resinous substances increases due to the oxidation of alkanic and naphthenic compounds.

Many studies have been conducted to investigate the relationship between changes in the basic physicochemical properties of oils and part wear [2]. This is a review of diagnostic and forecasting methods as well as the development of systems for monitoring the state of lubricating oils. However, the results of these studies are quite contradictory. A wide range of oils and additives used to improve its quality complicates the situation.

The issue of petroleum product quality control is critical because it affects the safety of operating environments and transportation safety. The current control methods are either complex and expensive or do not provide an unambiguous identification of the quality of petroleum products. Furthermore, standard methods for analyzing the quality of petroleum products typically necessitate a significant time investment. It is critical to develop new express methods for quality control and counterfeit detection using compact devices.

The efficient use of fuel and lubricants on ships is dependent on consistent quality control. The rationality of their use and environmental protection are also dependent on their quality. The rationality of their use and environmental protection are also dependent on their quality. The method of proton nuclear magnetic resonance (NMR) relaxometry with the inversion of the Laplace transform can be proposed as a new express method for non-destructive quality control.

The properties of petroleum products are analyzed by various physical and chemical methods, including radio-frequency spectroscopy methods. Most of these methods, however, are quite complex, costly, and time-consuming. The publication [3] is devoted to the creation of intelligent sensor systems for diagnostics and the development of online analysis methods for marine motor oil. A wide range of methods for analyzing oils during operation is presented in the handbook [4].

The work [5] aims to improve ship safety by employing effective methods for diagnosing marine diesel engines. The analysis of used motor oil provides critical information [6] about the condition of the engine.

The thermal degradation of fresh motor oils, base oils, and additives was determined using ^{1}H NMR spectroscopy, relaxometry, and diffusion methods in reference [7]. Only the base oil with no additives exhibits a significant change in the NMR spectrum after thermal treatment. According to low-field NMR relaxometry transverse relaxation is much more sensitive to changes in the dynamic behavior of molecules as temperature increases The T_2 relaxation time decreases during thermal degradation for both the base oil and the oil with additives, indicating that the degraded sample has molecular mobility. In contrast to the oil with additives, additional peaks appear in the base oil spectrum after thermal degradation in the region of 2.2-6 ppm and 7.3-8.8 ppm. These peaks are conditioned by new aromatic and hydrocarbon compounds resulting from the thermal degradation of the oil.

In [8], fresh and used motor oils exposed to the atmosphere were examined by NMR and other methods. The studies revealed new lines in the NMR spectrum for used oil in the range of 2.1-2.7 ppm and 6.8-7.2 ppm, which are due to the formation of new aromatic and aliphatic hydrocarbon products, respectively. The concentration of polycyclic aromatic hydrocarbons in used oil has been shown to be many times higher than in fresh motor oil.

In [9], various NMR results (^{1}H and ^{13}C 1D NMR, 2D correlation spectra, diffusion and relaxation experiments) are discussed and interpreted to gain insight into the aging process of motor oils. The article [10] explores approaches based on the gamma distribution model for processing NMR relaxometry and diffusometry data in the study of engine oil degradation. The work [11] is focused on studying the degradation of lubricating oil by changing the rate of proton spin-lattice relaxation using the magnetic field cycling method. The pros and cons of this technique are discussed.

In [12], we proposed using the NMR relaxation method with the Laplace transform inversion for the express analysis of petroleum products. The distributions of spin-lattice and spin-spin relaxation times T_1 and T_2 for low viscosity marine fuel, diesel fuel, M-100 fuel oil, and SN-150 and SN-500 base oils were determined using low-field NMR. The nature of the distributions for different petroleum products varies significantly, which is explained by the different composition of many hydrocarbons.

A method for determining the spin-spin NMR relaxation time of protons was proposed in publication [13] to estimate the service life of motor oils and control the degree of engine wear.

Several studies have been conducted in order to determine the relationship between changes in a number of the most important physicochemical parameters of oil and engine wear. However, the inconsistency of the obtained results causes us to proceed with caution.

The use of modern oils containing dispersant additives allows for a significantly increased service life in diesel engines. Only timely oil changes can ensure reliable engine operation with minimal wear of friction parts and the lowest consumption of lubricating oils. Premature oil changes also lead to increased engine wear.

In [12], to solve the problem of multicomponent distributions of relaxation times based on the method of minimizing the standard deviation and regularization [14], the generalized inversion algorithm [15] was used to separate the exponential decay of NMR signals.

Relaxometry is a broad category of NMR experiments that focus on measuring nuclear spin relaxation times to characterize the structural and dynamic properties of the sample. The main methodological difference between NMR relaxometry and other methods of relaxation in a weak field is that the data is analyzed in the time domain rather than the frequency domain analysis of the exponential decay or recovery of nuclear magnetization yields relaxation rates. The dynamics of rotational and translational diffusion, as well as chemical exchange processes, influence relaxation times. Multicomponent or multi-phase samples give samples of experimental data, which may contain areas with clearly different T_2 or T_1 values.

The paper [16] discusses various types of compact NMR relaxometers, typical pulse sequences, and applications for studying liquids, polymers, biological tissues, porous materials, etc.

Longitudinal relaxation T_1 relaxation and transverse relaxation T_2 carries information about internuclear distances and molecular motion correlation times. T_2 and the rate of spin-lattice relaxation measurements can be linked to different types of molecular fragment mobility.

At present, the development of various NMR methods in strong inhomogeneous constant and radio-frequency magnetic fields is increasingly progressing. Such NMR applications are offered, among other things, for testing various materials [17].

At the same time, NMR relaxometry provides information about the diffusion and molecular dynamics of substances and at the same time requires a minimum field homogeneity, in contrast to traditional methods of high-resolution NMR spectroscopy. Relaxometry in a weak magnetic field enables the use of small and portable devices as well as a diverse range of applications. In recent years, NMR relaxometry has received a new stimulus in connection with the development of stable algorithms for the numerical inversion of the Laplace transform, allowing it to obtain relaxation time distributions of relaxation times that carry information about the structure and dynamics of macromolecules [18].

The purpose of this work was to study fresh and used marine motor oils by high-resolution ^{1}H NMR as well as NMR relaxometry with Laplace transform inversion. This approach makes it possible to use the capabilities of both methods to determine the changes that occur in engine oil during the operation of a marine engine and solve the problem of engine diagnostics by means of used engine oil.

2. Methodology for Conducting Experimental Studies

High-resolution NMR spectra of hydrogen were obtained using a Varian 400 spectrometer in the Immanuel Kant Baltic Federal University's laboratory and processed with the MestReNova program. The proton NMR relaxation rates were measured on a Tecmag Apollo NMR-NQR spectrometer in a low magnetic field at a frequency of 13.65 MH and processed using the TNMR program. The relaxometer magnet is made up of two magnets that are 60x80x100 mm in size and are connected by a U-shaped magnetic circuit with a 25 mm gap. The magnetic field induction was 300 mT in the gap. The magnetic field inhomogeneity at the probe coil location was 0.1 mT/cm. The working coil of the probe measured 5.5 mm in diameter and 12 mm in length. A standard inversion-recovery pulse sequence was used to determine the distribution of T_1 spin-lattice relaxation times. The Carr-Purcell-Meiboom-Gill sequence was used to determine the distribution of T_2 spin-spin relaxation times. The Carr-Purcell-Meiboom-Gill sequence was used to obtain the distribution of T_2 spin-spin relaxation times. For the standard Carr-Purcell-Meibum-Gill pulse sequence, the NMR signal is described by the expression

$$M(t) = \int_0^\infty f_2\left(T_2\right) exp\left(-\tfrac{t}{T_2}\right) d\,T_2, \qquad (1)$$

where $M(t)$ is the measured signal as a function of time. To measure longitudinal relaxation using the inversion-recovery method, the signal can be represented by the expression:

$$M(t) = \int_0^\infty f_1\left(T_1\right)\left[1 - kexp\left(-\tfrac{t}{T_1}\right)\right] d\,T_1, \qquad (2)$$

where k=2 only for the case of complete inversion of the magnetization using the first RF pulse, $f_1(T_1)$ and $f_2(T_2)$ are distribution functions of relaxation times.

The study's subjects were marine oil, Total Disola M-4015 marine oil, intended for lubrication of medium and high-speed diesel engines, and engine oils 15W40 and 10W40.-4015 oil has a viscosity of 14cSt at 100 °C and a pour point of -9 °C. The viscosity of 15W40 and 10W40 oils at 100 °C is 12.6-16.3 centistokes, with a winter temperature limit of -20 °C and -25 °C, respectively. Samples of 10W40 and M-4015 oils were used in diesel engines for 300 hours. Samples of 15W40 oil were used for 250 and 500 hours.

The multi-exponential method of inversion of integral transformations according to the algorithm [15] was used in the work, as the samples under study are single-phase systems.

3. Results of Experimental Studies and Their Analysis

Marine lubricants, like other petroleum products, are made up of a diverse range of different substances. These are liquid hydrocarbons, as well as resins, asphaltenes, carbenes, and heteroatomic organic compounds to a lesser extent. in such multicomponent systems of paraffinic [for example, hexadecane (cetane) CH_3-$(CH_2)_{14}$-CH_3], naphthenic C_nH_{2n} series (for example, cyclodecane $C_{10}H_{20}$), and aromatic hydrocarbons (for example, alpha-methylnaphthalene $C_{10}H_7CH_3$) have different structures, molecular weight, and mobility of molecular fragments and molecules as a whole.

Paraffinic hydrocarbons have a linear or branched structure and can have up to forty carbon atoms in the chain. Naphthenes are mono- and polycyclic compounds in which carbon atoms are connected into cyclic structures by a single bond. Aromatic hydrocarbons are cyclic compounds that have an aromatic group attached to them.

Figure 1 shows high-resolution [1]H NMR spectra obtained for fresh and used 15W40 oil after 500 hours, respectively. The lines from hydrogen atoms, CH groups of paraffin and naphthenic chains, from CH_2 groups of paraffins, and CH_3 groups of saturated hydrocarbons are visible in the spectra. Both of these spectra (Figure 1), as well as those other petroleum products, are qualitatively similar and differ only in terms of intensity, width, and resolution. The spectra were integrated into the corresponding chemical shift regions to determine the quantitative composition of the samples' functional organic groups.

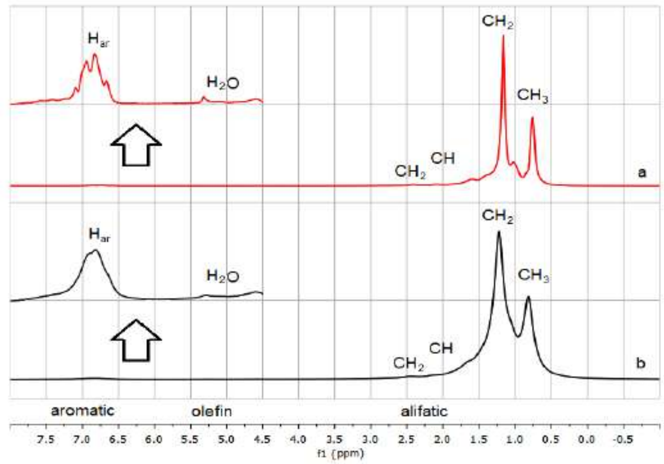

Figure 1. [1]H NMR spectrum (400 MHz) of the samples of fresh (a) and used for (500 h). (b) 15W40 marine engine oil. Signals of aromatic protons are shown at an enlarged scale

As shown in Table 1 and Figure 2, the molar content of CH_3 organic groups decreases and the content of CH groups increases in aliphatic hydrocarbons. Aside from M4015 oil, the content of hydrogen atoms in aromatic har compounds increases in used oils.

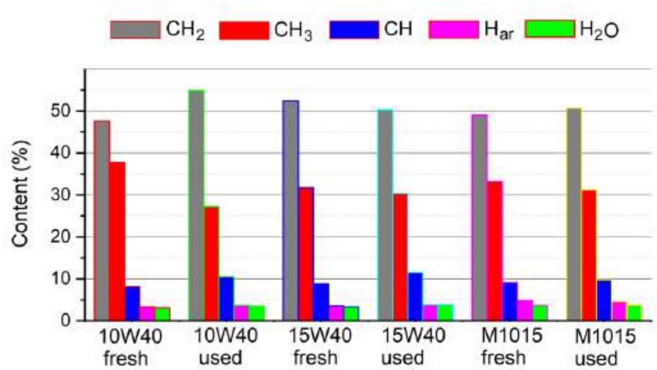

Figure 2. Changes in the content of various organic groups in [1]H NMR spectra of fresh and used motor oils

Table 1. Modular content of functional organic groups in samples of fresh and used oils from 1H NMR spectra (400 MHz)

Sample	H_{ar}	CH_2	CH	CH_3	H_20
Oil 10W40 (fresh)	3.3%	47.7%	8.2%	37.7%	3.1%
Oil 10W40 (used 300 hours)	3.7%	54.9%	10.5%	27.3%	3.5%
Oil 15W40 (fresh)	3.6%	52.5%	8.8%	31.8%	3.3%
Oil 15W40 (used 250 hours)	3.9%	50.3%	11.5%	30.4%	3.9%
Oil 15W40 (used 500 hours)	4.3%	50.3%	11.6%	29.7%	4.1%
Oil M4015 (fresh)	4.9%	49.0%	9.1%	33.2%	3.7%
M4015 oil (used 300 hours)	4.6%	50.7%	9.8%	31.2%	3.8%

The lines of the ^1H NMR spectra for fresh and used oils are most intense in the region of protons of aliphatic groups protons. The increase in the width of the lines in used oil is due to a change in its viscosity and density, as well as the fact that ferromagnetic particles appear in the oil during engine operation, changing the local magnetic fields. According to studies, the content of aromatic hydrocarbons in used oil generally increases when compared to fresh oil. There is also a redistribution of the molar content of aliphatic hydrocarbons' functional organic groups CH, CH2, and CH3.

The spectra of fresh and used motor oils show that there are no lines associated with the formation of new aliphatic and aromatic structures in the ranges of 2.2-6 ppm and 7.3-8.8 ppm. Förster et al. of [10] also came to the same result. This confirms the conclusion made in the publication [7] that additives affect the degradation of engine oil during engine operation. The NMR spectra of protons obtained in [10] are similar to the spectra shown in Figure 1. The largest decrease in the molar content of CH_3 groups from 37.7% to 27.3% is observed in used 10W40 oil and the largest increase in the content of CH groups from 8.8% to 11.5% in 15W40 engine oil.

When compared to fresh oil, both measured T_2 relaxation times for used 10W40 oil (21 ms and 63 ms) are shifted to shorter values (25 ms and 89 ms). The T_2 shifts to 15W40 oil. For used M-4015 oil roughly the T_2 relaxation times for used M-4015 oil are changed from 14 ms to 42 ms to 19 ms and 60 ms, respectively. This indicates an increase in the mobility of macromolecule functional groups caused by a decrease in the viscosity of the used oil.

The longitudinal T_1 relaxation times also have bimodal distributions and practically do not change for the studied used oils (30 ms and 100 ms) relative to the T_1 times for fresh oils. The average values of T_1 and T_2 relaxation times for fresh and used oils, obtained in [7] and [10], turned out to be close to those obtained in this study.

The results of studying high-resolution ^{13}C NMR spectra of motor oils show that these spectra have a significantly higher multiplicity than proton spectra. Simultaneously, the spectral lines of the used oil samples broaden insignificantly, and the ratio between the line intensities in the spectra hardly changes.

Engine oil properties change as a result of oxidation, decomposition, and thermal polymerization of hydrocarbons, which results in a change in the molar content of functional organic groups. The oil film oxidizes upon contact with heated parts of the cylinder and other parts. This leads to varnish formation and coking.

The times of longitudinal and transverse relaxation in NMR carries information about the times of correlation of different molecular motions. Measurements of the spin-spin and spin-lattice relaxation rates allow them to be correlated with the corresponding motions and are a reliable and fast NMR method for assessing the properties of materials [16].

Figures 3 and 4 show the results of a study of the distributions of T_1 and T_2 the relaxation times in 15W40 and 10W40 marine engine oils. The distributions of the relaxation times of fresh and used oil can be seen to differ from each other. The ratio of different hydrocarbons determines the relaxation time values. These macromolecules have different structures, molecular weights, and mobility of molecules and their fragments, which determine the relaxation times and the distribution characteristics. The different mobilities of the molecules also determine the multimodality of the distributions of spin-lattice relaxation times. Heavy molecules form short T_1 values, while light molecules cause long ones. The positions, width, and intensities of the peaks in the distributions depend not only on the composition of hydrocarbons but also on the presence and types of additives that improve certain properties of the motor oil, as well as on wear products.

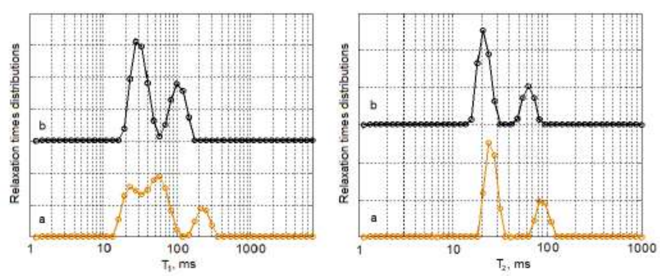

Figure 3. *Distributions of T_1 and T_2 relaxation times for fresh (a) and used for 500 hours (b) 15W40 oil*

In comparison to fresh oils, both peaks in the distribution of T_2 relaxation times shift toward shorter times in used motor oils. This could be due to an increase in the viscosity of used oils, which reduces the mobility of some hydrocarbons. The same happens with T_1 times for used 15W40 oil. The T_1 relaxation time peaks for used 10W40 oil practically do not shift in comparison to the peaks for fresh oil.

When analyzing relaxation times, it is necessary to consider their dependence on motor oil viscosity [10]. R2=1/T2 transverse relaxation rates are proportional to viscosity The higher the viscosity, the higher the transverse relaxation rate. Most often, the viscosity of engine oil typically increases as it degrades during operation. The oil's viscosity can rise for a variety of reasons, including incomplete combustion of the fuel-air mixture in the engine; thermal polymerization; oxidation, evaporation, sludge formation, water ingress into the oil; and mixing with air. The viscosity of the oil may increase due to the soot contamination and the formation of dissolved coke and oxides. This leads to viscous braking, poor lubrication of bearings, a decrease in engine power, a lack of smoothness in the set of revolutions, the appearance of a cavitation process, etc.

At the same time, thermal cracking may cause engine oil viscosity to decrease (destruction of oil molecules under the influence of high temperatures, i.e., the process opposite to polymerization). Shear deformation forces can cause destruction of macromolecules and reduce motor oil viscosity. Fuel can get into the lubricating oil, which also leads to a decrease in its viscosity. At low viscosity, a very thin oil film on rubbing parts leads to their intensive wear, engine overheating, the oil reduces cooling efficiency, and its oxidation increases.

Figure 5 depicts the distributions of T_1 and T_2 relaxation times for fresh and used M-4015 oil The lines shift here the region of longer times, indicating an increase in the mobility of molecular groups containing hydrogen atoms.

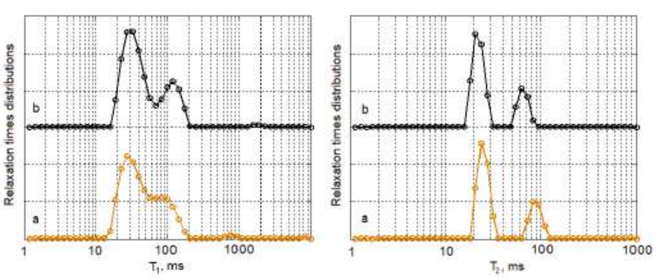

Figure 4. *Distributions of T_1 and T_2 relaxation times for fresh (a) and used for 300 hours (b) 10W40 oil*

Even unused engine oil contains a variety of substances including hydrocarbons blend, a viscosity modifier, additives (detergents, anti-corrosion, and so on.) that improve its properties. In fresh oil, the presence of thickening additives causes the formation of large particles (micelles). The viscosity modifier causes a change in the degree of aggregation in used oil.

Thus, depending on the causes (engine malfunctions), the influence on the distribution of relaxation times can change both in the direction of increasing T_1 and T_2 and in the direction of their decreasing. According to the nature of the T_1 and T_2 distributions, the level of aggregation or micellization of the viscosity modifier polymer decreases.

It can be assumed that the decrease in T_2 relaxation times in used oil is because proton relaxation times are very sensitive to the presence of ferromagnetic particles in liquids that appear in the oil during engine operation. Local magnetic fields change near these particles, which leads to a decrease in the relaxation time of protons of used engine oil molecules.

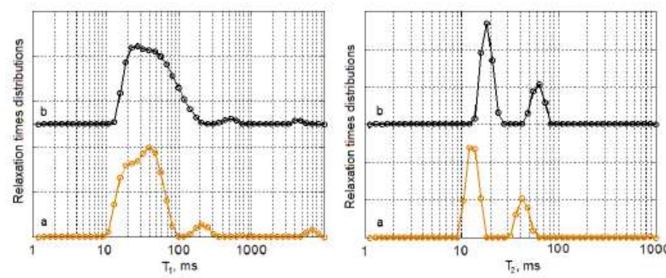

Figure 5. *Distributions of T_1 and T_2 relaxation times for fresh (a) and used for 300 hours (b) M-4015 oil*

4. Conclusion

In this work, samples of some fresh and used marine engine oils were experimentally studied by high-resolution ^{1}H NMR. It is shown that the largest decrease in the molar content of CH_3 groups from 37.7% to 27.3% occurred in used 10W40 oil, and the largest increase in the CH group content from 8.8% to 11.5% was observed in 15W40 engine oil.

Both obtained T_2 relaxation times for used 10W40 oil (21 ms and 63 ms) are shifted to a shorter range in the bimodal distribution when compared to fresh oil (25 ms and 89 ms). T_2 relaxation times for used M-4015 oil increased from 14 ms and 42 ms to 19 ms and 60 ms, respectively. This indicates an increase in the mobility of macromolecular functional groups caused by the decrease in viscosity. The distributions of longitudinal relaxation times also have a bimodal character (30 ms and 100 ms) and differ little between fresh and used oils.

The study's findings indicate that the NMR relaxometry method is appropriate for analyzing the state of engine oil and, as a result, for obtaining diagnostic data on the engine's state. In the future, we intend to use dielectric spectroscopy and magneto-optical methods to study and diagnose marine engine oils.

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Authorship Contributions

Concept design: N. Sinyavsky, Data Collection or Processing: I. Mershiev, Analysis or Interpretation: N. Sinyavsky, Literature Review: I. Mershiev, Writing, Reviewing and Editing: N. Sinyavsky.

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An Assessment of the Impacts of the Emission Control Area Declaration and Alternative Marine Fuel Utilization on Shipping Emissions in the Turkish Straits

Levent Bilgili

Bandırma Onyedi Eylül University Faculty of Maritime, Department of Naval Architecture and Marine Engineering, Balıkesir, Türkiye

Abstract

The Turkish Straits are critical waterways connecting the Mediterranean and the Black Sea. About 38,552 and 43,343 ships pass through the Strait of Istanbul and Strait of Canakkale annually, respectively, and their emissions into the air pose a threat to the regional and global environment, as well as to the people of the region. Herein, the effects of the declaration of the Sea of Marmara as an emission control area and the use of alternative fuels by ships on emission formation were examined. For this purpose, the data of the ships passing through the Turkish Straits were obtained, the engine powers were calculated based on the gross registered tonnage values of these ships, and the emission values were reached. Declaring the Sea of Marmara as an emission control area provides an 80% and 76% reduction in sulfur and nitrogen oxides, respectively. Carbon emissions remained the same. The use of liquefied natural gas dramatically reduces carbon emissions. Alternative fuels, especially liquefied natural gas, effectively reduce sulfur oxide emissions. Despite these positive effects, there seem to be many years ahead of the widespread use of alternative fuels due to the lack of technical and economic infrastructure. Thus, the declaration of the Sea of Marmara as an emission control area will positively affect both the population in the region and the region's environment.

Keywords: Alternative marine fuels, Ship emissions, Turkish Straits, ECA

1. Introduction

Ships consume 6.8% of the total fossil fuels in the world [1], and because of this consumption, 1,076 million tons of carbon dioxide equivalent (CO_2eq) greenhouse gas (GHGs) was produced in 2018, indicating a 9.3% increment compared to 2012. Ships are also responsible for 2.89% of the total anthropogenic emissions [2]. While the world's CO_2 production increased by 31.4% between 1970 and 2019, the value of CO_2 produced by ships increased by 76.8% over the same period [3]. If no measures are taken, ship-related emissions are expected to increase by 50% in 2050 compared with 2018 [2].

Only a small part of the 450 atmospheric pollutants produced from the internal combustion process in ships are harmful enough to be evaluated, and only this group is produced above a negligible level [4]. These are listed as ozone-depleting substances, nitrogen oxides (NO_x), sulfur oxides (SO_x), particulate matter (PM), and volatile organic compounds (VOCs) and are regulated by the International Convention for the Prevention of Pollution from Ships (MARPOL 73/78) Annex-VI. Additionally, although ship-related carbon emissions are excluded in the Kyoto Protocol [5] and the Paris Convention [6], the Initial Strategy on Reduction of GHG Emissions from Ships report

Address for Correspondence: Levent Bilgili, Bandırma Onyedi Eylül University Faculty of Maritime, Department of Naval Architecture and Marine Engineering, Balıkesir, Türkiye
E-mail: lbilgili@bandirma.edu.tr
ORCID ID: orcid.org/0000-0001-9431-5289

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published by the International Maritime Organization in 2018 offers short-, medium-, and long-term solutions for the decarbonization of ships and plays a guiding role. This strategy aims to reduce ship-related carbon emissions by 40% by 2030 and by 70% by 2050 compared to 2008 [7].

The harmful effects of ship-borne atmospheric emissions are well known, especially CO_2 [8-12], NO_x [13-15], sulfur dioxide (SO_2) [4,14-16], and PM [17-22] are pollutants that have often been emphasized.

Various national and international restrictions have been applied to reduce the effects of these pollutants, among which the regulations contained in MARPOL 73/78 Annex-VI are the most important. The most effective regulations proposed by Annex-VI are Regulations 13 and 14, which contain various restrictions for NO_x and SO_x, respectively. According to Regulation 13, ships are classified as having engines <130 RPM, 130-1999 RPM, and >2000 RPM and as Tier I effective after January 1, 2000, Tier II effective after January 1, 2011, and Tier III [Emission Control Areas (ECAs) only] restrictions effective after January 1, 2016. According to Regulation 14, the allowed fuel sulfur content of 4.5% before January 1, 2012, in regions outside the ECA has been reduced to 0.5% as of January 1, 2020, and this rate has been applied as 0.1% since January 1, 2015, in the ECA regions. In addition to these rules, ships sailing in the European Union waters cannot use fuel containing >0.5% sulfur since January 1, 2020. Similarly, as of January 1, 2020, China has set a maximum sulfur content of 0.1% of the fuel used by ships sailing in its territorial waters and the Yangtze and Xi-Jiang Rivers. The ECA regions include the coasts of North America, US waters in the Caribbean, the Baltic Sea, and the North Sea. Additionally, some studies have declared the Mediterranean as an ECA region as of January 1, 2025 [23].

Despite the measurable positive effects of these restrictions, it is also an essential requirement to take stricter measures. Therefore, in addition to conventional fossil fuels, the tendency to alternative fuels that can replace them has been one of the important issues recently. Suppose the ECA declaration is insufficient due to the risk that it lacks the desired effect in reducing CO_2 and other GHGs and other emissions simply because it proposes a transition from one fossil fuel to another, alternative fuels are increasingly relied upon to improve air quality.

The Sea of Marmara and the Turkish Straits, in addition to being an important waterway with heavy ship traffic, are extremely vulnerable to adverse environmental impacts from ship emissions due to the dense settlement around them. Despite this importance, the literature on ship emissions in this region is limited. The first study on the subject was conducted in 2001, and the total amount of emissions in the Strait of Istanbul and Strait of Canakkale was measured as 353,625 and 347,221 t, respectively [24]. Another study in 2008 focused on ship emissions in the Sea of Marmara, and the amounts of CO_2, NO_x, SO_2, CO, VOCs, and PM produced according to 2003 data were 5,451,224, 111,039, 87,168, 20,281, 5801, and 4762 t, respectively, measured in [25]. In a recent study, the number of total petroleum hydrocarbons measured in water at the outlets of the Turkish Straits and polycyclic aromatic hydrocarbons measured in sediments varied between 1.7-11.6 μg/l and 120-2912 ng/g, respectively [26].

Herein, data about the ships passing through the Strait of Istanbul and Strait of Canakkale, which can be declared ECA after the Mediterranean, were compiled for 2021, and first, the emissions in the current situation were calculated. Then, the emission reduction that may occur in the declaration of the ECA announcement was evaluated. Finally, the scenarios for the widespread use of biodiesel, ethanol, liquefied natural gas (LNG), and methanol were created and the gains to be achieved in using these fuels were calculated. These fuels were chosen because, first, their emission factor data can be accessed since the emission factor inventory of all alternative fuels has not yet been completed. Second, the possibility that these selected fuels have already found use and will be preferred more widely in the near future. The research question of the study seeks to find an answer for which option, alternative fuels, or ECA declaration, provides a more environmentally friendly solution. Herein, only the strait passages were considered, and no calculation was made about the cruise of the ships in the Sea of Marmara. The results of the study will contribute to the declaration of the Sea of Marmara and the Black Sea as the ECA and will provide support for promoting alternative fuel use.

2. Materials and Methods

The Turkish Straits are two important waterways separating Europe and Asia, connecting the Black Sea to the Mediterranean. The Strait of Istanbul is located at 41°07’10” N and 29°04’31” E, whereas the Strait of Canakkale is located at 40.2° N and 26.4° E. The transit routes of the two straits are shown in Figures 1 and 2:

Figure 1. *Route to the Strait of Istanbul*

Figure 2. *Route to the Strait of Canakkale*

While 38,552 (7,168,719 gross registered tonnages) transits were made through the Strait of Istanbul in 2021, the number of passages made through the Strait of Canakkale is 43,343 (11,665,114 gross registered tonnages). While the average transit time of the Strait of Istanbul is 1.8 h, the Strait of Canakkale is crossed in 3.3 h on average. In the emission calculations, all the passages made by the ships in the north-south and south-north directions are included in the calculation. The data were obtained from the Ministry of Transport and Infrastructure of the Republic of Turkey and the Directorate General of Coastal Safety.

Since the fuel consumption data were not recorded, the calculations were conducted according to the engine power method. The formula suggested by Trozzi [27] is as follows:

$$E_{Trip,i,j,m} = \sum_p \left[T_p \sum_e \left(P_e \times LF_e \times EF_{e,i,j,m,p} \right) \right] \quad (1)$$

where;

ETrip: Total emissions (t)

T: Voyage duration (h)

P: Engine power (kW)

LF: Load factor (%)

EF: Emission factor (g/kWh or g/MJ)

p: Voyage phases

e: Engine category

i: Pollutant type

j: Engine type

m: Fuel type

Since there is no engine power of the ships in the data obtained regarding the strait passages, the equations presented in Table 1 were used to determine the engine power depending on the gross registered tonnage:

Table 1. *Engine power-gross registered tonnage equations (y as engine power, x as gross registered tonnage)*

Ship Types	Equation	Reference
General Cargo	$y = 5.3799x^{0.7633}$	[28]
Bulk Carrier	$y = 66.728x^{0.4826}$	
Tanker	$y = 18.189x^{0.6093}$	
Container Ship	$y = 2.5008x^{0.8801}$	
Reefer	$y = 1.2462x^{0.9783}$	
Ro-Ro	$y = 692.09x^{0.2863}$	
Passenger	$y = 0.6379x + 1411.5$	
Fishing	$y = 19.266x^{0.6658}$	
Other	$y = 77.806x^{0.5283}$	
Tugs	$y = 27.303x^{0.7014}$	[29]

Table 2. *Emission factors*

Fuel Type/Pollutant	CO_2	SO_2	CO	HC	NO_x	PM	Unit	Reference
VLSFO (0.5% sulfur)	588	1.85	1.0	0.6	14.4	0.2	g/kWh	[30]
ULSFO (0.1% sulfur)	588	0.37	1.0	0.6	3.4	0.2	g/kWh	
Biodiesel (SVO)	-	0.37	-	-	17.1	0.19	g/kWh	[31]
Biodiesel (FAME)	-	0.36	-	-	17.9	0.18	g/kWh	
Ethanol	257.04*	-	-	-	-	-	g/kWh	[32]
LNG	201.96*	-	-	-	-	-	g/kWh	
	205.2*	-	1.008*	-	0.612*	0.0324*	g/kWh	[33]
	198.72*	-	-	-	-	-	g/kWh	[34]
	446.0	0.88	0.79	-	8.76	0.34	g/kWh	[35]
	412.0	0.003	-	-	1.17	0.027	g/kWh	[31]
Methanol	248.76*	-	-	-	-	-	g/kWh	[32]
	522	-	-	-	3.05	-	g/kWh	[31]
	548.2	-	0.54	-	2.16	-	g/kWh	[36]

*The units presented in g/kWh are given in g/MJ in the original references

Table 3. *Emissions for Strait of Istanbul*

Fuel Type/Pollutant	CO_2	SO_2	CO	HC	NO_x	PM
VLSFO (0.5% sulfur)	199,716.6	628.4	339.7	203.8	4981.0	67.9
ULSFO (0.1% sulfur)	199,716.6	125.7	339.7	203.8	1154.8	67.9
Biodiesel (SVO)	-	125.7	-	-	5808.1	64.5
Biodiesel (FAME)	-	122.3	-	-	6079.8	61.1
Ethanol	87,304.7	-	-	-	-	-
LNG	68,596.5	-	-	-	-	-
	69697.0	-	342.4	-	207.9	11.0
	67,496.1	-	-	-	-	-
	151,485.7	298.8	268.3	-	2975.4	115.5
	139,937.5	1.0	-	-	397.4	9.2
Methanol	84,492.3	-	-	-	-	-
	172,299.4	-	-	-	1035.9	-
	186,198.4	-	183.4	-	733.7	-

Since the gross registered tonnage value of the ships is known, the approximate engine power of the ships can be obtained using the equations presented in Table 1. The cruise time, which is another variable in the formula, is kept separately for each ship and is available as a data set. The engine load of the ships was accepted as 0.8 during cruising. Emission factors are presented in Table 2 for different fuels:

3. Results and Discussions

Tables 3 and 4 present the emission values obtained for the Strait of Istanbul and Strait of Canakkale for 2021, respectively. The emission values are arranged according to the reference order given in Table 2.

The difference between the current situation and the ECA declaration is evident in the first two lines of Tables 3 and 4. Accordingly, the carbon-based emissions (CO_2, CO, and HC) and PM values are unaffected by the ECA declaration. Furthermore, although there is a positive correlation between PM and SO_x emissions, ECA regulations do not seem to provide a direct reduction for PM. However, 80% and 76% reductions were observed in SO_x and NO_x amounts, respectively.

Biodiesels were evaluated as SVO and FAME herein. SVO refers to the biodiesel used directly as fuel, and FAME is a type of fuel called real biodiesel [37,38]. According to the results, biodiesel decreased SO_x formation by ~80% and increased NO_x formation by ~25%. The reason for this may be that biodiesel is used in the form of a mixture with diesel fuel instead of direct use, and this may change the in-cylinder temperature. The lack of a significant effect on PM

Table 4. *Emissions for the Strait of Canakkale*

Fuel Type/Pollutant	CO_2	SO_2	CO	HC	NO_x	PM
VLSFO (0.5% sulfur)	567,598.4	1785.8	965.3	579.2	13,900.4	193.1
ULSFO (0.1% sulfur)	567,598.4	357.2	965.3	579.2	3282.0	193.1
Biodiesel (SVO)	-	357.2	-	-	16,506.7	183.4
Biodiesel (FAME)	-	347.5	-	-	17,278.2	173.8
Ethanol	248,121.6	-	-	-	-	-
LNG	194,952.7	-	-	-	-	-
	198,080.3	-	973.0	-	590.8	31.3
	191,825.1	-	-	-	-	-
	430,525.3	849.5	762.6	-	8456.1	328.2
	397,705.0	2.9	-	-	1129.4	26.1
Methanol	240,128.9	-	-	-	-	-
	503,888.4	-	-	-	2944.2	-
	529,179.3	-	521.3	-	2085.1	-

may also be due to the same reason. The reduction in SO_x and PM emissions is an expected result because biodiesels do not contain sulfur [39-45]. Although studies have shown that biodiesel reduces carbon emissions slightly [46-49], there are also studies showing the opposite. [41,50]. Despite the studies showing that the use of biodiesel reduces NO_x emissions [46,47,51,52], some other studies have shown that this decrement is insignificant [42]. Some studies have indicated that using biodiesel may even increase NO_x emissions [41,53,54].

Ethanol has the chemical formula C_2H_5OH and is the simplest alcohol. It has been observed that ethanol reduces CO_2 emissions by >50%. Studies have proven that ethanol has a reducing effect on PM and NO_x emissions [55]; however, it has been observed that it increases HC emissions [56].

Although it is impossible to reach a definite conclusion due to the different emission factors used for LNG, it is clear that CO_2 emissions have decreased. Also, the use of LNG has a reducing effect on SO_x, NO_x, and PM. LNG is the most studied alternative fuel, and its characteristics are well known. Since LNG does not contain sulfur, it is known to reduce SO_x and PM emissions [57-61]. LNG has also been proven to reduce NO_x emissions in accordance with the Tier-III restrictions [62-64] and to reduce CO_2 [65-68].

Methanol is simple alcohol with the chemical formula CH_3OH. The use of methanol did not dramatically reduce the carbon emissions, but reduced NO_x emissions by 85%. Since it does not contain sulfur, SO_x and PM formation is not expected [55,69-72]. Although it is thought that methanol can reduce NO_x emissions in accordance with the Tier-III restrictions, [69] there are also arguments against it [72].

As seen from the tables and discussions, the expected effects of alternative fuel use on emissions remain unclarified. Some studies support alternative fuels, whereas others offer opposing views. According to the findings obtained herein, there is no fully effective solution for CO_2 emissions from LNG. The reducing effect of fuels, especially LNG, on SO_x emissions is obvious. Significant positive effects were also observed on NO_x and PM, except for biodiesels. The reducing effect of alternative fuels, especially on SO_x and NO_x, is due to the necessity of complying with the restrictions in the scope of MARPOL Annex-VI. This international regulatory pressure is a significant driver for shipowners, companies and fuel manufacturers. However, carbon-zero fuels, such as hydrogen, are highly preferable energy sources for decarbonization, which is another important issue. Biodiesels can be considered a carbon-neutral option as vegetable-based fuels in the carbon cycle. Although the ECA declaration is an ineffective solution for decarbonization at the first stage, it is a very effective method for reducing SO_x and NO_x emissions.

4. Concluding Remarks

Ship emissions are an essential issue that can have very harmful effects, especially for the population living in coastal areas. Ship emissions have been considered a critical issue recently due to their effects on human health, city structures, and global climate change. The Strait of Istanbul and Strait of Canakkale host heavy ship traffic as a significant waterway connecting the Sea of Marmara to the Black Sea and the Mediterranean Sea. Thus, it is inevitable that ship emissions will occur intensively in these regions.

To avoid the negative effects of these emissions, the ships' tendency to use alternative fuels or the declaration of the region as the ECA seem to be two important methods. However, alternative fuels are still in the trial phase, and it will be many years before the establishment of sufficient technical and economic infrastructure for implementing these fuels on all ships, which increases the importance of the ECA declaration. The ECA declaration of the Mediterranean Sea, including the region up to the entrance of the Strait of Canakkale in the Aegean Sea, as of January 1, 2025, will ensure that the Sea of Marmara will also have significant environmental benefits. Herein, the environmental benefits, which positively affect the protection of both the environment and population, to be obtained as a result of the ECA declaration of the Sea of Marmara have been observed. Additionally, it is thought that the development of Annex-VI and ECA rules to cover not only SO_x and NO_x emissions, but also carbon emissions will provide significant benefits.

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