ORDU UNIVERSITY

https://dergipark.org.tr/tr/pub/trjmms

Volume: 9 Issue: 2 DECEMBER 2023 TURKISH JOURNAL OF **MARITIME** AND **MARINE** SCIENCES

ORDU UNIVERSITY

ORDU UNIVERSITY FATSA FACULTY OF MARINE SCIENCES 2003

Volume: 9 Issue: 2 DECEMBER 2023

TURKISH JOURNAL OF **MARITIME** AND **MARINE** SCIENCES

e-ISSN: 2564-7016

TURKISH JOURNAL OF MARITIME AND MARINE SCIENCES

The Turkish Journal of Maritime and Marine Sciences is published by Ordu University
On Behalf of Fatsa Faculty of Marine Sciences

Correspondence Address: Ordu University, Fatsa Faculty of Marine Sciences 52400
Fatsa / Ordu, TURKEY

Web site: http://dergipark.gov.tr/trjmms

Tel: +90 (452) 423 50 53
Fax: +90 (452) 423 99 53
E-mail: trjmms@hotmail.com / trjmms@odu.edu.tr
Sort of Publication: Biannually
Publication Date and Place: 01/12/2023, ORDU, TURKEY
Publishing Kind: Online

TRJMMS ARTICLE SUBMISSION POLICY

1. Turkish Journal of Maritime and Marine Sciences publication language is either Turkish or English, however publications submitted in Turkish should have an English abstract. This Journal is published twice a year.
2. Submitted work shouldn't have been published before (except as oral and poster presentation), the copyright of the work shouldn't have been transferred to anywhere and the work shouldn't be under review in another journal for publication.
3. The type of the submitted work (original research, brief report, technical notes and review) must be indicated.
4. It will not be published elsewhere in English, in Turkish or in any other language, without the written consent of the copyright-holder.
5. It is important for the submission file to be saved in the valid format of the template of word processor used.
6. References of information must be indicated.
7. To avoid unnecessary errors, you are strongly advised to use the 'spell-check' and 'grammar-check' functions of your word processor.
8. Author(s) is/are fully responsible for his/her/their works published in the Journal.
9. A work submitted to the Journal is forwarded to the publishing committee by the editor and evaluated by two or more referees selected by this committee. A work must be approved by the publishing committee and the referees in terms of both scientific content and writing format in order to be accepted for publication. A work rejected for publication is returned to the author(s). A work for which the referee or the editors requested any revisions is sent back to the author(s) for correction according to the given comments and suggestions. Author(s) has/have to convince the publishing committee and the referee(s) about the comments and the suggestions he/she/they disagree(s) with while giving the necessary explanations. Depending on the revision by the author(s) and/or the referee reports for publication, publishing committee decides whether the work is accepted or rejected.
10. A work accepted for publication is sent to the author(s) for the final control before publishing in order to rewrite it according to writing style and format of the Journal. Finally, author(s) approved version of the work is queued for publishing.
11. A person may have two works, as a first author, at most in the same issue.
12. Articles submitted for a possible publication in the journal have been checked with *iThenticate* program to compose similarity report. This report is sent to the editorial board to be checked. If the program detects more than 25 percentage similarity except that the references, the editorial board requests the revisions from the authors. If the necessary changes does not make in 30 days, the article is declined. If the similarity rate is very high, the article is declined, too.
13. Authors are obliged to comply with the TRJMMS Submission Policy.
14. TRJMMS does not charge any article submission or processing charges.

TRJMMS ETHICAL PRINCIPALS AND PUBLICATION POLICIES

- Turkish Journal of Maritime and Marine Sciences (TRJMMS) is an international, refereed, multidisciplinary scientific and technology journal that has been published at least 2 times a year since 2015. Turkish Journal of Maritime and Marine Sciences (TRJMMS) it is committed to provide a platform where highest standards of publication ethics are the key aspect of the editorial and peer-review processes.
- The editorial process for a manuscript to the Turkish Journal of Maritime and Marine Sciences (TRJMMS) consists of a double-blind review, which means that both the reviewer and author identities are concealed from the reviewers, and vice versa, throughout the review process.
- If the manuscript is accepted in the review stage of the Editorial Process then, the submission goes through the editing stage, which consists of the processes of copyediting, language control, reference control, layout and proofreading. Reviewed articles are treated confidentially in Turkish Journal of Maritime and Marine Sciences (TRJMMS).
- **Papers submitted to Turkish Journal of Maritime and Marine Sciences (TRJMMS) are screened for plagiarism with the iThenticate plagiarism detection tool. In case that the editors become aware of alleged or proven scientific misconduct, they can take the necessary steps. The editors have the right to retract an article whether submitted to Turkish Journal of Maritime and Marine Sciences (TRJMMS) or published in Turkish Journal of Maritime and Marine Sciences (TRJMMS).**
- **Following the completion of the editing stage, the manuscript is then scheduled for publication in an issue of the Turkish Journal of Maritime and Marine Sciences (TRJMMS). The articles which are submitted to Turkish Journal of Maritime and Marine Sciences (TRJMMS) to be published are free of article submission, processing and publication charges. The accepted articles are published free-of-charge as online from the journal website. The articles that are accepted to appear in the journal are made freely available to the public via the journal's website.**
- Turkish Journal of Maritime and Marine Sciences (TRJMMS) has chief editor, section editors and an editorial board. Turkish Journal of Maritime and Marine Sciences (TRJMMS) has an open access policy which means that all contents are freely available without charge to the user or his/her institution. Users are allowed to read, download, copy, distribute, print, search, or link to the full texts of the articles, or use them for any other lawful research purposes.
- **Publication ethics of the Turkish Journal of Maritime and Marine Sciences (TRJMMS) are mainly based on the guidelines and recommendations which are published by the Committee on Publication Ethics (COPE), Council of Science Editors (CSE) and Elsevier's Publishing Ethics for Editors statements. It must be obeyed research and publication ethics in the article submitted by authors.**

The duties and responsibilities of all parties in the publishing process including editors, authors and others are defined below.

<u>The Responsibilities of the Authors</u>

1. Authors are responsible for the scientific, contextual, and linguistic aspects of the articles which are published in the journal. The views expressed or implied in this publication, unless otherwise noted, should not be interpreted as official positions of the Institution.
2. Authors should follow the "Author Guidelines" in Turkish Journal of Maritime and Marine Sciences (TRJMMS)'s web page on DergiPark.
3. Authors should conduct their researches in an ethical and responsible manner and follow all relevant legislation.
4. Authors should take collective responsibility for their work and for the content of their publications.
5. Authors should check their publications carefully at all stages to ensure that methods and findings are reported accurately.
6. Authors must represent the work of others accurately in citations, quotations and references.
7. Authors should carefully check calculations, data presentations, typescripts/submissions and proofs.
8. Authors should present their conclusions and results honestly and without fabrication, falsification or inappropriate data manipulation. Research images should not be modified in a misleading way.
9. Authors should describe their methods to present their findings clearly and unambiguously.
10. Authors accept that the publisher of Turkish Journal of Maritime and Marine Sciences (TRJMMS) holds and retains the copyright of the published articles.
11. Authors are responsible to obtain permission to include images, figures, etc. to appear in the article.
12. In multi-authored publications - unless otherwise stated - author rankings are made according to their contributions.
13. Authors should alert the editor promptly if they discover an error in any submitted.
14. Authors should follow the TRJMMS Article Submission Policy regarding that the submitted work is original and has not been published elsewhere in any language.
15. Authors should work with the editor or publisher to correct their work promptly if errors are discovered after publication.
16. If the work involves chemicals, procedures or equipment that have any unusual hazards inherent in their use, the authors must clearly identify these in the manuscript.
17. If the work involves the use of animals or human participants, the authors should ensure that all procedures were performed in compliance with relevant laws and institutional guidelines and that the appropriate institutional committee(s) has approved them; the manuscript should contain a statement to this effect.
18. Authors should also include a statement in the manuscript that informed consent was obtained for experimentation with human participants. Because the privacy rights of human participants must always be preserved. It is important that authors have an explicit statement explaining that informed consent has been obtained from human participants and the participants' rights have been observed.
19. Authors have the responsibility of responding to the reviewers' comments promptly and cooperatively, in a point-by-point manner.

The Responsibilities of the Reviewers

1. Peer review process has two fundamental purposes as follow: The first purpose is to decide whether the relevant article can be published in Turkish Journal of Maritime and Marine Sciences (TRJMMS) or not and the second purpose is to contribute to the improvement of the weaknesses of the related article before the publication.
2. The peer review process for an article to the Turkish Journal of Maritime and Marine Sciences (TRJMMS) consists of a double-blind review, which means that both the reviewer and author identities are concealed from the reviewers, and vice versa, throughout the review process. Reviewed articles are treated confidentially in Turkish Journal of Maritime and Marine Sciences (TRJMMS).
3. Reviewers must respect the confidentiality of peer review process.
4. Reviewers must refrain from using the knowledge that they have obtained during the peer review process for their own or others' interests.
5. Reviewers should definitely be in contact with the Turkish Journal of Maritime and Marine Sciences (TRJMMS) if they suspect about the identity of the author(s) during the review process and if they think that this knowledge may raise potential competition or conflict of interest.
6. Reviewers should notify the Turkish Journal of Maritime and Marine Sciences (TRJMMS) in case of any suspicion regarding the potential competition or conflict of interest during the review process.
7. Reviewers should accept to review the studies in which they have the required expertise to conduct an appropriate appraisal, they can comply with the confidentiality of the double-blind review system and that they can keep the details about the peer review process in confidential.
8. Reviewers should be in contact with the Turkish Journal of Maritime and Marine Sciences (TRJMMS) in order to demand some missing documents, following the examination of the article, supplementary files and ancillary materials.
9. Reviewers should act with the awareness that they are the most basic determinants of the academic quality of the articles to be published in the journal and they should review the article with the responsibility to increase academic quality.
10. Reviewers should be in contact with the Turkish Journal of Maritime and Marine Sciences (TRJMMS) editors if they detect any irregularities with respect to the Publication Ethics and Responsibilities.
11. Reviewers should review the articles within the time that has been allowed. If they can not review the article within a reasonable time-frame, then they should notify the journal as soon as possible.
12. Reviewers should report their opinions and suggestions in terms of acceptance / revision / rejection for the manuscript in the peer review process through the Referee Review Form which is provided by DergiPark.
13. In case of rejection, reviewers should demonstrate the deficient and defective issues about the manuscript in a clear and concrete manner in the provided Referee Review Form.
14. Review reports should be prepared and submitted in accordance with the format and content of the Referee Review Form which is provided by Turkish Journal of Maritime and Marine Sciences (TRJMMS).
15. Review reports should be fair, objective, original and prudent manner.
16. Review reports should contain constructive criticism and suggestions about the relevant article.

The Responsibilities of the Editors

1. Editors are responsible of enhancing the quality of the journal and supporting the authors in their effort to produce high quality research. Under no conditions do they allow plagiarism or scientific misconduct.
2. Editors ensure that all submissions go through a double-blind review and other editorial procedures. All submissions are subject to a double-blind peer-review process and an editorial decision based on objective judgment.
3. Each submission is assessed by the editor for suitability in the Turkish Journal of Maritime and Marine Sciences (TRJMMS) and then, sent to the at least two expert reviewers.
4. Editors are responsible for seeking reviewers who do not have conflict of interest with the authors. A double-blind review assists the editor in making editorial decisions.
5. Editors ensure that all the submitted studies have passed initial screening, plagiarism check, review and editing. In case the editors become aware of alleged or proven scientific misconduct, they can take the necessary steps. The editors have the right to retract an article. The editors are willing to publish errata, retractions or apologies when needed.

TRJMMS OPEN ACCESS POLICY

TRJMMS is an open access journal. The term open access gives the right of readers to read, download, distribute, copy, print, search, or link to the full texts of the articles free of charge. This is in accordance with the BOAI definition of open access. According to BOAI (Budapest Open Access Initiative); By “open access” to peer-reviewed research literature, its free availability on the public internet, permitting any users to read, download, copy, distribute, print, search, or link to the full texts of these articles, crawl them for indexing, pass them as data to software, or use them for any other lawful purpose, without financial, legal, or technical barriers other than those inseparable from gaining access to the internet itself. The author(s) and copyright holder(s) grant(s) to all users a free access to articles.

TRJMMS PLAGIARISM POLICY

Plagiarism can take place in two forms:

1. Author(s) deliberately copy someone else’s work and claim it as own work.
2. Author(s) copy their own previously published material either in full or in part without providing appropriate references called as “self-plagiarism” or “duplicate publication”

Every manuscript submitted for publication to TRJMMS is checked for plagiarism after submission and before being sent to reviewer for evaluation.“iThenticate” is used to detect instances of overlapping and similar text in submitted manuscript. Depending on this report, the articles can be declined or can be submitted to the editor to be evaluated.

TRJMMS ADVERTISEMENT POLICY

1. All advertisements depend on approval of the Publisher or Editor.
2. Scientific content and decisions made by editorial board have not been affected by advertising.
3. Advertisements are separate from the scientific content.
4. Sales and marketing of the products within the accepted advertising are unfeasible.
5. Editor or publisher of the journal is not responsible for advertisement and its content. This responsibility entirely belongs to owner of advertising.
6. Accepted advertisement can be placed on any page approved by the editor or publisher.
7. Advertising is done according to the contract between advertising company and journal management.
8. Advertising content has not included any distinction of language, religion, race, gender, age, disability and etc.
9. Advertising that contrary to society and publication ethics must not be published.
10. Advertising that produced according to national rules and fulfilling their obligations such as license are accepted for publishing.
11. Advertisements must be prepared in accordance with competition laws and other relevant regulations.
12. Journal management shall not be liable for pecuniary loss due to errors of the advertising content.

CONTENT

Research Article
Turkish Journal of Maritime and Marine Sciences

DOI: 10.52998/trjmms.1272543
Volume: 9 Issue: 2 (2023) 66-81

Impacts of the Form Design and Operational Factors on the Energy Consumption of a Solar-Powered Boat: A System Dynamics Approach

Güneş Enerjili Bir Teknenin Enerji Tüketimi Üzerinde Form Tasarımı ve İşletme Faktörlerinin Etkileri: Bir Sistem Dinamiği Yaklaşımı

Türk Denizcilik ve Deniz Bilimleri Dergisi

Cilt: 9 Sayı: 2 (2023) 66-81

Burak GÖKSU[1], Onur YÜKSEL[1,*]

[1]*Zonguldak Bulent Ecevit University, Maritime Faculty, Marine Engineering Department, Zonguldak, Turkiye*

ABSTRACT

This research paper aims to design a solar-powered boat and analyze the effects of environmental and form-related factors on power consumption and battery duration by utilizing a system dynamics approach-based simulation. The boat form is designed as the planing hull and its hull resistance analysis was ensured in Maxsurf package program. PV panels with 548 W power output and two battery packs with 4660 Wh capacity were placed on the hull body to employ an electric motor with a 10-kW nominal power output. Two MPPTs were implemented in the system to increase solar system efficiency. The relationships between all system components were modelled in Vensim software to observe battery endurance changes under different conditions. Results demonstrated that the ideal vessel speed is calculated to be around 7 knots with roughly 8 hours of battery duration for the designed boat. A critical stage of charge for sailing is 40% since 1.63 hours of cruising time may be achieved while maintaining a speed of 5 m/s (9.72 knots). Indeed, the boat's rising trim angle shortens the battery discharge time; thus, navigation by no trim angle is the most effective usage for the vessel.

Keywords: Solar-powered boat, System dynamics, Photovoltaic system, Renewable energy

Article Info
Received: 28 March 2023
Revised: 29 May 2023
Accepted: 29 May 2023

[*](corresponding author)
E-mail: onur.yuksel@beun.edu.tr

To cite this article: Göksu, B., Yüksel, O., (2023). Impacts of the Form Design and Operational Factors on the Energy Consumption of a Solar-Powered Boat: A System Dynamics Approach, *Turkish Journal of Maritime and Marine Science* 9 (2): 66-81. doi: 10.52998/trjmms.1272543.

ÖZET

Bu araştırma makalesi, güneş enerjisiyle çalışan bir tekne tasarlamayı ve çevresel ve biçimle ilgili faktörlerin güç tüketimi ve batarya süresi üzerindeki etkilerini sistem dinamiği yaklaşımına dayalı bir simülasyon kullanarak analiz etmeyi amaçlamaktadır. Tekne formu, kayma gövdesi olarak tasarlanmış ve gövde direnci analizi Maxsurf paket programında yapılmıştır. 548 W güç çıkışına sahip PV paneller ve 4660 Wh kapasiteli iki adet pil paketi, 10 kW nominal güç çıkışına sahip bir elektrik motorunu çalıştırmak için gövde gövdesine yerleştirilmiştir. Güneş enerjisi sistemi verimliliğini artırmak için sistemde iki adet MPPT kullanılmıştır. Tüm sistem bileşenleri arasındaki ilişkiler, farklı koşullar altında pil dayanıklılık değişikliklerini gözlemlemek için Vensim yazılımında modellenmiştir. Sonuçlar, tasarlanan tekne için ideal tekne hızının yaklaşık 8 saat batarya kullanım süresi ile 7 knot hesaplandığını göstermiştir. %40 şarj durumu seyir için kritik bir olarak belirlenmiştir, çünkü hız 5 m/s (9,72 knot) sabit tutularak %40 seviyesinde 1,63 saat seyir süresi sağlanabilmektedir. Teknenin artan trim açısı akünün deşarj süresini kısaltmaktadır ve trim açısı olmadan seyir tekne için en etkili kullanım olarak belirlenmiştir.

Anahtar sözcükler: Güneş enerjili tekne, Sistem dinamikleri, Fotovoltaik sistem, Yenilenebilir enerji

1. INTRODUCTION

Technological improvements and the growth of population yield a remarkable increase in the energy demand around the Globe (Kannan and Vakeesan, 2016). Fossil fuels have met the raised energy demand since the 1800s; however, the world has faced crucial environmental issues because of exploiting fossil fuels. The emerging problems can be classified as major environmental accidents, water pollution, marine pollution, land use and sitting impact, solid waste disposal, hazardous air pollutants, poor air quality, acid rain, stratospheric ozone depletion, and global climate change. In addition, fossil fuel reserves have been depleted since they are non-renewable sources. That's why the utilization of Renewable Energy Sources (RESs) in every industry becomes a more significant issue considering the current environmental and economic situation in the World (Dincer, 2000; Kannan and Vakeesan, 2016; Mueller and Wallace, 2008).

The maritime transportation industry unquestionably harms environmental factors (Eyring *et al.*, 2005). A 2021 analysis from the International Energy Agency noted that international maritime freight transit accounts for around 2% of energy-based CO_2 emissions. (Connelly and Idini, 2022). Over the past ten years, the International Maritime Organization (IMO) has established ambitious objectives to reduce greenhouse gas emissions from maritime traffic. The IMO has set a target of at least a 40% decrease in carbon emissions from 2008 to 2030 (Ivanova, 2021). The Energy Efficiency Existing Ship Index (EEXI), released on June 17, 2021, replaced the Energy Efficiency Design Index (EEDI) to lower carbon emissions from existing ships. Using the weight of the cargo carried and the distance travelled, EEXI determines the ship's energy efficiency and displays its carbon emissions (Spinelli *et al.*, 2022). The EEXI-linked Carbon Intensity Indicator (CII) reduction factor measures how much operation-based carbon intensity has been reduced. If a marine vessel has 5000 gross tons (GT) or more, its CII performance must be monitored annually, and the CII and EEXI documentation has to be completed by January 1, 2023. Passenger ships and oceangoing freight boats with 400 GT or more must compute their EEXI. The approaching, brief deadline prompts the vessel's crew to use and improve energy-efficient technology and alternative energy sources (Konur *et al.*, 2023; S. Wang *et al.*, 2021).

Some significant challenges and issues exist in the field of RESs. The most crucial ones can be listed as survivability, reliability, and affordability. The decided system's resource selection must consider precise projected effective operating circumstances. A well-integrated renewable energy system results in fewer interactions between the parts. The design parameters of the system will be assessed and chosen using numerical modelling tests and calculations (Mueller and Wallace, 2008). Different types of energy sources and their potentials are considered when determining a renewable energy source for a system. In the literature, the potentials of alternative energy sources are examined under the following five different aspects (Hoogwijk and Graus, 2008):

- Theoretical potential is the highest level of potential. This only accounts for natural and climate parameter constraints.
- The geographical potential is a theoretical potential reducing factor that most renewable energy sources have geographical restrictions, e.g., land use and land cover. The geographical potential is the theoretical potential constrained by the resources in geographical regions.
- The technical potential is further reduced geographical potential due to technical limitations in conversion efficiency.
- Economic potential is the technical potential for cost levels considered competitive.
- Market potential refers to the total amount of renewable energy that can be applied on the market, considering market potential, energy demand, competing technologies, costs and subsidies of renewable energy sources, and obstacles. The market potential, including opportunities, may be greater than theoretically the economic potential, but it will turn into potential market potential due to potential hindrances.

Solar-powered boats are becoming increasingly popular for recreational and daily use since they are quiet, reliable, maintenance-free, and simple to operate. The case boat in this study, which will be used for both transportation and pleasure without polluting the environment, is constantly charged by the sun throughout daytime hours, eliminating the need for fossil fuel replenishment. This single-passenger capacity concept vessel can transfer energy from the main line during the time it is moored to the dock on cloudy days or is heavily utilized. This design, which enables personal use, is intended for use in touristic areas such as Izmir and regions with year-round long sunlight hours.

2. LITERATURE REVIEW

Considering the information given before in this research and the goals set by IMO, solar energy utilization is a reasonable choice for marine vessels. Especially for small ships, the electric motor, battery, and photovoltaic (PV) combination can provide decent propulsion. Small marine vessels can now use battery and electric motor propulsion due to technological enhancements to guarantee zero-emission ships (Solangi *et al.*, 2011). The all-electric ship (AES) and hybrid-powered ship concepts have been the subject of some research papers published in the previous decade. Nóbrega and Rössling, (2012) presented a design for a pleasure ship having a hybrid propulsion unit. The calculations and analyses have been carried out for the PV panel and diesel engine. Rivera-Solorio *et al.* (2013) designed and constructed an AES by utilizing computational fluid dynamics (CFD) within the scope of a student project. Cupelli *et al.* (2015) reviewed the technological progress of network architectures and approaches for AESs regarding network stability. Kabir *et al.* (2017) retrofitted a conventional ferry into a solar-powered boat with 1 kW solar panels and 9600 Wh energy storage units. Batteries that are fully charged can propel the vessel 60 kilometers at a speed of 3 knots. Balsamo *et al.* (2017) presented a novel energy management strategy (EMS) for a hybrid storage system involving batteries and supercapacitors for an AES using a simulation written in MATLAB/Simulink environment. Banjarnahor *et al.* (2017) designed a wind and solar energy harvester to supply energy for a refrigerator in a fishing boat. Solar panels provided daily 815-817 Wh of energy while wind turbines ensured 43-62 Wh that met the energy demand of the fishing boat. Nasirudin *et al.* (2017) introduced a methodology to optimize and determine the size of a PV system considering the minimum cost. The golden search algorithm is utilized to gather minimum propulsion power, and the Simplex algorithm is used to reduce battery and PV module costs. The optimal design is found as 32 PV modules (8.96 kW) and 32 batteries (34.56 kWh), while water line dimensions are 14.44 meters long, 4.37 meters wide, 0.852 meters deep, and 16.258 tons in total displacement. The PV system's annual capital cost is around $3557. Tamunodukobipi *et al.* (2018) analyzed the design of a solar-powered light weigh leisure AES. The ship had the catamaran form, and the resistance was calculated as 740 N at 5 knots using Savitsky and CAHI techniques. 3 HP of Electric motors and batteries having 235 Ah capacity were chosen, regarding the propulsion system the size of the PV module was determined. Kurniawan and Shintaku (2018) ensured a control strategy for PV power distribution in an AES. When the PV array voltage is kept above 95 V, the maximum power from the PV panel can be obtained with 99% efficiency. Chao *et al.* (2018) conducted research that involved a design for a PV power distribution of a marine vessel system having ten PV panels, a maximum power point tracker (MPPT), and a controller. The proposed system improved energy efficiency by approximately 28%, while the solar system met 40-50% of total power depending on sunlight exposure. Leung and Cheng, (2018) ensured an analysis based on various case studies for a solar-powered ship design. The results depicted that PV panel utilization can reduce up to 77.42% of CO_2, depending on the panel efficiency. Obaid *et al.* (2019) designed and simulated a hybrid electric-powered boat that includes a fuel cell, wind, and solar energies with an MPPT system. The simulation's outcomes can be used to indicate how the electric boat can keep going even when the wind and sun irradiance change. Pakhmode *et al.* (2019) provided a solar-powered water surface garbage gathering ship design to prevent water pollution and to assist with safety and security-related duties.

System Dynamics (SD) approach is one of the system thinking methodologies that avoids most jargon and complex explanations while operating in a whole-system approach (Hjorth and Bagheri, 2006). SD has been utilized to evaluate energy systems and their environmental sustainability in various fields. Anand *et al.* (2006) applied the SD approach to evaluate the reduction of CO_2 emissions from the cement industry. Results showed that based on an integrated reduction scenario introduced in the paper, a 42% reduction in CO_2 emissions can be ensured. Aslani *et al.* (2014) discussed and analyzed energy dependency and the impact of the policies in Finland. Despite Finland's projected 7% increase in power and heating demand by 2020, analysis indicates that import dependence will decline by 1% to 7%, depending on the scenarios used. Pizzitutti *et al.* (2017) carried out research that comprises a decision-support framework for tourism management in the Galapagos Islands of Ecuador using the SD method. The remarkable issues for the region to enlarge the human occupation are found as the unique natural ecosystem of the Islands is under threat from an increasing number of invasive species, and the capacity of the Galapagos National Park to receive tourists is quickly being reached. Esmaieli and Ahmadian (2018) conducted a simulation of the long-term electricity market using the SD method to observe the impact of the current and proposed research and development encouragements on wind energy investments. The outcomes showed that the suggested incentive was more successful than other well-known encouragements. Gravelsins *et al.* (2018) modelled the flexibility of energy generation using the SD method. Findings demonstrated that the limitations of intermittent power generation from renewable sources that can be integrated into the power system are raised by the consequences of technological disruption in the model. Jia *et al.* (2019) investigated the impact of the air pollution charging fee (APCF) policy to lower haze pollution in China using a dynamic simulation based on the SD approach. The simulation results demonstrated that the APCF policy successfully achieved the beneficial scenario of pollution reduction and congestion release. Liu *et al.* (2019) assessed the energy performance gaps of green offices in China using an SD methodology. The findings suggest that building managers should focus more on interactions with regular tenants and less on messages with austerity inhabitants to raise occupant awareness of energy conservation.

Pereira *et al.* (2020) analyzed the effects of energy change in medium-sized industries on the sustainability of small and medium industries using the combination of the fuzzy cognitive mapping and SD method. The experts validated the model's performance, and the authors also examined their constructivist, process-oriented framework's benefits, drawbacks, and implications for both study and practice. Pan *et al.* (2021) provided an SD simulation to evaluate the effectiveness of trading policies related to carbon emission reduction. Results indicated that a successful emission reduction could be achieved with the utilization of multiple policies. Joshi *et al.* (2021) ensured an SD-based simulation to assess the effect of the policies on recycling lead-acid batteries. Although a very high subsidy can result in the closure of regulated and unregulated recycling businesses, the authors' findings show that subsidizing formal batteries can minimize the amount of lead excretion. Baskoro *et al.* (2021) evaluated the coal utilization scenarios in Indonesia using the SD methodology. The findings indicate that Indonesia's coal production will rise in the future. Among these scenarios, an environmentally oriented scenario can lead to 33.5% of coal, 19.4% of oil, 7.8% of gas, and 39.3% of RES usage. Mobaseri *et al.* (2021) investigated waste reduction in the food industry and its environmental impact using the SD methodology. Based on the findings, annual food demand and energy consumption increases will be 1.35% percent and 3.31%, respectively. In these conditions, pollution emissions increase by 4% annually, reaching 1.13 million tons in 2031. Sheheryar *et al.* (2021) estimated CO_2 emission reduction through the utilization of ultrahigh-performance concrete instead of ordinary Portland cement concrete using the SD method. Results indicated that the usage of mentioned concrete can reduce CO_2 emission by 17%. Stasinopoulos *et al.* (2021) conducted an SD approach-based analysis of the GHG emission reduction potential using an autonomous vehicle fleet. The findings revealed that the greenhouse gas intensity of the energy supply and fuel efficiency of internal combustion engine vehicles have the greatest impact on reducing greenhouse gas emissions. Although the benefits may be offset by autonomous vehicles' inefficiency and increased demand. Ye *et al.* (2021) analyzed the efficiency of a certified emission reduction scheme in China and its impacts on CO_2 emissions through case scenarios using the SD approach. Findings depicted that the double trading market scenario compared to the baseline scenario can produce much extra cost savings over time. Daneshgar and Zahedi (2022) assessed the probability and generation capacity of hydropower plants using the data gathered from Karun 1 and SD approach. Different scenarios were tried regarding water release methods and cost limits. The findings depicted that the most profited scenario provided 3047 $/MW for two years and was the discharging of 15% of the dam. Francis and Thomas (2022) presented a methodology named dynamic life cycle sustainability assessment based on SD methodology. The case study findings demonstrate that underestimating general sustainability impacts by around 50% and specific environmental impacts by about 12% when time-dependent dynamic factors are ignored in building sustainability assessments. Kong *et al.* (2022) examined the impact of carbon reduction amendments on the maritime supply chain using a case-based SD approach. The outcomes demonstrate that shore power has a huge potential for lowering emissions. Shadman *et al.* (2022) investigated the implementation, future, and role of RES in Malaysia by utilizing the SD approach in terms of aspects of energy security. The results indicated that Malaysia's total environmental sustainability can be improved, and its reliance on energy imports can be decreased. Eftekhari Shahabad *et al.* (2022) explored the impacts of the incentives for solar panels utilized in houses using SD methodology through a case study in Iran. Results highlighted that it is vital to implement additional policies in addition to subsidies, such as building sizable renewable power plants or deconstructing outdated inefficient fossil fuel power plants.

The first part of the literature review involved the RES-powered ship and illustrated that the AES concept was analyzed majorly in terms of ship design, EMS optimization, microgrid enhancements, economic analysis, route optimization, and component sizing. The second part of the review was about SD approach-based simulations about energy modelling, energy dependency analysis, and PV panel utilization in various fields such as cement and automotive industries. Studies also investigated emission reduction strategies and predictions of energy source distribution by using the SD approach. The review depicted that there has been a research gap in the evaluation and enhancement of the solar-powered marine vessel's performance by utilizing SD methodology. This study's objectives include designing a solar-powered boat and using an SD approach-based simulation to examine how environmental and form-related elements affect power consumption and battery life. The SD technique is a well-known and practical methodology that can successfully simulate this kind of dynamic system. The boat form is designed as the planing hull type and its analysis were ensured in Maxsurf software. Boats with planing hulls are made to rise up and glide over the water when enough power is applied (Savitsky, 1964). PV panels with 548 W power output and two battery packs with 4660 Wh capacity were placed on the hull body to employ an electric motor with a 10-kW nominal power output. Two MPPTs were implemented in the system to increase efficiency. Vensim software was used to simulate the relationships between every system component to track variations in battery endurance under various circumstances. The main motivation is to optimize the energy demand for components of PV-powered boats and to attain increased battery discharge time.

3. SYSTEM DESCRIPTION

The investigated system configuration involves PV panels, MPPT, battery sets, an electric motor and propeller, and the hull. The specifications of the system components shown in the diagram are presented in Table 1.

Four of SP-137 model solar panels were selected to produce energy to be used in the system. Two pairs of panels are connected in series, and then both are connected in parallel to obtain 48 volts and keep the panel output amperage value low. The output voltage of the solar panels varies according to the amount of irradiation on the panel surfaces. Hence, a device, which restricts the flow direction, must be added to the system after each panel pair. Diodes direct electric current in one direction and are the most compatible items for this purpose (Ellenbogen and Christopher Love, 2000). Two high-performance lithium-ion batteries are connected in series and each battery is fed by one MPPT to obtain the voltage that will fill the batteries from the solar panels. A battery has a 25.9 V nominal output voltage and due to the series connection of the batteries, approximately 50 V output voltage will be attained. This connection is needed for the 48 V electric motor input value. The required power of the electric motor is adjusted with Torqeedo remote throttle. The setting will change the angular velocity of the propeller to reach the desired speed of the boat. In Figure 1, the schematic of the system is illustrated.

Table 1. Selected components of the system

PV panels	MPPT	Battery	MCU	Electric motor and propeller	Hull
Solbian SP-137 137 Watt 24 V 5.7 A Eff.%22.5 Monocristal silicon cells	Outback Flexmax 80 12-60 VDC battery charge voltage Eff. %98	Torqeedo Power 26-104 High-performance lithium battery 25.9 nominal voltage 180 A max discharge	Torqeedo top mounting throttle	Torqeedo Cruise 10.0 R electric motor 48 V nominal voltage 10kW input power Eff.%56 and v32/p10k propeller	4900 mm overall length, 700 mm molded beam, and 800 mm depth fiberglass planing hull

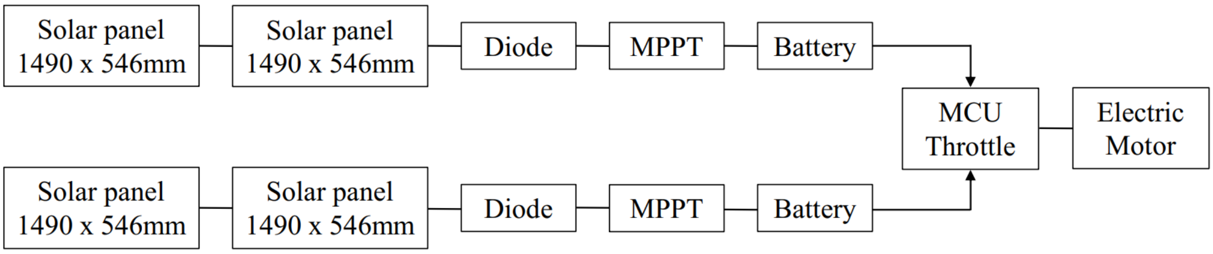


Figure 1. Diagram of system components

Each solar panel consists of 44 PV cells, and a PV cell has an area of 165 cm^2. Thus, a solar panel has a total area of 0.726 m^2. Four solar panels will be used in the system so that the total PV cell area will reach 2.9 m^2. The total theoretical power output is calculated as 548 watts. The selected Flexmax80 model MPPT can work up to 60 VDC and has an 80-amperage maximum output current. Each lithium battery has 4660 W maximum discharge power, so the designed system will have 9320 W power. This total capacity will be controlled by the motor control unit (MCU) (Torqeedo top mounting throttle) to provide power to the motor from batteries. Torqeedo Charger Power 26-104 model battery chargers will fill the batteries when the irradiation is insufficient. During the boat hull design phase, the total weight of the system's equipment and the driver's weight were evaluated, and the hull was formed regarding the weights given in Table 2.

Table 2. Weights of the system components

Component	Weight (kg)
4 x Solar panel	8
2 x MPPT	11
2 x Lithium battery	48.6
Electric motor	61.3
Driver	75
Miscellaneous	25
Hull	50
Total	278.9

The total weight of the solar-powered boat has reached 278.9 kg. Hence, the displacement of the boat must be this value. Moreover, when the boat's draft is at 165 mm, it gives 278.4 kg displacement weight. To calculate the power output from the PV panels, solar radiation data of the Izmir Gulf, where the boat is designed to operate, are used. The mean of monthly irradiation values is used in the calculations. Figure 2 indicates the monthly irradiation data for the Izmir region.

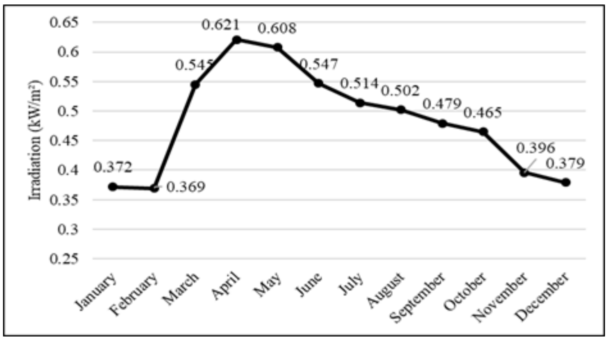


Figure 2. Irradiation values of Izmir (Cedar Lake Ventures, 2022)

4. MODELING

Hull design calculations have been provided using Maxsurf software which is a commonly used naval architecture program in similar projects and academic studies (Bentley, 2022). The designed hull is considered a chined hull form when the boat reaches the required planing speed, and hydrodynamic forces can lift the total boat weight (Lindbergh and Ahlstrand, 2020). To optimize a photovoltaic system, it is necessary to determine the functions and locations of the components in the system. Also, the relationship between the components of the system must be defined. The whole system from where the energy is produced to where it is consumed is shown in Figure 3.

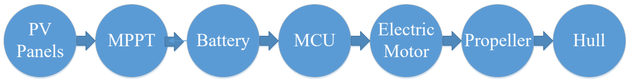


Figure 3. Solar-powered boat energy flow

The power of the PV system is generated as voltage in solar cells, which is converted by MPPT to the maximum power point at the highest voltage value. An MPPT is a DC-DC converter attached between the solar panels and their load to obtain optimum matching. The output power characteristics of the PV system as functions of solar irradiation and temperature curves are not linear and are influenced by irradiation and temperature. These continuous fluctuations affect the PV operating point; therefore, it must be fixed at the best voltage. The required energy for the electric motor is provided from batteries with the help of MCU that adjust the battery output voltage regarding the power by the electric motor. Depending on the desired speed, the interaction between hull and water varies, and consequently, electric motor needs various power consumption values. The trim angle and the propeller velocity are also affected by boat speed, and due to the change in ship resistance, the total power needed is altered by direct or indirect factors of the whole PV-powered boat (Walker, 2001).

The relationship between power consumption, battery discharge, and PV Panel battery charge has been explained by using the SD approach. The system model is developed in Vensim which provides a dynamic SD-based simulation environment (Ventana Systems, 2015). SD is a strategy for analyzing and handling dynamic issues in intricate feedback. The following steps make up the approach for system dynamics modelling (Gravelsins *et al.*, 2018):

- Specifying the dynamic problem's definition and the modelling's objective,
- Developing the dynamic hypothesis based on the researched system's structure,
- Establishing the fundamental elements of the model as a set of parameters, feedback loops, and ticks (which accumulate flows and govern stock level),
- Validation of the model,
- Testing the policies to identify the most important variables that can be altered to improve the system's undesirable behavior.

The electric motor consumes power while the batteries are being charged by the panels. Battery endurance time stands out in this system. When all irradiation values are suitable, all batteries can be charged from 0% to 100% in approximately 17 hours with PV panels. At this point, effective usage of the solar-powered boat becomes prominent. Relationships among boat hull resistance at various speeds, total panel power, propulsion efficiency, and total battery capacity must be well adjusted to attain long battery durations for usage. For this purpose, all variables in the system were mapped in Figure 4 with Vensim software. To observe battery endurance time according to alterations of all parameters.

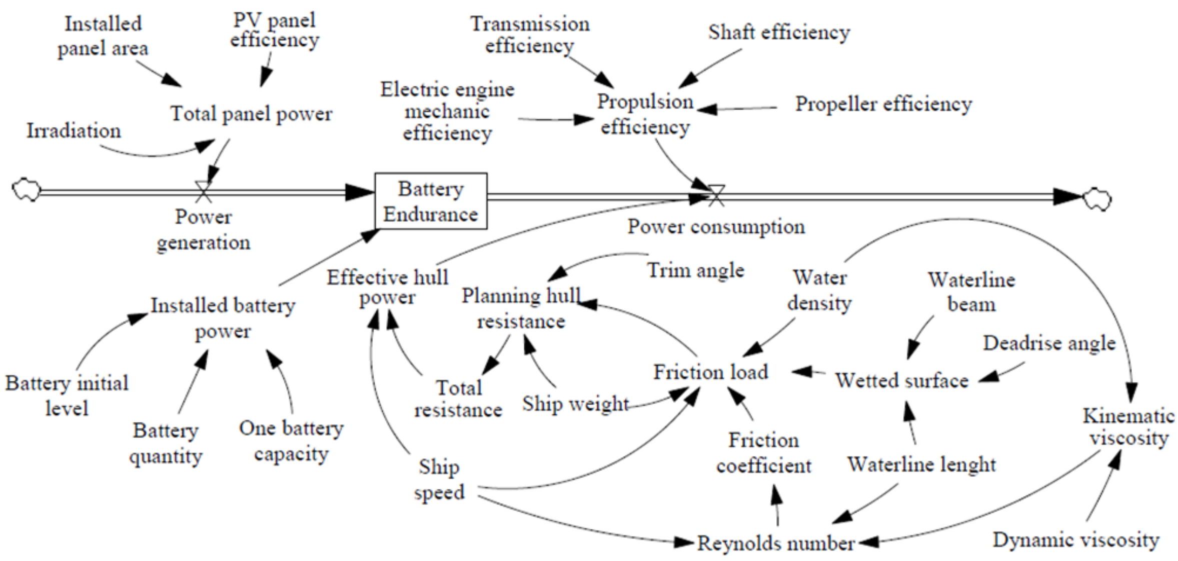


Figure 4. System dynamics model of the solar boat

The resistance of a ship at a given speed is the towing force at that velocity in smooth water. If there are no appendages on the boat, this value is named bare hull resistance. The required power to overcome this resistance is calculated using Equation 1.

$$P_E = R_T \times V \quad (1)$$

where P_E is effective power (kW), R_T represents total resistance (kN), and V is the velocity in m/s (Lewis, 1998). R_T has some components, generally R_H (bare hull drug), R_{AP} (appendages drag), R_A (air drag) and R_{PAR} (parasitic drag) are considered to calculate ship resistance (Lindbergh and Ahlstrand, 2020). The bare hull resistance value equals the addition of pressure and frictional resistance. Appendage drag includes shaft bosses and brackets, rudders, stern frames, etc. Air drag is affected by the above-water part of the main hull and superstructures because of the movement of the boat through the air (Saral and Köse, 2020). The calculation of R_T is shown in Equation 2 (Lewis, 1998).

$$R_T = R_H + R_{AP} + R_A + R_{PAR} \quad (2)$$

In this study, the R_A air drag value is considered zero because of the lack of above-water area and superstructure body. Also, due to the type of selected electric motor, there is no rudder, and the total electric motor efficiency calculated from the producer R_{AP} is ignored. R_{PAR} is neglected not only because it has a lower effect but also because the technology implementation has improved (Lewis, 1998). Since these neglected resistance components, the calculation has been ensured under the assumption of R_T= R_H. All the used formulas belong to the Savitsky method, which is one of the methods of calculating the bare hull resistance of planing hulls (Lindbergh and Ahlstrand, 2020). According to the Izmir Gulf's annual mean sea water temperature (18.5ºC), kinematic viscosity will be used v=1.055 m^2/s. The water density of the seawater in Izmir Gulf is taken as 1025 kg/m^3 (Eronat, 2017; Pazi and Ozturk, 2012).
Equation 3 illustrates the formula for calculating the energy produced by PV panels (Aijjou *et al.*, 2019).

$$E = A_p * \eta * H_a * P_r \quad (3)$$

where the energy in kWh is referenced as E, A_p is the solar panel area (m^2), η represents the efficiency of the panel, and P_r is the performance ratio that involves all losses on the system (accepted as 0.75), and average solar radiation is represented as H_a.
The Coulomb counting method is used to estimate the battery's state of charge (SoC).

Equation 4 shows how the SoC calculation is mathematically formulated over time. (Saxena *et al.*, 2016; Sepasi *et al.*, 2015).

$$SoC(t) = SoC(0) - \left(\int_0^t \eta \cdot I(t)/C_{av}\right) \qquad (4)$$

where $SoC(0)$ represents the initial charge SoC, $SoC(t)$ is the SoC at time t, C_{av} is the available battery capacity, $I(t)$ is the charge/discharge current at the time t, and the Coulumbic efficiency is accepted as 1.

5. RESULTS AND DISCUSSION

Impacts of the initial battery level, trim angle, and boat speed variations have been investigated through an SD simulation formed in Vensim software. Table 3 and Figure 5 indicate the variation of power consumption in kW and battery duration in hours regarding boat speed changed from 4 m/s to 8 m/s (7.78 knots to 15.55 knots). The initial speed value is selected as 4 m/s since the Savitsky planing hull calculations don't involve the lower speed values. The maximum output power of the electric motor (10 kW) limits the peak speed at 8 m/s which met the desired velocity.

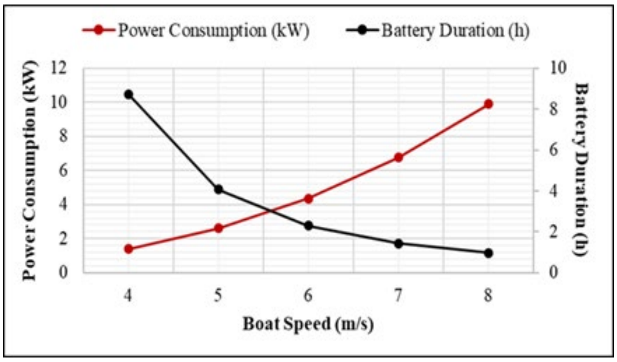


Figure 5. Relation between boat speed, power consumption, and battery duration

Table 3. Required power and battery duration change regarding boat speed

Boat speed (m/s)	Boat speed (knot)	Power consumption (kW)	Battery duration (hours)
4	7.78	1.38	8.73
5	9.72	2.60	4.07
6	11.66	4.36	2.30
7	13.61	6.77	1.44
8	15.55	9.90	0.97

The battery duration is found satisfactory at lower speeds. At 7.78 knots, the boat provides an acceptable usage time for achieving daily duties. The planing form chosen for this vessel helped to ensure these convincing outcomes. For the latter analysis, the boat speed was kept constant at 5 m/s, and it is accepted that the boat has no trim angle. Relationship between initial battery levels and durations were examined for the SoC of 40% to 100% of battery level and illustrated in Figure 6.

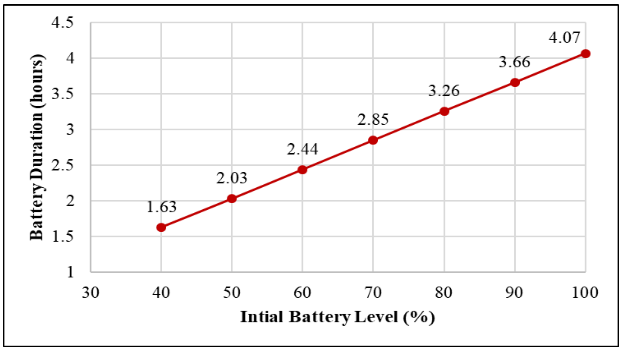


Figure 6. The relation between initial battery level and battery duration at 5 m/s boat speed

The four-hour cruise time is likely to be used near the shore when starting with full batteries. It is calculated that even at the 40% level, the batteries run for over an hour and a half. This is a very promising result for this boat design. In the following analysis, boat speed has been taken to a constant value of 5 m/s and the battery charge level has been 80%. Also, at 5 m/s speed and with no trim angle condition, power consumption has been obtained as 2.60 kW. Besides, in the same conditions with an 80% battery level, the battery duration was 3.26 hours. Moreover, when the effect of increased trim angle on battery endurance and power consumption analysis has been conducted, approximately up to 4% battery duration could be lost at a 10-degree trim angle. Indeed, the trim angle effect on navigation time, with an 80% charged battery pack, is shown in Figure 7. The findings related to the trim angle are in line with the experimental study conducted by Giraldo-Pérez *et al.*, (2022) for various hull types including planing hull. The optimum vessel speed was found at 7.78 knots which also complies with the studies using similar boat designs for all-electric ships. Ozden and Demir, (2009) determined the speed of the optimal speed at around 5-7 knots for small solar boats utilized in a solar boat contest while Yüksel *et al.*, (2023) depicted the optimal speed at around 8-11 knots for a solar boat having similar design aspects considering the hull resistance calculations.

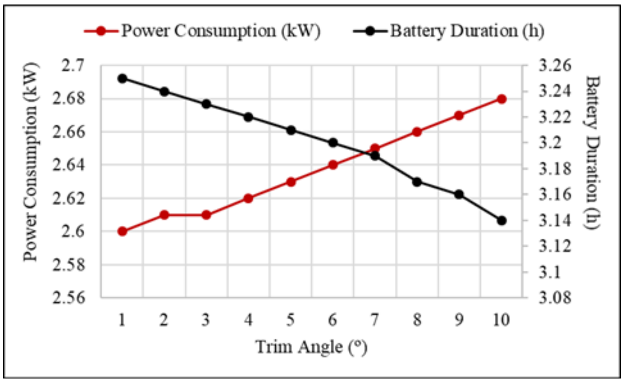


Figure 7. The relation among a trim angle, power consumption, and battery duration

As seen in Figure 7, the increased trim angle affects the power consumption negatively and reduces the battery duration. These results show that using the boat without a trim angle will reduce power consumption and will affect the navigation time positively. When the effect of an increase in trim value on battery duration is analyzed, a continuous decline in the boat's operational time is determined. Particularly when the 7-degree trim angle is surpassed, it is difficult to perform reliable estimates due to the uncertainties resulting from fluctuations in the curve.

6. CONCLUSION

The research paper aimed to design a solar-powered boat and analyze the effects of environmental and form-related factors on power consumption and battery duration by utilizing a system dynamics approach-based simulation. The boat design had the planing hull form, and its analysis was ensured in Maxsurf software. PV panels with 548 W power output and two battery packs with 4660 Wh capacity were placed on the hull body to employ an electric motor with a 10-kW nominal power output. Two MPPTs were implemented in the system to increase efficiency. The relationships between all system components were modelled in Vensim software to observe battery endurance changes under different conditions.
The main findings driven from the study can be listed as:

- The vessel speed is at 4 m/s (7.78 knots) for no trim condition with approximately 8.73 hours of maximum battery duration.
- The optimum boat speed is suggested at the intersection point of Battery duration and Power consumption curves in Figure 5.
- At 40% battery level and with 5 m/s (9.72 knots), 1.63 hours cruising time was obtained, and it can be said that below 40% battery level becomes a critical level for cruising.
- Start with a battery charge of more than 80% whenever possible.
- The rising trim angle decreases the battery duration thus, the most efficient trim angle to navigate the boat is zero.
- If it is obligatory to operate the vessel with any trim angle, the 7-degree limit should not be exceeded.

The research presented a simulation of battery charging and discharging of a solar boat using the system dynamics methodology. In this way, an interface was created that dynamically calculates how long the battery will last regarding the boat speed, charge rate, and trim angle. The utilization of the system dynamics-based approach is a divergent aspect of the paper. The study can be beneficial for naval architects and marine engineers working for shipyards, academic institutions, and investors interested in solar-powered leisure boats. Future research might include calculations that involve more detailed irradiation computations, usage of larger battery cells to extend the vessel's operating period, the economic evaluation of system design, real-time installation of the designed vessel configuration, and benchmarking of the study's results.

Nomenclature

Notation	Parameter	Unit
A_p	Total PV panel area	m^2
C_{av}	Available battery capacity	Ah
E	Produced energy by PV panels	kWh
H_a	Average solar radiation value	kW/m^2
$I(t)$	Charge/discharge current at any time	A
P_E	Effective power	kW
P_r	PV system performance ratio	-
R_A	Boat upper structure wind resistance	kN
R_{AP}	Boat underwater appendages resistance	kN
R_H	Bare boat hull resistance	kN
R_{PAR}	Boat hull fouling resistance	kN
R_T	Total resistance	kN
v	Kinematic viscosity	m^2/s
V	Boat velocity	m/s
t	Time	s
η	Efficiency ratio of PV panels	-

AUTHORSHIP CONTRIBUTION STATEMENT

Burak GÖKSU: Conceptualization, Methodology, Validation, Formal Analysis, Writing - Original Draft, Writing-Review and Editing, Data Curation, Software. **Onur YÜKSEL:** Conceptualization, Methodology, Writing - Original Draft, Writing-Review and Editing, Visualization.

CONFLICT OF INTERESTS

The authors declare that for this article they have no actual, potential, or perceived conflict of interests.

ETHICS COMMITTEE PERMISSION

No ethics committee permissions are required for this study.

FUNDING

No funding was received from institutions or agencies for the execution of this research.

ORCID IDs

Burak GÖKSU:
https://orcid.org/0000-0002-6152-0208
Onur YÜKSEL:
https://orcid.org/0000-0002-5728-5866

7. REFERENCES

Aijjou, A., Bahatti, L., Raihani, A., (2019). Influence of Solar Energy on Ship Energy Efficiency: Feeder Container Vessel as Example. *International Journal of Electrical Energy* 7(1): 21–25. doi:10.18178/ijoee.7.1.21-25.

Anand, S., Vrat, P., Dahiya, R.P., (2006). Application of a system dynamics approach for assessment and mitigation of CO2 emissions from the cement industry. *Journal of Environmental Management* 79(4): 383–398. doi:10.1016/j.jenvman.2005.08.007.

Aslani, A., Helo, P., Naaranoja, M., (2014). Role of renewable energy policies in energy dependency in Finland: System dynamics approach. *Applied Energy* 113: 758–765. doi:10.1016/j.apenergy.2013.08.015.

Balsamo, F., Capasso, C., Miccione, G., Veneri, O., (2017). Hybrid Storage System Control Strategy for All-Electric Powered Ships. *Energy Procedia* 126: 1083–1090. doi:10.1016/j.egypro.2017.08.242.

Banjarnahor, D.A., Hanifan, M., Budi, E.M., (2017). Design of Hybrid Solar and Wind Energy Harvester for Fishing Boat. *IOP Conference Series: Earth and Environmental Science* 75(1): 1–7. doi:10.1088/1755-1315/75/1/012007.

Baskoro, F.R., Takahashi, K., Morikawa, K., Nagasawa, K., (2021). System dynamics approach in determining coal utilization scenario in Indonesia. *Resources Policy* 73(September 2020): 102209. doi:10.1016/j.resourpol.2021.102209.

Bentley, What is MAXSURF?, (2022). Accessed Date: 22.03.2023, https://www.bentley.com/software/maxsurf/ is retrieved.

Cedar Lake Ventures, İzmir Bölgesinde Yıl Boyu İklim ve Hava Durumu, (2022). Accessed Date: 06.12.2022, https://tr.weatherspark.com/y/94320/İzmir-Türkiye-Ortalama-Hava-Durumu-Yıl-Boyunca is retrieved.

Chao, R.M., Lin, H.K., Wu, C.H., 2018. Solar-powered boat design using standalone distributed PV system. Proceedings of 4th IEEE International Conference on Applied System Innovation 2018, ICASI 2018, 31–34. doi:10.1109/ICASI.2018.8394259.

Connelly, E., Idini, B., International Shipping, (2022). Accessed Date: 05.12.2022,. https://www.iea:reports/international-shipping is retreived.

Cupelli, M., Ponci, F., Sulligoi, G., Vicenzutti, A., Edrington, C. S., El-Mezyani, T., Monti, A., (2015). Power Flow Control and Network Stability in an All-Electric Ship. *Proceedings of the IEEE* 103(12): 2355–2380. doi:10.1109/JPROC.2015.2496789.

Daneshgar, S., Zahedi, R., (2022). Investigating the hydropower plants production and profitability using system dynamics approach. *Journal of Energy Storage* 46(December 2021): 103919. doi:10.1016/j.est.2021.103919.

Dincer, I., (2000). Renewable energy and sustainable development: A crucial review. *Renewable and Sustainable Energy Reviews* 4(2): 157–175. doi:10.1016/S1364-0321(99)00011-8.

Dutta, W., Ankan, S.T., Khan, M.Z.R., 2020. Design of a sustainable electric boat with renewable energy based charging system. *Proceedings of 2020 11th* International Conference on Electrical and Computer Engineering, ICECE 2020, 242–245. doi:10.1109/ICECE51571.2020.9393125.

Eftekhari Shahabad, M., Mostafaeipour, A., Hosseini Nasab, H., Sadegheih, A., Ao Xuan, H., (2022). A new model to investigate effects of subsidies for home solar power systems using system dynamics approach: A case study. *Sustainable Energy Technologies and Assessments* 49(November 2021): 101706. doi:10.1016/j.seta.2021.101706.

Ellenbogen, J.C., Christopher L.J., (2000). Architectures for molecular electronic computers: 1. Logic structures and an adder designed from molecular electronic diodes. *Proceedings of the IEEE* 88(3): 386–426. doi:10.1109/5.838115.

Eronat, C., (2017). An overview on İzmir Bay physical oceanography. *Ege Journal of Fisheries and Aquatic Sciences* 34(1): 1–9. doi:10.12714/egejfas.2017.34.1.01.

Esmaieli, M., Ahmadian, M., (2018). The effect of research and development incentive on wind power investment, a system dynamics approach. *Renewable Energy* 126: 765–773. doi:10.1016/j.renene.2018.04.009.

Eyring, V., Köhler, H.W., Van Aardenne, J., Lauer, A., (2005). Emissions from international shipping: 1. The last 50 years. *Journal of Geophysical Research D: Atmospheres* 110(17): 171–182. doi:10.1029/2004JD005619.

Francis, A., Thomas, A., (2022). A framework for dynamic life cycle sustainability assessment and policy analysis of built environment through a system dynamics approach. *Sustainable Cities and Society* 76: 103521. doi:10.1016/j.scs.2021.103521.

Gaber, M., Hamad, M., El-banna, S., El-Dabah, M., (2021). an Intelligent Energy Management System for Ship Hybrid Power System Based on Renewable Energy Resources. *Journal of Al-Azhar University Engineering Sector* 16(60): 712–723. doi:10.21608/auej.2021.187967.

Giraldo-Pérez, E., Betancur, E., Osorio-Gómez, G., (2022). Experimental and statistical analysis of the hydrodynamic performance of planing boats: A Comparative study. *Ocean Engineering* 262(July 2022): 112227. doi:10.1016/j.oceaneng.2022.112227.

Gravelsins, A., Bazbauers, G., Blumberga, A., Blumberga, D., Bolwig, S., Klitkou, A., Lund, P.D., (2018). Modelling energy production flexibility: System dynamics approach. *Energy Procedia* 147: 503–509. doi:10.1016/j.egypro.2018.07.060.

Gupta, V.K., Potumarthi, R., O'Donovan, A., Kubicek, C.P., Sharma, G.D., Tuohy, M.G., (2014). Bioenergy Research: An Overview on Technological Developments and Bioresources. In: "Bioenergy Research: Advances and Applications". Elsevier. doi:10.1016/B978-0-444-59561-4.00002-4.

Haseltalab, A., Wani, F., Negenborn, R.R., (2022). Multi-level model predictive control for all-electric ships with hybrid power generation. *International Journal of Electrical Power and Energy Systems* 135: 107484. doi:10.1016/j.ijepes.2021.107484.

Hein, K., Murali, R., Xu, Y., Aditya, V., Gupta, A.K., (2022). Battery thermal performance oriented all-electric ship microgrid modeling, operation and energy management scheduling. *Journal of Energy Storage* 48 (October 2021): 103970. doi:10.1016/j.est.2022.103970.

Hein, K., Xu, Y., Aditya, V., Gupta, A.K., (2022). A probabilistic risk-averse approach for energy storage sizing in all-electric ship. *Journal of Energy Storage* 55(PA): 105392. doi:10.1016/j.est.2022.105392.

Hjorth, P., Bagheri, A., (2006). Navigating towards sustainable development: A system dynamics approach. *Futures* 38(1): 74–92. doi:10.1016/j.futures.2005.04.005.

Hoogwijk, M., Graus, W., Global Potential of Renewable Energy Sources: A Literature Assessment, (2008). Accessed Date: 05.12.2022, https://www.academia.edu/download/40266225/Global_Potential_of_Renewable_Energy_Sou20151122-786-1y8t0a9.pdf is retrieved.

Ivanov, G., (2022). All-Electric Cargo Ships Data Analysis and Efficiency vs Fuel Ships Comparison. *International Journal of Marine Engineering Innovation and Research* 7(1): 33–40. doi:10.12962/j25481479.v7i1.12379.

Ivanova, G., 2021. Analysis of the Specifics in Calculating the Index of Existing Marine Energy Efficiency EEXI in Force since 2023. *2021* 13th Electrical Engineering Faculty Conference, BulEF 2021. doi:10.1109/BulEF53491.2021.9690805.

Jia, S., Liu, X., Yan, G., (2019). Effect of APCF policy on the haze pollution in China: A system dynamics approach. *Energy Policy* 125(October 2018): 33–44. doi:10.1016/j.enpol.2018.10.012.

Joshi, B.V., Vipin, B., Ramkumar, J., Amit, R.K., (2021). Impact of policy instruments on lead-acid battery recycling: A system dynamics approach. *Resources, Conservation and Recycling* 169 (August 2020): 105528. doi:10.1016/j.resconrec.2021.105528.

Kannan, N., Vakeesan, D., (2016). Solar energy for future world: - A review. *Renewable and Sustainable Energy Reviews* 62: 1092–1105. doi:10.1016/j.rser.2016.05.022.

Kong, Y., Liu, J., Chen, J., (2022). Exploring the carbon abatement measures in maritime supply chain: a scenario-based system dynamics approach. *International Journal of Production Research*. doi:10.1080/00207543.2022.2088427.

Konur, O., Yuksel, O., Aykut Korkmaz, S., Ozgur Colpan, C., Saatcioglu, O.Y., Koseoglu, B., (2023). Operation-dependent exergetic sustainability assessment and environmental analysis on a large tanker ship utilizing Organic Rankine cycle system. *Energy* 262: 125477. doi:10.1016/j.energy.2022.125477.

Kulkarni, H.S., Wani, K.V., Sonawane, G.D., Bhoi, C.P., Mahale, M., (2020). Design and Fabrication of Solar Boat. *International Research Journal of Engineering and Technology* 7(6): 2968–2973.

Kurniawan, A., Shintaku, E., 2018. Control of photovoltaic system connected to DC bus in all-electric ship. Proceeding - ICAMIMIA 2017: International Conference on Advanced Mechatronics, Intelligent Manufacture, and Industrial Automation, 110–115. doi:10.1109/ICAMIMIA.2017.8387568.

Leung, C.P., Cheng, K.W.E., 2018. Zero emission solar-powered boat development. *2017 7th* International Conference on Power Electronics Systems and Applications - Smart Mobility, Power Transfer and Security, PESA 2017, 1–6. doi:10.1109/PESA.2017.8277736.

Lewis, E.V., (1998). *Principles of naval architecture second revision* 2nd Edition. New Jersey, The Society of Naval Architects and Marine Engineers.

Lindbergh, E., Ahlstrand, F., (2020). Methods to Predict Hull Resistance in the Process of Designing Electric Boats. M.Sc. Thesis, Kth Royal Institute of Technology.

Liu, P., Lin, B., Wu, X., Zhou, H., (2019). Bridging energy performance gaps of green office buildings via more targeted operations management: A system dynamics approach. *Journal of Environmental Management* 238: 64–71. doi:10.1016/j.jenvman.2019.02.111.

Lutful Kabir, S.M., Alam, I., Rezwan Khan, M., Hossain, M.S., Rahman, K.S., Amin, N., 2017. Solar powered ferry boat for the rural area of Bangladesh. 2016 International Conference on Advances in Electrical, Electronic and Systems Engineering, ICAEES 2016, 38–42. doi:10.1109/ICAEES.2016.7888005.

Mobaseri, M., Mousavi, S. N., Haghighi, M.H.M., (2021). Environmental effects of food waste reduction using system dynamics approach. *Energy Sources, Part A: Recovery, Utilization and Environmental Effects* 1–19. doi:10.1080/15567036.2021.2000066.

Mueller, M., Wallace, R., (2008). Enabling science and technology for marine renewable energy. *Energy Policy* 36(12): 4376–4382. doi:10.1016/j.enpol.2008.09.035.

Nasiri, S., Parniani, M., Blaabjerg, F., Peyghami, S., 2022. Analysis of All-Electric Ship Motions Impact on PV System Output Power in Waves. *2022* IEEE Transportation Electrification Conference and Expo, ITEC 2022, 450–455. doi:10.1109/ITEC53557.2022.9813953.

Nasirudin, A., Chao, R.M., Utama, I.K.A.P., (2017). Solar powered boat design optimization. *Procedia Engineering* 194: 260–267. doi:10.1016/j.proeng.2017.08.144.

Nóbrega, J.C. de C., Rössling, A., (2012). Development of solar powered boat for maximum energy efficiency. *Renewable Energy and Power Quality Journal* 1(10): 302–307. doi:10.24084/repqj10.299.

Obaid, W., Hamid, A.K., Ghenai, C., 2019. Wind-fuel-cell-solar hybrid electric boat power design with MPPT system. 2019 8th International Conference on Modeling Simulation and Applied Optimization, ICMSAO 2019, 8–12. doi:10.1109/ICMSAO.2019.8880330.

Ozden, M.C., Demir, E., 2009. The successful design and construction of solar/electric boats Nusrat and Muavenet: An Overview. Ever Monaco 2009 Conferences on Ecological Vehicles and Renewable Energies, Monaco, 27-29.

Padwad, D., Naidu, H.K., 2022. A Review of Electrical Boat Vehicle Solar Generation for Energy Sustainability and Development. International Conference on Emerging Trends in Engineering and Technology, ICETET, 2022-April. doi:10.1109/ICETET-SIP-2254415.2022.9791663.

Pakhmode, K.H., Dudhe, R.R., Waghmare, G.S., Kamble, D.A., Dhenge, K., (2019). Solar powerd water surface garbage collecting boat. *International Research Journal of Engineering and Technology* 3223: 3223–3225.

Pan, X., Li, M., Xu, H., Guo, S., Guo, R., Lee, C.T., (2021). Simulation on the effectiveness of carbon emission trading policy: A system dynamics approach. *Journal of the Operational Research Society* 72(7): 1447–1460. doi:10.1080/01605682.2020.1740623.

Pazi, I., Ozturk, C., (2012). Deniz Suyu Fiziksel Özelliklerinin Ölçülmesi Ve Değerlendirilmesi. Su Ürünleri Akademik Bildiriler Yayım Sistemi, 375–382.

Perčić, M., Frković, L., Pukšec, T., Ćosić, B., Li, O. L., Vladimir, N., (2022). Life-cycle assessment and life-cycle cost assessment of power batteries for all-electric vessels for short-sea navigation. *Energy* 251. doi:10.1016/j.energy.2022.123895.

Pereira, I.P.C., Ferreira, F.A.F., Pereira, L.F., Govindan, K., Meidutė-Kavaliauskienė, I., Correia, R.J.C., (2020). A fuzzy cognitive mapping-system dynamics approach to energy-change impacts on the sustainability of small and medium-sized enterprises. *Journal of Cleaner Production* 256. doi:10.1016/j.jclepro.2020.120154.

Pizzitutti, F., Walsh, S.J., Rindfuss, R.R., Gunter, R., Quiroga, D., Tippett, R., Mena, C.F., (2017). Scenario planning for tourism management: a participatory and system dynamics model applied to the Galapagos Islands of Ecuador. *Journal of Sustainable Tourism* 25(8): 1117–1137. doi:10.1080/09669582.2016.1257011.

Rivera-Solorio, C., García-Cuéllar, A.J., Flores, A., (2013). Design and construction of a boat powered by solar energy with the aid of computational tools. *International Journal of Engineering Education* 29(2): 380–387.

Saxena, S., Hendricks, C., Pecht, M., (2016). Cycle life testing and modeling of graphite/LiCoO2 cells under different state of charge ranges. *Journal of Power Sources* 327: 394–400. doi:10.1016/j.jpowsour.2016.07.057.

Saral, D., Köse E., (2020) Geleneksel Karadeniz Tipi Balıkçı Gemisinin HAD ile Sakin Sudaki Direnç Analizleri**.** *Turkish Journal of Maritime and Marine Sciences* 6(2): 207-223**.**

Savitsky, **D., (1964).** Hydrodynamic design of planing hulls. *Marine Technology and SNAME News* 1(4): 71-95.

Sepasi, S., Ghorbani, R., Liaw, B.Y., (2015). Inline state of health estimation of lithium-ion batteries using state of charge calculation. *Journal of Power Sources* 299: 246–254. doi:10.1016/j.jpowsour.2015.08.091.

Shadman, S., Chin, C.M.M., Sakundarini, N., Yap, E.H., Fairuz, S., Wong, X.Y., Khalid, P.A., Karimi, F., Karaman, C., Mofijur, M., Koyande, A.K., Show, P.L., (2022). A system dynamics approach to pollution remediation and mitigation based on increasing the share of renewable resources. *Environmental Research* 205: 112458. doi:10.1016/j.envres.2021.112458.

Sheheryar, M., Rehan, R., Nehdi, M.L., (2021). Estimating CO_2 emission savings from ultrahigh performance concrete: A system dynamics approach. *Materials* 14(4): 1–22. doi:10.3390/ma14040995.

Solangi, K.H., Islam, M.R., Saidur, R., Rahim, N.A., Fayaz, H., (2011). A review on global solar energy policy. *Renewable and Sustainable Energy Reviews* 15(4): 2149–2163. doi:10.1016/j.rser.2011.01.007

Spinelli, F., Mancini, S., Vitiello, L., Bilandi, R.N., De Carlini, M., (2022). Shipping Decarbonization: An Overview of the Different Stern Hydrodynamic Energy Saving Devices. *Journal of Marine Science and Engineering* 10(5). doi:10.3390/jmse10050574.

Stasinopoulos, P., Shiwakoti, N., Beining, M., (2021). Use-stage life cycle greenhouse gas emissions of the transition to an autonomous vehicle fleet: A System Dynamics approach. *Journal of Cleaner Production* 278: 123447. doi:10.1016/j.jclepro.2020.123447.

Tamunodukobipi, D., Samson, N., Sidum, A., (2018). Design Analysis of a Lightweight Solar Powered System for Recreational Marine Craft. *World Journal of Engineering and Technology* 6(2): 441–456. doi:10.4236/wjet.2018.62027.

Tercan, Ş.H., Eid, B., Heidenreich, M., Kogler, K., Akyürek, Ö., (2021). Financial and Technical Analyses of Solar Boats as A Means of Sustainable Transportation. *Sustainable Production and Consumption* 25: 404–412. doi:10.1016/j.spc.2020.11.014.

Ventana Systems, Vensim Software, (2015). Accessed Date: 05.12.2022, https://vensim.com/ is retrieved.

Walker, G., (2001). Evaluating MPPT converter topologies using a MATLAB PV model. *Journal of Electrical and Electronics Engineering* 21(1): 49–56.

Wang, B., Peng, X., Zhang, L., Su, P., (2022). Real time power management strategy for an all-electric ship using a predictive control model. *IET Generation, Transmission and Distribution* 16(9): 1808–1821. doi:10.1049/gtd2.12419.

Wang, S., Psaraftis, H.N., Qi, J., (2021). Paradox of international maritime organization's carbon intensity indicator. *Communications in Transportation Research* 1: 100005. doi:10.1016/j.commtr.2021.100005.

Wen, S., Zhao, T., Tang, Y., Xu, Y., Zhu, M., Fang, S., Ding, Z., (2021). Coordinated Optimal Energy Management and Voyage Scheduling for All-Electric Ships Based on Predicted Shore-Side Electricity Price. *IEEE Transactions on Industry Applications* 57(1): 139–148. doi:10.1109/TIA.2020.3034290.

Ye, F., Xiong, X., Li, L., Li, Y., (2021). Measuring the effectiveness of the Chinese Certified Emission Reduction scheme in mitigating CO2 emissions: A system dynamics approach. *Journal of Cleaner Production* 294: 125355. doi:10.1016/j.jclepro.2020.125355.

Zhang, H., Xu, X., (2020). Research and design of wind and solar complementary electric sightseeing boat. E3S Web of Conferences, 145. doi:10.1051/e3sconf/202014502056.

Zhao, T., Qiu, J., Wen, S., Zhu, M., (2022). Efficient Onboard Energy Storage System Sizing for All-Electric Ship Microgrids Via Optimized Navigation Routing under Onshore Uncertainties. *IEEE Transactions on Industry Applications* 58(2): 1664–1674. doi:10.1109/TIA.2022.3145775.

Yüksel, O., Göksu, B., Bayraktar, M., (2023). Propulsion and photovoltaic charging system parameter computation for an all-electric boat. *Ships and Offshore Structures* 1–14. doi:10.1080/17445302.2023.2195239.

Research Article
Turkish Journal of Maritime and Marine Sciences

DOI: 10.52998/trjmms.1277070
Volume: 9 Issue: 2 (2023) 82-96

Classification of Ship Propeller Types and Energy-Saving Devices Under Technology Developments

Teknolojik Gelişmeler Kapsamında Gemi Pervane Tipleri ve Enerji Tasarruf Cihazlarının Sınıflandırılması

Türk Denizcilik ve Deniz Bilimleri Dergisi

Cilt: 9 Sayı: 2 (2023) 82-96

Murat BAYRAKTAR [1,*], Onur YÜKSEL[1], Burak GÖKSU[1]
[1]*Zonguldak Bülent Ecevit University, Maritime Faculty, Zonguldak, Turkey*

ABSTRACT

The propulsion system and its components need to be thoroughly analyzed and optimized for marine vessels to operate as efficiently as possible in applications where new builds or retrofitting are performed. Gearboxes, bearings, and other transmission equipment in the component of the power transmission from ship engine, which is the primary source of propulsion for most marine vessels, to propeller cause a variety of losses. To maximize propulsive efficiency, propeller selection should be performed precisely on the basis of ship type, operation mode, and area. Propulsion efficiency, fuel consumption, robustness, reliability, emissions, vibration, cavitation, complexity and cost are investigated in both conventional propellers and cutting-edge technology in propeller systems. This study will guide academicians, experts, and sector stakeholders in determining which propeller type will be more efficient for marine vessels since propulsion efficiency is critical for the sustainability of maritime transportation.

Keywords: Energy efficiency, Propeller types, Marine vessels, Propulsion system

Article Info
Received: 04 April 2023
Revised: 10 July 2023
Accepted: 17 July 2023

[*](corresponding author)
e-mail: bayraktarmurat@beun.edu.tr

To cite this article: Bayraktar, M., Yüksel, O., Göksu, B., (2023). Classification of Ship Propeller Types and Energy-Saving Devices Under Technology Developments, *Turkish Journal of Maritime and Marine Sciences* 9 (2): 82-96. doi: 10.52998/trjmms.1277070.

ÖZET

Sevk sistemi ve bileşenlerinin, yeni inşaların veya güçlendirmenin gerçekleştirildiği uygulamalarda deniz taşıtlarının mümkün olduğunca verimli çalışması için kapsamlı bir şekilde analiz edilmesi ve optimize edilmesi gerekir. Çoğu deniz taşıtının ana itme kaynağı olan gemi makinelerinden pervaneye güç aktarımı bileşenindeki dişli kutuları, yataklar ve diğer aktarma ekipmanları çeşitli kayıplara neden olmaktadır. Sevk verimini en üst düzeye çıkarmak için pervane seçimi tam olarak gemi tipine, operasyon moduna ve alana göre yapılmalıdır. Pervane verimliliği, yakıt tüketimi, sağlamlık, güvenilirlik, emisyonlar, titreşim, kavitasyon, karmaşıklık ve maliyetler hem geleneksel pervanelerde hem de en son teknoloji pervane sistemlerinde incelenmektedir. Bu çalışma, deniz taşımacılığının sürdürülebilirliği için itme verimliliği kritik öneme sahip olduğundan, akademisyenlere, uzmanlara ve sektör paydaşlarına deniz taşıtları için hangi pervane tipinin daha verimli olacağını belirlemede yol gösterici olacaktır.

Anahtar sözcükler: Enerji verimliliği, Pervane çeşitleri, Deniz taşıtları, Sevk sistemi

1. INTRODUCTION

The team in the design department conducts ship resistance evaluations that primarily impact ship service speed, propeller selection, installed engine power, and propeller RPM (Abramowskiet *et al.*, 2010). The right propeller selection is a crucial factor to come over the total resistance at the specified service speed considering the installed ship engine power output in order to guarantee that the analysis is as effective as possible (Gharbi *et al.*, 2018). Distinct or comparable propeller types are deployed for each ship type, with the greatest diversity in propeller size occurring when both ship and propeller types are included. How much of the ship's main engine's power is transmitted to the propeller is a crucial factor when selecting a propeller. Figure 1 describes the power transmission process of a ship, including indicated to thrust horsepower phase.
The downward force exerted on the piston as a result of the combustion of the delivered fuel is referred to as the indicated horsepower. The bore of the cylinder, the cylinder stroke length, indicated pressure, and engine revolution are the primary factors used to calculate indicated power (IHP). The rate between the engine's indicated power to the maximum power (MP) that can be obtained from the amount of fuel injected to combustion chamber per second ($\dot{m}_f$) based on low calorific value (LCV) in which there is not any loss of power expressed as indicated thermal efficiency (η_{ite}).

$$\eta_{ite} = \frac{\text{IHP}}{\dot{m}_f \cdot \text{LCV}} \tag{1}$$

Calculated by measuring the amount of torque at the engine coupling output, brake horsepower (BHP) represents the useful work performed by the engine. The ratio between MP and BHP is describes as brake thermal efficiency (η_{bth}).

$$\eta_{bth} = \frac{\text{BHP}}{\text{MP}} \tag{2}$$

The power measured over the shaft is shaft horsepower (SHP), and the losses between brake horsepower and shaft horsepower are caused by transmissions and bearings. After all shaft-line losses, the power supplied to the propeller is referred to as delivered horsepower (DHP). The ratio between DHP and BHP defines shaft transmission efficiency (η_s).

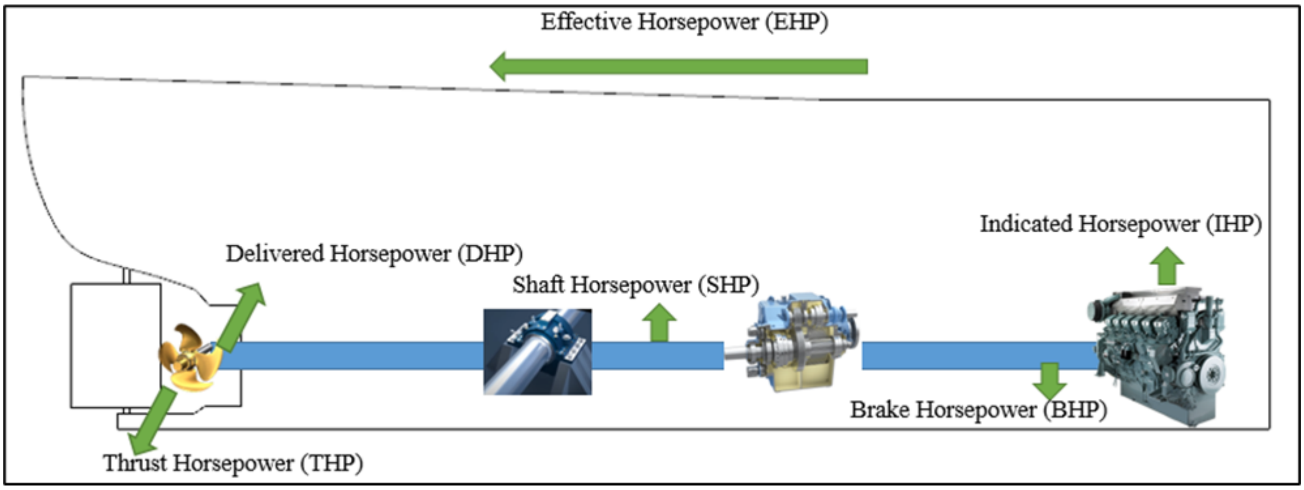


Figure 1. Ship Powertrain Systems

$$\eta_s = \frac{\text{DHP}}{\text{BHP}} \tag{3}$$

The power derived from the propeller is referred to as thrust horsepower, and the majority of efficiency losses between DHP and THP are attributable to propeller efficiency which is the ratio between DHP and THP defines propeller efficiency (η_p). Propeller type, number of blades and dimensions are fundamental factors on propeller efficiency throughout the operations.

$$\eta_p = \frac{\text{THP}}{\text{DHP}} \tag{4}$$

Effective horsepower (EHP) is based on the resistance components that occur at a given speed and the ratio of EHP to THP is described as hull efficiency (η_h).

$$\eta_h = \frac{\text{THP}}{\text{EHP}} \tag{5}$$

In current diesel engines, the transmission of power from the connection to the propeller results in a power loss of between 8 and 10 percent (Ganesan, 2012; Kuiken, 2017). Figure 2 provides a full description of the propeller's terminology and geometry.

Propeller geometry is based on the propeller root and tip, propeller blade surfaces, and propeller hub. The connection points of the propellers to the hub are referred to as the propeller root, while the outermost portions are referred to as the propeller tips. The high-pressure side is the propeller's face and is responsible for propelling the flow ahead. The low-pressure side, on the other hand, is the back of the propeller and generates suction power.

The leading edge of the propeller is the first region to cut off the water flow, and the trailing edge is where the water flow leaves the propeller blade. Pitch refers to the amount of forward movement gained each completed propeller rotation. In addition, the discrepancy between the actual pitch and the predicted pitch is known as a slip. Figure 3 defines the propeller-critical parameters rake and skew (Michigan Wheel, 2000; Çelik, 2010).

The blade's fore or aft slant with respect to a line perpendicular to the propeller's rotational axis is described as the rake. Blade slants towards the aft and the forward end of the hub are described as positive and negative rakes respectively. Skew is the transverse sweeping of a blade such that looking at the blades from the front or back is described as an asymmetrical shape in Figure 3 (Michigan Wheel, 2000). Disc area, propeller sections, expanded outlines, blades outlines and areas are described in Figure 4.

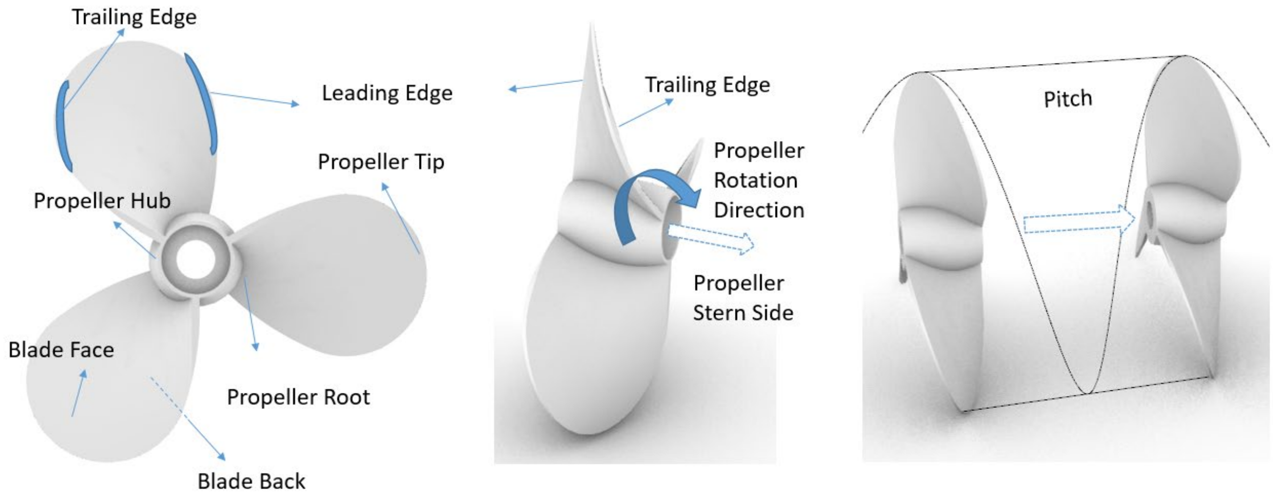


Figure 2. Propeller geometry and terms

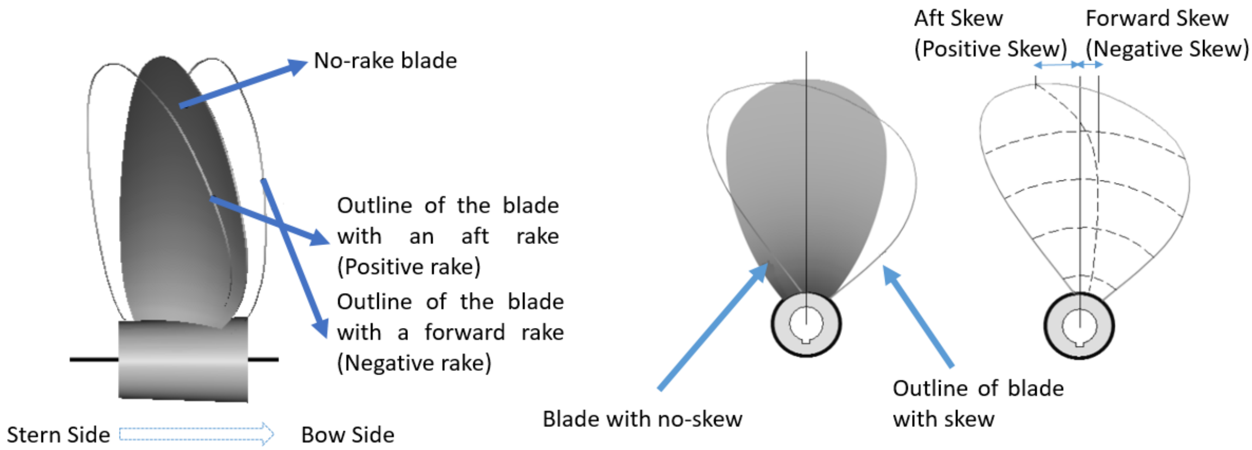


Figure 3. Rake and skew of the propeller

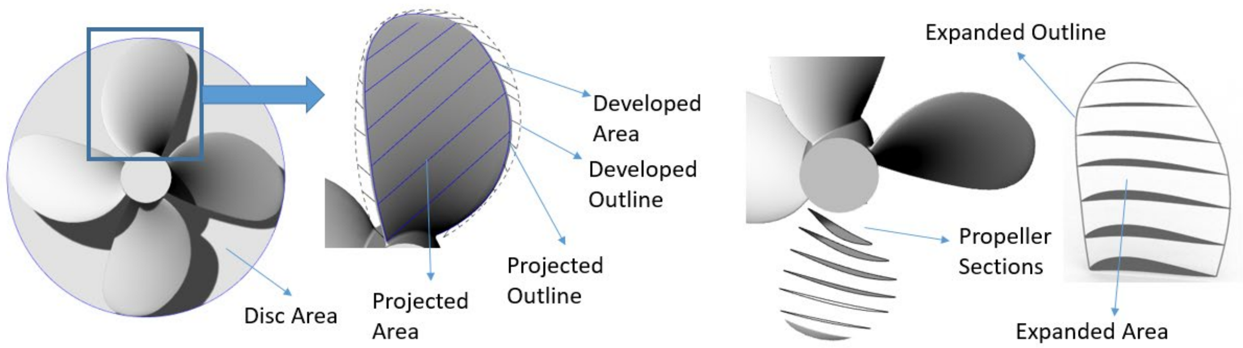


Figure 4. Disc area, propeller sections, expanded outlines, blades outlines and areas

The area of the circle which is drawn based on propeller tips refer to disc area and it is calculated using the propeller diameter (D).

$$\text{Disc Area} = \frac{\pi D^2}{4} \tag{6}$$

The ratio of blade areas to disc area is expressed as the blade area ratio (BAR). Projected outline is the viewed plotting from the face or the back of the propeller blade in which the shaft centerline and the view are on the same axis and also in which plotting area is described as Projected area. Developed outline in which the propeller blades are separated from the propeller hub and their pitch value is reduced to zero so that helically based views are acquired. The area remaining inside developed outline is developed area. Expanded outline in which the chord lengths are plotted around the directrix at the appropriate radial stations. The outline is created by laying off the chord length along a straight line at each radius r. The propeller is changed from a helix to a flat plane in the expanded view. Expanded area is the area covering along the outline drawing. In addition, projected area, developed area and expanded area to total disc area are expressed as Projected Area Ratio (PAR), Developed Area Ratio (DAR) and Expanded Area Ratio (EAR) respectively (Roh, 2006; Hydrocomp, 2007). Each ratio differs according to the propeller type and the applied vessel types. Propeller types and features have been explained in detail in the second part.

2. PROPELLER TYPES AND FEATURES

Cavitation, vibration, underwater noise level, propulsion efficiency, and maneuverability are crucial aspects to consider while selecting a ship's propeller (Carlton, 2018). In this paper, the diversified propeller types and their efficiency improvement applications have been investigated in terms of specified criteria. Fixed pitch propeller (FPP), controllable pitch propeller (CPP), ducted propellers, contra-rotating propellers (CRP), Z-drive units, podded azimuthing propellers, waterjet propulsion, tandem propellers, super cavitating or surface-piercing propellers, cycloidal propeller, overlapping propeller, grim vane wheel propeller, tip vortex free, contracted loaded tip (CLT), Mewis ducted propeller, Kappel propeller, paddle wheels have been evaluated as propeller types. In addition, propeller boss cap fins (PBCF), Grothues spoilers, and an asymmetric stern are considered auxiliary applications that improve the propeller's effectiveness. Figure 4 describes each propeller and efficiency-enhancing technique.

FPPs as implied by the name provide constant thrust with each turn of its fixed pitch (Kongsberg, 2009; Carlton, 2018; Wärtsilä, 2018). In ship operations where maximum efficiency is needed, the FPP is favored due to its robustness, dependability, ease of troubleshooting, short maintenance interval, and simple construction (MAN-ES, 2022; Wärtsilä, 2018). Throughout maintenance and repair operations, FPP may be disassembled and reassembled rapidly and without difficulty (Kongsberg, 2009). The number of blades on this type of propeller ranges between two and seven, with additional blades being utilized for military applications. Three-blade FPP propellers are commonly used on tugboats and fishing boats, but four-, five-, and six-blade propellers are utilized on ocean-going merchant vessels such as container ships, tankers, dry cargo ships, passenger ships, and bulk carriers (Kongsberg, 2009; Carlton, 2018; Wärtsilä, 2018). Similar to tugboats and fishing boats, 2 or 3-blade FPPs are preferred in small-scale special-purpose ships (Carlton, 2018). In addition to these vessels, FPPs are also deployed on polar ships and drilling ships. This circumstance demonstrates that FPP propellers can be fitted on a variety of ship types (Kongsberg, 2009). The FPP hub diameters range from 0.16 to 0.25 times the diameter of the entire propeller, based on the values of the dimensions obtained thus far from FPP applications (Carlton, 2018). Fins fitted to propeller end caps reduce fuel usage by 2%. FPP propellers have the potential to boost thrust efficiency in a variety of applications, and their installation may be accomplished at minimal expense. Due to its low installation costs, this equipment can recoup its initial investment expenditures in as little as one year, and it contributes significantly to fuel savings and emissions reduction (Wärtsilä, 2018).

CPP system permits the modification of propeller pitch by means of a hydraulic mechanism that gives interference to the blade angles to accommodate different loading situations throughout the operation of marine vessels. This enables CPP to fulfill varied power requirements without a transmission and to deliver improved mobility. In addition, the primary engine speed and cylinder pressures remain constant throughout operation. This not only contributes significantly to performance and efficiency, but also greatly reduces noise and vibration levels. In addition, the CPP system is capable of providing ships with reverse thrust (Carlton, 2018; Falzarano, 2018). CPP is commonly utilized by ships with medium- and low-speed ship engines in the maritime industry, where about 20,000 vessels are equipped with CPP systems (Tupper and Rawson, 2001; Molland, 2008; Carlton, 2018; Wärtsilä, 2018b). CPP is ideal for ferries, passenger ships, ice-class vessels, general cargo ships, tugboats, and navy vessels whose engine loads fluctuate significantly during operation (Carlton, 2018; Falzarano, 2018) as well as being appropriate for marine vessels that conduct dynamic positioning operations (Wärtsilä, 2018b; Ren *et al.*, 2019). CPP has a big market share since there is a constant relationship between revolutions per minute and torque in FPP, whereas this coefficient fluctuates with the amount of pitch in CPP (Molland, 2011). CPP is performed with very low efficiency losses of up to two to three percent, which provide fuel consumption and remove fuel-based harmful emissions. CPP is appropriate for retrofitting applications that emphasize this propeller type. Additionally, it has a lighter weight than conventional propellers and a structure that is exceptionally reliable (Falzarano, 2018; Wärtsilä, 2018b). CPP systems are highly beneficial on ships that already have shaft generators or have the possibility to install them in order to serve accommodation loads or other electrical requirements (Wärtsilä, 2018b; Ren *et al.*, 2019). As in FPP, fins and nozzles are integrated into CPP, and efficiency increase is acquired (Wärtsilä, 2018b; Ren *et al.*, 2019). In contrast to traditional propeller types, CPP propellers have a more complex structure, which raises initial investment and maintenance costs (ATZ Martec, 2021). When the Blade Area Ratio (BAR) is close to 0.8, CPP transfer of greater powers in large-scale maritime boats is problematic, and excessive cavitation occurs (Tupper and Rawson, 2001).

Ducted Propellers have a circular, fixed channel that can be redirected based on the flow around the propeller. This channel, which features a hydrofoil part, must be designed so that its inner surface and the propeller tips are in close proximity. An increase in the distance between them causes efficiency losses (Wartsila, 2022). There are ducted propeller types that slow down or accelerate the flow on the propeller according to their nozzle structure (Villa *et al.*, 2020; Falzarano, 2018). The enhanced thrust efficiency of the propeller is a result of the accelerated flow through the ducted area, and vice versa. Ducted Propellers are deployed on tugboats, anchor handling tug supply (AHTS), trawlers, general cargo ships, fishing vessels, research vessels, and marine vessels operating in inland waters (Falzarano, 2018; Becker Marine Systems, 2022; Kortpropulsion, 2022). Ducted propellers are also referred to as Kort nozzles since the company Kort Propulsion got the first patents in this field that are regarded as a benchmark (Carlton, 2018). FPP or CPP type of propellers are utilized in ducted propeller systems (Carlton, 2018). Three distinct nozzles have been integrated into the CPP based on B and Kaplan series model propeller and thrust efficiency has been boosted to the upper levels by increasing the flow velocity rate on the propeller (Bhattacharyya *et al.*, 2016; Bahatmaka *et al.*, 2017). In contrast, cavitation and noise are minimized when the flow velocity on the propeller is slowed in a ducted propeller system. This is particularly beneficial for military applications involving huge cargo ships and tankers (Falzarano, 2018). The construction and structure of the nozzle are vital to its performance, as it improves maneuverability, reduces propeller degradation, and facilitates DP operations (Becker Marine Systems, 2022). CPPs have the ability to be utilized by maritime vessel nozzles with a diameter of up to 5,300 millimeters. This system generates around fifty percent of the total thrust at relatively moderate speeds, but at high speeds it can cause additional resistance (Carlton, 2018). With the enhancements made to nozzle propellers, the bollard force of tugboats operating at zero knots is raised by 5 percent. In addition, a 3% to 4% increase in efficiency can be achieved in towing operations when the tugboat is operated between 2 and 8 knots. With the exception of all other low-speed procedures, improvements in excess of 2% are offered (Bhattacharyya *et al.*, 2016; Bahatmaka *et al.*, 2017).

Counter-rotating propellers (CRP) are comprised of two propellers that rotate in opposite directions on the same axis. Typically, the outer propeller is smaller in size and has a different number of blades than the inner propeller. CRP propellers are 5–7% more efficient than standard propellers. Due to the existence of a second propeller, CRP application in marine boats is hampered by added weight, increased maintenance expenses, a high initial investment, and a complicated structure (Tupper and Rawson, 2001; Falzarano, 2018). While CRPs are highly efficient in high-speed outboard engines, their use in long shaft applications on large ships presents numerous mechanical challenges. The lower stresses on CRP propellers provide advantages in terms of cavitation and noise compared to traditional propellers. CRPs employ both conventional and pod propellers, enabling their employment on large ships (Carlton, 2018).

In contrast to traditional propellers, Z-Drive Units that transfer power to the propeller via bevel gears and shaft brackets are not required. Z-Drive Units are highly maneuverable without a rudder, which minimizes rudder maintenance expenses, and have the potential to be utilized with a nozzle. Vibration, cavitation, and noise emission reduction are the primary features of this system (Falzarano, 2018). Podded Azimuthing Propellers (Azipod) allow 360^0 maneuverability without the use of a steerable gear propulsion system thanks to the podded AC electric motor. In addition to their exceptional maneuverability, Azipod offer up to 20% lower fuel consumption than conventional propulsion systems. As pod propellers, Azimuth Stern Drive (ASD) is the most common propulsion technology for tugboats. Specified pod propeller systems feature two propellers that function as tandem or counterrotating propellers (Falzarano, 2018; ABB, 2022). CRP Azipod applications deliver greater than 10% efficiency on fast ferries and ultra-large container ships, and CRP Azipod hybrid systems enhance the level of comfort on cruise ships (ABB, 2022; Wartsila, 2022)

Particularly prevalent in high-speed maritime boats with high-speed engines is the incidence of cavitation (Carlton, 2018). In some instances where the Azipod technology is integrated into a ducted system, large power outputs of up to 7.5 MW are achieved. In many applications, the use of flaps and fins has also improved maneuverability and cruising performance (Falzarano, 2018; ABB, 2022). Although Azipod devices are inapplicable to very big vessels, they are commonly utilized on icebreakers and passenger vessels. They have the ability to install up to 17 Megawatts aboard icebreaker ships whose Azipod towing systems are highly effective (ABB, 2022). “Harmony of the Seas” is one of the largest cruise ships in the world and is operated with a 20000 kW Azipod propulsion unit (Carlton, 2018; Wartsila, 2022). Azipod provides the easy loading and unloading of vehicles, particularly on Ro-Pax ships that permit the utilization of maximum loading area onboard (ABB, 2022). The distinction between azimuth and pod propellers is the installation location of the motor drive and the Z and L types of the most common drive units (Carlton, 2018). Z-Drives thrusters provide fuel consumption reduction, prolonged maintenance interval, increased hydrodynamic efficiency, high customer satisfaction and improved maneuverability without rudders (Thrustmaster, 2013; Hanninen, 2023). L-drive thrusters consist of motor, flexible coupling, gear coupling and propeller. Thanks to its simplified system, they provide lower fuel consumption, and high efficiency in a wide speed range with minimum energy losses. They are especially suitable for tugboat operations (Konsberg, 2021; Manngard, 2022). The installation of the Azipod propulsion unit gives advantages over conventional propulsion systems in which the existence of a stern tube, liner, and shaft bearing are the primary obstacles (Wartsila, 2022). In hybrid applications for this type of technology, vibrations occur when optimization studies are not conducted correctly (Carlton, 2018). Azipod systems compensate for the weight and moment problems associated with tandem propellers, allowing for more efficient operations (Carlton, 2018). From 1 MW to 7 MW, compact Azipod systems can be placed on ships for operation in coastal and open waters. The use of permanent magnet synchronous motors in these systems eliminates the need for additional rotor cooling, making the system more suitable for marine vessels (Wartsila, 2022).

Waterjet propulsion systems in which high-velocity jet units displace water to produce thrust for ship operation. They are chosen over conventional systems due to their excellent manoeuvrability, ability to direct water flow without a rudder system, ease of operation in shallow seas, and low noise emission and vibration. In contrast to traditional propulsion systems, they have a significantly lower propulsion efficiency output at low speeds (Falzarano, 2018; Wartsila, 2022). Waterjet Propulsion systems can be utilized on a variety of ship types, including marine sports vehicles, jet skis, rescue boats, and diving support vessels (Falzarano, 2018). In Tandem propellers, multiple propellers are attached to the same shaft axis so that the required thrust is produced by multiple propellers and the weight is distributed at multiple points. The presence of numerous propellers decreases the risk of cavitation and spreads it throughout the propellers (Carlton, 2018; Falzarano, 2018). Multiple propellers generate significant bending moments and varying weight distributions, resulting in damage to the shaft bearings and shaft liner on the same axis (Carlton, 2018).

Supercavitation or Surface-Piercing High-revolution-rate propellers reduce the impact of cavitation in shallow water, therefore propellers are particularly beneficial under these conditions. Compared to traditional propellers, they are 20 to 25 percent more efficient. In low-speed applications where cavitation is low, however, they incur a 15% efficiency loss (Çelik, 2010). This type of propeller delivers exceptional operational efficiency on yachts and navy vessels that reach 40-45 knots in speed. High-speed yachts demand Surface-Piercing propellers with more than four blades. Typically, the propeller is completely submerged as the ship begins to cruise. At high speeds, the ship creates a planar movement in which half of the propeller diameter remains submerged in the water (Carlton, 2018; Falzarano, 2018). The Cycloidal Propeller possesses six or eight propeller blades with a vertical axis airfoil shape, is positioned at the bottom of the ship, and provides thrust in all directions. Two servo motors collaborate to generate the necessary thrust, with one providing forward and reverse motion and the other creating thrust in the transverse direction to conduct port and starboard movements. The Cycloidal Propeller is also known as the Voith-Schneider propeller, which is manufactured by one of the most well-known companies in this industry. The Voith-Schneider propeller has a high degree of maneuverability, allowing it to respond quickly to sudden congestions. The Voith Schneider propeller systems offer high dependability, low vibration and fuel consumption, as well as a reduction in noise emissions, particularly in places where currents, waves, and ice effects are significant and operations are challenging (Voith, 2022).

Overlapping propeller systems with propulsion generated by the rotation of overlapping or side-by-side propellers on different shafts, resulting in a complicated wake flow. They offer significant benefits in terms of field energy at low speeds, resulting in greater efficiency. When compared to single conventional propellers, there are fluctuations in torque and thrust. The optimal distance between shafts is equivalent to 0.8 times the required propeller diameter, and vertical distance has a considerable impact on vibration. Additionally, more cavitation occurs than with ordinary propellers, necessitating additional measures to reduce this development. Installation of this sort of propeller must therefore be performed with extra attention (Çelik, 2010; Anda *et al.*, 2011; Carlton, 2018). Grim Vane Wheel Propeller provides up to 10% energy savings and a 20% reduction in fuel consumption as a result of the grim wheels that are 20% larger in diameter than the propeller. Grim wheels also boost thrust, decrease drag on the rudder, and improve stopping power. Wheels typically utilized on cargo ships. Siem Curie, which carries vehicles, is one example of a cargo ship in this area (Çelik, 2010; Siem, 2020).

Tip Vortex Free TVF, in which circulation distribution is appropriately provided by the end plates of the propeller, gives up to 5 percent efficiency. Contracted Loaded Tip (CLT), which is based on TVF propellers, is deployed on more than 280 ships, including chemical tankers, Ro-Pax, and other ship types. CLT propellers are superior to conventional propellers in terms of maneuverability, vibration, and noise emissions, and they offer between 5 and 8 percent greater energy efficiency. In addition, initial investment costs are recouped within three to six months (Çelik, 2010; Gennaro and Gonzalez-Adalid, 2012). Compared to conventional propellers of the same power, Mewis Duct Propellers deliver faster cruising and greater energy savings at low speeds. This nozzle, which is located on the propeller's bow, is deployed in combination with fin systems. This method enhances net thrust by accelerating and smoothing the wake region, while reducing cavitation and vibration production. It is appropriate for tankers, bulk carriers, and multipurpose vessels (MPV). The bulk carriers had the greatest increase in efficiency at 6%-8%, followed by tankers at 5%-7% and MPVs at 3%-5%, respectively (Becker Marine Systems, 2022).

KAPPEL Propellers have a curved structure with their blade tips relative to the suction side and are up to 5 percent more efficient than standard propellers. There are uses for KAPPEL propellers with 3, 4, 5, and 6 blades on many types of ships. In the process of gaining a curved structure, a great deal of effort is required, and incorrect designs and outputs enhance the formation of vibration and loss of efficiency. Its first use is aboard MT NORDAMERIKA, a 35,000 DWT chemical tanker, and the resulting energy efficiency is close to 4%. The Kappel application executed on the 30,000 kW Ro-Ro saves 774,000 dollars. However, based on an endurance test, the pressure resistance levels of the latest generation of propellers are lower (DTU Mechanical Engineering, 2017; MAN Diesel Turbo, 2022; Wartsila, 2022). In addition to these technologies, paddle wheels were used in the 19th and early 20th centuries, and each wheel's thrust is proportional to the volume of water it moves as it turns. Paddle wheel installation is typically performed on the ship's port and side. It is uncommonly mounted near the ship's stern, except for this particular version (Falzarano, 2018).

Various applications are implemented to regulate the flow on the propeller, hence enhancing the propeller's efficiency. One of them is the Propeller Boss Cap Fins (PBCF), which reduce hub vortex and energy loss. PBCF reduces fuel consumption by about 3% to 5% and reduces CO_2 emissions by more than 9,000 tons, based on the results of its implementation on large container ships. PBCF may be effortlessly placed on ordinary propellers to reduce vibration and underwater noise. Alternatively, it reduces wearing on the rudder (MOL, 2015). Grothues spoilers are small, curved, triangular plates that are welded on both sides to the stern of the ship. The Grothues spoilers regulate the flow and boost the propeller's efficiency. As a result of an erroneous mounting location, the resistance of the ship's appendages increases, and full regularity of flow to the propeller is not obtained (Howden, 2019). In addition to offering up to 9 percent energy savings in model test studies, it reduces vibrations in ship applications with vibration issues (Bertram, 2012).

In a ship with an asymmetric stern, the port and starboard stern sides do not have the same hull shape. Asymmetric stern increases fuel economy by roughly 5% without any alterations to the propeller and without the use of fins or nozzles. Ships with high block coefficients yield the most efficient applications. Recently, RANS-based simulations have been done on various asymmetric sterns to determine the optimal design. According to towing tests conducted on a 3000 TEU container ship, 3% less energy is required to obtain comparable speeds compared to a symmetric stern (Çelik, 2010; DNV, 2022).

3. GENERAL ASSESSMENTS ON PROPELLER TYPES

Propeller types, their cost, complexity, resilience, manoeuvrability, noise and vibration levels, thrust efficiency, emission rates, maintenance intervals, fuel consumption reduction, and applicability have been described Table 1 according to ship type, based on academic research and industry data. For each type of propeller, critical spots are highlighted.

Table 1. Propeller types and characteristics

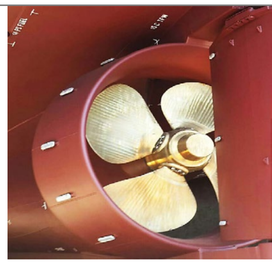
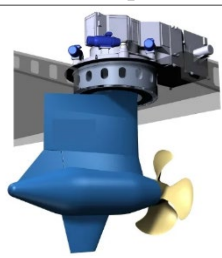
Fixed Pitch Propeller (FPP)	**Controllable Pitch Propeller (CPP)**	**Ducted Propellers**
		
• Simple Structure, Robustness, Reliability, Shorter Maintenance Intervals • Naval Ships, Container Ships, Tankers, Dry Cargo Ships, Passenger Ships, and Bulk Carriers	• Low Noise and Vibration Level, High Manoeuvrability • Passenger Ships, General Cargo Ships, Tugs, and Naval Ships	• Nozzle types that speed up or slow down the flow on the propeller • Cavitation and noise reduction • Up to 5% increased efficiency • Tugboats, Supply Vessels, Fishing Ships, General Cargo Ships
Contra-Rotating Propellers (CRP)	**Podded Azimuthing Propellers Azipod**	**Waterjet Propulsion**
		
• Complex structure • Added weight and extra maintenance efforts due to the secondary propeller. 5% to 7% energy efficiency gain	• 360^{o} maneuverability • Fuel consumption saving up to 20% Tugboats, Supply Vessels, Fast Ferries, and Ultra-Large Container Vessels	• Highly efficient at high speeds • High cost and difficulty of implementation for Large-scale vessels Marine Sports Boats, Jet Skis, Rescue Boats, and Diving Support Vessels

Table 1. Continued

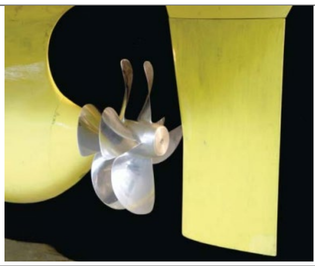
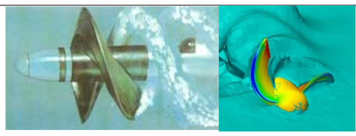
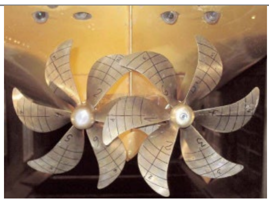
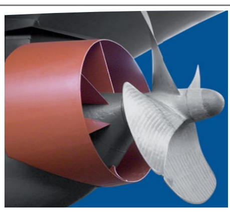
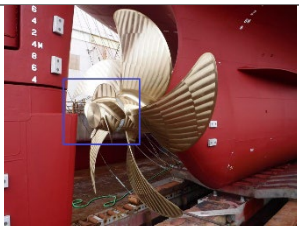
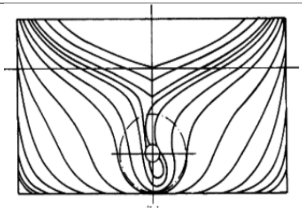
Tandem Propellers	**Supercavitating and Surface-Piercing Propellers**	**Cycloidal Propeller**
		
• Cavitation Reduction • Providing load distribution on propeller • Occurrence of excessive bending moment • Different weight distributions damage the shaft bearings and liner	• Providing 20%-25% efficiency when rotational speed and cavitation are high. On the contrary, 15% less efficient • Preferred in high speed boats. • Optimal design requires a lot of effort	• Providing 360o thrust • No need for rudder • Tugboats, Ferries and Support Vessels • Proven high reliability • Low vibration and reduced noise emissions
Overlapping propeller	**Grim Vane Wheel Propeller**	**Tip Vortex Free (TVF) and Contracted Loaded Tip (CLT)**
		
• Provides wake energy recovery • Torque and thrust fluctuations are generally occurred	• Energy saving up to between 5% and 10% • Providing extra thrust and reducing drag on the rudder	• Energy saving up to between 5% and 8% • Increasing maneuverability, reducing vibration and noise emissions
Mewis Duct	**KAPPEL Propeller**	**Paddle Wheels**
		
• Up to 8% fuel efficiency depending on the ship type • Cavitation and vibration reduction • Suitable for Tankers, bulk carriers	• Up to 5% efficiency increase • Fuel consumption and emission reduction • Low impact strength	• Propulsion from both port and side also aft side • More popular in the 19th and early 20th centuries

Table 1. Continued

Propeller Boss Cap Fins (PBCF)	Grothues spoilers	Asymmetric stern
		
• Fuel consumption reduction between 3% and 5% • Vibration and underwater noise reduction	• Up to 9% energy saving • Vibration reduction	• Up to 5% fuel efficiency • More efficient in ships with large block coefficient (C_b)

EEDI and EEXI were developed by IMO to minimize global carbon dioxide emissions from maritime vessels. Propeller selection is particularly important for these initiatives (Ren *et al.*, 2019). Numerous academic and maritime industry research have examined propellers in an effort to adapt global decarbonization plans. Kolakoti *et al.* (2013) and Gharbi *et al.* (2018) have performed experimental results based on the resistance calculation formulas and Wageningen B-series in which an interface is created in the MATLAB program that provides the selection of the propeller with minimum cavitation. The results are quite similar to the towing test data, which demonstrates the applicability of the interface. As a result, analysis may be performed with fewer resources and in less time. Kolakoti *et al.* (2013) prove that the difference between CFD and experimental results varies between approximately 4% and 6%.

In recent years, existing propeller improvements have garnered more attention than new propeller designs, and numerous computational fluid dynamics-based studies have been conducted. Xiong *et al.* (2013) described that the utilization of fins on the propeller hub cap provides an approximate 1% to 5% efficiency increase on the open water efficiency of CPP propeller. The simulations with the NACA 66 airfoil profiles installed at an angle of zero degrees and with a diameter of roughly 0.42 D of the propeller produce the most efficient results. Additionally, the fins have altered the flow pattern, preventing the creation of core vortices (Xiong *et al.*, 2013). Nouri *et al.* (2018) have performed RANS-based CFD analysis to investigate the hydrodynamic performance obtained from contra-rotating propellers (CRP). Bahatmaka *et al.* (2017) has analyzed the efficiency of 3 different nozzles that integrated into B series and Kaplan Series via CFD. At each nozzle, gains are realized in terms of force and torque, and throughout the studies, the greatest efficiency has been attained with 3.5% force and 4.4% torque, respectively. Mizzi *et al.* (2017) have performed an optimization study on 120 different PBCFs with CFD which based on RANS validated by experimental tests. Net energy efficiency gain of 1.3% is achieved with the most optimized PBCF. In order to improve the propulsion system efficiency of the 6000 TEU container ship, Lim *et al.* (2014) have utilized PBCF and hub cap together based on experimental test data and CFD analyses. Both are employed for the purpose of comparing and validating outcomes. Diversified hubcaps offer roughly 2% greater propulsion efficiency than conventional hubcaps. However, the usage of varied hub caps in conjunction with PBCF results in efficiency losses ranging from 2.7% to 7.5%. Diversified hub caps decrease hub vortex and raise torque coefficient, whereas combination diversified hub caps with PBCF enhance hub vortex, resulting in a decrease in torque coefficient.

Propeller selection according to ship type and added equipment to increase propulsion efficiency provide a certain amount of energy gain. That's why, Falzarano (2018) described that the utilization of renewable energy sources on ship propulsion systems such as wind, wave and solar energy are the main strategies in order to meet decarbonization targets (Falzarano, 2018). Prior to the maritime industry's full adaptation to renewable energy sources, the efforts performed to reduce carbon emissions and the attempt of existing systems with high efficiency are quite critical for the sustainability of maritime transportation.

4. RESULTS AND DISCUSSIONS

Selecting the optimal propeller will result in significant energy savings throughout ship operations, facilitating the ability for ship operators and owners to comply with International Maritime Organization (IMO) energy efficiency requirements. This paper outlines the types of propellers, their energy-saving rates, their applicability according to ship type, as well as technological advancements and other equipment that work in conjunction with the propeller to increase propeller efficiency in order to make the propeller selection process easier and faster. Although there are several propeller types, certain propellers, such as the FPP, CRP, CPP, Azipod, Ducted, and Cycloidal Propeller, are deployed more frequently than others in the marine industry. The most notable auxiliary equipment to boost propeller efficiency is PBCF, which has been the subject of current academic and commercial research since it can be simply and affordably integrated into existing propeller systems.

5. CONCLUSION

This study will serve as a valuable resource for academia, ship owners, operators, and industry stakeholders by outlining recent propeller system developments. In light of this study's findings, the design of the propellers to be integrated with PBCF will be based on computational fluid dynamics in a future study.

AUTHORSHIP CONTRIBUTION STATEMENT

Murat BAYRAKTAR: Conceptualization, Investigation, Data curation, Formal analysis, Methodology, Validation, Writing – original draft, Writing – review & editing.
Onur YÜKSEL: Conceptualization, Investigation, Visualization, Methodology, Validation, Writing – original draft, Writing – review & editing.
Burak GÖKSU: Conceptualization, Investigation, Visualization, Methodology, Validation, Writing – original draft, Writing – review & editing.

CONFLICT OF INTERESTS

The author(s) declare that for this article they have no actual, potential or perceived conflict of interests.

ETHICS COMMITTEE PERMISSION

No ethics committee permissions is required for this study

FUNDING

No funding was received from institutions or agencies for the execution of this research.

ORCID IDs
Murat BAYRAKTAR:
https://orcid.org/0000-0001-7252-4776
Onur YÜKSEL
https://orcid.org/0000-0002-5728-5866
Burak GÖKSU
https://orcid.org/0000-0002-6152-0208

6. REFERENCES

ABB, Azipod electric propulsion, (2022). Accessed Date: 17.04.2022, https://new.abb.com/marine/systems-and-solutions/azipod#large is retrieved.

Abramowski, T., Żelazny, K., Szelangiewicz, T., (2010). Numerical analysis of influence of ship hull form modification on ship resistance and propulsion characteristics Part III Influence of hull form modification on screw propeller efficiency. *Polish Maritime Research* 17(1): 10-13. doi: 10.2478/v10012-008-0060-2.

Anda, M., Iwasaki, Y., Ebira, K., (2011). Development of Overlapping Propellers. *Journal of the JIME* 46(3): 320-325. doi: 10.5988/jime.46.320.

ATZ Martec, Controllable Pitch Propellers (CPP), (2021). Accessed Date: 17.04.2022, https://atzmartec.com/wp-content/uploads/2021/07/AtZ-Brochure.pdf is retrieved.

Bahatmaka, A., Kim, D.J., Chrismianto, D., Setiawan, J.D., Prabowo, A.R., 2017. Numerical investigation on the performance of ducted propeller, MATEC Web of Conferences, Vol. 138, p. 07002, EDP Sciences.

Becker Marine Systems, Products, (2022). Accessed Date: 17.09.2022, https://www.becker-marine-systems.com/files/content/pdf/product_pdf/Becker_Product_Brochure.pdf is retrieved.

Bertram, V. (2012). *Practical Ship Hydromechanics*, Second Edition, Elsevier, London.

Bhattacharyya, A., Krasilnikov, V., Steen, S., (2016). Scale effects on open water characteristics of a controllable pitch propeller working within different duct designs. *Ocean Engineering* 112: 226-242. doi: 10.1016/j.oceaneng.2015.12.024.

Carlton, J. (2018). *Marine propellers and propulsion*, Butterworth-Heinemann, Oxford.

Çelik, F., Özel Sevk Sistemleri, (2010). Accessed Date: 12.09.2022, https://drive.google.com/file/d/1Sanv3Y9HCeCbM6NSxSPRmPEv7leT20jw/view is retrieved.

DNV, Cutting-edge asymmetric stern design, (2022). Accessed Date: 17.04.2022, https://www.dnv.com/maritime/advisory/asymmetric-stern-service.html is retrieved.

DTU Mechanical Engineering, KAPPEL Propeller. (2017). Accessed Date: 11.06.2022, https://www.mek.dtu.dk/english/Research/Feature_Articles/KAPPEL_Propeller is retrieved.

Falzarano, J. (2018). S*hip Resistance and Propulsion: Practical Estimation of Ship Propulsive Power*, Cambridge University Press, London.

Ganesan, V. (2012). *Internal combustion engines*, McGraw Hill Publishing Company, New Delhi.

Gennaro, G., Gonzalez-Adalid, J., 2012. Improving the propulsion efficiency by means of contracted and loaded tip (CLT) propellers. SNAME Symposium.

Gharbi, S., Zaoui, C., Bouaicha, H., Nejim, S., Dallagi, H., 2018. Ship electric propulsion system: Electric power estimation and propeller selection. 2018 International Conference on Advanced Systems and Electric Technologies (IC_ASET), pp. 241-248, Hammamet, Tunisia.

Hanninen, S., Viherialehto, S., Heideman, T., Maattanen, P., Arslan, A., 2023. Results From The World's Largest Arctic Ships and Advancements of Propulsion Technology, SNAME Offshore Symposium.

Howden, Alternative Methods to Reduce Resistance and Improve Propulsion, (2019). Accessed Date: 11.03.2022, https://www.howden.com/en-gb/articles/marine/reducing-fuel-consumption-in-shipping is retrieved.

Hydrocomp, A Hydrocomp Technical Report, (2007). Accessed Date: 18.12.2022, https://www.hydrocompinc.com/wp-content/uploads/documents/HC135-BladeAreaRatio.pdf is retrieved.

Kirmizi, M. (2015). Modeling and analysis of an in-line pump jet thruster for swimming robots. PhD. Thesis, Rice University.

Kolakoti, A., Bhanuprakash, T.V.K., Das, H.N., (2013). CFD analysis of controllable pitch propeller used in marine vehicle. *Global Journal of Engineering Design and Technology* 2(5): 25-33.

Kongsberg, Fixed pitch propellers, (2009). Accessed Date: 11.11.2022, https://www.kongsberg.com/contentassets/cc7a12403dda41d9934f7f259286e432/02.propeller_2p_14.10.09.pdf is retrieved.

Kongsberg, Azimuth thrusters, (2021). Accessed Date: 01.07.2023, https://www.kongsberg.com/contentassets/830f65761a9b4307ac32c10d35236243/36.azimuth-4p-22.04.21.pdf is retrieved.

Koronowicz, T., Krzemianowski, Z., Tuszkowska, T., (2010). A complete design of tandem co-rotating propellers using the new computer system. *Polish Maritime Research* 17(4): 17-25. doi: 10.2478/v10012-010-0031-2

Kortpropulsion, Kort Nozzles & Propellers, (2022). Accessed Date: 14.12.2022, https://www.kortpropulsion.com/products/kort-nozzles is retrieved.

Kuiken, K. (2017). *Diesel engines: for ship propulsion and power plants: from 0 to 100,000 kW*. Target Global Energy Training, Onnen.

Lim, S.S., Kim, T.W., Lee, D.M., Kang, C.G., Kim, S.Y., (2014). Parametric study of propeller boss cap fins for container ships. *International Journal of Naval Architecture and Ocean Engineering* 6(2): 187-205. doi: 10.2478/IJNAOE-2013-0172.

MAN Diesel Turbo, MAN Alpha Kappel tip-fin propellers ordered for the world's largest car carriers, (2022). Accessed Date: 21.09.2022, https://mandieselturbo.com/docs/default-source/shopwaredocuments/propeller-aft-ship---man-alpha-kappel-tip-fin-propellers.pdf?sfvrsn=2 is retrieved.

MAN-ES, FPPs–long-haul propulsion at the lowest operational costs, (2022). Accessed Date: 23.09.2022, https://www.man-es.com/marine/products/propeller-aft-ship/fpp is retrieved.

Manngård, M., Koene, I., Lund, W., Haikonen, S., Fagerholm, F.A., Wilczek, M., Toivonen, H.T., (2022). Torque estimation in marine propulsion systems. *Mechanical Systems and Signal Processing* 172 (108969): 1-18.

Michigan Wheel, Propeller Geometry: Terms and Definitions, (2000). Accessed Date: 09.09.2022, http://navalex.com/downloads/Michigan_Wheel_Propeller_Geometry.pdf is retrieved.

Misra, S.C., Gokarn, R.P., Sha, O.P., Suryanarayana, C., Suresh, R.V., (2012). Development of a four-bladed surface piercing propeller series. *Naval Engineers Journal* 124(4): 105-137.

Mizzi, K., Demirel, Y.K., Banks, C., Turan, O., Kaklis, P., Atlar, M., (2017). Design optimisation of Propeller Boss Cap Fins for enhanced propeller performance. *Applied Ocean Research* 62: 210-222. doi: 10.1016/j.apor.2016.12.006.

MOL, Energy-Saving Propeller Boss Cap Fins System Reaches Major Milestone, (2015). Accessed Date: 12.11.2022, https://www.mol.co.jp/en/pr/2015/15033.html is retrieved.

Molland, A.F., Turnock, S.R., Hudson, D.A. (2017). *Ship resistance and propulsion,* Cambridge university press.

Molland, A.F. (2008). *Marine engines and auxiliary machinery. The maritime engineering reference book: a guide to ship design, construction and operation*, Elsevier, New York.

Nouri, N. M., Mohammadi, S., Zarezadeh, M., (2018). Optimization of a marine contra-rotating propellers set. *Ocean Engineering* 167: 397-404. doi: doi.org/10.1016/j.oceaneng.2018.05.067.

Roh, M., Innovative Ship and Offshore Plant Design, (2016). Accessed Date: 08.09.2022, https://ocw.snu.ac.kr/sites/default/files/NOTE/07-ISOD Propeller%20&%20Main%20Engine%20Selection(160213).pdf is retrieved.

Ren, H., Ding, Y., Sui, C., (2019). Influence of EEDI (Energy Efficiency Design Index) on ship–engine-propeller matching. *Journal of Marine Science and Engineering* 7(12): 425. doi: 10.3390/jmse7120425.

Siem, Unique grims vane wheel system the siem curie, (2020). Accessed Date: 17.09.2022, https://siemshipmanagement.pl/content_news/unique-grims-vane-wheel-system-the-siem-curie/ is retrieved.

Thrustmaster, Z-Drıve Azımuthıng Thrusters, (2013). Accessed Date: 10.07.2023, https://www.thrustmaster.net/wp-content/uploads/2013/12/Z-Drives-for-Inland_Towboats-Brochure-2016-page-compressed.pdf is retrieved.

Tupper, E.C., Rawson, K.J., (2001). *Basic Ship Theory*, Elsevier, London.

Villa, D., Gaggero, S., Tani, G., Viviani, M., (2020). Numerical and experimental comparison of ducted and non-ducted propellers. *Journal of Marine Science and Engineering* 8(4): 257. doi: 10.3390/jmse8040257.

Voith, Voith Schneider Propeller VSP, (2022). Accessed Date: 10.09.2022, https://voith.com/corp-en/drives-transmissions/voith-schneider-propeller-vsp.html is retrieved

Warsila, High Performance Nozzle, (2017). Accessed Date: 16.09.2022, https://cdn.wartsila.com/docs/default-source/service-catalogue-files/propulsion-services/brochure-high-performance-nozzle.pdf is retrieved.

Wartsila, Fixed Pitch Propellers, (2018a). Accessed Date: 12.09.2022, https://cdn.wartsila.com/docs/default-source/product-files/gears-propulsors/propellers/brochure-o-p-propeller-fpp-opti-design.pdf is retrieved.

Wartsila, Controllable pitch propeller systems, (2018b). Accessed Date: 11.09.2022, https://www.wartsila.com/docs/default-source/product-files/gears-propulsors/propellers/brochure-o-p-cpp-propeller-systems.pdf is retrieved.

Wartsila, Kort nozzle, AZIPOD (Azimuthing Podded Drive), Waterjet propulsion, Voith-Schneider Propulsor (VSP), cycloidal propeller, KAPPEL propeller, (2022). Accessed Date: 18.07.2022, https://www.wartsila.com/encyclopedia/term is retrieved.

Xiong, Y., Wang, Z., Qi, W., (2013). Numerical study on the influence of boss cap fins on efficiency of controllable-pitch propeller. *Journal of Marine Science and Application* 12(1): 13-20. doi: 10.1007/s11804-013-1166-9.

Research Article
Turkish Journal of Maritime and Marine Sciences

DOI: 10.52998/trjmms.1311907
Volume: 9 Issue: 2 (2023) 97-109

Social and behavioral science trends in maritime studies: Keyword analysis

Denizcilik çalışmalarında sosyal ve davranışsal bilim eğilimleri: Anahtar kelime analizi

Türk Denizcilik ve Deniz Bilimleri Dergisi Cilt: 9 Sayı: 2 (2023) 97-109

Erdem KAN[1,*], Özgür TEZCAN[1]

[1]*Çanakkale Onsekiz Mart University, Marine Science and Technology Faculty, Terzioglu Campus, Çanakkale, Turkey*

ABSTRACT

It is known that the maritime industry is intertwined with scientific developments. Considering the number of scientific research and support projects, the relationship between the scientific community and the industry is getting stronger day by day. The research aims to determine the main trend in the articles published between 2011-2022 in the journals published in the field of maritime management and indexed in SSCI-Social Science Citation Index. To determine the trend in the field of maritime management, the keywords of 1528 articles published in 3 journals determined according to the limitations were analyzed. As a result of keyword and network analysis, ports, maritime transport, liner shipping, container terminals, and data envelopment analysis-DEA are the most used keywords. The most important result obtained as a result of this study is that the events in the world (war, pandemic, terrorism, piracy, etc.) are in a rapid upward trend in the field of maritime business management and the scientific community has shown a rapid reaction on these issues.

Keywords: Maritime research, Keyword analysis, Social sciences, Trends, SSCI

Article Info
Received: 08 June 2023
Revised: 20 July 2023
Accepted: 20 July 2023

[*](corresponding author)
E-mail: erdem.kan@comu.edu.tr

To cite this article: Kan, E., Tezcan, Ö., (2023). Social and behavioral science trends in maritime studies: Keyword analysis. *Turkish Journal of Maritime and Marine Sciences* 9(2): 97-109. doi:10.52998/trjmms.1311907.

ÖZET

Denizcilik sektörünün bilimsel gelişmelerle iç içe olduğu bilinmektedir. Bilimsel araştırma ve desteklenen proje sayılarına bakıldığında bilimsel camia ile sektör arasındaki ilişki her geçen gün kuvvetlenmektedir. Araştırmanın amacı, denizcilik yönetimi alanında yayınlanan ve SSCI'da indekslenen dergilerde 2011-2022 yılları arasında yayınlanan makalelerdeki ana eğilimi belirlemektir. Denizcilik işletmeleri yönetimi alanındaki eğilimin belirlenmesi amacıyla, kısıtlara göre belirlenen 3 dergide yayınlanan 1528 makalenin anahtar kelimeleri analiz edilmiştir. Anahtar kelime ve network analizi sonucunda limanlar, deniz taşımacılığı, liner taşımacılık, konteyner terminalleri ve veri zarflama analizi (DEA) en çok kullanılan anahtar kelimeler olarak karşımıza çıkmaktadır. Bu çalışma sonucunda elde edilen en önemli sonuç ise, dünyada yaşanan olayların (savaş, pandemi, terör, deniz haydutluğu vs.) denizcilik işletmeleri yönetimi alanı araştırmalarında hızla yükseliş trendine girmesi ve bilim camiasının bu konularla ilgili hızlı reaksiyon göstermesidir.

Anahtar sözcükler: Denizcilik araştırmaları, Anahtar kelime analizi, Sosyal bilimler, Trendler, SSCI

1. INTRODUCTION

In recent years, there has been a significant increase in the number of research and published articles on the maritime industry (Wang and Mileski, 2018). Due to the size of the seas in the world's ecosystem, it has an important place in people's lives. The hierarchy of management functions should carry out trade over the seas covering such a large area (Kapidani *et al*., 2020; Plink *et al*., 2021). Maritime transport is seen as the most important transport system of international trade. Industrialization, globalization, the increase in the world population, and the depletion of local resources cause the need for maritime transportation to increase day by day (Christiansen *et al*., 2007). The increase in the importance of maritime transport with each passing day causes an increase in the need for problems and solution proposals in this field. In this context, the number of scientific studies on the problems and innovative ideas in the field of maritime transport is increasing (Bai *et al*., 2021). Since maritime science is a multidisciplinary field, it is influenced by many mainstream scientific trends (Woo *et al*., 2011). When the articles written in the field of maritime management are examined, it is seen that studies on ports and waterways are dominant. Although qualitative methods are used to identify problems in such studies, quantitative research methods are often applied to produce some economic solutions (Shi and Li, 2017). The contribution of scientific studies to the developments in the field of maritime cannot be ignored. It is known that there are many economic, political, and managerial changes in the maritime field together with scientific approaches. (T. E. Notteboom *et al*., 2013).

When scientific publications related to maritime in the field of social sciences are examined, the most cited studies are effectiveness of operations (Carvalho and Marques, 2012; Chen *et al*., 2018; Siqueira *et al*., 2017; Verhoeven, 2010), policies (Eide *et al*., 2011; Verhoeven, 2010), sustainability *(Acciaro et al., 2014; Zis et al*., 2014), liner shipping networks (Álvarez, 2009; Ducruet *et al*., 2010), logistic hubs (Pettit and Beresford, 2009), marine accident analyzes (Uğurlu *et al*., 2015), port supply chain (Rodrigue and Notteboom, 2009), technological developments (Gharehgozli *et al*., 2016) and belt and road initiative (BRI) (Lee *et al*., 2018). When these studies are examined, it is observed that the first articles written about certain trending topics are accepted as pioneering by the articles that will come after them. After the year the articles were first published, many scientific publications are made regarding the solution of the identified problem, and the keywords of these most cited articles are frequently encountered in the studies. In the journals indexed within the scope of the Web of Science (WoS), there are few journals in the field of social sciences, especially focused on the field of maritime management. The number of articles published in these journals, which are few in number, is increasing day by day. In this case, it shows that the interest of the scientific community regarding the problems in the maritime field is increasing. When the contents of the studies are examined, the maritime industry has new research trends according to the developments in the world. A problem that arises anywhere in the world has a counterpart in the maritime industry. Industry stakeholders, who can adapt to the new situation in the face of wars (Kormych and Averochkina, 2022; Rožić *et al.*, 2022), epidemics (Guerrero *et al.*, 2022; Narasimha *et al.*, 2021; T. Notteboom *et al.*, 2021; Oyenuga, 2021), international relations and technological developments, establish a competitive advantage over their competitors. For this reason, it is known that the stakeholders operating in the maritime sector are in close contact with the scientific community regarding the problems they experience and follow all developments. When the results of the study are examined, it is seen that the trending topics in the world agenda are in the field of interest of scientific research on maritime management.

This research aims to determine the main trend in the articles published between 2011-2022 in the journals published in the field of maritime management and indexed in SSCI. The questions of the study created in this context:

- What are the main topics of maritime transport in the field of social sciences?
- Does the popularity of the studies change over time?
- Is the maritime industry affected by the negativities in the world, and is the scientific community seeking answers to these problems?

2. INPUTS

2.1. Maritime Policy & Management (MPM)

Journal of MPM is an international and multidisciplinary journal. The journal published its first issue in 1973. It has been indexed since 2009 within the scope of WoS. 767 articles were published in the journal between the years 2011-2022, which were covered within the scope of the research. The main topics of the publications according to the WoS categories are shown in Figure 1.

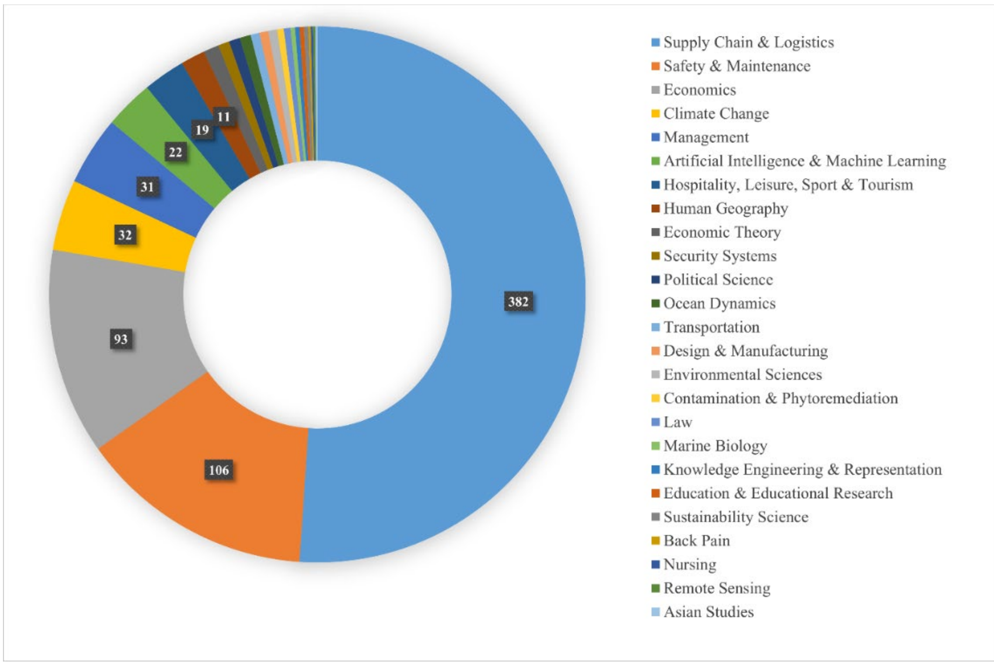


Figure 1. Subject Categories of Articles Published by MPM between 2011-2022 (Source: Authors)

Considering the publication topics of the journal, most articles were published on “Supply Chain & Logistics”. Later, articles were published on the main topics of Safety & Maintenance, Economics, Climate Change, and Management, respectively. According to the categories of article topics, the journal is in the category of social science journals publishing in the field of maritime.

2.2. Maritime Economics & Logistics (MEL)

MEL is a multidisciplinary journal in which international, peer-reviewed scientific articles are published. The journal was first published in 1999. It has been indexed in the WOS database since 2009. Within the scope of this research, all 280 articles published in the journal between 2011-2022 were included in the research. The main topics of the publications according to the WoS categories are shown in Figure 2.

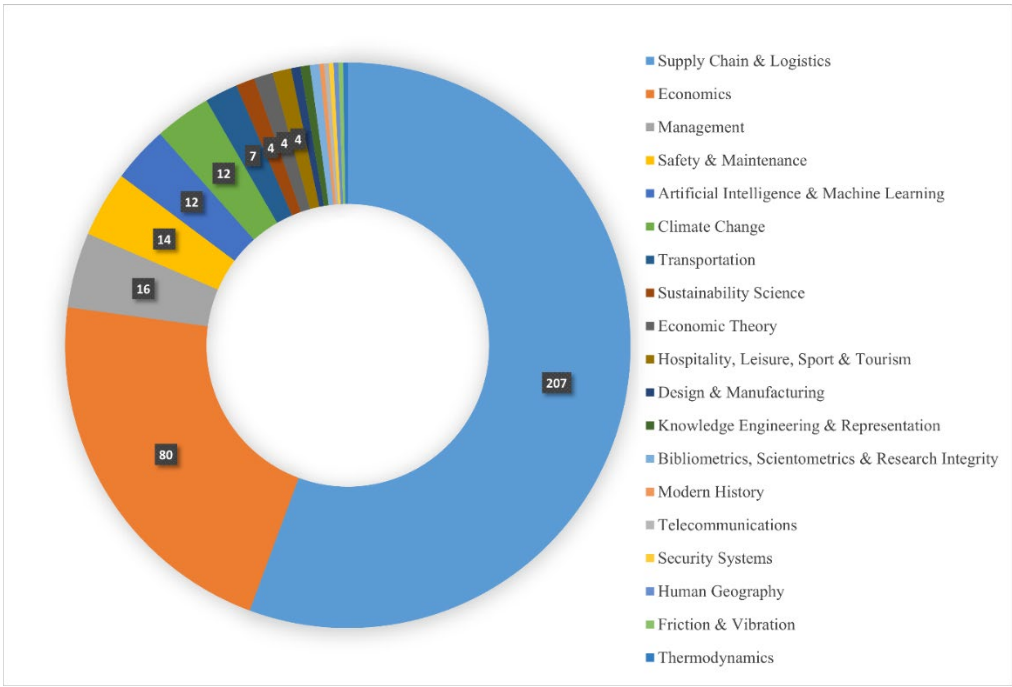


Figure 2. Subject Categories of Articles Published by MEL between 2011-2022 (Source: Authors)

When Figure 2 is examined, most of the articles published in the journal were published in the main subject category of "Supply Chain & Logistics". After this category, “Economics”, “Management”, Safety & Maintenance” main subject categories come respectively. When the main subject categories of the study are examined, it is understood that MEL is a journal that publishes in the field of social sciences and maritime.

2.3. International Journal of Shipping and Transport Logistics (IJSTL)

IJSTL is an international, peer-reviewed, and multidisciplinary scientific journal published in the field of maritime. The journal's first issue was published in 2009 and has been indexed in the WoS database since 2009. Within the scope of the research, 381 articles published between 2011-2022 were examined. The main topics of the publications according to the WoS categories are shown in Figure 3.
When Figure 3 is examined, the category with the most publications in IJSTL is Supply Chain

& Logistics. After this category, articles were published in the "Management", "Economics" and Safety & Maintenance" categories, respectively. When the journal topics are examined, IJSTL is a scientific maritime journal that publishes under social sciences.

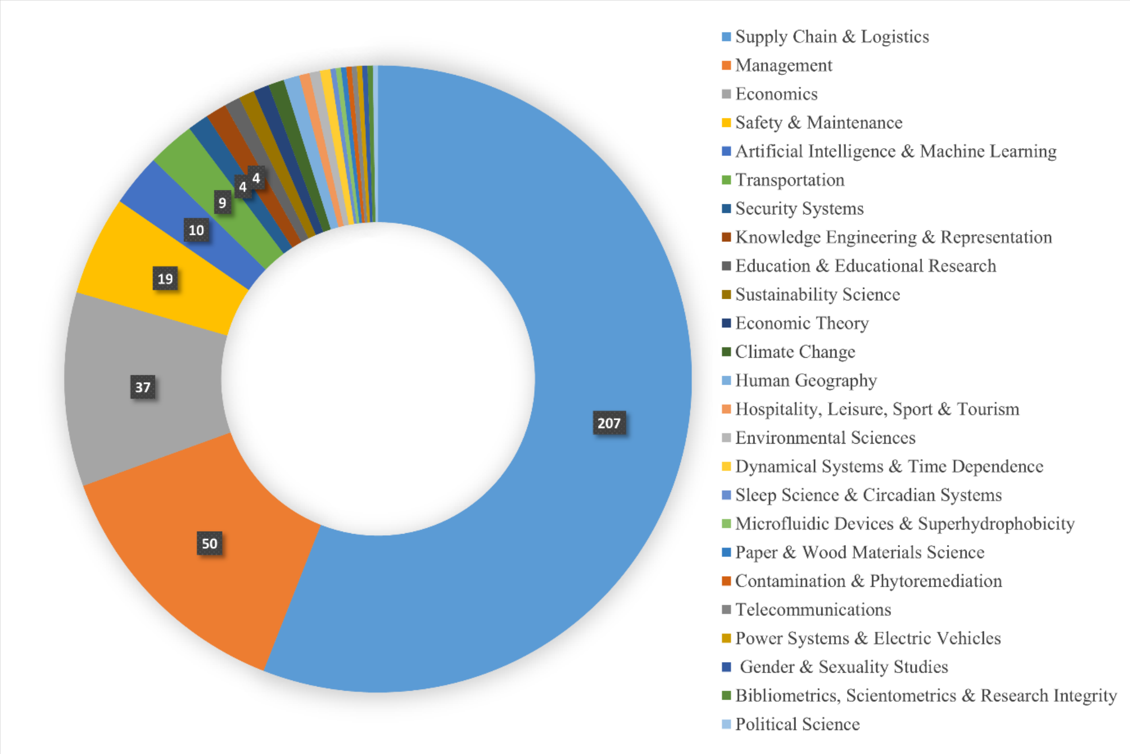


Figure 3. Subject Categories of Articles Published by IJSTL between 2011-2022 (Source: Authors)

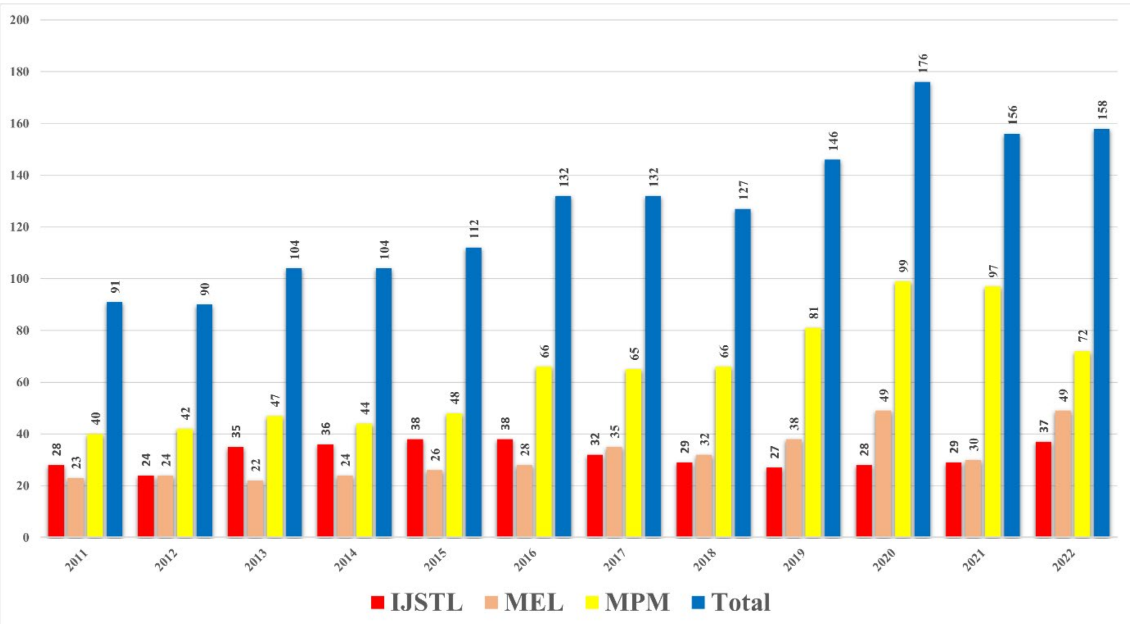


Figure 4. Distribution of the Number of Articles Published in Journals by Years (Source: Authors)

It is seen that there is an increase in the number of articles by years in the Maritime Policy & Management (MPM), Maritime Economics & Logistics (MEL), and International Journal of Shipping and Transport Logistics (IJSTL) examined within the scope of the study. Figure 4 shows the number of articles published by the journals by year. The increase in the number of scientific publications over the years shows that the scientific community is now more interested in the problems experienced in the maritime industry. When the number of articles published by years is examined, MPM increased the number of publications by 80%, MEL by 113%, and IJSTL by 32%. In total, the publication rate in SSCI journals publishing in the field of maritime increased by 73%.

3. MATERIAL AND METHODS

Keywords could be considered as the main indicators that signalize a study's subject area (Evans *et al*., 2013). Therefore, keyword analysis is a preferred method to analyze and interpret existing literature and to expose focal points in a field. This method has been used in various fields (Onwuegbuzie *et al*., 2015). Kevork and Vrechopoulos (2009), reviewed 396 relevant articles to the customer relationship management literature in 135 journals and exposed a view of keyword frequency in different categories. Nel *et. al*. (2011) took the same path to evaluate the keyword frequency of 417 articles published in a single journal in a selected period.

In line with the aim of the study, a two-step process was followed. As the first step, to reveal the keyword trends in maritime studies, keyword analysis has been conducted. In this study, a journal search was performed on the Web of Science database. The search was limited to the SSCI journals covering 'maritime' or 'shipping' statements in their names. During the journal determination phase, a search was also carried out using the statement 'marine', but since the published journals were related to marine biology and marine resources, those journals in that category were excluded from the research. As the result of this search, 3 journals (International Journal of Shipping and Transport Logistics, Maritime Economics & Logistics, and Maritime Policy & Management) were included in this study.

The articles in these journals were examined in 3 separate periods. There were 389 papers published in the years 2011 to 2014 containing 879 keywords, 503 in 2015 to 2018 containing 1742 keywords, and 636 in 2019 to 2022 containing 2428 keywords. After a depth examination of keywords in each period, the singular or plural form, or noun or verb form of the same keywords, and abbreviated keywords were combined. It was not preferred to perform semantic coding or categorization to reflect the actual form of used keywords. The keywords used less than 3 for each period were ignored. The interpretations for study trends were made by considering the most frequently mentioned 30 keywords for each period.

At the second stage, it was intended to present a network of keywords for each period. The network of selected keywords was exposed by the VosViewer Software and analysed. The results of the keyword analysis and network analysis were given in the below section.

4. RESULTS AND DISCUSSION

4.1. Keyword Analysis

To draw attention to the most used keywords, the top 30 keywords (a total of 58 different keywords in both periods) that emerged after the necessary combinations were made and ranked according to the frequency of use (see Table 1).

In the first period (2011-2014), due to the number of total published papers and their keywords being relatively low, the frequency of mentioned keywords is low, in parallel. In this period, as a research method, the 'data envelopment analysis (DEA)' (n=15) keyword is the most frequent one. Another method-based keyword 'analytical hierarchy process (AHP)' is also listed (n=5). With this, keywords focusing on the shipping concept (shipping; n=14, liner shipping; n=13, container shipping; n=10, short sea shipping; n=6, and dry bulk shipping; n=4) form the top of the list. Besides, keywords in the scope of port (port(s); n=11, port competition; n=3, and port security; n=3) stand out. Additionally, 'container terminal(s)' (n=9) and ‘efficiency’ (n=8) are also very frequent.

Due to piracy and armed robbery, security concerns have been raised in the first decade of the 21st century. Its reflection can be seen in the first period of the table as the keywords like; 'supply chain security', 'port security', and 'transport security'. Except this, the competitive approach was also showing itself by ‘competition’, ‘service quality’, and ‘port competition’.

The most frequent keyword in the second period (2015-2018) is ‘port(s) (n=24)’. Other keywords related to the port concept (port performance; n=7, port pricing; n=6, and port competition; n=6) are also listed. It is seen that the method-based keywords data envelopment analysis (dea) (n=21), and analytical hierarchy process (ahp) (n=14) are frequently mentioned. Besides, container-based keywords (container terminal(s); n=15, container(s); n=12, and container shipping; n=10) are also frequent. Additionally, shipping-based keywords (liner shipping; n=19, short sea shipping; n=14, and shipping; n=11) are visible in the upper half of the table.

The competitive approach is more visible in the studies of the second period. ‘customer satisfaction’ and ‘competitiveness’ keywords can be also counted in this context. Although efficiency is in the previous period, when evaluated together with the keywords ‘freight rate’ and ‘port pricing’, it indicates that economic concerns have risen in this period.

In the third period (2019-2022), the ‘maritime transportation’ is the most frequent one (n=27). Many keywords within the scope of shipping are listed (container shipping; n=20, shipping; n=18, liner shipping; n=15, autonomous shipping (ships); n=8, and maritime shipping; n=7). The keywords ‘port(s)’ (n=26) and ‘seaport(s)’ (n=11) are also frequent. It is seen that some new keywords emphasizing global warming and sustainability concerns (port efficiency; n=12, sustainability/sustainable development; n=11, climate change; n=9, autonomous shipping (ships); n=8) are at the top of the list. This points out that the concerns in this scope were increased.

In this period, the reflections of the worldwide pandemic crisis can be seen in the studies by the keyword ‘covid-19’ (n=10). Besides, China’s ‘Belt and road initiative (bri)’ become a new and frequently mentioned keyword. The ‘efficiency’ transformed to ‘port efficiency’ in this period.

Table 2 demonstrates the trend of the top 30 keywords over 12 years. Some of the keywords (belt and road initiative (bri), hinterland, container(s), seaport(s), literature review, maritime logistics, port efficiency, sustainability / sustainable transportation, and automatic identification system (ais)) do not exist in the first period. The keywords ‘transport logistics’ and ‘service quality’ are not seen in the third period. However, the ‘port efficiency’, ‘covid-19’, ‘maritime safety’, and ‘climate change’ keywords exist only in the third period. ‘port(s)’, and ‘maritime transport(ation)’ is the most used keywords, and they are in increasing trend. Although the shipping-based keywords (liner shipping, shipping, container shipping, and short sea shipping) are the most given keywords, they are in a decreasing trend in the last period except ‘container shipping’. Method-based keywords (data envelopment analysis (dea), and analytical hierarchy process (ahp) made a peak in the second period and entered a downtrend. ‘belt and road initiative (bri)’, ‘automatic identifications system (ais)’, ‘seaport(s)’, ‘port efficiency sustainability / sustainable development’ are the keywords that are in the most uptrend. ‘Covid-19’, ‘maritime safety’, and ‘climate change’, which were not mentioned in the previous period, showed high frequency in the last period.

Table 1. Keyword frequencies

No.	2011-2014 Keywords	f	2015-2018 Keywords	f	2019-2022 Keywords	f
1	data envelopment analysis (dea)	15	port(s)	24	maritime transport(action)	27
2	shipping	14	data envelopment analysis (dea)	21	port(s)	26
3	liner shipping	13	liner shipping	19	container terminal(s)	21
4	port(s)	11	container terminal(s)	15	container shipping	20
5	container shipping	10	analytical hierarchy process (ahp)	14	shipping	18
6	transport logistics	9	maritime transport / transportation	14	belt and road initiative (bri)	16
7	container terminal(s)	9	short sea shipping	14	liner shipping	15
8	maritime transport(ation)	9	container (s)	12	china	14
9	efficiency	8	logistics	12	port efficiency	12
10	supply chain security	6	china	11	Seaport(s)	11
11	supply chain	6	shipping	11	sustainability / sustainable development	11
12	short sea shipping	6	container shipping	10	covid-19	10
13	china	5	competition	8	maritime safety	10
14	analytical hierarchy process (ahp)	5	freight rate	7	automatic identification system (ais)	9
15	service quality	4	service quality	7	climate change	9
16	logistics	4	literature review	7	data envelopment analysis (dea)	9
17	finland	4	port performance	7	hinterland	9
18	optimization	4	structural equation modelling	7	risk assessment	9
19	simulation	4	efficiency	6	autonomous shipping (ships)	8
20	dry bulk shipping	4	dry bulk	6	container port(s)	8
21	confirmatory factor analysis	3	customer satisfaction	6	genetic algorithm	8
22	fuzzy logic	3	maritime logistics	6	literature review	7
23	regulation	3	northern sea route	6	maritime logistics	7
24	competition	3	port pricing	6	maritime shipping	7
25	risk management	3	port competition	6	regulation	6
26	usa	3	hinterland	6	cluster analysis	6
27	port competition	3	genetic algorithm	6	containers	6
28	port security	3	maritime	6	supply chain	6
29	transport	3	transport logistics	5	competition	6
30	transport security	3	competitiveness	5	port operations	6

Source: Authors

Considering the trend according to the periods, the number of studies and keywords gradually increased over periods. The average frequency of most keywords is also increasing. It is seen that the most mentioned keywords are almost the same except for minor ranking changes. The major topics of maritime studies are focusing on ports, maritime transportation, or shipping issues. While 'port(s)', and 'maritime transport(ation)' are increasing, shipping-based keywords are in a decreasing trend, in general. For all that, some sustainability-concerned keywords put forward in the third period. 'sustainability/sustainable development', 'port efficiency', and 'climate change' shows the maritime studies' interest in both the dimensions of sustainability, especially in economic and environmental. Additionally, the most increased keyword 'belt and road initiative (bri)' became a very popular topic in the last period. It is predicted that these keywords, which have increased rapidly in the last period, will be used more frequently in reviewed studies.

Table 2. Keyword trends by periods

	Keywords	**f (2011-2014)**	**f (2015-2018)**	Change %	**f (2019-2022)**	Change %	**Total**
1	port(s)	**11**	**24**	118	**26**	8	**61**
2	maritime transport(ation)	**9**	**14**	56	**27**	93	**50**
3	liner shipping	**13**	**19**	46	**15**	-21	**47**
4	container terminal(s)	**9**	**15**	67	**21**	40	**45**
5	data envelopment analysis (dea)	**15**	**21**	40	**9**	-57	**45**
6	shipping	**14**	**11**	-21	**18**	64	**43**
7	container shipping	**10**	**10**	0	**20**	100	**40**
8	china	**5**	**11**	120	**14**	27	**30**
9	short sea shipping	**6**	**14**	133	**5**	-64	**25**
10	analytical hierarchy process (ahp)	**5**	**14**	180	**5**	-64	**24**
11	logistics	**4**	**12**	200	**5**	-58	**21**
12	belt and road initiative (bri)	**-**	**4**	100	**16**	300	**20**
13	hinterland	**-**	**6**	100	**9**	50	**19**
14	container(s)	**-**	**12**	100	**6**	-50	**18**
15	competition	**3**	**8**	167	**6**	-25	**17**
16	efficiency	**8**	**6**	-25	**3**	-50	**17**
17	genetic algorithm	**3**	**6**	100	**8**	33	**17**
18	port efficiency	**-**	**5**	100	**12**	140	**17**
19	supply chain	**6**	**4**	-33	**6**	50	**16**
20	sustainability / sustainable development	**-**	**5**	100	**11**	120	**16**
21	seaport(s)	**-**	**4**	100	**11**	175	**15**
22	literature review	**-**	**7**	100	**7**	0	**14**
23	transport logistics	**9**	**5**	-44	**-**	-100	**14**
24	maritime logistics	**-**	**6**	100	**7**	17	**13**
25	automatic identification system (ais)	**-**	**3**	100	**9**	200	**12**
26	port competition	**3**	**6**	100	**3**	-50	**12**
27	service quality	**4**	**7**	75	**-**	-100	**11**
28	covid-19	**-**	**-**	-	**10**	100	**10**
29	maritime safety	**-**	**-**	-	**10**	100	**10**
30	climate change	**-**	**-**	-	**9**	100	**9**

Source: Authors

4.2. Keyword Network Analysis

The keyword analysis performed via VosViewer is given below. Figure 5, 6, and 7 demonstrates the keyword networks in periods. The size of any node represents the keyword frequency. The colors indicate the keywords clusters.

According to Figure 5, the strongest keywords in terms of total link strength are 'port(s)', 'shipping', 'transport logistics', and 'data envelopment analysis (dea)', respectively. While 'port(s)' are mostly linked to 'shipping', 'supply chain', 'service quality', and 'regulation'; 'shipping' is used with 'transport logistics', 'maritime transport(ation), 'service quality, 'and 'china'. The strongest link in this period is between 'supply chain security' and 'transport security'.

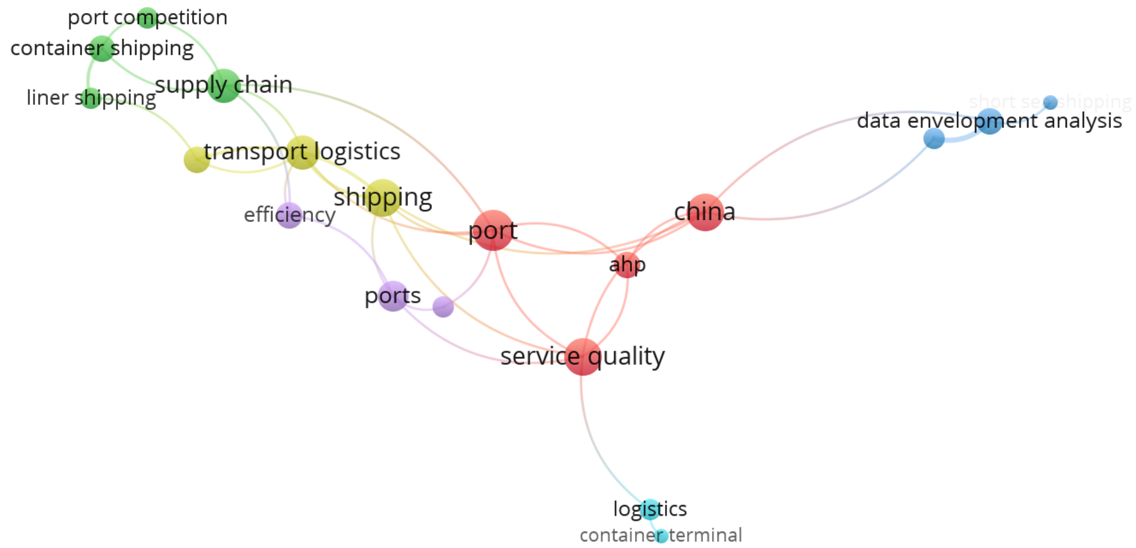


Figure 5. Network analysis of keywords co-occurrence in 2011-2014 (Source: Authors)

The strongest keywords in terms of total link strength in the 2015-2018 period are (Figure 6); 'data envelopment analysis (dea)', 'liner shipping', 'port(s)', and 'short sea shipping', respectively. The studies including 'data envelopment analysis (dea)' generally include 'container(s)', 'container shipping', 'liner shipping', and 'port(s)'. 'liner shipping' has a strong link with 'service quality', and 'logistics'. 'port(s)' and 'logistics' are used together. The strongest network in this period is between 'liner shipping' and 'logistics'.

In the last period (2019-2022), the strongest keywords in terms of total link strength are (Figure 7); 'maritime transport(ation)', 'shipping', 'climate change', and 'port(s)' respectively. 'shipping' has a strong network to 'regulation', 'port(s)', 'seaport(s). 'climate change' is also linked to same keywords. One of the new keywords 'belt and road initiative (bri)' is used together with 'port efficiency', 'seaport(s)', and 'china'. 'sustainability/sustainable development' is generally related to the shipping-based keywords. The 'covid-19 links show that there are studies on the pandemic linked to various topics.

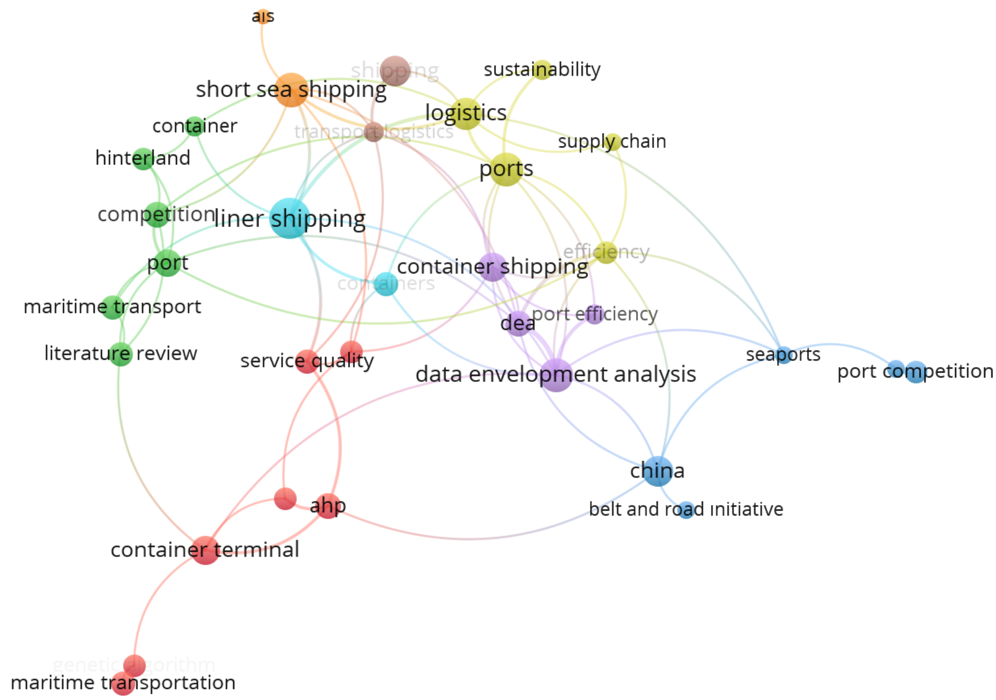


Figure 6. Network analysis of keywords co-occurrence in 2015-2018 (Source: Authors)

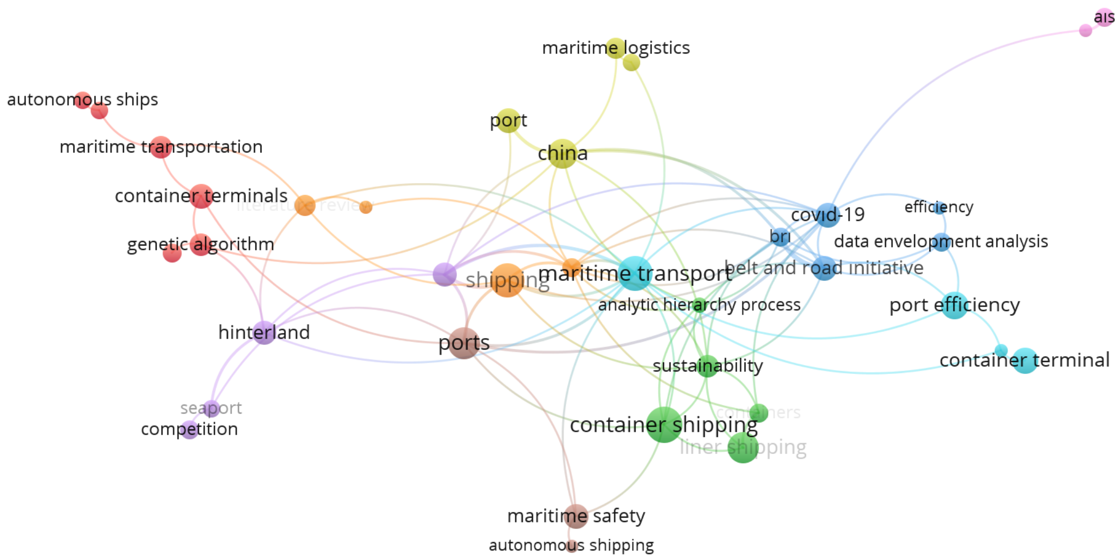


Figure 7. Network analysis of keywords co-occurrence in 2019-2022 (Source: Authors)

5. CONCLUSION

Within the scope of the research, the keywords of the articles published in the last 12 years of the three journals indexed in SSCI, which publishes in the field of maritime business management, were analyzed in equal periods. Along with the evaluation of the findings obtained from the keyword and network analysis, the most important result of this study is that the events in the world are quickly popular in the maritime industry and the scientific community reacts quickly. As a result of this research, it is seen that the research methods used in the studies in the field of maritime business management tend to be

multidisciplinary methods. The methods used in different fields in pioneering studies in the field of maritime business management are rapidly becoming popular and are used in much research. In the following period, overused methods enter a downward trend, and new methods are seen to be used. It is seen that the main themes of port and logistics are used throughout the studies. It has been determined that especially in the studies related to the main theme of the port, container transportation and liner transportation are emphasized.
Within the scope of the research, three journals that are purely maritime management journals were selected and analyzes were made for the articles published in these journals. In future studies, the study can be expanded by adding articles about maritime in journals whose main themes are transportation, logistics, etc.

AUTHORSHIP CONTRIBUTION STATEMENT

Erdem KAN: Conceptualization, Methodology, Validation, Resources, Writing - Original Draft, Writing-Review and Editing, Data Curation, Visualization.
Özgür TEZCAN: Conceptualization, Methodology, Validation, Formal Analysis, Resources, Writing - Original Draft, Writing-Review and Editing, Data Curation, Software, Visualization.

CONFLICT OF INTERESTS

The authors declare that for this article they have no actual, potential, or perceived conflict of interest.

ETHICS COMMITTEE PERMISSION

No ethics committee permissions are required for this study

FUNDING

No funding was received from institutions or agencies for the execution of this research.

ORCID IDs

Erdem KAN:
https://orcid.org/0000-0002-9834-5749
Özgür TEZCAN:
https://orcid.org/0000-0001-6222-4665

6. REFERENCES

Acciaro, M., Vanelslander, T., Sys, C., Ferrari, C., Roumboutsos, A., Giuliano, G., Lam, J.S.L., Kapros, S., (2014). Environmental sustainability in seaports: A framework for successful innovation. *Maritime Policy & Management* 41(5): 480–500. doi:10.1080/03088839.2014.932926.

Álvarez, J.F., (2009). Joint Routing and Deployment of a Fleet of Container Vessels. *Maritime Economics & Logistics* 11(2): 186–208. doi:10.1057/mel.2009.5.

Bai, X., Zhang, X., Li, K.X., Zhou, Y., Yuen, K.F., (2021). Research topics and trends in the maritime transport: A structural topic model. *Transport Policy* 102: 11–24. doi:10.1016/j.tranpol.2020.12.013.

Carvalho, P., Marques, R.C., (2012). Using non-parametric technologies to estimate returns to scale in the Iberian and international seaports. *International Journal of Shipping and Transport Logistics* 4(3): 286–302.

Chen, H.K., Chou, H.W., Hsieh, C.C., (2018). Operational and disaggregate input efficiencies of international container ports: An application of stochastic frontier analysis. *International Journal of Shipping and Transport Logistics* 10(2): 113–159.

Christiansen, M., Fagerholt, K., Nygreen, B., Ronen, D., (2007). Chapter 4 Maritime Transportation. In Handbooks in Operations Research and Management Science Vol. 14, pp. 189–284. Elsevier. doi:10.1016/S0927-0507(06)14004-9.

Ducruet, C., Lee, S.W., Ng, A.K.Y., (2010). Centrality and vulnerability in liner shipping networks: Revisiting the Northeast Asian port hierarchy. *Maritime Policy & Management* 37(1): 17–36. doi:10.1080/03088830903461175.

Eide, M.S., Longva, T., Hoffmann, P., Endresen, Ø., Dalsøren, S.B., (2011). Future cost scenarios for reduction of ship CO_2 emissions. *Maritime Policy & Management* 38(1): 11–37. doi:10.1080/03088839.2010.533711.

Evans, J.R., Foster, S.T., Guo, Z., (2013). A Retrospective View of Research in the Quality Management Journal: A Thematic and Keyword Analysis. *Quality Management Journal* 20(1): 37–47. doi:10.1080/10686967.2013.11918090.

Gharehgozli, A.H., Roy, D., De Koster, R., (2016). Sea container terminals: New technologies and OR models. *Maritime Economics & Logistics* 18(2): 103–140. doi:10.1057/mel.2015.3.

Guerrero, D., Letrouit, L., Pais-Montes, C., (2022). The container transport system during Covid-19: An analysis through the prism of complex networks. *Transport Policy* 115: 113–125. doi:10.1016/j.tranpol.2021.10.021.

Kapidani, N., Bauk, S., Davidson, I.E., (2020). Digitalization in Developing Maritime Business Environments towards Ensuring Sustainability. *Sustainability* 12(21): 9235. doi:10.3390/su12219235.

Kevork, E.K., Vrechopoulos, A.P., (2009). CRM literature: Conceptual and functional insights by keyword analysis. *Marketing Intelligence & Planning* 27(1): 48–85. doi:10.1108/02634500910928362.

Kormych, B., Averochkina, T., (2022). Ukrainian Maritime Industry under Fire: Consequences of Russian Invasion. *Lex Portus* 8: 7.

Lee, P.T.W., Hu, Z.H., Lee, S.J., Choi, K.S., Shin, S.H., (2018). Research trends and agenda on the Belt and Road (B&R) initiative with a focus on maritime transport. *Maritime Policy & Management* 45(3): 282–300. doi:10.1080/03088839.2017.1400189.

Narasimha, P.T., Jena, P.R., Majhi, R., (2021). Impact of COVID-19 on the Indian seaport transportation and maritime supply chain. *Transport Policy* 110: 191–203. doi:10.1016/j.tranpol.2021.05.011.

Nel, D., Van Heerden, G., Chan, A., Ghazisaeedi, M., Halvorson, W., Steyn, P., (2011). Eleven years of scholarly research in the Journal of Services Marketing. *Journal of Services Marketing* 25(1):, 4–13. doi:10.1108/08876041111107014.

Notteboom, T.E., Pallis, A.A., De Langen, P.W., Papachristou, A., (2013). Advances in port studies: The contribution of 40 years Maritime Policy & Management. *Maritime Policy & Management* 40(7): 636–653. doi:10.1080/03088839.2013.851455.

Notteboom, T., Pallis, T., Rodrigue, J.P., (2021). Disruptions and resilience in global container shipping and ports: The COVID-19 pandemic versus the 2008–2009 financial crisis. *Maritime Economics & Logistics* 23(2): 179–210. doi:10.1057/s41278-020-00180-5.

Onwuegbuzie, A., Leech, N., Collins, K., (2015). Qualitative Analysis Techniques for the Review of the Literature. The Qualitative Report. doi:10.46743/2160-3715/2012.1754.

Oyenuga, A., (2021). Perspectives on the impact of the COVID-19 pandemic on the global and African maritime transport sectors, and the potential implications for Africa's maritime governance. *WMU Journal of Maritime Affairs* 20(2): 215–245. doi:10.1007/s13437-021-00233-3.

Pettit, S.J., Beresford, A.K.C., (2009). Port development: From gateways to logistics hubs. *Maritime Policy & Management* 36(3): 253–267. doi:10.1080/03088830902861144.

Plink, N., Semeoshenkova, V., Eremina, T., Ershova, A., Mushket, I., (2021). Improvement of Maritime Management as a Key Aspect of Sustainable Development and Blue Growth in the Russian Federation. *Journal of Marine Science and Engineering* 9(11): 1212. doi:10.3390/jmse9111212.

Rodrigue, J.P., Notteboom, T., (2009). The terminalization of supply chains: Reassessing the role of terminals in port/hinterland logistical relationships. *Maritime Policy & Management* 36(2): 165–183. doi:10.1080/03088830902861086.

Rožić, T., Naletina, D., Zając, M., (2022). Volatile Freight Rates in Maritime Container Industry in Times of Crises. *Applied Sciences* 12(17): 8452. doi:10.3390/app12178452.

Shi, W., Li, K.X., (2017). Themes and tools of maritime transport research during 2000-2014. *Maritime Policy & Management* 44(2): 151–169. doi:10.1080/03088839.2016.1274833.

Siqueira, G.A., Jr, I.C.L., Cunha, L.C.D., Guimarães, V.D.A., Guabiroba, R.C.D.S., (2017). Analysis of technical efficiency and eco-efficiency in container terminals. *International Journal of Shipping and Transport Logistics* 9(5): 562–579.

Uğurlu, Ö., Köse, E., Yıldırım, U., Yüksekyıldız, E. (2015). Marine accident analysis for collision and grounding in oil tanker using FTA method. *Maritime Policy & Management* 42(2): 163–185. doi:10.1080/03088839.2013.856524.

Verhoeven, P., (2010). A review of port authority functions: Towards a renaissance? *Maritime Policy & Management* 37(3): 247–270. doi:10.1080/03088831003700645.

Wang, P., Mileski, J., (2018). Strategic maritime management as a new emerging field in maritime studies. *Maritime Business Review* 3(3): 290–313. doi:10.1108/MABR-06-2018-0019.

Woo, S.H., Pettit, S.J., Kwak, D.W., Beresford, A.K.C., (2011). Seaport research: A structured literature review on methodological issues since the 1980s. *Transportation Research Part A: Policy and Practice* 45(7): 667–685. doi:10.1016/j.tra.2011.04.014.

Zis, T., North, R.J., Angeloudis, P., Ochieng, W.Y., Harrison Bell, M.G., (2014). Evaluation of cold ironing and speed reduction policies to reduce ship emissions near and at ports. *Maritime Economics & Logistics* 16(4): 371–398. doi:10.1057/mel.2014.6.

Research Article
Turkish Journal of Maritime and Marine Sciences

DOI: 10.52998/trjmms.1294701
Volume: 9 Issue: 2 (2023) 110-118

The effect of *Tenebrio molitor* larva meal instead of fish meal on growth performance and feed efficiency in juvenile Nile tilapia (*Oreochromis niloticus*) diets

Jüvenil Nil tilapia (*Oreochromis niloticus*) rasyonlarında balık unu yerine *Tenebrio molitor* larva ununun büyüme performansı ve yemden yararlanma üzerine etkisi

Türk Denizcilik ve Deniz Bilimleri Dergisi

Cilt: 9 Sayı: 2 (2023) 110-118

Seval DERNEKBAŞI [1,*], İsmihan KARAYÜCEL[2]

[1]*University of Sinop, Fisheries and Aquaculture Faculty, Department of Aquaculture, Sinop, Turkey*

ABSTRACT

The aim of this study was to evaluate the effects of feeding Nile tilapia juvenile (*Oreochromis niloticus*) with diets based on fish meal (FM) and *Tenebrio molitor* (TM) larvae meal on growth performance and feed efficiency. For this purpose, three diets were prepared: Control diet (FM); without *T. molitor* larvae meal, insect diet (TM); 100% of fish meal has been replaced by *T. molitor* larvae meal and mixture diet (FM/TM); 50% of FM has been replaced by *T. molitor* larvae meal. Each treatment was tested in three replications over a 46-day. In the experiment, 1-month-old Nile tilapia juveniles with an average weight of 0.12±0.001 g were used. At the end of the experiment, the best growth was in the FM group, followed by the TM group and FM/TM group, the differences being significant except for FM and TM groups ($P<0.05$). Weight gain was also in line with growth rates. The SGR was 5.35%, 5.27% and 5.21% in FM, TM and FM/TM groups, respectively, and The difference between FM and FM/TM groups was statistically significant ($P<0.05$). The best FCR was in the FM group which was similar to TM diet ($P<0.05$). The worst FCR was in the group fed FM/TM diet with a significant difference from the other treatments. The PER changed between 0.87±0.07 and 1.42±0.04 with significant differences among the treatments. The survival rate was 100% in all groups. The data obtained showed that TM has the potential to be used as a protein source in diets of juvenile tilapia.

Keywords: Nile tilapia juveniles, *Oreochromis niloticus*, Mealworm, Growth.

Article Info
Received: 09 May 2023
Revised: 14 August 2023
Accepted: 16 August 2023

* (corresponding author)
E-mail: sdernekbasi@sinop.edu.tr

To cite this article: Dernekbaşı,S., Karayücel, İ., (2023). The effect of *Tenebrio molitor* larva meal instead of fish meal on growth performance and feed efficiency in juvenile Nile tilapia (*Oreochromis niloticus*) diets, *Turkish Journal of Maritime and Marine Sciences* 9 (2): 110-118. doi: 10.52998/trjmms.1294701.

ÖZET

Bu çalışmanın amacı, Nil tilapiya yavrularının (*Oreochromis niloticus*) balık unu (FM) ve *Tenebrio molitor* (TM) larva unu bazlı diyetlerle beslenmesinin büyüme performansı ve yem verimliliği üzerindeki etkilerini değerlendirmektir. Bu amaçla üç diyet hazırlanmıştır: Kontrol diyeti (FM); *T. molitor* larva unu içermeyen, böcek diyeti (TM); balık ununun %100'ü *T. molitor* larva unu ile değiştirilmiş ve karışım diyeti (FM/TM); FM'nin %50'si *T. molitor* larva unu ile değiştirilmiştir. Deneme 46 gün boyunca üç tekrarlı olarak test edilmiştir. Denemede, ortalama ağırlığı 0.12±0,001 g olan 1 aylık Nil tilapiya yavruları kullanılmıştır. Deneyin sonunda, en iyi büyüme FM grubunda gerçekleşmiş, bunu TM grubu ve FM/TM grubu izlemiş, FM ve TM grupları dışındaki farklar önemli bulunmuştur (P<0.05). Ağırlık artışı da büyüme oranlarıyla uyumluydu. SGR değerleri uygulamalar arasında karşılaştırılabilirdi (P>0.05). SGR, FM, TM ve FM/TM gruplarında sırasıyla %5.35, %5.27 ve %5.21, ve FM ile FM/TM grupları arasındaki fark istatistiksel olarak önemli bulunmuştur (P<0,05). En iyi FCR, TM diyetine benzer olan FM grubunda tespit edilmiştir (P<0.05). En kötü FCR, diğer uygulamalardan önemli bir farkla FM/TM diyetiyle beslenen grupta görülmüştür. PER 0.87±0.07 ile 1.42±0.04 arasında değişmiş ve uygulamalar arasında önemli farklılıklar görülmüştür. Tüm gruplarda yaşama oranı %100 olmuştur. Elde edilen veriler, TM'nin protein kaynağı olarak kullanılma potansiyeline sahip olduğunu göstermiştir.

Anahtar sözcükler: Nil tilapiya yavruları, *Oreochromis niloticus*, Unkurdu, Büyüme.

1. INTRODUCTION

Fish meal (FM) is the primary ingredient for juvenile fish, but is becoming more and more expensive. Alternative feed sources are required since faith in fishmeal has been questioned recently for social, economic, and environmental reasons (Tran *et al.,* 2015). Insects are promising in animal nutrition due to high nutritional, short intergenerational periods, low carbon emissions in their production, and easy and low production costs (Lange and Nakamura, 2023). Existing studies show that insects can convert 8-9% low-quality protein-containing food wastes into 44-61% good-quality insect protein in a period of 3-4 months under controlled conditions (Ramos-Elorduy, 1997).

Tenebrio molitor is an insect species that has the feature of being a model organism due to its features such as being an easily cultivated species in the laboratory environment, having low breeding and feeding costs, being able to be grown in large numbers in a unit area, short intergenerational time, and easy determination of its characteristics (Özsoy and Gündoğdu 2017). Therefore, *T. molitor* stands out as a promising species for mass production among insects (Ramos-Elorduy *et al.,* 2002; Ghaly and Alkoaik, 2009). *T. molitor* larvae have high protein content (37-47%) as well as high-fat content (Finke, 2002; Ramos-Elorduy *et al*., 2002; Ghaly and Alkoaik, 2009; Huang *et al*., 2011). The dried larvae of *T. molitor*, which is rich in unsaturated fatty acids, have a fat content of 46% (Siemianowska *et al.,* 2013; Ravzanaadii *et al.,* 2012). *T. molitor* meal have used as a protein source in diets of pet animals, broiler chick (Ramos-Elorduy *et al.,* 2002; Marco *et al.,* 2015) and fish (Gasco *et al.,* 2014; Ng *et al.,* 2001; Belforti *et al.,* 2016)

Juvenile fish, regardless of their feeding habit, require nutritionally high-quality diets based on FM under intensive farming conditions and are completely dependent on nutritionally complete diets (Tacon 1988). Insect proteins have become a valuable protein source juvenile fish (Odesanya *et al.,* 2011; Barroso *et al*., 2014; Henry *et al.,* 2015). Previous studies on tilapia fry have demonstrated that, when compared to FM-based control diets, meals from both housefly larvae (*Musca domestica*) and blowfly larvae (*Chrysomya megacephala*) can replace up to 100% of FM in practical diets without impairing fish performance. However, there is still room for the investigation of the dietary use of TM for juvenile Nile tilapia.

In recent years Ulva species have become important macroalgae investigated as a dietary component for a wide range of fish species. The inclusion of Ulva meal at low levels in the diet has resulted in improved growth, feed utilization, physiological activity, disease resistance, carcass quality and reduced stress response (Wassef *et al*., 2005; Valente *et al*., 2006). Furthermore, Ulva meal has been successfully used as a feed ingredient for tilapia and its addition to diets has shown that it can improve carcass composition (Güroy *et al*., 2007; Azaza *et al*., 2008). Ergün *et al*. (2009) reported that the addition of 5% of Ulva meal to diets improved growth performance, feed efficiency, nutrient utilization and body composition of *Oreochromis niloticus*. Therefore, in this study, a 3% *Ulva lactuca* meal was added to diets prepared with two different levels of TM (50% and 100%), and its effects on growth performance and feed efficiency of juvenile Nile tilapia were evaluated.

2. MATERIAL AND METHOD

2.1. Experimental Design and Feeding

The study was carried out at Sinop University Fisheries Faculty Research Center. In the experiment, 1-month-old Nile tilapia juveniles were used. The average weight of 0.12±0.001 g. The fish were distributed to nine square tanks (4 L) in groups of ten. Three diets were tested with three replications for 46 days. In order to keep the water in the tanks at a constant temperature, all aquariums were placed in a 100*50*40 L glass aquarium containing water, and the temperature of the water in the tanks and the aquarium 26ºC using a thermostatic heater. In addition, a water circulation motor was used to distribute the water in the glass aquarium evenly. The water quality parameters were monitored and recorded on a weekly basis.

Fish in all groups were hand fed twice a day (at 09:00 am and 15:00 pm) to apparent satiety under a natural light regime. Experimental tanks were daily siphoned and discharged water was renewed with fresh water afterwards.

2.2. Diet ingredients and formulation

T. molitor larvae obtained from a local producer for production purposes were first placed in a racked rearing system designed to be produced under laboratory conditions. *T. molitor* larvae placed in this rearing system were fed with potatoes or lettuce on a bed of whole wheat flour, cereal bran and rice bran (Figure 1).

Figure 1. A racked rearing system, adult insects and mealworms

After the larvae were transformed into insect form, they started to produce offspring regularly and were harvested before reaching the prepupa stage. *T. molitor* larvae produced for use in the study were frozen at -20°C. The *T. molitor* larvae were dried in an oven and homogenized by grinding just before the preparation of experimental diets.

All raw materials used in feed formulation were sieved and put into a mixer. After mixing homogeneously, water was added and mixing was continued. Since the fish were very small, no pelletizing was done. The feeds removed from the mixer were placed on separate trays and dried at 50ºC. The dried feeds were ground into powder and used as powder feed. Finally, they were stored in sealed feed boxes in the refrigerator. All feeds were used from the refrigerator during the experiment.

Three experimental diets were formulated in which fish meal was substituted with TM at different levels (Table 1):

- Control diet (FM): without TM
- Insect diet (TM): 100% of FM replaced by TM
- Mixture diet (FM/TM): 50% of FM replaced by TM

Other ingredients to be used in the feed formulation were obtained from a commercial feed company (SÜRSAN A.Ş.).

2.3. Chemical composition analysis of diets

The analyses of the chemical composition of feed ingredients and diets were performed according to the standard methods of AOAC (1995). The gross energy of the diets was estimated assuming 23.6 kJ/g protein, 39.5 kJ/g lipid and 17 kJ/g nitrogen-free extracts.

2.4. Calculations

Weight gain (WG, g) = (final body weight − initial body weight) (1)

Specific growth rate (SGR, %/day) = [(ln final body weight − ln initial body weight)/days] × 100. (2)

Protein efficiency ratio (PER) = wet weight gain/total protein given (3)

Feed conversion ratio (FCR) = feed intake/wet weight gain (4)

2.5. Statistical analysis

Anderson-Darling and Levene's tests were used for homogeneity of variances and equality of variance of groups, respectively. Square root transformations of percentage data, the significance of differences in growth and feed utilization variables among the treatments was tested using a one-way analysis of variance (ANOVA), followed by Tukey's method for multiple comparisons. Differences were considered significant when $P < 0.05$. Statistical analyses were performed using Minitab 17 software for Windows.

3. RESULTS

The inclusion levels of various ingredients in the experimental diets and their respective proximate composition are given in Table 1. Water temperature, dissolved oxygen, and pH varied slightly throughout the experiment and ranged from 26.2 to 28.1°C, 3.14 to 4.87 g/L, and 7.5 to 8.33, respectively.

At the end of the 46-day experimental period, juvenile tilapia showed the highest growth when fed FM diet, followed by TM and FM/TM diets. The growth differences were only significant between fish fed the control and FM/TM diets ($P<0.05$). Weight gain displayed a similar trend. The SGR was 5.35%, 5.27% and 5.21% in FM, TM and FM/TM groups, respectively. The difference between FM and FM/TM groups was statistically significant ($P<0.05$). The best FCR was in fish fed the FM diet, followed by those on TM diet without a statistically significance ($P>0.05$, Table 2).

Table 1. Formulation (g/kg) and proximate composition (%) of the experimental diets

	Experimental Diets		
	FM	**TM**	**FM/TM**
Nutrient (g kg^{-1})			
Fish meal	180	-	110
Tenebrio molitor	-	280	170
Soybean meal	303	283	270
Wheat flour	300	230	243
Corn protein	150	150	150
Fish oil	50	10	10
Ulva lactuca meal	-	30	30
Vitamin premix(*)	3	3	3
Mineral premix(*)	3	3	3
Astaxanthin	1	1	1
Dicalcium phosphate	10	10	10
Proximate Composition (%)			
Moisture	3.46	2.87	3.79
Protein	42.85	41.05	42.99
Lipid	8.99	8.61	7.60
Ash	5.87	5.57	6.24
NFE[1]	38.83	41.90	39.37
Gross energy (kJg^{-1})[2]	20.26	20.21	19.84

[*] Vitamin-mineral premix (mg/kg premix): vitamin A, 210000 IU; Vitamin D_3, 35000 IU; vitamin E, 7000 mg; vitamin K_3, 322 mg; vitamin B_1, 588 mg; vitamin B_2, 252 mg; vitamin B_6, 294 mg; vitamin B_{12}, 826 mcg; niacin, 1400 mg; biotin, 7583 mcg; 182 mg folic acid, pantothenic acid, 1722 mg; inositol, 17220 mg; vitamin C, 933.31 mg; Ca, 1414mg.
[1]NFE=100-(%protein+ %lipid+ %ash+ %moisture)
[2]Gross energy is calculated according to 23.6 kJ g^{-1} protein, 39.5 kJ g^{-1} lipid and 17 kJ g^{-1} NFE

Table 2. Growth performance and feed efficiency of Nil tilapia juvenile fed the 3 experimental diets for 46 days

	Experimental Groups		
	FM	**TM**	**FM/TM**
IBW (g)	0.12±0.002^a	0.12±0.001^a	0.11±0.003^a
FBW (g)	1.36±0.16^b	1.32±0.16^b	1.24±0.12^a
WG (g)[1]	1.25±0.09^b	1.21±0.09^b	1.13±0.07^a
SGR(%)[2]	5.35±0.19^a	5.27±0.16^{ab}	5.21±0.18^b
FCR[3]	3.29±0.05^a	3.48±0.23^a	5.79±0.50^b
PER (%)[4]	1.42±0.04^c	1.21±0.10^b	0.87±0.07^a
Survival (%)	100^a	100^a	100^a

Data are reported as mean ± standard errors of three replicates (3). Means with different superscript letter in a row are significantly different (p>0.05). IBW: Initial body weight, FBW: Final body weight. replicates.

The highest FCR was in the group fed FM/TM diet, being significantly different from the control.

The PER was calculated as 1.42±0.04 for the FM group, 1.21±0.10 for the TM group, and 0.87±0.07 for the FM/TM group and PER values were significantly different among the diets. The survival rate was 100% in all groups.

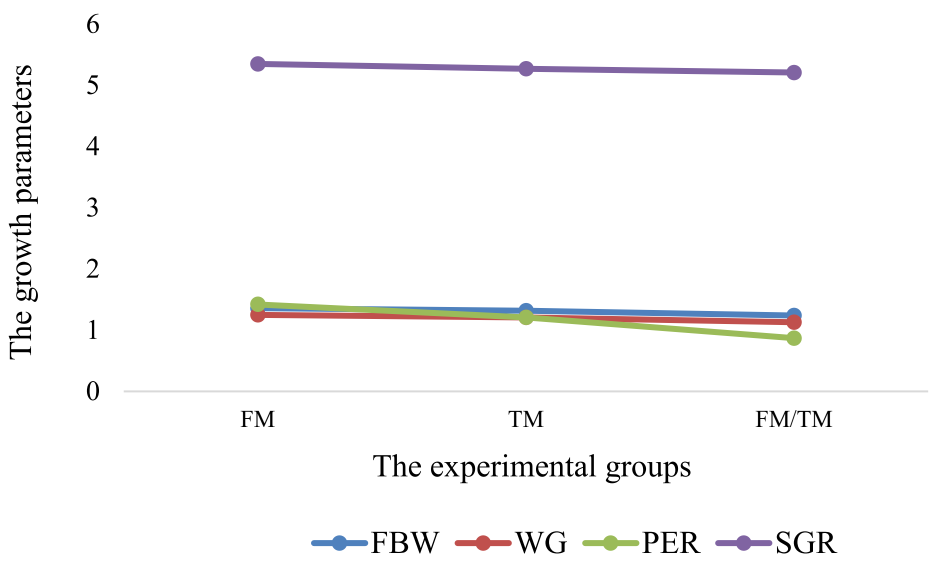


Figure 2. Distribution of specific growth rate (SGR), final body weight (FBW), weight gain (WG), and protein efficiency ratio (PER) values of Nil tilapia juveniles by groups

4. DISCUSSIONS

Today, feed formulation strategies take into account the nutritional quality of feed ingredients as well as cost, availability and sustainability. The TM produced for the purpose of replacement of dietary FM in the present study showed lower protein and higher lipid contents than FM. Dietary use of TM results in a reduction of dietary fish oil due to higher levels of TM.

In the current study, the highest growth, weight gain and protein efficiency rate were determined in the control group, followed by the TM and FM/TM groups in discending order. Gasco *et al.* (2014) reported that rainbow trout (*Oncorhynchus mykiss*) fed diets with up to 50% can be used without decreasing growth performance, thus saving fish meal protein. Gasco *et al.* (2016) reported that a full-fat Tenebrio molitor meal can be included up to 25% in the diets of European sea bass fry (*Dicentrarchus labrax*) without affecting their growth performance, while fish performance was negatively affected at a higher TM inclusion level (50%). Similarly, Ng *et al.* (2001) reported that African catfish (*Clarias gariepinus*) showed good growth performances when up to 35% TM meal was added to their diet. On the contrary, Roncarati *et al.* (2015) reported reduced growth when catfish (*Ameiurus melas*) fingerlings were fed a diet containing TM larval meal. In an experiment using the same amounts of TM (25% and 50%) in gilthead sea bream (*Sparus aurata*) diets, Piccolo *et al.* (2017) reported that dietary inclusion of 25% TM in the diet did not have any negative effects on final weight, specific growth rate, weight gain, protein efficiency ratio or feed conversion ratio of the fish, but at the inclusion level of (50%) a deteriorated nutrient digestibility was the case without detrimental effect on growth performance. Ng *et al.* (2001) reported that *T. molitor* larvae in both, live feed or meal form, were a good potential source of protein source and could replace up to 40% of FM component in practical diets for African catfish. Additionally, it was noted that catfish fed a diet containing a combination of mealworm and catfish pellet grew as well as or better than fish fed commercial catfish diet (Ng *et al.,* 2001). Interestingly, in the present study, the group fed with a 100% TM-supplemented diet showed a better growth rate than the group fed with a 50% TM-supplemented diet and had almost the same growth rate as the control group. This may be due to the *Ulva lactuca* added to the diet. However, although the same amount of *Ulva lactuca* was added to both groups, the TM group showed better growth. Further research on the use of *Ulva lactuca* in combination with TM

should be conducted to provide a definite explanation for this. As a matter of fact, Turan (2006) reported that the addition of red clover (*Trifolium pratense*) as a growth-promoting agent in tilapia (*Oreochromis aureus* Linnaeus) may improve feed utilization in fish, resulting in a higher growth rate. Also, according to Diab *et al*. (2008), Nile Tilapia fry fed diets enriched with medicinal plants showed faster growth than those fed a control diet. Medicinal plants have been used with similar success for common carp (*Cyprinus carpio*), guppy (*Poecilia reticulate*) and cichlid (*Cryptoheros nigrofasciatus*) (Yılmaz *et al*., 2006; Çek *et al*., 2007a,b).
Dietary protein plays an important role in determining fish growth rate. Accurate information on the protein requirements of fish is crucial for any aquaculture enterprise because of the high cost of protein components, which are generally required at high levels by most fish (NRC, 1993). Tubin *et al.* (2020) stated that it was possible to include up to 10% of TM in the diets of juvenile tilapia reared in biofloc systems without any loss growth performance, carcass composition, somatic and hematological indices. Sánchez-Muros *et al.* (2016) reported that the use of TM (TM has been partially or completely replaced by both SM and FM) instead of FM in tilapia diets, partial or complete replacement of SM with TM reduced feed intake in vitro and protein digestibility did not affect the amino acid composition of muscle. However, the inclusion of TM at both levels tested (25% and 50%) reduced growth by about 29% and also affected the fatty acid profile of the muscle. The results in the literature are partially in agreement with those obtained in this study, suggesting the need for further studies.

5. CONCLUSIONS

The study evaluated the effects of feeding Nile tilapia juveniles with FM and TM based diets on growth performance and feed efficiency. In conclusion, the main conclusion of this study is that TM can be used as a protein source in juvenile tilapia diets without a reduction in growth performance, thus saving fish meals and oil. But, more research is needed on the nutritional value of insects for fish. *T. molitor* larvae meal is an innovative raw material and its use as an alternative feed raw material to fish meal in fish diets seems promising. In addition, industrial-scale processes should be developed for the production of insect-based fish feeds, taking into account their impact on the environment, food safety and society, and their production should be promoted. In this way, both a new raw material will be brought to aquaculture and a new business area will be provided.

AUTHORSHIP CONTRIBUTION STATEMENT

Seval DERNEKBAŞI: Conceptualization, Methodology, Validation, Formal Analysis, Resources, Writing - Original Draft, Writing-Review and Editing, Data Curation, Software, Visualization, Supervision, Project administration. **İsmihan KARAYÜCEL:** Conceptualization, Methodology, Validation, Formal Analysis, Resources, Writing - Original Draft, Writing-Review and Editing, Data Curation, Software, Visualization, Supervision, Project administration.

CONFLICT OF INTERESTS

The author(s) declare that for this article they have no actual, potential or perceived conflict of interests.

ETHICS COMMITTEE PERMISSION

Authors declare that this study was conducted in accordance with ethics committee procedures of human or animal experiments.

FUNDING

No funding was received from institutions or agencies for the execution of this research.

ORCID IDs

Seval DERNEKBAŞI:
https://orcid.org/0000-0001-5735-2486
İsmihan KARAYÜCEL:
https://orcid.org/0000-0003-2520-7545

6. REFERENCES

AOAC, (1995). *Official methods of analysis* (16th ed.). Washington, DC: Association of Official Analytical Chemists**.**

Azaza, M.S., Mensi, F., Ksouri, J., Dhraief, M.N., Brini, B., Abdelmouleh, A., Kraïem, M.M., (2008). Growth of Nile tilapia (*Oreochromis niloticus* L.) fed with diets containing graded levels of green algae Ulva meal (*Ulva rigida*) reared in geothermal waters of southern Tunisia. *J. Appl. Ichthyol.* 24: 202–207.

Barroso, F.G., de Haro, C., Sánchez-Muros, M.J., Venegas, E., Martínez Sánchez, A., Pérez-Bañón, C., (2014). The potential of various insect species for use as food for fish. *Aquaculture* 422–423: 193–201.

Belforti, M., Gai, F., Lussiana, C., Renna, M., Malfatto, V., Rotolo, L., Marco, M.D., Dabbou, S., Schiavone, A., Zoccarato, I., Gasco, L., (2015). *Tenebrio* molitor meal in rainbow trout (*Oncorhynchus mykiss*) diets: Effects on Animal Performance, Nutrient Digestibility and Chemical Composition of Fillets. *Italian Journal of Animal Science* 14: 670-676.

Cek, S., Turan, F., Atik, E., (2007a). Masculinization of convict cichlid (*Cichlasomanigro fasciatum*) by immersion in *Tribulusterrestris extracts*. *Aquacult. Int.* 15: 109- 119.

Cek, S., Turan, F., Atik, E., (2007b). The effects of gokshura, *Tribulusterrestris*, on sex differentiation of guppy, *Poecilia reticulata*. *Pak. J. Biol. Sci.* 10: 718-725.

Gasco, L., Belforti, M., Rotolo L., Lussiana, C., Parisi G., Terova G., Roncarati A., Gai, F., (2014). Mealworm (*Tenebrio molitor*) as a potential ingredient in practical diets for rainbow trout (*Oncorhynchus mykiss*). Abstract book Conference “Insects to Feed The World” The Netherlands 14-17 May.

Gasco, L., Henry, M., Piccolo, G., Marono, S., Gai, F., Renna, M., Lussiana, C., Antonopoulou, E., Mola, P., Chatzifotis, S., (2016). *Tenebrio molitor* meal in diets for European sea bass (*Dicentrarchus labrax* L.) juveniles: Growth performance, whole body composition and in vivo apparent digestibility. *Animal Feed Science and Technology* 220: 34-45.

Diab, A.S., Aly, S.M., John, G., Abde-hadi, Y., Mohammed, M.F., (2008). Effect of garlic black seed and blogen as immunostimulants on the growth andsurvival of Nile tilapia *Oreochromis niloticus* (Teleostei: Cichlidae), and their response to artificial infection with *Pseudomonas fluorescence*. *Afr. J. Agric. Res.* 33: 63-68

Ergün, S., Soyutürk, M., Güroy, B., Güroy, D., Merrifield, D., (2009). Influence of Ulva meal on growth, feed utilization, and body composition of juvenile Nile tilapia (*Oreochromis niloticus*) at two levels of dietary lipid. *Aquacult. Int.* 17: 355–361. doi: 10.1007/s10499-008-9207-5.

Finke, M.D., (2002). Complete nutrient composition of commercially raised invertebrates used as food for insectivores. *Zoo. Biology* 21: 269- 285.

Ghaly, AE., Alkoaik, FN. (2009). The yellow mealworm as a novel source of protein. *American Journal of Agricultural and Biological Sciences* 4(4): 319-331.

Güroy, B.K., Cirik, Ş., Güroy, D., Sanver, F., Tekinay, A.A., (2007). Effects of *Ulva rigida* or *Cystoseira barbata* meals as a feed additive on growth performance, feed utilization, and body composition in Nile tilapia, *Oreochromis niloticus*. *Turk. J. Vet. Anim. Sci.* 31: 91–97

Henry, M., Gasco, L., Piccolo, G., Fountoulaki, E., (2015). Review on the use of insects in the diet of farmed fish: Past and future. *Animal Feed Science and Technology* 203: 1–22.

Huang, Q., Hu, J., Zhou, D.G., Sun, L., Ruan, H.B., Wang, X.N., Chen, G., Zhu, T.H., Yang, C.P., Yang, W., (2011). Comparison of growth, development, survivorship and food utilization of two color varieties of *Tenebrio molitor* (Coleoptera: Tenebrionidae). *Acta Entomologica Sinica* 54(3): 286- 292.

Lange, K.W., Nakamura, Y., (2023). Potential contribution of edible insects to sustainable consumption and production. *Frontiers in Sustainability*, 4: 1-5.

Marco, M.D., Martínez, S., Hernandez, F., Madridb, J., Gai, F., Rotolo L., Belforti, M., Bergeroa, D., Katz, H., Dabboud, S., Kovitvadhi, A., Zoccarato, I., Gascoc, L., Schiavonea, A., (2015). Nutritional value of two insect larval meals (*Tenebrio molitor* and *Hermetia illucens*) for broiler chickens: Apparent nutrient digestibility, apparentileal amino acid digestibility and apparent metabolizable energy. *Animal Feed Science and Technology* 209: 211– 218.

Ng, W.K., Liew, F.L., Ang, L.P., Wong, K.W., (2001). Potential Of mealworm (*Tenebrio molitor*) as an alternative protein source in practical diets for African catfish, *Clarias gariepinus*. *Aquaculture Research* 32 (Suppl.1): 273-280.

NRC, (1993). *Nutrient Requirements of Fish and Shrimp.* National Academies Press, Washington D.C.

Özsoy, A.N., Gündoğdu, E., (2017). *Tenebrio molitor* L. (Un Kurdu)' de Büyüme ve Gelişim Karakterlerine Ait Genetik Parametre Tahminleri. *Süleyman Demirel Üniversitesi Ziraat Fakültesi Dergisi* 12(2): 90-99.

Odesanya, B.O., Ajayi, S.O., Agbaogun, B.K.O., Okuneye, B., (2011). Comparative evaluation of nutritive value of maggots. *International Journal of Engineering Research* 2: 1–5.

Ogunji, J., Toor, R.U.A.S., Schulz, C.. Kloas, W., (2008). Growth performance, nutrient utilization of Nile tilapia *Oreochromis niloticus* fed housefly maggot meal (magmeal) diets. *Turkish Journal of Fisheries and Aquatic Sciences* 147: 141–147.

Piccolo, G., Iaconisi, V., Marono, S., Gasco, L., Loponte, R., Nizza, S., (2017). Effect of *Tenebrio molitor* larvae meal on growth performance, in vivo nutrients digestibility, somatic and marketable indexes of gilthead sea bream (*Sparus aurata*). *Anim. Feed Sci. Technol.* 226: 12–20. doi: 10.1016/j.anifeedsci.2017.02. 007

Ramos-Elorduy, J., Gozález, E.A., Hernáz A.R.., Pino, J.M., (2002). Use of *Tenebrio molitor* (Coleoptera: Tenebrionidae) to recycle organic wastes and as feed for broiler chickens. *J. Veterinary Entomology* 95(1): 214-220.

Ravzanaadii, N., Kim, S.H., Choi, W.H., Hong, S.J., Kim, N.J. (2012). Nutritional value of mealworm, *Tenebrio molitor* as food source. *Int. J. Indust. Ent.* 25(1): 93-98.

Roncarati, A., Gasco, L., Parisi, G., Terova, G., (2015). Growth performance of common catfish (*Ameiurus melas* Raf.) fingerlings fed mealworm (*Tenebrio molitor*) diet. *J. Insects Food Feed.* 1: 233-240.

Sánchez-Muros, M.J., De Haro, C., Sanz, A., Trendzado, C.E., Villareces, S., Barroso, F.G., (2016). Nutritional evaluation of *Tenebrio molitor* meal as fishmeal substitute for tilapia (*Oreochromis niloticus*) diet. *Aquaculture Nutrition* 22: 943-955.

Siemianowska, E., Kosewska, A., Aljewicz, M., Skibniewska, K., Polak, L., Jarocki, A., Jędras, M., (2013). Larvae of mealworm (*Tenebrio molitor* L.) as European novel food. *Agricultural Sciences* 4: 287-291.

Tacon, A.G.J., (1988). The nutrition and feeding of farmed fish and shrimp - a training manual. 3. Feeding methods, FAO Field Document, Project GCP/RLA/075/ITA "Support to the Regional Aquaculture Activities for Latin America and the Caribbean", Field Document No. 7/E, Brasilia, Brazil, 208 pp.

Tran, G., Heuzé, V., Makkar, H.P.S., (2015). Insects in fish diets. *Animal Frontiers* 5(2): 37–44. doi: 10.2527/af.2015-0018.

Tubin, J.S.B., Paiano, D., Hashimoto, G.S.O., Furtado, W.E., Martins, M,L., Durigon, E., Emerenciano, M.G.C., (2020). *Tenebrio molitor* meal in diets for Nile tilapia juveniles reared in biofloc system. *Aquaculture,* 519: 734763.

Turan, F., (2006). Improvement of growth performance in Tilpia (*Oreochromis niloticus* Linnaeus) by supplementation of red clover (*Trifolium pratense*) in diets. *Israeli Journal of Aquaculture – Bamidgeh* 58: 34- 38

Valente, L.M.P., Gouveia, A., Rema, P., Matos, J., Gomes, E.F., Pinto, I.S., (2006). Evaluation of three seaweeds *Gracilaria bursa-pastoris*, *Ulva rigida* and *Gracilaria cornea* as dietary ingredients in European sea bass *Dicentrarchus labrax* juveniles. *Aquaculture* 252: 85–91.

Wassef, E.A., El-Sayed, A.F.M., Kandeel, K.M., Sakr, E.M., (2005). Evaluation of *Pterocla dia* and *Ulva* meals as additives to gilthead seabream *Sparus aurata* diets. *Egypt Journal of Aquatic Research* 31: 321–332.

Yilmaz, E., Genc, M.A., Cek, S., Mazlum, Y., Genc, E., (2006). Effects of orally administered *Ferula coskunli* (Apiaceae) on growth, body composition and histology of common carp, *Cyprinus carpio*. *J. Anim. Vet. Adv.* 5: 1236-1238.

Research Article
Turkish Journal of Maritime and Marine Sciences

DOI: 10.52998/trjmms.1358814
Volume: 9 Issue: 2 (2023) 119-128

First record of *Sebastes schlegelii* Hilgendorf, 1880 along the Turkish Black Sea coast – new addition to the alien species inventory

Sebastes schlegelii Hilgendorf, 1880 türünün Türkiye'nin Karadeniz kıyısından ilk kaydı – yabancı tür envanterine yeni bir ilave

Türk Denizcilik ve Deniz Bilimleri Dergisi

Cilt: 9 Sayı: 2 (2023) 119-128

Murat BİLECENOĞLU[1,*], M. Baki YOKEŞ[2], Mehmet AYDIN[3]

[1]*Department of Biology, Faculty of Science, Aydın Adnan Menderes University, Aydın, Turkey*
[2]*AMBRD Laboratories, Hanımefendi Sokak, No: 160/9, Şişli, İstanbul, Turkey*
[3]*Department of Fisheries Technology Engineering, Fatsa Faculty of Marine Sciences, Ordu University, Ordu, Turkey*

ABSTRACT

Sebastes schlegelii is a typical bottom dwelling boreal species, whose native distribution range includes Japan, Korean peninsula and China. This northwest Pacific originated species has recently been recorded from the Crimean and Caucasian coast (northern Black Sea), whose introduction was assumed to be either by balast waters or the acclimatization of *Crassostrea gigas* (Pacific oyster). On 16 August 2023, a single *S. schlegelii* specimen with 20.6 cm standard length and 282.1 g in weight was captured off Ünye, Ordu coast (southeastern Black Sea), which was previously an unreported fish from the Turkish marine waters. Detailed morphometric and meristic characteristics are presented in the paper, and species identification was further confirmed by genetic analysis. Available information reveals this alien species to be fished regularly, although in small quantities, indicating a presumably established population in the region. The species should be treated as a potentially invasive fish, since it may negatively influence to the local biodiversity through interspecific competition. Close monitoring of its existing population is strongly suggested.

Keywords: Alien species, Human-mediated introduction, Biological invasion, Sebastinae

Article Info
Received: 12 September 2023
Revised: 15 September 2023
Accepted: 15 September 2023

*(corresponding author)
E-mail: mbilecenoglu@adu.edu.tr

To cite this article: Bilecenoğlu, M., Yokeş, M.B., Aydın, M. (2023). First record of *Sebastes schlegelii* Hilgendorf, 1880 along the Turkish Black Sea coast – new addition to the alien species inventory, *Turkish Journal of Maritime and Marine Sciences* 9 (2): 119-128. doi: 10.52998/trjmms.1358814.

ÖZET

Sebastes schlegelii, doğal dağılım alanı Japonya, Kore yarımadası ve Çin'i kapsayan tipik bir demersal boreal türdür. Kuzeybatı Pasifik kökenli bu tür, yakın zamanda Kırım ve Kafkasya kıyılarında (Kuzey Karadeniz) kaydedilmiş olup, ekosisteme girişinin ya gemilerin balast suları ya da *Crassostrea gigas*'ın (Pasifik istiridyesi) yetiştiriciliği ile alakalı olduğu varsayılmaktadır. 16 Ağustos 2023 tarihinde Ordu Ünye açıklarında (Güneydoğu Karadeniz) 20,6 cm standart boyda ve 282,1 g ağırlığında bir *S. schlegelii* örneği elde edilmiş olup, türün daha önce Türkiye denizlerinde var olduğuna dair bir kayıt bulunmamaktadır. Bu makalede detaylı morfometrik ve meristik karakterler sunulmuş olup, tür tayini genetik analiz ile de doğrulanmıştır. Mevcut bilgiler, söz konusu yabancı türün küçük miktarlarda da olsa düzenli olarak avlandığını ortaya koymakta ve bölgede muhtemelen başarılı bir popülasyonun oluştuğunu göstermektedir. Bu tür potansiyel olarak istilacı bir balık olarak kabul edilmelidir, zira interspesifik rekabet yoluyla yerel biyolojik çeşitliliği olumsuz yönde etkileme ihtimali bulunmaktadır. Mevcut popülasyonun yakından takip edilmesi büyük önem taşımaktadır.

Anahtar sözcükler: Yabancı tür, Insan kaynaklı katılım, Biyolojik istila, Sebastinae

1. INTRODUCTION

Rockfishes of the genus *Sebastes* are represented by 108 species worldwide (Froese and Pauly, 2023), majority occurring around an Asian center near Japan in the north Pacific and north American center off the Gulf of California (about 96 sp.), with very few numbers of species also distributing in the north Atlantic, south Pacific, and south Atlantic (Love *et al*., 2002). Rockfishes are live bearing (ovoviviparous) species, characterized by having a suborbital stay, a round pectoral fin, 13 to 15 dorsal fin spines, ridges and spines on head, and venom glands on spines of dorsal, anal and pelvic fins (Kai *et al*., 2013; Froese and Pauly, 2023). Taxonomy of the genus is currently a matter of dispute, since it includes morphologically similar species with significant overlaps in morphometric and meristic characters, and many species showing great variation in body coloration depending on their habitat, which causes significant difficulties in precise identification based solely on morphology (Chen, 1986; Kai and Nakabo, 2013). There is also no complete agreement on the family assignment for *Sebastes*; some authors place the genus under Sebastidae based on an extensive examination of myological and osteological characters (i.e., Ishida, 1994), while others prefer maintaining the subfamily Sebastinae under Scorpaenidae regarding the results of comparative analysis of the complete mitochondrial genomes of rockfishes (Jia *et al*., 2020).

According to a recent critically assessed and updated checklist of Mediterranean marine fishes, no representatives of *Sebastes* were confirmed to occur in any parts of the basin (Kovačić *et al*., 2021). However, the dogtooth grouper (*Epinephelus caninus*) record given a decade ago from the southwest Crimean coastal waters by Boltachev and Karpova (2013) turned out to be a misidentification of the Korean rockfish *S. schlegelii* Hilgendorf, 1880, in which additional individuals of the species were recently collected from the same region as far as to Caucasian coast along the northern Black Sea (Karpova *et al*., 2021), indicating the presence of an established population. This boreal species has a very limited natural distribution range in the northwest Pacific, including Japan, Korean peninsula, and China (Froese and Pauly, 2023), and its occurrence in the Black Sea strongly indicates a human mediated introduction, either by ships ballast waters or during the acclimatization of the Pacific oyster (*Crassostrea gigas*) (Karpova *et al*., 2021).

This interesting fish has started to appear in the artisanal fishery catch along the eastern Black

Sea coast of Turkey by the early March 2023, and the authors have received several photographs of the captured individuals (including juveniles) from the local fishermen since then, but collection of a specimen for precise species identification has recently been possible. With reference to the existence of several closely related species with similar appearances among the genus *Sebastes*, we carried out both morphological and molecular analyses for the identification process, which positively revealed the species to be *S. schlegelii*. The Korean rockfish is not only a first record for the Turkish marine ichthyofauna, but also a new addition to the existing list of alien species (Çınar *et al*., 2021). This paper aims to present the occurrence of *S. schlegelii* along the Turkish Black Sea coast, by briefly discussing its potential invasion in the area.

2. MATERIAL AND METHODS

On August 16, 2023, a single specimen of *S.schlegelii* was captured off the Ordu/Ünye coast (eastern Black Sea coast of Türkiye) from a depth of 5 m using a trammel net (Figure 1). The fish was immediately photographed and transferred to the laboratory (Fatsa Faculty of Marine Sciences, Ordu University) for further analysis.

All morphometric measurements and meristic counts were performed on the fresh specimen. Body proportions were expressed as percentages of standard length (SL) and head length (HL).

Measurements and counts are as defined by Eschmeyer (1965, 1969), while terminology of spines follow Randall and Eschmeyer (2001). SL was measured from the tip of the snout, and the last two soft rays of both dorsal and anal fins were counted as single rays. Following Kai *et al*. (2013), body depth 1 was measured as the distance between the origins of the first dorsal fin spine and the pelvic fin spine, body depth 2 as the distance between the origins of the last dorsal fin spine and the first anal fin spine.

For genetic analysis, DNA was extracted from fin tissue by using Genomic DNA Isolation Kit (AMBRD) according to the user's manual. Mitochondrial cytochrome oxidase subunit I (COI) sequences were partially amplified using the primers FishF1 and FishR1 (Ward *et al*., 2005). The PCR mixture and amplification protocol was the same as used by Ward *et al*. (2005). Sequencing was carried out by Macrogen Europe (Amsterdam, Netherlands). Sequence was manually checked, by ChromasPro v.1.5 (Technelysium Pty. Ltd., Australia). The 5' terminal with high background and 3' primer sequence were trimmed. 655bp of COI sequence is deposited in the NCBI GenBank under the accession number OR523689.

Figure 1. Lateral view of the fresh *Sebastes schlegelii* specimen (20.6 cm SL) captured off Ordu coast, Black Sea (Türkiye).

3. RESULTS AND DISCUSSION

Proportional morphometric characters of the single *S. schlegelii* individual are presented in Table 1, which also includes a comparison with previous data given by Karpova *et al*. (2021). Description of the specimen is as follows. Body robust, slightly compressed laterally, with large head covered with spines. Three lachrymal spines, third one slightly pointing posteroventrally. Nasal, preocular and postocular spines are present; the superior cranial spines and suborbital ridge are weakly developed. Five spines on the preopercle, second one the longest. Opercle with two flattened spines, upper one larger than the lower, both directed posteriorly; lower opercular spine slightly extends its posterior margin. Supracleithral spine simple with acute tip. Dorsal fin continuous with 13 spines and 11 soft rays, gradually increasing in length to 5th spine, thereafter decreasing in length to 12th spine, 13th spine longer than 12th spine, forming anterior support of soft dorsal fin. Broad based and fan like pectoral fins with 18 rays. Pelvic fins thoracic with one spine and 5 soft rays. Anal fin with 3 spines and 6 soft rays. Caudal fin rounded, with 15 rays. Body covered by ctenoid scales. Lateral line with 44 pored scales. Mouth large, oblique; maxilla without ridge running along its length and extending to posterior rim of eye. The ground color of the body is light brown, with many dark spots scattered irregularly. The belly is light green to grayish. Two distinct dark bands extend radially from the eye, upper one extending to the first preopercular spine, lower one to the fourth preopercular spine. Maxilla with a dark stripe. A dark brown blotch located over the pectoral fin base. Morphometric measurements, meristic counts and the color of the Turkish Black Sea individual are in accordance with previous descriptions of *S. schlegelii* in its native range (Hilgendorf, 1880; Steindachner and Döderlein, 1884; Chen, 1986) and its introduced ecosystems (Kai and Soes, 2019; Boltachev and Karpova, 2013; Karpova *et al*., 2021).

There are only a few different proportions, such as predorsal, postorbital and snout lengths (see Table 1) in comparison to specimens previously captured from the Black Sea (Karpova *et al*., 2021), which may be related to the size of the examined individuals. Despite of these minor morphometric differences, the NCBI Blast analysis revealed that the generated COI sequence is 100% identical with *S. schlegelii* from Gyounggi-do, south Korea (NC_005450; Kim and Lee, 2004) and Yeosu, south Korea (HM180869; Kim *et al*., 2012), providing further genetic support on the correct identification.

First observation of *S.schlegelii* along the eastern Black Sea coast of Türkiye was made on March 06, 2023, in which an approximately 18 cm SL specimen was captured from a depth of 10 m off Giresun using a trammel net (60 mm mesh size) (Figure 2A). An additional individual was later captured at a depth of 8 m from Perşembe/Okçulu coast (Ordu) again with a trammel net (56 mm mesh size) (Figure 2B). The occurrence of the species was also a subject to the regional newspapers, and the news of a captured individual (erroneously presented as a dusky grouper, *Epinephelus marginatus*) from Gideros (Kastamonu, Cide) was shared (Figure 2C; Ünal, 2023). The last photograph shared by the artisanal fishermen was from Fatsa coast of Ordu (Figure 2D). According to the local fishermen of Ordu, *S. schlegelii* is regularly being captured for the last couple of months, although in relatively small quantities.

Table 1. Proportional measurements of *Sebastes schlegelii* specimen, in comparison with the previous Black Sea records (Karpova *et al*., 2021).

	Karpova *et al*. (2021)	Present Study
Number of specimens	5	1
TL, cm	32.5-39.1	24.5
SL, cm	27.7-33.1	20.6
W, g	710.0-1151.2	282.1
(% of SL)		
Body depth 1	-	36.5
Body depth 2	-	30.1
Caudal peduncle depth	10.2-10.5	9.7
Predorsal length	33.0-35.8	27.1
Postdorsal length	12.5-13.1	13.3
Prepelvic length	37.4-38.9	39.0
Preanal length	67.8-69.2	66.7
Prepectoral length	33.6-35.5	29.8
Distance between pelvic and pectoral fins	4.7-5.2	4.7
Distance between pelvic and anal fins	18.8-30.2	22.4
Dorsal fin base length	62.5-62.7	60.8
Anal fin base length	15.5-16.4	15.9
Pectoral fin length	21.2-22.9	25.2
Pelvic fin length	20.3-20.6	22.7
Caudal fin length	21.1-21.2	13.4
Head length	35.5-40.1	34.0
(% of HL)		
Snout length	29.7-32.0	19.8
Upper jaw length	47.2-49.4	45.5
Eye diameter	18.3-21.1	18.7
Postorbital length	52.5-52.5	61.5

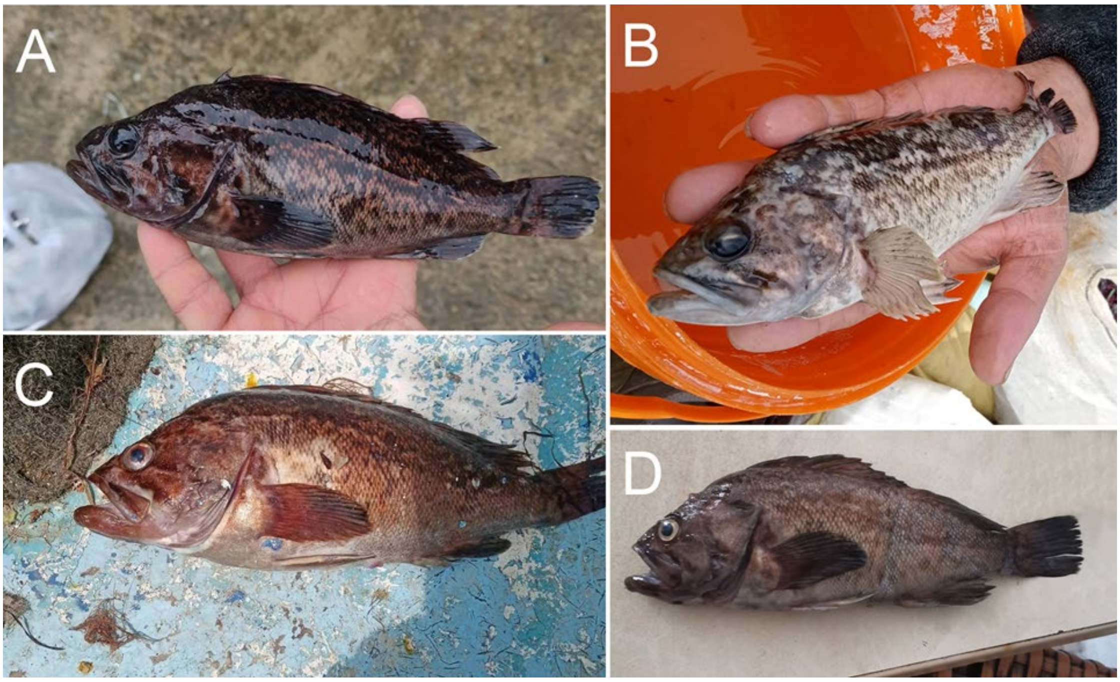


Figure 2. Previous sightings of *Sebastes schlegelii* from the Turkish Black Sea coast. A) Giresun (March 06, 2023, 10 m depth), B) Ordu/Perşembe (April 27, 2023, 8 m depth), C) Kastamonu/Cide (June 13, 2023, depth unknown), D) Ordu/Fatsa (June 16, 2023, depth unknown).

The photographic evidence clearly indicates that the species has already spread through a large area along the Turkish Black Sea coast (Figure 3), and a wider distribution range should be suspected.

Sebastes schlegelii is mainly a marine species inhabiting depths ranging 3 to 100 m and can also be found in brackish waters and even entering estuaries of rivers, which is one of the most common rockfishes in the Northwestern Pacific coasts (Parin *et al*., 2002; Dyldin *et al*., 2021). It can attain a total length of 65 cm and over 3 kg in weight (Froese and Pauly, 2023). Similar to its congenerics, the species is carnivorous feeding mainly on fish (Gobiidae, Engraulidae, Ammodytidae), shrimps (*Alpheus sp*.) and crabs (Zhang *et al*., 2014) and can display cannabalistic behaviour (Park *et al*., 2007). *Sebastes schlegelii* is a commercially exploited fish throughout its native distribution range, and also an important cultured species for stock enhancement; artificially raised juveniles have been released to enhance fisheries production since the 1980s (Wang *et al*., 2017). Despite of their diversity in form and function, *Sebastes spp*. are generally limited to cool-temperate ecosystems, while warm, oligotrophic waters represent a significant barrier to their spread (Hyde and Vetter, 2007), yet *S. schlegelii* represents a unique case and can survive wide range of water temperatures from 5° to 28°C (Chen *et al*., 2021).

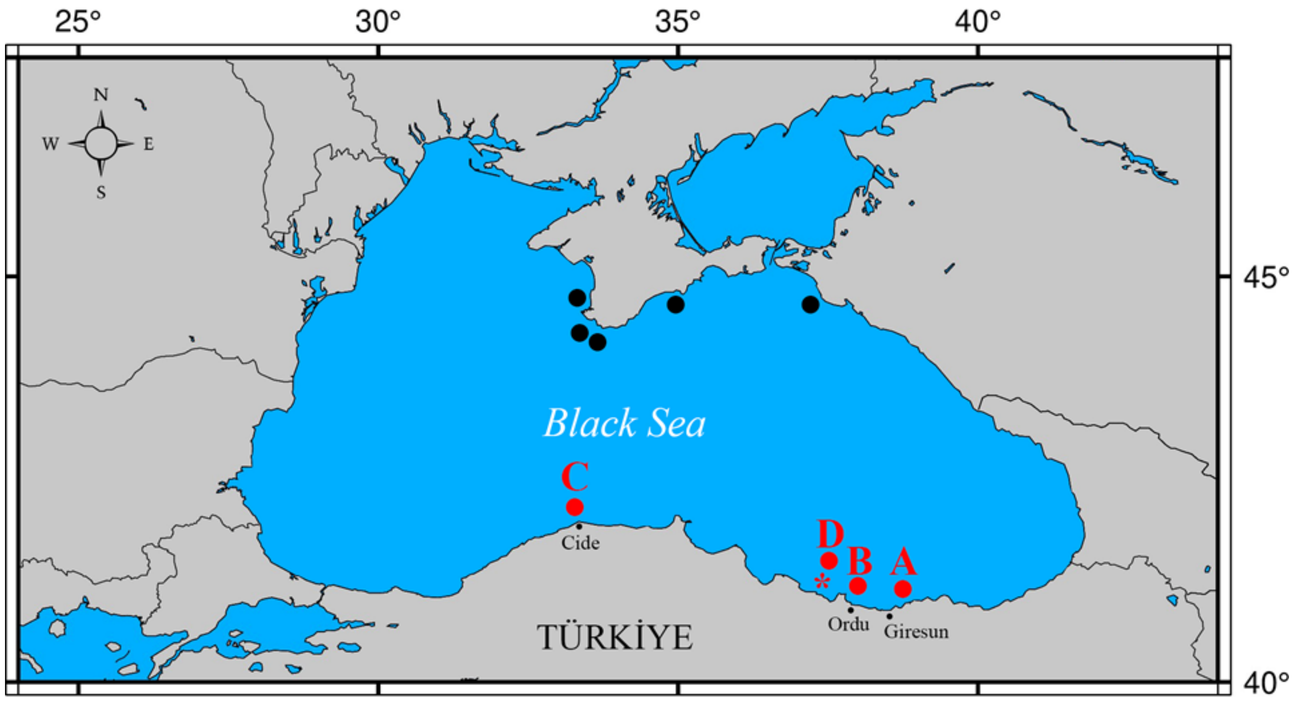


Figure 3. Records of *Sebastes schlegelii* from the Black Sea. Black dots retrieved from Karpova *et al*. (2021), red dots denote observations from the Turkish coastline, letters correspond to individuals presented in Fig.2 (locality of the captured individual in this study indicated with an asterix).

Pacific oysters (*C.gigas*) are one of the most globalized highly commercial bivalves that have been introduced to 66 countries outside their native range (northwest Pacific) for aquaculture purposes (Herbert *et al*., 2016). They were first introduced to the northern Black Sea coastal waters from the Sea of Japan during the 1980s, with active attempts for its acclimatization since then (Krapal *et al*., 2019; Aydın and Gül, 2021). Establishment of Pacific oyster sea farms have been continuing along the Crimean coast during the last two decades without any quarantine measures taken, and this activity have been suggested as the major and most rational explanation for the introduction of northwest Pacific originated *S. schlegelii*, without ruling out the possibility of passive transport in ballast water tanks of a ship (Karpova *et al*., 2021). Above mentioned vectors are also suspected for the Korean rockfish introduced to the Dutch coastline (Kai and Soe, 2009). Following the first occurrence of *S. schlegelli* in the northern Black Sea during 2013, four additional adult individuals were collected from Crimean and Caucasian coasts in 2019 from depths of 3 to 15 m, indicating the presence of an established population (Karpova *et al*., 2021). The species have rapidly reached the southern Black Sea coasts, especially the southeastern region, presumably by the larval and/or juvenile dispersal through the prevailing currents. Korean rockfish adults are not capable of extending their ranges, since they are characterized by strong site fidelity (Zhang *et al*., 2015), but the pelagic larvae and juveniles of this species can easily migrate to great distances (Gudkov, 2010). The pelagic juvenile phase of *S. schlegelii* may last several months to a year, in which they utilize different habitats including the drifting seaweeds, suggesting their opportunistic habitat selection (Moser and Boehlert, 1991; Nagasawa and Domon, 1997).

With reference to the sudden occurrence of the species along the Turkish Black Sea coast with observations from discrete localities, we may assume the establishment of *S. schlegelii* is an ongoing process in the region. In case that the species increases its population density, multifaceted impacts maybe expected. Competition with the native black scorpionfish (*Scorpaena porcus*) for food and space seems to be quite likely, as also suggested by Karpova *et al*. (2021). Due to the high commercial value of the species in the NW Pacific, it may also contribute to the artisanal fishery catch of the Black Sea. Most *Sebastes sp*. are known to bear venom glands in dorsal, anal and pelvic fins, but no envenomation caused by Korean rockfish were reported and Froese and Pauly (2023) considers the species to be harmless to humans.

4. CONCLUSIONS

The semi-enclosed Black Sea, which has long been deteriorated by the combined effects of eutrophication, habitat loss, increased annual sea surface water temperatures and overexploitation of natural resources, is one of the most prone ecosystems in the world to the invasion of alien species. The basin is characterized by high primary production, brackish water body, low local species richness and wide biotope diversity, which provide favorable conditions for the introduction of alien taxa that can establish successful populations at unoccupied ecological niches, especially in the absence of local competitors (Zenetos *et al*., 2003; Leppäkoski *et al*., 2009). Although Black Sea hosts the least number of alien species (28 sp.) along the Turkish coast, an increase of 25% in the alien inventory was observed during the last decade (2010-2020), indicating the rapid changes in the local diversity and the necessity of urgent measures to be taken (Çınar *et al*., 2021).

Sebastes schlegelii can survive wide ranges of temperatures (5° to 28°C; Chen *et al*., 2021) and is highly tolerant to waters with varying salinities (i.e., estuaries, brackish waters; Dyldin *et al*., 2021), and Black Sea ecosystem perfectly meet these conditions. As a precautionary approach, every single alien species, casual or established, should be treated as potential invaders, underlining the necessity and importance of carrying out bioecological research to better understand their life histories. So, the sudden appearance of Korean rockfish in Türkiye should thus be taken seriously, and closely monitored.

ACKNOWLEDGEMENTS

Special thanks to Mr. Olcay Şen and Mr. Tevfik Çelebi for providing *Sebastes schlegelii* information, and Mr. Samet Erat (Directorate of Agriculture and Forestry, Ünye District) for transferring us the specimen captured by Mr. Murat Kıdıkoğlu. The authors are grateful to Dr. Yoshiaki Kai (Kyoto University, Japan) for confirming the species identification.

AUTHORSHIP CONTRIBUTION STATEMENT

Murat BİLECENOĞLU: Conceptualization, Methodology, Writing - Original Draft, Writing-Review and Editing, Data Curation. **M. Baki YOKEŞ:** Methodology, Validation, Formal Analysis, Writing-Review and Editing, Data Curation. **Mehmet AYDIN:** Conceptualization, Methodology, Resources, Writing - Review and Editing, Data Curation, Supervision.

CONFLICT OF INTERESTS

The author(s) declare that for this article they have no actual, potential or perceived conflict of interests.

ETHICS COMMITTEE PERMISSION

No ethics committee permissions is required for this study.

FUNDING

No funding was received from institutions or agencies for the execution of this research.

ORCID IDs

Murat BİLECENOĞLU:
https://orcid.org/0000-0001-5111-4997
M. Baki YOKEŞ:
https://orcid.org/0000-0002-9440-4561
Mehmet AYDIN:
https://orcid.org/0000-0003-1163-6461

5. REFERENCES

Aydin, M., Gül, M., (2021). Presence of the Pacific oyster (*Crassostrea gigas* Thunberg, 1793) in the Black Sea. *Journal of Anatolian Environment and Animal Sciences* 6(1): 14-17. doi: 10.35229/jaes.800160.

Boltachev, A., Karpova, E., (2013). First record of dogtooth grouper *Epinephelus caninus* (Valenciennes, 1834), Perciformes, Serranidae, in the Black Sea. *Bioinvasions Records* 2(3): 257-261. doi: 10.3391/bir.2013.2.3.14.

Chen, L., (1986). Meristic variation in *Sebastes* (Scorpaenidae), with an analysis of character association and bilateral pattern and their significance in species separation. *NOAA Technical Report NMFS* 45: 1-17.

Chen, Y., Shan, X., Ovando, D., Yang, T., Dai, F., (2021). Predicting current and future global distribution of black rockfish (*Sebastes schlegelii*) under changing climate. *Ecological Indicators* 128: 107799. doi: 10.1016/j.ecolind.2021.107799.

Çinar, M.E., Bilecenoglu, M., Yokes, M.B., Ozturk, B., Taskin, E., Bakir, K., Dogan, A., Acik, S., (2021). Current status (as of end of 2020) of marine alien species in Turkey. *PLoS ONE* 16: e0251086. doi: 10.1371/journal.pone.0251086.

Dyldin, Y.V., Fricke, R., Hanel, L., Vorobiev, D.S., Interesova, E.A., Romanov, V.I., Orlov, A.M., (2021). Freshwater and brackish water fishes of Sakhalin Island (Russia) in inland and coastal waters: an annotated checklist with taxonomic comments. *Zootaxa* 5065: 1-92. doi: 10.11646/zootaxa.5065.1.1.

Eschmeyer, W.N., (1965). Western Atlantic scorpionfishes of the genus Scorpaena, including four new species. *Bulletin of Marine Science* 15(1): 84-164.

Eschmeyer, W.N., (1969). A systematic review of the Scorpionfishes of the Atlantic Ocean (Pisces: Scorpaenidae). *Occasional Papers of the California Academy of Sciences* 79: 1-143.

Froese, R., Pauly, D., (2023). FishBase. World Wide Web electronic publication. www.fishbase.org, version (06/2023).

Gudkov, P.K., (2010). New findings of warm-water fish in Sakhakin. *Journal of Ichthyology* 50(1): 137-139.

Herbert, R.J.H., Humphreys, J., Davies, C.J., Roberts, C., Fletcher, S., Crowe, T.P., (2016). Ecological impacts of non-native Pacific oysters (*Crassostrea gigas*) and management measures for protected areas in Europe. *Biodiversity and Conservation* 25: 2835–2865. doi: 10.1007/s10531-016-1209-4.

Hilgendorf, F.M., (1880). Uebersicht über die japanischen Sebastes-Arten. *Sitzungsberichte der Gesellschaft Naturforschender Freunde zu Berlin*, 166-172.

Hyde, J.R., Vetter, R.D., (2007). The origin, evolution, and diversification of rockfishes of the genus *Sebastes* (Cuvier). *Molecular Phylogenetics and Evolution* 44: 790–811. doi:10.1016/j.ympev.2006.12.026.

Ishida, M., (1994). Phylogeny of the suborder Scorpaenoidei (Pisces: Scorpaeniformes). *Bulletin of Nansei National Fisheries Research Institute* 27: 1-112

Jia, C., Zhang, X., Xu, S., Yang, T., Yanagimoto, T., Gao, T., (2020). Comparative analysis of the complete mitochondrial genomes of three rockfishes (Scorpaeniformes, *Sebastiscus*) and insights into the phylogenetic relationships of Sebastidae. *Bioscience Reports* 40 (12): BSR20203379. doi: 10.1042/BSR20203379.

Kai, Y., Muto, N., Noda, T., Orr, J.W., Nakabo, T., (2013). First record of the rockfish *Sebastes melanops* from the western North Pacific, with comments on its synonymy (Osteichthyes: Scorpaenoidei: Sebastidae). *Species Diversity* 18: 175-182. doi: 10.12782/sd.18.2.175.

Kai, Y., Nakabo, T., (2013). Taxonomic review of the *Sebastes pachycephalus* complex (Scorpaeniformes: Scorpaenidae). *Zootaxa* 3637(5): 541-560. doi: 10.11646/zootaxa.3637.5.3

Kai, Y., Soes, D.M., (2009). A record of *Sebastes schlegelii* Hilgendorf, 1880 from Dutch coastal waters. *Aquatic Invasions* 4(2): 417-419. doi: 10.3391/ai.2009.4.2.23.

Karpova, E.P., Tamoykin, I.Yu., Kuleshov, V.S., (2021). Findings of the Korean rockfish *Sebastes schlegelii* Hilgendorf, 1880 in the Black Sea. *Russian Journal of Marine Biology* 47(1): 29-34.

Kim, D.W., Yoo, W.G., Park, H.C., Yoo, H.S., Kang, D.W., Jin, S.D., Min, H.K., Paek, W.K., Lim, J., (2012). DNA barcoding of fish, insects, and shellfish in Korea. *Genomics and Informatics* 10(3): 206-11. doi: 10.5808/GI.2012.10.3.206.

Kim, I.C., Lee, J.S., (2004). The complete mitochondrial genome of the rockfish *Sebastes schlegeli* (Scorpaeniformes, Scorpaenidae). *Molecules and Cells* 17(2): 322-328.

Kovačić, M., Lipej, L., Dulčić, J., Iglesias, S.P., Goren, M., (2021). Evidence-based checklist of the Mediterranean Sea fishes. *Zootaxa* 4998: 1-115. doi: 10.11646/zootaxa.4998.1.1

Krapal, A.M., Ioniţă, M., Caplan, M., Buhaciuc-Ioniţă., E., (2019). Wild Pacific oyster *Magallana gigas* (Thunberg, 1793) populations in Romanian Black Sea waters – friend or foe?. *Travaux du Muséum National d'Histoire Naturelle "Grigore Antipa"* 62(2): 175-183. doi: 10.3897/travaux.62.e49074.

Leppäkoski, E., Shiganova, T, Alexandrov, B., (2009). European enclosed and semi-enclosed seas. In: "Biological Invasions in Marine Ecosystems: Ecological, Management, and Geographic Perspectives" (Editors: G. Rilov, J.A. Crooks), Ecological Studies vol.204, pp. 529-547, Springer, Berlin.

Love, M.S., Yoklavich, M., Thorsteinson, L., (2002). *The rockfishes of the northeast Pacific*, 404 p., University of California Press, Berkeley.

Moser, H.G., Boehlert, G.W., (1991). Ecology of pelagic larvae and juveniles of the genus *Sebastes*. *Environmental Biology of Fishes* 30: 203-224.

Nagasawa, T., Domon, K., (1997). The early life history of kurosoi, *Sebastes schlegeli* (Scorpaenidae), in the Sea of Japan. *Ichthyological Research* 44(2-3): 237–248. doi:10.1007/bf02678703.

Parin, N.V., Fedorov, V.V., Sheiko, B.A., (2002). An annotated catalogue of fish-like vertebrates and fishes of the seas of Russia and adjacent countries: Part 2. Order Scorpaeniformes. *Journal of Ichthyology* 42(Suppl.1): S60-S135.

Park, K.D., Kang, Y.J., Huh, S.H., Kwak, S.N., Kim, H.W., Lee, H.W., (2007). Feeding ecology of *Sebastes schlegeli* in the Tongyeong marine ranching area. *Korean Journal of Fisheries and Aquatic Sciences* 40(5): 308-314.

Randall, J.E., Eschmeyer, W.N., (2001). Revision of the Indo-Pacific scorpionfish genus *Scorpaenopsis*, with descriptions of eight new species. *Indo-Pacific Fishes* 34: 1-79.

Steindachner, F., Döderlein, L., (1884). Beiträge zur Kenntniss der Fische Japan's. (III.). *Denkschriften der Kaiserlichen Akademie der Wissenschaften in Wien, Mathematisch-Naturwissenschaftliche Classe* 49: 171-212.

Ünal, S., (2023). Akdeniz'de görülen o balık Cide'de yakalandı. Accessed Date: 12.06.2023. https://www.kastamonuistiklal.com/akdenizde-gorulen-o-balik-cidede-yakalandi is retrieved.

Wang, L., Wu, Z., Liu, M., Liu, W., Zhao, W., Liu, H., Zhang, P., You, F., (2017). Length-weight, length-length relationships, and condition factors of black rockfish *Sebastes schlegelii* Hilgendorf, 1880 in Lidao Bay, China. *Thalassas* 33(1): 57–63. doi:10.1007/s41208-017-0021-6.

Ward, R., Zemlak, T., Innes, B., Last, P., Hebert, P., (2005). DNA barcoding Australia's fish species. *Philosophical Transactions of the Royal Society of London, Series B, Biological Sciences* 360: 1847-1857. doi:10.1098/rstb.2005.1716.

Zenetos, A., Todorova, V., Alexandrov, B., (2003). Marine biodiversity changes in the Mediterranean and Black Sea regions. International Conference on the Sustainable Development of the Mediterranean and Black Sea Environment, 28 May–1 June, Thessaloniki, Greece.

Zhang, B., Li, Z., Jin, X., (2014). Food composition and prey selectivity of *Sebastes schlegeli*. *Zhongguo Shui Chan Ke Xue* 21: 134-141.

Zhang, Y., Xu, Q., Alós, J., Liu, H., Xu, Q., Yang, H., (2015). Short-term fidelity, habitat use and vertical movement behavior of the black rockfish *Sebastes schlegelii* as determined by acoustic telemetry. *PLoS ONE* 10(8): e0134381. doi: 10.1371/journal.pone.0134381.

Research Article
Turkish Journal of Maritime and Marine Sciences

DOI: 10.52998/trjmms.1365603
Volume: 9 Issue: 2 (2023) 129-147

Application of combined SWOT and AHP (A'WOT): A case study for maritime autonomous surface ships

SWOT ve AHP (A'WOT) yöntemlerinin birlikte uygulanması: otonom yüzey gemileri çalışması

Türk Denizcilik ve Deniz Bilimleri Dergisi Cilt: 9 Sayı: 2 (2023) 129-147

Hasan UĞURLU[1,*]
[1]Giresun University, Giresun Vocational School, Giresun, Türkiye

ABSTRACT

Increasing operational costs, the growth in ship tonnage, loss of lives, and the human factor in maritime accidents have driven the inevitable emergence of Maritime Autonomous Surface Ships (MASSs) in the world's seas. However, the universal establishment of laws and regulations for autonomous ships is still pending. Moreover, challenges arise due to the scarcity of personnel for immediate response to mitigate the impact of ship accidents and uncertainties linked to the absence of commercial autonomous voyages in international waters. Utilizing SWOT analysis as a strategic management approach enables the identification of strengths and weaknesses in a situation, awareness of related opportunities for leveraging those strengths, examination of threats, and formulation of measures against potential risks. This study encompasses a comprehensive evaluation of the positive and negative aspects of autonomous surface vehicles, encompassing their capabilities, advantages, challenges, and disadvantages. It employs SWOT analysis and the Analytic Hierarchy Process (AHP) method to facilitate strategic planning necessary for the widespread adoption of autonomous ships.

Keywords: Autonomous ship, MASS, SWOT analysis, AHP, A'WOT.

Article Info
Received: 24 September 2023
Revised: 2 October 2023
Accepted: 2 October 2023

[*](corresponding author)
E-mail: dr.hasan.ugurlu@gmail.com

To cite this article: Uğurlu, H., (2023). Application of Combined SWOT and AHP (A'WOT): A Case Study for Maritime Autonomous Surface Ships, *Turkish Journal of Maritime and Marine Science* 9 (2): 129-147. doi: 10.52998/trjmms.1365603.

ÖZET

Artan işletme maliyetleri, büyüyen gemi tonajları, can kayıpları, gemi kazalarında insan faktörünün büyük etkisi gibi nedenler otonom yüzey gemilerinin (MASS) yakın gelecekte kaçınılmaz olarak dünya denizlerinde seyir yapacak olmasını tetikleyen başlıca faktörlerdir. Ancak henüz otonom teknelerle ilgili yeterli uluslararası kanun ve yönetmeliklerin olmayışı, gemi kazaların sonuçlarının büyüklüğünü ve kazanın etkilerini azaltacak ilk müdahaleyi yapacak personel olmayışı, halihazırda otonom gemilerin uluslararası sularda ticari seferler yapmaması nedeniyle mevcut olan belirsizlikler ve otonom gemilere duyulan güvensizlik günümüzde otonom su üstü araçlarının yaygınlaşması önündeki en büyük engellerdir. SWOT analizi ile ele alınan bir durumun ya da konunun güçlü ve zayıf yönlerini keşfetmek, bunlarla ilgili fırsatların farkına varmak ve bu fırsatlardan yararlanmak, tehditleri incelemek ve ortaya çıkabilecek risklere karşı önlem almak mümkün olmaktadır. Bu çalışmada otonom su üstü araçlarının yetenekleri, sundukları fırsatlar, avantajları, doğurabileceği sorunlar, dezavantajları gibi olumlu ve olumsuz yönleri bir bütün olarak ele alınmış, uzman görüşlerine göre geliştirme stratejileri önerilmiştir. Otonom gemilerin yaygın olarak benimsenmesi için gerekli olan stratejik planlamayı kolaylaştırmak amacıyla SWOT analizi ve Analitik Hiyerarşi Süreci (AHP) yöntemleri kullanılmıştır.

Anahtar sözcükler: Otonom gemiler, MASS, SWOT analizi, AHP, A'WOT

1. INTRODUCTION

Numerous studies underscore that maritime transport should be viewed as a "human system" and treated accordingly (Hetherington *et al.*, 2006). Human error often plays a role in maritime accidents, and its consideration tends to emerge only after a loss has occurred (Harati-Mokhtari *et al.*, 2007; Yildiz *et al.*, 2021). Recently, examining human contributions to maritime accidents has gained paramount importance in the industry. Similar to aviation and other transportation sectors, human error is a primary factor in preventable maritime accidents. Research, statistics, and investigations into accident causes reveal that human error, whether directly or indirectly, accounts for 70% to 96% of accidents (Ugurlu and Cicek, 2022). There's a consensus among researchers that the human factor is the primary cause and predominant influence behind maritime accidents. Over time, the impact and proportion of the human factor in maritime accidents have remained largely consistent (O'Neil, 2003). One of the most effective strategies to mitigate accidents stemming from human error and subsequently enhance ship safety involves increasing automation to support decision-making processes where appropriate (S. Yang *et al.*, 2007). This is particularly pertinent in the context of unmanned and autonomous ships, which are less prone to human-specific circumstances that might lead to accidents.

Strategic management involves the systematic utilization of an organization's resources to accomplish its defined goals and objectives. Crafting a strategy includes a range of assessments involving risks and resources, counteracting potential risks, and optimizing resource allocation in pursuit of significant goals. This strategic management process unfolds through three key stages: strategy formulation, strategy implementation, and strategy evaluation (David, 2011). The SWOT analysis stands as a pivotal tool within strategic planning, serving as a linchpin for both strategy formulation and evaluation. SWOT analysis is a strategic planning technique employed to assess the strengths, weaknesses, opportunities, and threats facing organizations. This analysis extends two critical advantages to organizations: Firstly, it acts as a diagnostic tool, offering insights into the present status of the organization. The initial components of the analysis, designated by the letters S and W, facilitate self-awareness by uncovering the organization's strengths and weaknesses. Strengths signify the organization's internal capacities that set it apart from competitors, while weaknesses denote the internal aspects where the organization lags behind its rivals. On the other hand, external factors—namely opportunities and threats—evaluate how the organization can navigate the industry landscape. Opportunities involve external factors that can yield positive outcomes for the organization, while threats comprise external factors that pose risks to the organization's continued existence. Consequently, the subsequent phase of the analysis delves into situational assessments with a forward-looking perspective, centered on potential future developments rather than the current state. This aspect inherently relies more on subjective data and estimations.

1.1. Motivations

As human beings, we all possess certain capabilities and limitations. For instance, humans excel in the discernment and recognition of patterns. No machine worldwide can interpret graphics and data on a radar screen as proficiently as a trained individual. Conversely, our memory capacity and the swiftness and precision with which we calculate numbers are somewhat restricted, whereas computers outperform us significantly in these aspects. In addition to these inherent characteristics, human performance is influenced by internal factors such as motivation and fatigue, alongside the knowledge and skills we acquire. The physical work environment directly impacts an individual's performance. For instance, the human body functions optimally within a specific temperature range. Performance tends to decline when temperatures deviate from this range and ceases entirely under extreme conditions (Wu *et al.*, 2020). Given the geographical and meteorological conditions of our planet and the ability of ships to navigate all the world's seas, achieving an ideal physical work environment is often unattainable. Adverse sea conditions and ship vibrations can impede movement and dexterity, leading to stress and fatigue. Constrained economic circumstances may also heighten the propensity for risk-taking (Rothblum, 2000).

In spite of the prevailing reservations surrounding autonomous ships due to the inherent uncertainty, valuable insights can be gleaned from incidents involving autonomous surface vehicles, as well as the lessons derived from accidents caused by human factors. Regardless of the terminology employed (autonomous), it remains the case that the design, software, and decision-making mechanisms of these systems are ultimately developed by humans. Furthermore, autonomous ships offer the distinct advantage of being operable in three distinct modes: manned, remote-controlled, and fully autonomous (Dittmann *et al.*, 2021). Over the course of a voyage, it is feasible to alter the autonomy levels through dynamic autonomy. For instance, when approaching a congested port, an autonomous surface vehicle can be under the control of an operator onshore, with the capacity to switch to full autonomy upon entering low-traffic waters. By minimizing the subjective human elements in maritime navigation and substituting them with an intelligent Decision-Making (DM) system for navigation and collision avoidance, it is plausible to reduce maritime accidents and their associated causes. A substantial proportion of mishaps and erroneous decisions at sea can result in the loss of life and environmental catastrophes (L. P. Perera, 2009). In a study conducted by (Mokhtari and Khodadadi, 2013), involving over 1,800 Iranian officers, queries were posed to identify strategies for mitigating human errors. Based on the obtained findings, the following measures were selected as potential remedies for negligence:

- Increasing the automation level,
- More control and surveys,
- More usage of alert signs,
- More accurate working standards, and
- More accurate Programming Maintenance Services (PMS)

The findings undeniably demonstrate that officers engaged in conventional maritime operations also share the belief that autonomous systems hold the potential for enhanced safety. The adoption of autonomous ships has the capacity to reduce the frequency of maritime accidents attributed to human error, owing to reduced human participation in the operational processes, albeit with the introduction of new risks and challenges (Utne *et al.*, 2017).

The aforementioned scenarios have precipitated an accelerated shift towards autonomy. The circumstances conducive to the emergence of economically viable solutions for unmanned and fully autonomous cargo and passenger vessels are ripening. It has been clearly articulated that the objective is to surpass the safety standards of autonomous surface vessels in comparison to their manned counterparts (Ahvenjärvi, 2016). Over the past quarter-century, the heightened capabilities in computational power and communication technologies, the advent of more advanced sensor systems, and reduced costs have spurred the utilisation of MASSs in novel domains such as mine clearance, environmental data collection and monitoring, naval exploration, as well as surface and submarine military applications. Prominent ongoing and large-scale research and development initiatives in Europe within this domain encompass the EU-funded MUNIN project (MUNIN, 2016) and DNV GL's Norwegian ReVolt project, which receives support from Transnova (DNV, 2017). Furthermore, a significant European undertaking is the AAWA project (Laurinen, 2019), backed by a consortium of Finnish enterprises and the Finnish Innovation Finance Agency TEKES. Additionally, the companies Yara and Kongsberg have jointly constructed an autonomous and fully electric container ship named 'Yara Birkeland' (Yara, 2021).

The existing body of literature offers valuable contributions comprising various facets of safety concerning autonomous ship operations, including security and cyber threats (Issa *et al.*, 2022), risk models and their management (Utne *et al.*, 2020), and risk assessments (Wróbel *et al.*, 2017). In particular, numerous studies within the domain of autonomous ships have concentrated their efforts on the enhancement of technical systems to avoid collisions. These enhancements encompass target detection (Zhang *et al.*, 2023), path planning (C. Yang *et al.*, 2023), collision avoidance algorithms (Yuan and Gao, 2022), and the adaptation of COLREGs for application to autonomous ships (Du *et al.*, 2022). However, given the anticipated expansion of MASSs into more intricate missions and diverse weather conditions, these platforms necessitate a heightened degree of autonomy to prevent an escalation of operator workload while simultaneously upholding elevated safety standards.

Various motivations, aside from the human factor, drive the transition towards autonomous ships. The absence of accommodation in unmanned vessels can yield cost savings, reduce tonnage and save space, consequently allowing ships to provide a greater cargo capacity (Laurinen, 2016). As living quarters become superfluous, vessels can become smaller, giving rise to more adaptable transportation solutions that can supplant road and rail transport for short to medium distances (Rødseth and Nordahl, 2017). Furthermore, it can enhance access to potentially dangerous maritime regions and diminish the occurrence of piracy incidents, as personnel cannot be held as ransom (AGCS, 2017). Additionally, the utilisation of MASSs can contribute to environmentally friendly shipping by reducing energy consumption. For instance, the unmanned, fully autonomous, electrically powered ReVolt concept ship is anticipated to offer substantial cost savings exceeding one million Euros annually when compared to a diesel-powered vessel (Alfheim *et al.*, 2018).

The unique strengths of a human operator in managing a complex system lie in their adaptability and creativity. The human capacity to respond effectively to unforeseen situations positively influences system safety. In contrast, a pre-programmed computer system possesses limited adaptability to handle exceptional and unanticipated scenarios. This could be considered a vulnerability of autonomous ships when compared to conventional vessels operated by human personnel. However, this drawback of autonomous surface vehicles is gradually diminishing as technological advancements enable computer systems to learn and adapt (Cui *et al.*, 2022). This adaptability becomes particularly crucial in challenging situations for autonomous ships. For instance, scenarios involving multiple simultaneous sensor failures or deliberate disruption of communication equipment by hackers can result in undesirable consequences. Another advantage of conventional ships is their capability to execute immediate onboard responses in the event of an accident. (Wróbel *et al.*, 2017) conducted an examination of maritime accidents across eight distinct categories and found that autonomous

surface vehicles reduce the likelihood of accidents. However, upon scrutinizing the outcomes of these accidents, it becomes evident that their impact exceeds that of conventional ships. Furthermore, the response of autonomous ships to potential accidents remains uncertain.
In light of the information presented herein and derived from the conducted studies, it becomes evident that all other prerequisites have matured, except for the comprehensive legal procedures and international regulations necessary for the deployment of autonomous surface vehicles in maritime navigation, as well as the capacity to initiate immediate responses in the event of an accident. The insights gleaned from these studies highlight that even the officers serving aboard vessels are now cognizant of the imperative need for MASSs.
The principal objective of this research is to assess the competitiveness of autonomous ships within the maritime industry and to recommend strategic planning approaches for their enduring sustainability. To achieve this, a comprehensive methodological approach is utilised, incorporating SWOT analysis and the Analytical Hierarchy Process (AHP) for conducting the analysis. The remainder of the study is organized as follows: The second section focuses on identifying SWOT factors and development strategies based on a review of existing literature. In the third section author presents the application of the SWOT-AHP method to the proposed factors and strategies. The results and discussions stemming from the study are presented in the fourth section. Finally, the fifth section contains the conclusions drawn from the study.

2. SWOT-AHP (A'WOT) METHOD

A seven-step methodology was adhered to in the study. The flowchart illustrating the quantified SWOT analysis (A'WOT) is depicted in Figure 1.

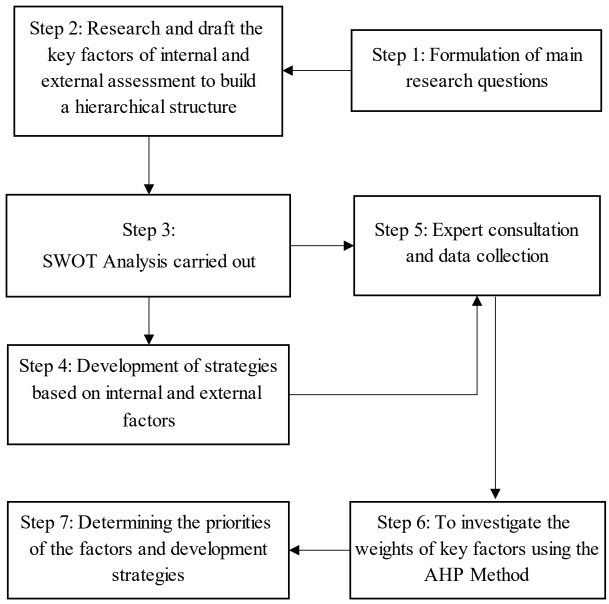


Figure 1. Flowchart of the A'WOT analysis pattern.

2.1. Describing SWOT Factors

Utilizing SWOT analysis, an effective strategy should be devised by amplifying strengths, mitigating weaknesses, capitalizing on opportunities, and safeguarding against threats (Shinno *et al.*, 2006). Given the significance of SWOT analysis in the context of strategic planning within the maritime sector, the objective of this section's study is to assess MASSs through SWOT analysis on the global stage. The aim is to sustain and enhance their strengths, address and rectify their weaknesses, prioritize opportunities, and proactively mitigate threats.
To assess the competitiveness of autonomous vessels, the following four primary research questions were formulated for SWOT analysis.
Question 1: What are the strengths that can encourage its development?
This question was formulated to ascertain the advantages that MASS possess, enabling them to establish competitiveness.
Question 2: What weaknesses will hinder its development?
This question investigates the shortcomings that MASS may exhibit, that is, the areas where MASS is deficient and requires enhancement.
Question 3: What opportunities are there to contribute to development?

This question explores the favourable circumstances that can facilitate a positive impact on the future development of MASS. This includes considering how MASS can contribute to society and the potential benefits it can deliver.

Question 4: What are the threats to be considered in future planning?

This question examines the challenges and obstacles that MASS may encounter. This includes assessing potential consequences that could pose threats to the environment and society, as well as identifying factors that may impede its development.

Using these questions SWOT analysis matrix is developed to identify the strengths, weaknesses, opportunities, and threats of the MASSs in the maritime sector. A total of 31 SWOT factors are finalized for the competitiveness evaluation and for deriving four future strategies (Table 1).

Utilizing these questions, a SWOT analysis matrix has been constructed to identify the strengths, weaknesses, opportunities, and threats associated with MASS within the maritime sector. A comprehensive set of 31 SWOT factors has been determined for the assessment of competitiveness and the formulation of four prospective strategies (Table 1).

To ensure the objectivity of the study, a comprehensive review of the literature was conducted to investigate the various scenarios, advantages, disadvantages, and future prospects pertaining to autonomous ships. Based on this literature research, SWOT factors were identified. In the selection of SWOT factors associated with autonomous ships, careful consideration was given to factors documented in the pertinent studies within the literature (Table A1- Appendix I).

The SWOT approach entails systematic and comprehensive examination of factors associated with management, technology, or planning. SWOT analysis involves the comparison of strengths, weaknesses, opportunities, and threats, combining these four elements to suggest SO (Strengths-Opportunities), WO (Weaknesses-Opportunities), ST (Strengths-Threats), and WT (Weaknesses-Threats) components. Subsequently, after summarising the issues within these four strategic directions, these matters are incorporated into the context of strategic planning for implementation. A development strategies model for autonomous ships, involving diverse interpretations and the formulation of strategies through SWOT evaluation, taking into account the factors outlined in Table 1, is presented in Figure 2.

SWOT analysis, when used effectively, can serve as a robust foundation for strategy development. However, SWOT analysis exhibits certain limitations in the evaluation and measurement phases within the strategic decision-making process. Most articles addressing SWOT analysis offer merely descriptive accounts of the analysis, with only a few employing quantified assessments. This may result in an under utilisation of the analytical method, given the inherent complexity of planning processes, which often involve a multitude of criteria and interdependencies. In the conventional SWOT analysis framework, a significant limitation lies in the inability to quantitatively measure the importance of decision factors, rendering it exceedingly challenging to gauge which factors exert the most profound influence on strategic decision-making (Shrestha *et al.*, 2004). Consequently, SWOT analysis may not provide a comprehensive evaluation of the strategic decision-making process. To address this shortcoming, the Analytical Hierarchy Process (AHP) methodology is employed to ascertain weights and quantitatively assess the relative significance of each factor within the SWOT analysis development strategy.

2.2. AHP Method

The Analytical Hierarchy Process (AHP) represents a potent tool for structuring and modelling, particularly in scenarios involving multi-criteria decision-making. AHP is a methodology that takes into account both objective and subjective assessment criteria when determining the optimal choice, relying on priorities derived from pairwise comparisons of the evaluation criteria. Successfully applied across various management domains (Li and Yuen, 2022), AHP dissects complex problems into constituent parts and subsequently

Table 1. Factors identified through the SWOT approach

SWOT Group	Abbreviation	SWOT Factors
(S)	S.1	Safer than manned ships (for human-related cases)
	S.2	Being resistant to human biological and emotional changes (i.e., cold, hot, fatigue, stress)
	S.3	Ability to make quick decisions
	S.4	Ability to evaluate data from many sources and perform multiple analyzes
	S.5	Ability to determine risk priority
	S.6	Ability to act under COLREG and local navigational rules
	S.7	Ability to learn
	S.8	24 hours of continuous monitoring of the environment and targets
	S.9	Easy to test their reaction to events
	S.10	Remote and easy troubleshooting of software errors and deficiencies
(W)	W.1	Still requires human intervention (i.e., in case of an accident)
	W.2	Limited remote intervention in case of technical failure
	W.3	Still in the testing phase and not yet applied to commercial ships
	W.4	Difficult to develop software at the infrastructure stage
	W.5	Inability to interpret and adapt to events in unexpected situations
(O)	O.1	Promising more environmentally friendly transportation (i.e., no crew-related pollution, fuel savings, and use of renewable energy)
	O.2	The maturation of technological developments for autonomy day by day
	O.3	Reduced ship size and increased carrying capacity due to lack of living quarters
	O.4	Lower operating cost (i.e., no personnel expenses)
	O.5	Ability to access dangerous and unsafe marine areas
	O.6	Effective use for minesweeping, research, data collection, and military purposes
	O.7	More and more people and institutions are interested in the subject
	O.8	Uncover new workforce areas related to operations and software
(T)	T.1	Prejudice towards autonomous vehicles
	T.2	Possible reactions as people will replace
	T.3	Skilled workforce and training gap for management and operation
	T.4	The immaturity of its legal and regulatory status
	T.5	Unknown interaction with manned ships
	T.6	Being vulnerable to cyber attacks
	T.7	Potential for job loss for existing seafarers
	T.8	The potential for new types of risks to emerge

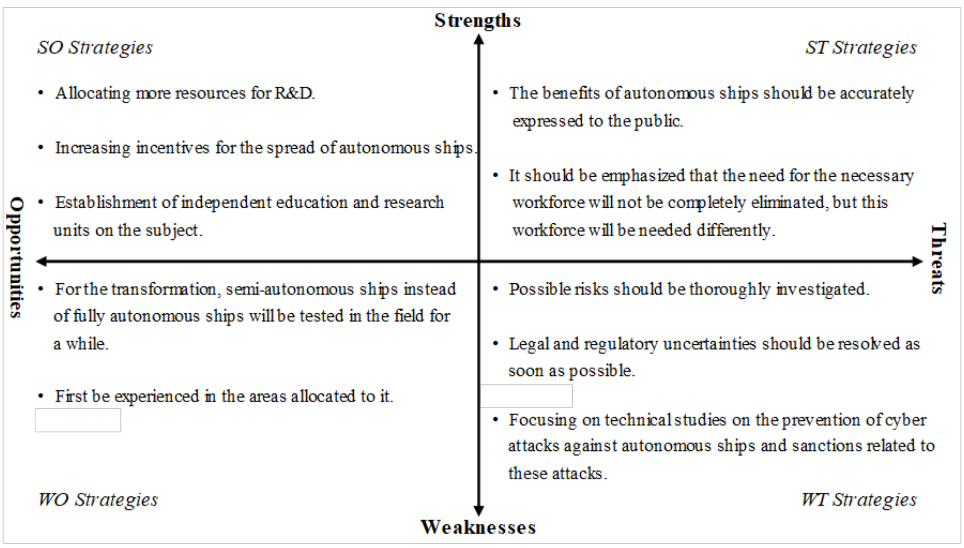


Figure 2. Four-quadrant development strategy model for autonomous ships

integrates all the solutions derived for these components. By amalgamating intuition, emotions, judgement, and rationality, AHP explain all the factors influencing a decision and streamlines the decision-making process. The advantages of AHP encompass its capacity to analyse decision attributes both qualitatively and quantitatively, along with its adaptability in goal-setting (Mahapatra *et al.*, 2021). However, AHP has certain disadvantages, which include its high computational demands even for small-scale problems. It also possesses a subjective nature, relying on individuals to translate their emotions and preferences into numerical judgments. Additionally, as the number of alternatives and criteria increases, the method requires a larger amount of pairwise comparisons, which can lead to increased time and effort. Moreover, over time, the inconsistency of the matrices may increase due to a loss of focus and concentration on the subject. The AHP Method consists of five stages. These are: 1-hierarchy construction, 2- pairwise comparison, 3- deriving relative weights, 4- checking the consistency ratio and 5- synthesizing results.

3. IMPLEMENTATION OF AHP-SWOT (A'WOT) METHOD

The next stage for prioritizing SWOT factors and development strategies obtained from the literature is to use the AHP Method to assess and rank them based on their relative importance.

3.1. Hierarchy construction

In the study, AHP was employed to establish priorities among the SWOT factors. The problem was structured into a four-stage hierarchical process, which involves the identification of SWOT factors, the categorization of these factors, the derivation of strategies through the combination of these groups, and ultimately the formulation of recommended development strategies (Figure 3) to enable measurement of the strategic factor groups and fundamental strategies identified through SWOT analysis via AHP. The inherent complexity of this approach can present implementation challenges; however, the fortunate availability of software tools designed to automate the mathematically intensive aspects has alleviated these difficulties. For this study, Microsoft Excel was chosen and utilised to quantitatively assess all the factors and strategies.

3.2. Pairwise comparison

Pairwise comparisons are conducted among the SWOT factors within each respective SWOT group. During these pairwise comparisons,

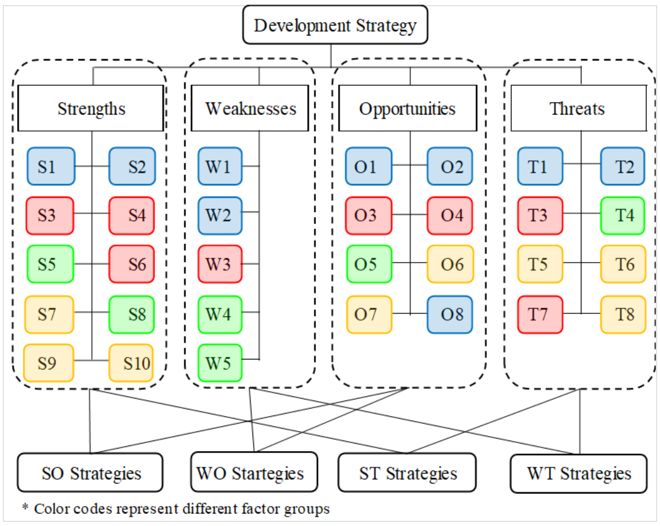


Figure 3. Hierarchical structure of A-WOT analysis

individuals tasked with evaluating the factors in the questionnaire are asked to provide judgements based on two key questions: 1) 'Which factor is more preferred (important) when comparing factor 1 with factor 2?' and 2) 'How much more preferred is one factor over the other factor?' At each stage, the criteria are assessed through pairwise comparisons according to their levels of influence. In the AHP, these multiple pairwise comparisons are made using Saaty's standardized comparison scale (Table 3), which encompasses nine levels (Saaty, 1987). Subsequent to these comparisons, the relative priorities of the SWOT factors are calculated using the eigenvalue approach within the framework of the AHP technique. Expert opinions were sought to establish the weights for the factor groups. As a criterion for selecting the experts whose opinions were solicited, having a minimum of two studies on autonomous surface vehicles was stipulated. Insights were gathered from 10 researchers engaged in the field of MASS, including individuals from the private sector and predominantly academics affiliated with universities. Recognizing the significance of diverse perspectives, experts with expertise in various domains such as law, technology, maritime, shipbuilding, and environmental matters relevant to autonomous ships were specially chosen. The occupational backgrounds of these experts encompassed master mariners, shipbuilders, lawyers, software developers, and engineers.

Table 3. Pairwise comparison scale

Importance	Explanation
1	Two criteria contribute equally to the objective
3	Experience and judgment slightly favor one over another
5	Experience and judgment strongly favor one over another
7	Criterion is strongly favored and its dominance is demonstrated in practice
9	Importance of one over another affirmed on the highest possible order
2, 4, 6, 8	Used to represent a compromise between the priorities listed above

Despite identifying a total of 31 SWOT factors, we have restructured these factors into 15 coherent groups to enhance clarity regarding our objectives. Opinions from all experts are collected in a single matrix by taking the geometric mean. The pairwise comparison matrix (referred to as the A matrix), a square matrix with dimensions 15x15, is presented in the Appendix II.

Comparisons are conducted for values located above the diagonal of the comparison matrix. For comparisons below the diagonal, the following formula is employed.

$$a_{ij} = 1 / a_{ji} \tag{3.1}$$

3.3 Deriving relative weights

To determine the weights of the factors in their entirety, 15 column vectors, each comprising 15 components, and B-column vectors are constructed from the column vectors constituting the comparison matrix.

$$B_i = \begin{bmatrix} b_{11} \\ b_{21} \\ b_{31} \\ . \\ . \\ . \\ b_{151} \end{bmatrix}, \quad b_{ij} = a_{ij} / \sum_{i=1}^{n} a_{ij} \tag{3.2}$$

When the 15 B-column vectors are consolidated in matrix form, the normalized matrix C is constructed and displayed in Appendix III.

Utilising the equation below, the arithmetic mean of the row elements within the C matrix is computed to determine the relative importance (weight) of values for the factors in relation to each other, subsequently yielding the W column vector, commonly referred to as the priority vector.

$$w_i = \sum_{j=1}^{n} c_{ij} / n \tag{3.3}$$

$$W = \begin{bmatrix} w_1 \\ w_2 \\ w_3 \\ . \\ . \\ . \\ w_{15} \end{bmatrix} \tag{3.4}$$

Within the SWOT Matrix, established through SWOT analysis to assess the position of autonomous ships within the sector, the weights for four factors each in the categories of strengths, opportunities, and threats, and three factors in the category of weaknesses were determined. The weight values for the complete set of 15 factors are presented in Table 4. Following the decomposition of the problem and the construction of the hierarchy, the prioritisation process commences to define the relative importance of each criterion as outlined in Table A2 (Appendix IV).

3.4 Checking consistency ratio

To compute the eigenvalue (λ), denoted as such, the D column vector is generated by multiplying the comparison matrix A with the priority vector

W. The λs for each evaluation factor are derived by dividing the reciprocal elements of the D vector by the W vector as per equation (3.5). Using the formula below, the λ for the comparison is calculated.

$$E_i = d_i / w_i \quad (i = 1, 2, 3, \ldots 15) \tag{3.5}$$

$$\lambda = \sum_{i=1}^{n} E_i / n \tag{3.6}$$

After determining λ, the Consistency Index (CI) can be computed using the equation provided below. In our study, this value was determined to be 0.0439.

$$CI = \frac{\lambda - 1}{1 - n} \tag{3.7}$$

The CI is divided by the standard correction value referred to as the Random Index (RI), as detailed in Table 5, to yield the Consistency Ratio (CR). The CR, as a result of calculations, was determined to be 0.0276.

$$CR = CI / RI \tag{3.8}$$

Table 5. Random consistency index

Size of Matrix (n)	**Random Consistency Index (RI)**
1	0
2	0
3	0.58
4	0.90
5	1.12
6	1.24
7	1.32
8	1.41
9	1.45
10	1.49
11	1.51
12	1.54
13	1.56
14	1.57
15	1.59

A CR value below 0.10 signifies that the comparisons are consistent. If the CR value exceeds 0.10, it implies the presence of a computational error within the AHP or inconsistency in the comparisons. The CR serves as a means to examine the consistency of the one-to-one comparisons made between the factors. The result is within the acceptable compliance rate limits, as it is below 10%. Therefore, the inconsistency is considered acceptable.

3.5. Synthesizing results

The distribution of importance percentages among the decision points is ascertained by iteratively repeating the comparisons and matrix operations, equating to the number of factors (15 times). Following each comparison operation, mx1 dimensional S column vectors are generated, illustrating the percentage allocations to the decision points of the factors. The resulting mx15 dimensional K decision matrix, comprising 15m x 1 dimensional S column vectors, is presented below.

$$K = \begin{bmatrix} s_{11} & s_{12} & \cdots & s_{115} \\ s_{21} & s_{22} & \cdots & s_{215} \\ . & & & . \\ . & & & . \\ . & & & . \\ s_{m1} & s_{m2} & \cdots & s_{m15} \end{bmatrix} \tag{3.9}$$

By performing matrix multiplication between the decision matrix and the W column vector, the L column vector, referred to as the 'Priority Vector Matrix,' is generated. This vector depicts the percentage allocation of the decision points and establishes their order of significance.

$$L = \begin{bmatrix} 0.735 \\ 1.395 \\ 1.155 \\ 1.005 \\ 0.81 \\ 0.495 \\ 0.585 \\ 0.705 \\ 0.96 \\ 0.735 \\ 1.395 \\ 1.245 \\ 1.005 \\ 0.9 \\ 1.905 \end{bmatrix}$$

The results obtained indicate which factors should receive the most attention. In order of priority, it was found that T4, S2, O4, and T1 are the factors that need to be considered the most. The factors in order of priority, along with their descriptions, are as follows:

T4- Threats related to unknown issues, security, and risks.

S2- Strengths in data processing speed and analysis capability.

O4- Opportunities related to safety and security.

T1- Threats of negative reactions and prejudice.

The procedure carried out earlier for the SWOT factor groups was applied to derive the development strategies as follows:

$$A = \begin{bmatrix} 1.000 & 1.568 & 2.167 & 1.431 & 1.888 & 0.826 & 2.543 & 0.987 & 1.159 & 1.284 \\ 0.638 & 1.000 & 1.097 & 1.135 & 1.134 & 0.728 & 1.625 & 0.503 & 0.964 & 0.885 \\ 0.461 & 0.691 & 1.000 & 1.196 & 1.038 & 0.768 & 1.661 & 0.515 & 0.738 & 0.872 \\ 0.699 & 0.881 & 0.836 & 1.000 & 1.175 & 0.851 & 2.491 & 0.530 & 0.608 & 0.749 \\ 0.530 & 0.882 & 0.963 & 0.851 & 1.000 & 0.777 & 2.666 & 0.441 & 0.538 & 0.671 \\ 1.210 & 1.374 & 1.338 & 1.175 & 1.287 & 1.000 & 3.640 & 0.746 & 1.170 & 1.131 \\ 0.393 & 0.616 & 0.609 & 0.402 & 0.375 & 0.275 & 1.000 & 0.322 & 0.454 & 0.545 \\ 1.013 & 1.987 & 1.940 & 1.888 & 2.267 & 1.340 & 3.108 & 1.000 & 1.669 & 1.710 \\ 0.863 & 1.038 & 1.356 & 1.644 & 1.858 & 0.855 & 2.203 & 0.599 & 1.000 & 0.768 \\ 0.779 & 1.129 & 1.147 & 1.311 & 1.491 & 0.884 & 1.835 & 0.585 & 1.302 & 1.000 \end{bmatrix}$$

$$C = \begin{bmatrix} 0.132 & 0.140 & 0.174 & 0.119 & 0.140 & 0.099 & 0.112 & 0.158 & 0.121 & 0.134 \\ 0.084 & 0.090 & 0.088 & 0.094 & 0.084 & 0.088 & 0.071 & 0.081 & 0.100 & 0.092 \\ 0.061 & 0.062 & 0.088 & 0.099 & 0.077 & 0.092 & 0.073 & 0.083 & 0.077 & 0.091 \\ 0.092 & 0.079 & 0.067 & 0.083 & 0.087 & 0.103 & 0.109 & 0.085 & 0.063 & 0.078 \\ 0.070 & 0.079 & 0.077 & 0.071 & 0.074 & 0.094 & 0.117 & 0.071 & 0.056 & 0.070 \\ 0.160 & 0.123 & 0.107 & 0.098 & 0.095 & 0.120 & 0.160 & 0.120 & 0.122 & 0.118 \\ 0.052 & 0.055 & 0.049 & 0.033 & 0.028 & 0.033 & 0.044 & 0.052 & 0.047 & 0.057 \\ 0.134 & 0.178 & 0.156 & 0.157 & 0.168 & 0.161 & 0.136 & 0.161 & 0.174 & 0.178 \\ 0.114 & 0.093 & 0.109 & 0.137 & 0.137 & 0.103 & 0.097 & 0.096 & 0.104 & 0.080 \\ 0.103 & 0.101 & 0.092 & 0.109 & 0.109 & 0.106 & 0.081 & 0.094 & 0.136 & 0.104 \end{bmatrix}$$

The development strategies with the highest weight, in order of priority, are WT1, SO1, WO1 and WT2. These strategies have been identified as the most important for our study's development based on their respective weights (Table 6). In general, it appears that the WT values have the highest weight in the analysis, suggesting that addressing weaknesses and mitigating threats is a crucial aspect of this study's development strategy.

The CR value of 0.099, although it is at the limit, indicates that the generated AHP model is relatively consistent. While it's close to the threshold of 0.1, the fact that it's below this limit suggests that the expert opinions and the model's calculations are reasonably consistent and reliable for this study analysis. After analyzing the consistency ratio of the results, priority values were ultimately determined and are presented with L vector. Therefore, the top three development strategies that should receive the highest emphasis are WT1, SO1, and WO1, respectively. This highlights the significance of concentrating on aspects where internal weaknesses and external threats exist in order to enhance and safeguard the outcomes of the study.

Table 6. Weight values of SWOT development strategies

Strategy Groups	Development Strategies	Local Weights	Global Weights
(SO)	1) Allocating more resources for R&D.	0.445	0.133
	2) Increasing incentives for the spread of autonomous ships.	0.291	0.087
	3) Establishment of independent education and research units on the subject.	0.264	0.079
(ST)	1) The benefits of autonomous ships should be accurately expressed to the public.	0.521	0.085
	2) It should be emphasized that the need for the necessary workforce will not be completely eliminated, but this workforce will be needed differently.	0.479	0.078
(WO)	1) For the transformation, semi-autonomous ships instead of fully autonomous ships will be tested in the field for a while.	0.731	0.122
	2) First be experienced in the areas allocated to it.	0.269	0.045
(WT)	1) Possible risks should be thoroughly investigated.	0.431	0.160
	2) Legal and regulatory uncertainties should be resolved as soon as possible	0.288	0.107
	3) Focusing on technical studies on the prevention of cyber attacks against autonomous ships and sanctions related to these attacks.	0.280	0.104

$$L = \begin{bmatrix} 1.33 \\ 0.87 \\ 0.79 \\ 0.85 \\ 0.78 \\ 1.22 \\ 0.45 \\ 1.60 \\ 1.07 \\ 1.04 \end{bmatrix}$$

4. RESULTS AND DISCUSSION

As a result, when analyzing the overall results of the study, it becomes evident that threats (33.7%) and strengths (28.6%) within the SWOT factors are areas that require more attention, as indicated by the examination of expert opinions. Additionally, the aspect of opportunities (25.3%) also holds a significant priority similar to the former two factor groups. Notably, the study's outcomes suggest that experts regard the weaknesses of MASSs (12.6%) as comparatively less critical than the other three factor categories. When assessing the SWOT factors based on expert opinions and ranked using the AHP method within their respective fields, the following priorities were observed:

a. Shipbuilders:
- The most important factors were T4, T1, S2, and T3, with priority values of 2.242, 1.919, 1.471, and 1.446, respectively.
- The least significant factors for shipbuilders were W2 and W3, with priority values of 0.363 and 0.375.

b. Technology Experts (MASS-related):
- T4, S4, O4, and S3 were emphasized as crucial factors, with priority values of 1.863, 1.582, 1.523, and 1.172, respectively.
- Factors O1 and S1 had the lowest priority values at 0.390 and 0.4, respectively.

c. Mariners:
- Significant factors for mariners included O4, S2, T4, and S3, with priority values of 2.059, 1.753,1.290, and 1.140, respectively.
- T3 and W2 were identified as the least important factors among mariners, with priority values of 0.454 and 0.608.

d. Legal Expert:
- Prioritized factors for the legal expert were W1, T4, T3, and T2, with priority values of 3.538, 2.915, 2.215, and 1.487, respectively.
- S3 and S4 were rated as the least significant factors for the legal expert, with a priority value of 0.315.

These results highlight the varying perspectives of experts from different fields regarding the importance of SWOT factors in the context of autonomous ships.

In summary, when considering the evaluations both in general and according to the fields of expertise, T4 emerges as the most crucial factor. Following T4, O4 holds significant importance. This indicates that experts believe that addressing unknown issues, security problems, and risks related to MASS should be the primary focus. Interestingly, despite these concerns, experts also see safety and security-related opportunities as highly significant, suggesting that the main preoccupation and aspiration within the field of MASSs revolve around safety and security issues. Furthermore, the analysis reveals that experts, except for lawyers, do not generally view the weaknesses of MASSs as major concerns. Legal gaps and infrastructure deficiencies, which pose significant obstacles to the widespread adoption of autonomous vessels, are not considered substantial issues by experts in fields other than law.

When analyzing the responses provided by experts with experience in MASSs, it becomes evident that professionals from different fields prioritize various aspects related to autonomous vessels. In the assessment of development strategies, shipbuilders assign the highest priority to strategies WT1, WO1, WT3, and SO1, with respective values of 0.227, 0.134, 0.130, and 0.123. On the other hand, engineers and academics specializing in autonomous ship technology emphasize strategies SO1, WO1, and WT1, with priority values of 0.176, 0.142, and 0.123, respectively. Mariners view strategies SO1, WT1, WO1, and SO2 as significant, with priority values of 0.141, 0.137, 0.122, and 0.118, respectively. Lastly, the legal expert highlights the importance of strategies WT1, WT2, and WT3, with a score of 0.183. Based on these evaluations, WT1 emerges as the most critical strategy, both overall and within specialized domains. SO1 and WO1 strategies closely follow. Interestingly, the strategy aimed at addressing the lack of a legal framework for autonomous ships, a significant barrier to their widespread adoption, is particularly emphasized by the legal expert.

5. CONCLUSION

In this research article, the study aimed to determine the strategic management of MASSs in comparison to manned ships, based on existing literature, and to propose strategies for their improvement and mitigation of weaknesses by leveraging expert opinions. To achieve this, a hybrid approach combining SWOT analysis, a strategic management method, and the AHP

Method, a technique commonly employed in multi-criteria decision making, was employed. Given the multifaceted literature of MASSs, experts from various domains were consulted to assess the factors influencing autonomous ships, and the gathered data underwent a comprehensive evaluation. This extensive analysis yielded several noteworthy findings:

- Experts highlighted the paramount importance of addressing unknown issues, security concerns, and risks related to MASSs. Safety and security emerged as top priorities for researchers and practitioners in this field.
- Legal gaps and the lack of a suitable legal infrastructure were identified as significant barriers to the widespread adoption of autonomous ships. Lawyers, in particular, emphasized the need to address these issues.
- The most critical issues among threats are related to the unknown, security, and risk, accounting for 12.7% in terms of priority.
- The least significant factor group is weaknesses, encompassing human, software, technological weaknesses, and lack of experience. Software and technological weaknesses are rated the lowest at 4.9%.
- The highest priority group among the suggested development strategies for MASSs is the weakness-threat group, with a priority value of 37.1%. The strengths-opportunities group follows closely with a priority value of 29.9%.
- Weaknesses-Threats and Strengths-Opportunities development strategies collectively dominate with a total rate of 67%.

Based on the results obtained, the third stage of the SWOT Analysis, which is strategy evaluation, is outlined as follows. The data obtained from this research clearly indicate that experts in the field of MASSs prioritize taking precautions against potential threats and further developing existing strengths. These findings emphasize the importance of addressing unknown factors, security, and risk as primary threats in the development of MASSs. Strategies aimed at mitigating weaknesses and capitalizing on strengths, especially in response to threats and opportunities, play a significant role in shaping the future of autonomous ship technology. While there are numerous SWOT analysis studies on autonomous ships in the literature, this research has made a valuable contribution by providing a structured decision-making framework that quantifies the importance of each factor. This approach helps guide future research and development efforts in the autonomous ship industry, filling a crucial gap in the existing body of knowledge.

In this study, the research questions related to the competitiveness of autonomous ships compared to manned ships were effectively addressed through SWOT analysis. The opinions of experts in the field of autonomous ships were invaluable in providing insights into the strengths, weaknesses, opportunities, and threats of this technology. However, it's worth noting that the experts consulted in this study represent a specific range of expertise. To achieve a more comprehensive evaluation, future research could aim to gather opinions from a broader spectrum of experts, covering various domains related to autonomous ships. By doing so, a more holistic perspective on the strengths, weaknesses, opportunities, and threats of autonomous ships could be obtained, leading to more informed decision-making and further advancements in the field.

Overall, this study has made a significant contribution to various sectors related to autonomous ships, including shipbuilders, researchers, rule-making authorities, sailors, and lawyers. It offers valuable guidance on which factors and strategies should be prioritized in the context of autonomous ships, both presently and in the future.

AUTHORSHIP CONTRIBUTION STATEMENT

Hasan UĞURLU: Conceptualization, Methodology, Validation, Formal Analysis, Resources, Writing - Original Draft, Writing-Review and Editing, Data Curation, Software, Visualization.

CONFLICT OF INTERESTS

The author declares that for this article they have no actual, potential or perceived conflict of interests.

ETHICS COMMITTEE PERMISSION

Author declares that this study was conducted in accordance with Ethics Committee of Social Sciences, Science and Engineering Sciences Research. The study received ethics committee approval from Giresun University with file number 2023/09.

FUNDING

No funding was received from institutions or agencies for the execution of this research.

ORCID IDs

Hasan UĞURLU:
https://orcid.org/0000-0002-0778-9265

6. REFERENCES

Allianz Global Corporate and Specialty SE (AGCS). Safety and Shipping Review 2017, (2017). Accessed Date: 21.04.2023, https://commercial.allianz.com/news-and-insights/reports/shipping-safety.html is retrieved.

Ahvenjärvi, S., (2016). The human element and autonomous ships. *TransNav: International Journal on Marine Navigation and Safety of Sea Transportation* 10(3).

Alfheim, H.L., Muggerud, K., Breivik, M., Brekke, E.F., Eide, E., Engelhardtsen, Ø., (2018). Development of a dynamic positioning system for the revolt model ship. *IFAC-PapersOnLine* 51(29): 116-121.

Burmeister, H., Bruhn, W., (2015). Designing an autonomous collision avoidance controller respecting COLREG. *Maritime-Port Technology and Development* 83-88.

Cui, K., Li, H., Jing, Y., Liu, L., Wang, D., (2022). Reduced-and Full-order Concurrent Learning Extended State Observers for Fully Adaptive Anti-disturbance Surge Speed Tracking Control of Autonomous Surface Vehicles. IEEE 25th International Conference on Intelligent Transportation Systems (ITSC).

Dallolio, A., Agdal, B., Zolich, A., Alfredsen, J.A., Johansen, T.A., (2019). Long-endurance green energy autonomous surface vehicle control architecture. OCEANS 2019 MTS/IEEE, Seattle.

David, F.R., (2011). Strategic management concepts and cases. Pearson.

Dittmann, K., Hansen, P.N., Papageorgiou, D., Jensen, S., Lützen, M., Blanke, M., (2021). Autonomous surface vessel with remote human on the loop: System design for stcw compliance. *IFAC-PapersOnLine* 54(16): 224-231.

Det Norske Veritas (DNV), G., (2017). The ReVolt. A new inspirational ship concept. Accessed Date: 21.05.2023, https://www.dnvgl.com/technologyinnovation/revolt/ is retrieved.

Du, Z., Negenborn, R.R., Reppa, V., (2022). COLREGS-Compliant collision avoidance for physically coupled multi-vessel systems with distributed MPC. *Ocean Engineering* 260: 111917.

Evensen, M.H., (2020). Safety and security of autonomous vessels, Based on the Yara Birkeland project, Master Thesis, The University of Bergen, Bergen.

Harati-Mokhtari, A., Wall, A., Brookes, P., Wang, J., (2007). Automatic Identification System (AIS): a human factors approach. *Journal of Navigation* 60(3): 373-389.

Hetherington, C., Flin, R., Mearns, K., (2006). Safety in shipping: The human element. *Journal of safety research* 37(4): 401-411.

Issa, M., Ilinca, A., Ibrahim, H., Rizk, P., (2022). Maritime Autonomous Surface Ships: Problems and Challenges Facing the Regulatory Process. *Sustainability* 14(23): 15630.

Jessee, M.S., Chiou, T., Krepps, A.S., Prengaman, B.R., (2017). A gaze based operator instrumentation approach for the command of multiple autonomous vehicles. IEEE Conference on Control Technology and Applications (CCTA).

Jin, K., Wang, H., YI, H., Liu, J., Wang, J., (2018). Key technologies and intelligence evolution of maritime UV. *Chinese Journal of Ship Research* 13(6): 1-8.

Kaminski, D., (2016). Who's to blame when no one is manning the ship: JDSupra.

Perera, L.P., Guedes Soares, C., (2009). Autonomous guidance and navigation based on the COLREGs rules and regulations of collision avoidance. Advanced Ship Design for Pollution Prevention.

Laurinen, M., (2016). Remote and autonomous ships: The next steps. *AAWA Adv Auton Waterborne Appl* 88.

Laurinen, M., (2019). Advanced Autonomous Waterborne Applications Initiative AAWA, AAWA Seminar–Helsinki, Finland.

Li, S., Fung, K., (2019). Maritime autonomous surface ships (MASS): implementation and legal issues. *Maritime Business Review* 4(4): 330-339.

Li, X., Yuen, K.F., (2022). Autonomous ships: A study of critical success factors. *Maritime Economics & Logistics* 24(2): 228-254.

Mahapatra, D., Katiyar, R., Parida, R., Kumar, D., (2021). A fuzzy multi-criteria approach for evaluating the contribution of freight transportation towards India's Nationally Determined Contributions (NDCs). *International Journal of Production Research* 59(9): 2857-2884.

Mokhtari, A., Khodadadi, H., (2013). An Empirical Survey on the Role of Human Error in Marine Incidents. *TransNav: International Journal on Marine Navigation and Safety of Sea Transportation* 7(3).

Munim, Z.H., Haralambides, H., (2022). Advances in maritime autonomous surface ships (MASS) in merchant shipping. *Maritime Economics & Logistics* 24(2): 181-188.

Maritime Unmanned Navigation through Intelligence in Networks, MUNIN. Research in Maritime Autonomous Systems Project Results and Technology Potentials, (2016). Accessed Date: 28.04.2023, http://www.unmannedship.org/munin/wp-content/uploads/2016/02/MUNIN-final-brochure.pdf is retrieved.

Nippon Yusen Kaisha (NYK), (2019). NYK conducts world's first maritime autonomous surface ships trial. Accessed Date: 27.04.2023, https://www.nyk.com/english/news/2019/20190930_01.html is retrieved

O'Neil, W.A., (2003). *The human element in shipping*, Springer.

Pedrozo, R.P., (2019). US employment of marine unmanned vehicles in the South China Sea. *The South China Sea* (pp. 217-229): Routledge.

Porathe, T., (2017). Is COLREG enough? Interaction between manned and unmanned ships. Marine Navigation: Conference Proceedings 12th International Conference on Marine Navigation and Safety of Sea Transportation, TransNav 2017.

Ramos, M.A., Thieme, C.A., Utne, I.B., Mosleh, A., (2020). Human-system concurrent task analysis for maritime autonomous surface ship operation and safety. *Reliability Engineering & System Safety* 195: 106697.

Ringbom, H., (2019). Regulating autonomous ships-concepts, challenges and precedents. *Ocean Development & International Law* 50(2-3): 141-169.

Rødseth, N., Nordahl, H., (2017). Definition of autonomy levels for merchant ships. Norwegian Forum for Autonomous Ships (NFAS) Conference.

Rothblum, A.M., (2000). Human error and marine safety. National Safety Council Congress and Expo, Orlando, FL.

Saaty, R.W., (1987). The analytic hierarchy process-what it is and how it is used. *Mathematical modelling* 9(3-5): 161-176.

Shinno, H., Yoshioka, H., Marpaung, S., Hachiga, S., (2006). Quantitative SWOT analysis on global competitiveness of machine tool industry. *Journal of engineering design* 17(03): 251-258.

Shrestha, R.K., Alavalapati, J.R., Kalmbacher, R.S., (2004). Exploring the potential for silvopasture adoption in south-central Florida: an application of SWOT–AHP method. *Agricultural systems* 81(3): 185-199.

Stateczny, A., Gierlowski, K., Hoeft, M., (2022). Wireless local area network technologies as communication solutions for unmanned surface vehicles. *Sensors* 22(2): 655.

Ugurlu, H., Cicek, I., (2022). Analysis and assessment of ship collision accidents using Fault Tree and Multiple Correspondence Analysis. *Ocean Engineering* 245: 110514.

Utne, I.B., Sørensen, A.J. Schjølberg, I., (2017). Risk management of autonomous marine systems and operations. ASME 36th International Conference on Ocean, Offshore and Arctic Engineering, 2017. American Society of Mechanical Engineers Digital Collection.

Utne, I.B., Rokseth, B., Sørensen, A.J., Vinnem, J.E., (2020). Towards supervisory risk control of autonomous ships. *Reliability Engineering & System Safety* 196: 106757.

Veal, R., Tsimplis, M., Serdy, A., (2019). The legal status and operation of unmanned maritime vehicles. *Ocean Development & International Law* 50(1): 23-48.

Wang, K., Li, J., Xu, M., Chen, Z., Wang, J., (2022). LiDAR-Only Ground Vehicle Navigation System in Park Environment. *World Electric Vehicle Journal* 13(11): 201.

Wróbel, K., Montewka, J., Kujala, P., (2017). Towards the assessment of potential impact of unmanned vessels on maritime transportation safety. *Reliability Engineering & System Safety* 165: 155-169.

Wu, H., Wu, Y., Sun, X., Liu, J., (2020). Combined effects of acoustic, thermal, and illumination on human perception and performance: A review. *Building and Environment* 169: 106593.

Yang, C., Zhao, Y., Cai, X., Wei, W., Feng, X., Zhou, K., (2023). Path Planning Algorithm for Unmanned Surface Vessel Based on Multiobjective Reinforcement Learning. *Computational Intelligence and Neuroscience* 2023.

Yang, S., Li, L., Suo, Y., Chen, G., (2007). Study on construction of simulation platform for vessel automatic anti-collision and its test method. IEEE International Conference on Automation and Logistics.

Yara, I., (2021). Yara to start operating the world's first fully emission-free container ship. Accessed Date: 05.05.2023, https://www.yara. com/corporate-releases/yara-to-start-operating-the-worlds-first-fully-emission-free-container-ship/ is retrieved

Yildiz, S., Uğurlu, Ö., Wang, J., Loughney, S., (2021). Application of the HFACS-PV approach for identification of human and organizational factors (HOFs) influencing marine accidents. *Reliability Engineering & System Safety* 208: 107395.

Yuan, W., Gao, P., (2022). Model Predictive Control-Based Collision Avoidance for Autonomous Surface Vehicles in Congested Inland Waters. *Mathematical Problems in Engineering* 2022.

Zanella, T.V., (2020). The Environmental Impacts of the "Maritime Autonomous Surface Ships" (MASS). *Veredas do Direito* 17: 367.

Zhang, M., Zhao, D., Sheng, C., Liu, Z., Cai, W., (2023). Long-Strip Target Detection and Tracking with Autonomous Surface Vehicle. *Journal of Marine Science and Engineering* 11(1): 106.

Zhou, X.Y., Liu, Z.J., Wang, F.W., Ni, S.K., (2018). Collision risk identification of autonomous ships based on the synergy ship domain. Chinese Control and Decision Conference (CCDC).

Appendix I

Table A1. Reference studies to identify SWOT factors

Author(s), Year	Article Name	Related Factor(s)
(Burmeister and Bruhn, 2015)	Designing an autonomous collision avoidance controller respecting COLREG.	S6, O1, O4, O8
(Laurinen, 2016)	Remote and autonomous ships: The next steps.	W2, W4, W1, T6, O3
(Kaminski, 2016)	Who's to blame when no one is manning the ship.	O1, O3, O4, T1, T4, T6, S2, S8
(Jessee *et al.*, 2017)	A gaze-based operator instrumentation approach for the command of multiple autonomous vehicles.	W5
(Porathe, 2017)	Is COLREG enough? Interaction between manned and unmanned ships.	T5, S6
(Wróbel *et al.*, 2017)	Towards the assessment of potential impact of unmanned vessels on maritime transportation safety.	S1, W1, T8
(Zhou *et al.*, 2018)	Collision risk identification of autonomous ships based on the synergy ship domain.	S5
(Jin *et al.*, 2018)	Key technologies and intelligence evolution of maritime UV.	O2, O6, O7, W2, S7
(NYK, 2019)	NYK conducts world's first maritime autonomous surface ships trial.	W3
(Li and Fung, 2019)	Maritime autonomous surface ships (MASS): implementation and legal issues.	S1, T2, T6, T7, T8, O1, O4, O7, W4
(Veal *et al.*, 2019)	The legal status and operation of unmanned maritime vehicles.	T1, T3, T4, T8, O6
(Dallolio *et al.*, 2019)	Long-endurance green energy autonomous surface vehicle control architecture.	S2, S4, S6, S8, O1, O6
(Pedrozo, 2019)	US employment of marine unmanned vehicles in the South China Sea.	S1, O4, O5, O6, O7, S2
(Ringbom, 2019)	Regulating autonomous ships-concepts challenges and precedents.	O7, O8, T4, T8, W1, S3, S4, S5, S6, S8
(Evensen, 2020)	Safety and security of autonomous vessels Based on the Yara Birkeland Project.	W2, T6, T8, O3, O5, S1
(Ramos *et al.*, 2020)	Human-system concurrent task analysis for maritime autonomous surface ship operation and safety.	T8, W3
(Wu *et al.*, 2020)	Combined effects of acoustic, thermal, and illumination on human perception and performance: A review.	S2
(Utne *et al.*, 2020)	Towards supervisory risk control of autonomous ships	S1, S3, S4, S5, S7, O1, O4, W1
(Zanella, 2020)	The Environmental Impacts of the "Maritime Autonomous Surface Ships".	O1, O4, T4, T6, T8, S1, W1
(Dittmann *et al.*, 2021)	Autonomous surface vessel with remote human on the loop: System design for STCW compliance.	O2, O8, S1, S4, W1, T3
(Munim and Haralambides, 2022)	Advances in maritime autonomous surface ships (MASS) in merchant shipping.	T2, T7, O2, O7
(Issa *et al.*, 2022)	Maritime Autonomous Surface Ships Problems and Challenges Facing the Regulatory Process.	O2, O7, O8, T3, T4, T6, W2, S1
(Cui *et al.*, 2022)	Reduced-and Full-order Concurrent Learning Extended State Observers for Fully Adaptive	S7

	Anti-disturbance Surge Speed Tracking Control of ASVs.	
(Wang *et al*., 2022)	LiDAR-Only Ground Vehicle Navigation System in Park Environment.	S9
(Stateczny *et al*., 2022)	Wireless local area network technologies as communication solutions for unmanned surface vehicles.	S10

Appendix II

$$A = \begin{bmatrix}
1 & 0.424 & 0.535 & 0.57 & 0.661 & 1.302 & 0.933 & 1.672 & 1.125 & 1.365 & 0.545 & 0.683 & 0.74 & 0.812 & 0.423 \\
2.362 & 1 & 1.077 & 1.838 & 1.201 & 1.663 & 1.431 & 2.844 & 2.229 & 2.069 & 1.863 & 0.997 & 1.143 & 1.192 & 0.601 \\
1.864 & 0.926 & 1 & 1.349 & 1.055 & 1.528 & 1.054 & 1.33 & 1.597 & 1.712 & 1.49 & 1.061 & 1.175 & 1.353 & 0.554 \\
1.741 & 0.541 & 0.742 & 1 & 0.845 & 1.374 & 0.974 & 1.876 & 1.633 & 1.692 & 1.39 & 0.721 & 0.867 & 1.192 & 0.489 \\
1.513 & 0.833 & 0.948 & 1.184 & 1 & 1.713 & 1.625 & 1.016 & 0.803 & 0.856 & 0.409 & 0.674 & 0.662 & 0.73 & 0.285 \\
0.768 & 0.601 & 0.654 & 0.728 & 0.581 & 1 & 1.19 & 0.503 & 0.533 & 0.474 & 0.308 & 0.298 & 0.385 & 0.393 & 0.186 \\
1.072 & 0.699 & 0.949 & 1.026 & 0.611 & 0.839 & 1 & 0.585 & 0.554 & 0.643 & 0.376 & 0.376 & 0.392 & 0.505 & 0.242 \\
0.598 & 0.352 & 0.356 & 0.533 & 0.985 & 1.99 & 1.709 & 1 & 0.791 & 0.887 & 0.345 & 0.733 & 0.981 & 1.103 & 0.505 \\
0.909 & 0.449 & 0.626 & 0.612 & 1.246 & 1.876 & 1.804 & 1.266 & 1 & 2.825 & 0.98 & 0.896 & 0.846 & 1.162 & 0.634 \\
0.732 & 0.483 & 0.584 & 0.591 & 1.168 & 2.112 & 1.554 & 1.051 & 0.352 & 1 & 0.55 & 0.711 & 0.668 & 1.21 & 0.478 \\
1.832 & 0.537 & 0.671 & 0.719 & 2.443 & 3.249 & 2.656 & 2.879 & 1.02 & 1.809 & 1 & 1.735 & 1.79 & 1.816 & 0.877 \\
1.463 & 1.003 & 0.943 & 1.412 & 1.484 & 3.361 & 2.662 & 1.365 & 1.116 & 1.407 & 0.576 & 1 & 1.895 & 2.097 & 0.58 \\
1.351 & 0.875 & 0.851 & 1.153 & 1.51 & 2.595 & 2.551 & 1.019 & 1.201 & 1.498 & 0.559 & 0.523 & 1 & 1.396 & 0.398 \\
1.231 & 0.839 & 0.739 & 0.839 & 1.37 & 2.543 & 1.979 & 0.907 & 0.949 & 0.826 & 0.551 & 0.473 & 0.716 & 1 & 0.866 \\
2.365 & 1.783 & 1.804 & 2.044 & 3.512 & 5.451 & 4.137 & 1.981 & 1.431 & 2.094 & 1.141 & 1.721 & 2.492 & 1.149 & 1
\end{bmatrix}$$

Appendix III

$$C = \begin{bmatrix}
0.048 & 0.037 & 0.043 & 0.037 & 0.034 & 0.04 & 0.034 & 0.079 & 0.069 & 0.064 & 0.045 & 0.054 & 0.047 & 0.047 & 0.052 \\
0.114 & 0.088 & 0.086 & 0.118 & 0.061 & 0.051 & 0.052 & 0.134 & 0.136 & 0.098 & 0.154 & 0.079 & 0.073 & 0.07 & 0.074 \\
0.09 & 0.082 & 0.08 & 0.086 & 0.054 & 0.047 & 0.039 & 0.062 & 0.098 & 0.081 & 0.123 & 0.084 & 0.075 & 0.079 & 0.068 \\
0.084 & 0.048 & 0.059 & 0.064 & 0.043 & 0.042 & 0.036 & 0.088 & 0.1 & 0.08 & 0.115 & 0.057 & 0.055 & 0.07 & 0.06 \\
0.073 & 0.073 & 0.076 & 0.076 & 0.051 & 0.053 & 0.06 & 0.048 & 0.049 & 0.04 & 0.034 & 0.053 & 0.042 & 0.043 & 0.035 \\
0.037 & 0.053 & 0.052 & 0.047 & 0.03 & 0.031 & 0.044 & 0.024 & 0.033 & 0.022 & 0.025 & 0.024 & 0.024 & 0.023 & 0.023 \\
0.052 & 0.062 & 0.076 & 0.066 & 0.031 & 0.026 & 0.037 & 0.027 & 0.034 & 0.03 & 0.031 & 0.03 & 0.025 & 0.03 & 0.03 \\
0.029 & 0.031 & 0.029 & 0.034 & 0.05 & 0.061 & 0.063 & 0.047 & 0.048 & 0.042 & 0.029 & 0.058 & 0.062 & 0.064 & 0.062 \\
0.044 & 0.04 & 0.05 & 0.039 & 0.063 & 0.058 & 0.066 & 0.059 & 0.061 & 0.134 & 0.081 & 0.071 & 0.054 & 0.068 & 0.078 \\
0.035 & 0.043 & 0.047 & 0.038 & 0.059 & 0.065 & 0.057 & 0.049 & 0.022 & 0.047 & 0.046 & 0.056 & 0.042 & 0.071 & 0.059 \\
0.088 & 0.047 & 0.054 & 0.046 & 0.124 & 0.1 & 0.097 & 0.135 & 0.062 & 0.085 & 0.083 & 0.138 & 0.114 & 0.106 & 0.108 \\
0.07 & 0.088 & 0.076 & 0.091 & 0.075 & 0.103 & 0.098 & 0.064 & 0.068 & 0.066 & 0.048 & 0.079 & 0.12 & 0.123 & 0.071 \\
0.065 & 0.077 & 0.068 & 0.074 & 0.077 & 0.08 & 0.094 & 0.048 & 0.074 & 0.071 & 0.046 & 0.041 & 0.063 & 0.082 & 0.049 \\
0.059 & 0.074 & 0.059 & 0.054 & 0.07 & 0.078 & 0.073 & 0.043 & 0.058 & 0.039 & 0.046 & 0.038 & 0.045 & 0.058 & 0.107 \\
0.114 & 0.157 & 0.145 & 0.131 & 0.179 & 0.167 & 0.152 & 0.093 & 0.088 & 0.099 & 0.094 & 0.137 & 0.158 & 0.067 & 0.123
\end{bmatrix}$$

Appendix IV

Table A2. Weight values of SWOT factor groups for A'WOT Analysis

SWOT Group	Factor Group	Local Weights	Global Weights
(S)	1) Strengths over humans (including factors S1 and S2).	0.171	0.049
	2) Strengths in data processing speed and analysis capability (including factors S3, S4, and S6)	0.325	0.093
	3) Strengths related to risk measurement and situational awareness ability (including factors S5 and S8)	0.269	0.077
	4) Strengths of software advantages (including factors S7, S9, and S10)	0.234	0.067
(W)	1) Weaknesses relative to the human (including factors W1 and W2)	0.429	0.054
	2) Technical and software weaknesses (including factor W3)	0.262	0.033
	3) Weaknesses due to lack of experience (including factors W4 and W5)	0.310	0.039
(O)	1) Opportunities to reduce cost (including factors O3 & O4)	0.186	0.047
	2) Opportunities related to technological and environmental factors (including factors O1, O2, and O8)	0.253	0.064
	3) Opportunities for the diversity of applications, and increased interest (including factors O6 and O7)	0.194	0.049
	4) Opportunities related to safety and security (including factor O5)	0.368	0.093
(T)	1) Threats of negative reactions and prejudice (including factors T1 and T2)	0.246	0.083
	2) Threats related to lack of legal status (including factor T4)	0.199	0.067
	3) Threats related to workforce and labor issues (including factors T3 and T7)	0.178	0.060
	4) Threats related to unknown issues, security, and risks (including factors T5, T6, and T8)	0.377	0.127

Reviewer List of Volume 9 Issue 2 (2023)

Denizcan KOLUKISA	Sabancı University	Turkey
Ebru YILMAZ	Ordu University	Turkey
Emin Deniz ÖZKAN	Dokuz Eylül University	Turkey
Emre KAHRAMANOĞLU	İzmir Katip Çelebi University	Turkey
Erhan AKSU	Karadeniz Technical University	Turkey
Hasan Batuhan Emre ÖZDOĞAN	Isparta University of Applied Sciences	Turkey
Ömer ARSLAN	Dokuz Eylül University	Turkey
Özkan UĞURLU	Ordu University	Turkey
Refik ÖZYURT	Ordu University	Turkey
Selahattin Alp ERKURTULMUŞ	Yalova University	Turkey
Serdar YILDIZ	World Maritime University	Sweden
Süleyman ÖZDEMİR	Sinop University	Turkey
Uğur KARADURMUŞ	Bandırma On Yedi Eylül University	Turkey

Volume: 9 Issue: 2 is indexed by