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TURKISH NAVAL ACADEMY
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MİLLİ SAVUNMA ÜNİVERSİTESİ
DENİZ HARP OKULU DEKANLIĞI
DENİZ BİLİMLERİ VE MÜHENDİSLİĞİ DERGİSİ

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Owner on Behalf of the Turkish Naval Academy
Deniz Harp Okulu Dekanlığı Adına Sahibi ve Sorumlusu
Prof. Dr. Cemalettin ŞAHİN

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Deniz Bilimleri ve Mühendisliği Dergisi (DBMD); uluslararası düzeyde, hakemli, çok disiplinli, 2003 yılından bu yana yılda iki kez yayımlanan (Haziran ve Aralık), bilim ve teknoloji dergisidir. Dergide; **Bilgisayar, Makine, Gemi İnşa, Elektrik/Elektronik, Endüstri Mühendisliği** ile **Temel/Sosyal Bilimler** alanlarında bilimsel nitelikli araştırma makaleleri, derlemeler, teknik notlar, kitap incelemeleri, editöre mektuplar ile konferans ve toplantıların genişletilmiş raporlarına yer verilmektedir. Dergi, deniz bilimleri ve mühendisliğinin teori ve uygulamalarına bilimsel katkı sağlamayı ve ilgili alanlarda bilgi paylaşımını amaçlamaktadır. Dergide yer alan makaleler İngilizce olarak yayımlanmaktadır.

Açık erişimli yayın politikası izleyen Deniz Bilimleri ve Mühendisliği Dergisi değişik bilimsel bakış açılarını okuyucularına sunmaktadır. Dergide yayınlanan makalelerin bilim, içerik ve dil bakımından sorumluluğu yazarlarına aittir. Doğrudan veya dolaylı olarak ifade edilen görüşler Deniz Harp Okulu’nun resmi görüşleri olarak görülmemelidir.

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EDITORIAL

FOREWORD

We are pleased to present the June 2024 issue of the Journal of Naval Sciences and Engineering (JNSE). This issue continues our commitment to advancing the theory and applications of naval sciences and engineering, covering a wide range of topics including Electrical and Electronics Engineering, Mechanical/Naval Engineering, Naval Architecture and Marine Engineering, Computer Science and Engineering, and Industrial Engineering/Operations Research.

In this issue, we feature a study on the design prioritization for semi-submersible naval ships, which highlights the operational and functional priorities determined through a Fast-Decision survey. Another paper evaluates the performance and economic feasibility of wave energy generation in the Black Sea, offering insights into renewable energy solutions for maritime applications. We also present a reliability evaluation of the deck machinery and galley equipment of bulk carriers, emphasizing the importance of proactive maintenance strategies. Additionally, a study on scheduling problems for Navy helicopter pilots proposes innovative solutions to optimize workload management and enhance operational efficiency.

We extend our gratitude to the authors for their valuable contributions and to our reviewers for their rigorous evaluations, which help maintain the high standards of JNSE. Since the second issue of 2022, we have been providing DOIs within 10 days after a paper is accepted and the page layout is completed, ensuring timely and accessible dissemination of research.

We look forward to continuing to share important research with our community and thank you for your continued support.

Fatih ERDEN, Ph.D.
Editor-in-Chief

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Naval Architecture and Marine Engineering/Gemi İnşaatı ve Gemi Makineleri Mühendisliği

RESEARCH ARTICLE

**An ethical committee approval and/or legal/special permission has not been required within the scope of this study.*

DESIGN PRIORITIZATION STUDY FOR A SEMI-SUBMERSIBLE NAVAL SHIP BASED ON FAST DECISION METHOD

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ABSTRACT

Recently, number of countries included various types of special operations crafts to their navies. One type of these crafts is called semi-submersible naval ship, which utilizes superior properties of a submarine and a surface ship. This paper presents general characteristic design features of these type of ships. Additionally, a design prioritization study based on a Fast-Decision survey was carried to determine the importance of different design features of such ships. Survey participants were chosen from experienced naval officers who served the–Navy. The responses are analyzed and presented with bar charts which shows the order of importance of the different design parameters. Results reveals that the most important operational tasks for a semi-submersible naval ship are naval special operations capability and ability to infiltrate, dodge and operate in hostile waters while the most important functional features are high maneuverability in surface operations and low acoustic detectability in underwater operations. In addition, it appears that the size of the control room and engine room is more important than the ship's ability to be transported by another vehicle. The authors are intended to make conceptual designs for semi-submersible naval ships and investigate their hydrodynamic features in future studies.

Keywords: *Semi-Submersible Naval Ship, Design Prioritization, Fast Decision Method*

YARI DALGIÇ ASKERİ GEMİLER İÇİN HIZLI KARAR ALMA METONUNA DAYALI TASARIM ÖNCELİKLENDİRME ÇALIŞMASI

ÖZ

Son yıllarda pek çok ülke donanmalarına çeşitli türlerde özel harekât gemileri eklemektedir. Bu gemilerin türü hem bir denizaltının hem de bir yüzey gemisinin üstün özelliklerini birleştirmektedir ve yarı dalgıç askeri gemiler olarak adlandırılmaktadır. Bu makale yarı dalgıç askeri gemilerin genel karakteristik tasarım özelliklerini açıklamaktadır. Ayrıca, farklı tasarım özelliklerinin ne ölçüde önemli olduğunu belirlemek amacıyla, hızlı karar alma anket araştırmasına dayanan bir tasarım önceliklendirme çalışması da yürütülmüştür. Anket çalışmasının katılımcıları Türk Donanmasında görev yapan tecrübe sahibi deniz subayları arasından seçilmiştir. Yanıtlar incelenmiş ve farklı tasarım unsurlarının önem sırasını gösteren çubuk grafikler halinde sunulmuştur. Sonuçlar bir yarı dalgıç askeri gemi için en önemli operasyonel görevlerin deniz özel harekât yeteneği ile sızma, sıyrılma ve düşman sularda operasyon yeteneği olduğunu, en önemli işlevsel özelliklerinin ise yüzey operasyonlarında yüksek manevra kabiliyeti ve su altı operasyonlarında düşük akustik iz olduğunu ortaya koymaktadır. Buna ek olarak, kumanda odası ve makine dairesi genişliğinin geminin bir başka araçla taşınabilmesine kıyasla daha önemli olduğu anlaşılmaktadır. Yazarlar gelecekteki çalışmalarında yarı dalgıç askeri gemiler için kavramsal tasarımlar yapmayı ve bu gemilerin hidrodinamik özelliklerini incelemeyi amaçlamaktadır.

Anahtar Kelimeler: *Yarı dalgıç askeri gemiler, Tasarım Önceliklendirmesi, Hızlı Karar Alma Metodu.*

1. INTRODUCTION

It is estimated that the first maritime activities date back to 4000 BC while the idea of an underwater ship dates back to the 16th century (Bevan, 1999; Davis, 1995). The underwater technology has utmost importance in the defense industry. This is understandable considering that most of the world's surface is covered by oceans and the ocean depth in open water reaches thousands of meters. Underwater ships have several advantages over surface ships which can be briefly listed as follows:

a) Most surface platforms are outfitted with limited underwater detection sensor suits and have limited engagement capabilities underwater.

b) Many long-range effective weapons on surface ships are absolute against underwater targets.

c) Satellite detection is not effective underwater.

d) Craft with underwater operational capabilities are combat effective due to their stealth features and are more flexible and have a wider operating area.

These advantages have led to the effective use of submarines since World War I. In recent years, countries have begun to procure more versatile special-operation ships in their navies in addition to the submarines. These ships can perform various multi-objective tasks and one of these special-operation ship types is called semi-submersible naval ships.

A semi-submersible naval ship is a special purpose warship that can operate both underwater and surface by utilizing the advantageous features of a submarine and of a surface ship. With water ballast operation, they can minimize their radar cross-sectional area so that they can perform some special-purpose military missions by infiltrating hostile waters.

Today number of countries have semi-submersible ships in their navies. It is understood that, on the other hand, academic research in the open literature on such ships is rather limited since, as with all naval ships, information about such ships is confidential.

Semi-submersible vessels have the superior features of both surface-operated and subsea-operated vessels. These ships, which are mostly under 25 meters in size, can reach speeds of up to 50 knots on the surface, just like a fast transport boat, and have high maneuverability. Their most distinctive feature under water is that they can operate undetected by sailing at low speed with electric propulsion. In this sense, semi-submersible military infiltration ships can be considered as fast transport boats with diving capabilities.

There are various difficulties in the design and production of semi-submersible ships because they have the superior features of both a surface ship and a submarine. Since they are mostly both diesel-driven and electric driven, they have two separate propulsion systems. Particularly when sailing on surface, ships are required to have high speed and maneuverability, and this requires providing sufficient space for two different propulsion system during the design phase. This requires increasing the beam of the ship or block coefficient of the hull. Both solutions result in an increase in hull resistance and therefore power requirement. For this reason, it is of great importance to attain a fulfilling general arrangement and hull form in the early stages of the design.

The aim of this study is to provide practical and convenient information on the design features and design constraints of the semi-submersible naval ships.

2. LITERATURE REVIEW

Semi-submersible naval ships are classified under special operations crafts combining the features of submarines and some features of surface ships. Countries including USA, Russia, North Korea and Italia developed various submersible and semi-submersible designs.

The first example of a true semi-submersible, named KETA, was built in Russian Empire in 1904 as a torpedo boat with a length of 7 meters and powered by a 10-kW motor (Rassol, 2005). Boat had a twin hull construction; lower part was for water ballast while the operator was located at the upper part. KETA was able to dive and operate under sea at 8 meters depth for only 3-5 minutes. Starting from 1970s, North Korea produced several semi-submersible ships to run agents to the South Korea which are derived from fast speed fishing boats. One of the newest class of these ships is called TAEDONG-B whose characteristics are given in Table 1 (Sutton, 2015a).

Table 1. *Main Characteristics of Taedong-B (Sutton, 2015a).*

Lenght	17 m
Beam	3,3 m
Height	3,5 m
Displacement	22 ton
Maximum speed at surface	40 knots
Dalmış halde maksimum hız	3 knots
Operating Depth	3 m
Power Plants	2 diesel engines and 2 electric motors

Taedong-B has a striking design having two electric-motor operated propellers each side of the hull in addition to the two-diesel engine operated aft propellers. Buoyancy is controlled by water ballast operations a diving angle is determined by two fins located on either side of the hull. Ship is also equipped with two torpedo tubes for defense purposes. Fig. 1 shows the profile view of Taedong-B.

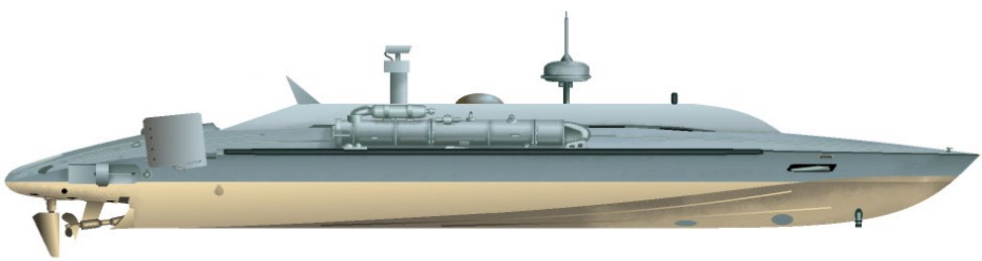

Figure 1. *Profile View of Taedong-B (Sutton, 2015a).*

SEALION (Fig. 2), a 24 m long semi-submersible ship with a planning hull, was introduced by USA Navy Forces in 2014 (Sutton, 2017). The craft was classified as combatant craft heavy and is powered by two 1100 kW diesel engines by which over 30 knots speed is attained. Crew compartment, suitable for seven crew, is located at fore part while diesel engines and gen-sets are set about amidships and propulsion and maneuvering are achieved by two waterjets at the stern.

Figure 2. *SEALION II Combatant Craft Heavy (Sutton, 2017).*

An important example, COMBUSIN's semi-submersible (Fig. 3), which is part of the Italian Navy, was designed specifically for counter-terrorism, commando and sabotage operations and first entered service in the 1970s. All technical specifications about the ship are kept as a military secret; however, it has been observed that the ship, which resembles a powerful motorboat, is at least 13 meters long and can reach a speed of over 30 knots (Sutton, 2015b).

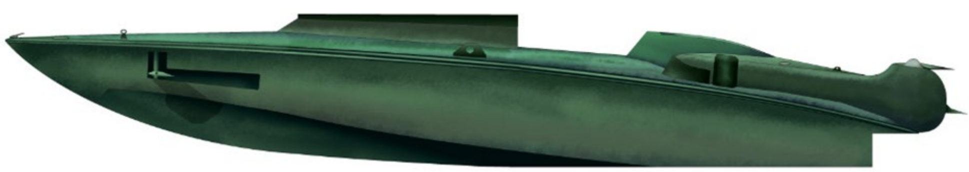

Figure 3. *COMBUSIN's Semi-submersible Boat (Sutton, 2015b).*

Another Italian submersible, which is specially designed for fast swimmer delivery, is Cos.Mo.S 'Nessie' and its details were shared by expert Lino Mancini (Sutton, 2016). This vehicle, designed for transporting 6 soldiers, had an arrow like bow form and equipped with two 500 HP diesel engines. Diesel engines were used for surface operations while the ship is equipped with additional electric motor for under water operations. Detailed plans of Cos.Mo.S 'Nessie' are shown in Fig. 4.

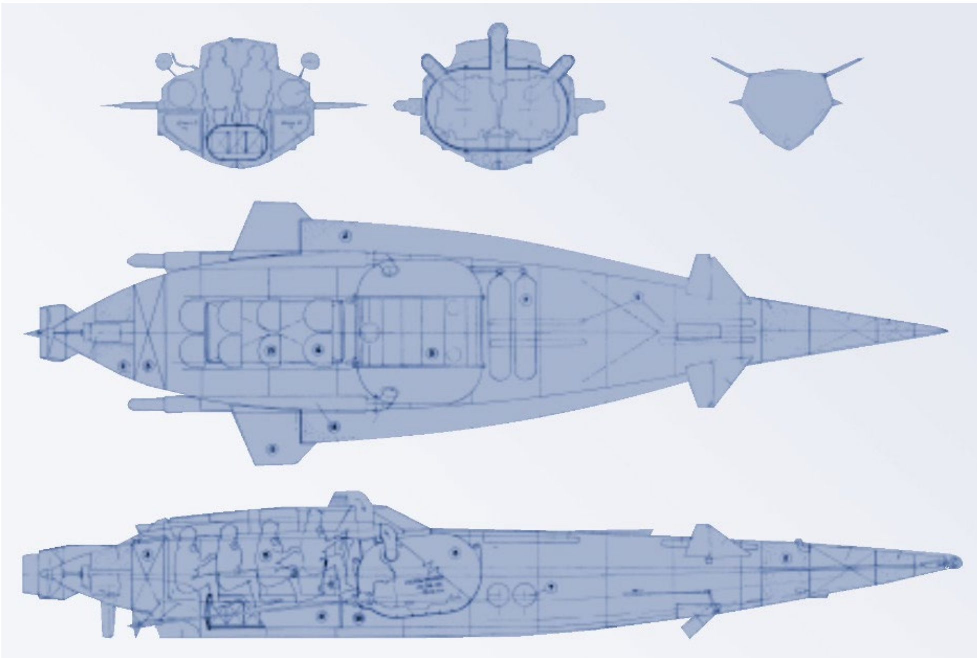

Figure 4. *Plans of the Swimmer Delivery Vehicle Cos.Mo.S 'Nessie' (Sutton, 2016).*

3. METHODOLOGY

To achieve a successful and versatile design, it is essential to avoid considering single design parameter independently since most of the times these parameters shares interacting features and losing control of the interactions of different design parameters may result in a poor outcome (Joubert, 2004). According to Burcher and Rydill (1995) all design parameters should be considered like pieces of a puzzle where any changes in a piece requires some adjustments to the other pieces. Papanikolaou (2014) considered a ship as a system, which is composed of smaller subsystems, and suggested that a ship design should be considered as a complex optimization problem where all the functional objectives and interactions of the components should be kept in view. As a result, a naval architect should look at the whole picture when designing a semi-submersible ship and make a comprehensive prioritization in design parameters while determining all limitations to reach desired outcome.

3.1. General Features of a Semi-Submersible Naval Ship

In the last century, radar, sonar, etc. technological developments in remote sensing systems have pushed countries to add submersible and semi-submersible ships to their navies. Although semi-submersible boats are not large warships, they provide advantages especially in operations such as intelligence gathering, reconnaissance and surveillance due to their ability to hide from systems such as radar and sonar. Operational tasks of a semi-submersible naval ship can be listed as follow:

a) Intelligence, surveillance and reconnaissance,

b) Ability to infiltrate, dodge, operate in hostile waters

c) Electronic and acoustic warfare,

d) Fast Seal Delivery,

e) Naval special operations,

f) Support in amphibious operations,

g) Counterterrorism,

h) Asymmetric warfare.

In that respect, following functional features should be sustained:

a) Ability to achieve high service speed in surface operations,

b) Ability to shallow dive for under water operations,

c) Low radar and sonar detectability,

d) High maneuverability, especially in surface operations.

The main purpose of this study is to prioritize these functional features and operational tasks which directly affect the design of the ship. To do that a fast decision questionnaire is prepared and experienced naval officers serving in the Turkish Naval Forces were asked to answer the survey questions.

3.1. Fast Decision Method

The fast decision (FD) method is used to make an optimum decision among many given alternatives swiftly. The FD method is a quasi-multi-criteria decision analysis that has been considered a significant method due to its mathematical properties of methods applicable to solve judgment problems. The appropriate data have been derived by using comparisons in which the decision-maker considered one alternative at a time, while looking and considering the whole picture. These comparisons were used to obtain the weights of importance of the decision criteria, and the relative performance measures of the alternatives. The FD method gives the suitable decision that best suits the goals and evaluates alternative solutions. The main advantage of the FD method is, unlike some other decision-making methods, the judgements are very strict, and the decision-maker sees the whole picture at once. Additionally, FD method is ranking choices in the order of their effectiveness. For these reasons, FD method is used to rank functional and operational parameters which affects the design of a semi-submersible ship.

The mathematics of the FD method is presented. The alternatives or the parameters are given by $\{Q_1, Q_2, \ldots, Q_m\}$ and parameter coefficients (or weights) by $\{a_1, a_2, \ldots, a_m\}$, where m is the number of compared alternatives (or the parameters). The parameter coefficients (or weights) can be given in the following form:

Parameter coefficients, a_i can be defined as:

$$a_i = \frac{1}{n} \cdot \frac{\sum_{k=1}^{n} Q_{ki}}{\sum_{r=1}^{m} Q_{ir}}, \quad i = 1,2, \ldots, m \tag{1}$$

where m is the number of parameters, n is the number of survey participants, Q_{ki} is the answer of the survey participant number k, to the question number i.

Once the parameters of the decision-making process are determined, the coefficients, which determines the importance of these parameters in the total decision-making function, can be quickly determined using FD methods. The salient points to consider here are as follows:

a) The parameters and coefficients should be included on a single page. In this way, the participants filling out the survey can see all the parameters that make up the decision-making in a single view. In this way, they can also see the other parameters while evaluating a single parameter.

b) In fact, this decision-making method is a generalization of the process in which the experts of a subject make the appropriate choice among the alternatives by self-intuition.

c) The simplicity of the scaling to be used to determine the importance of the parameters makes the work of the participant who will make the evaluation easier. There are no standard scales on this method, but the following scales (Table 2) or similar can be used:

Table 2. *The scale for the judgments used in Fast Decision Method*

Scale	Scale	Judgments
1	1	Zero important
2		Very slight important
3	2	Slight important
4		Between slight and moderate important
5	3	Moderate important
6		Between strong and moderate important
7	4	Strong important
8		Between strong and extreme important
9		Extreme important
10	5	Utmost important

4. RESULTS AND DISCUSSION

Thirty-eight naval officers with 5 – 10 years of experience in the service who serve for Turkish Navy were asked to evaluate twenty different design parameters with an FD survey. All the respondents were male and residing in Marmara region. The main advantage of the method is that the participants can see all parameters easily which enables them to consider all parameters as a whole rather than focusing each parameter one by one. As a result, a complete and comprehensive prioritization of the parameters can be attained.

Fig. 5 shows calculated parameter coefficients (PC) for different design features of a semi-submersible naval ship. Due to the formulation of the FD method, total score of the PCs equals to one, thus, graph is limited to 0.06. The figure shows that a semi-submersible should include large number of functional features; there is only a small difference between the parameter coefficients of high maneuverability in surface operations, which has the highest score (PC = 0.0588), and low visual detectability in under water operations, which has the 13th highest score (PC = 0.0569). Additionally, it can be deduced from the figure that it is of utmost importance for a semi-submersible naval ship to include following features:

a) High maneuverability in surface operations,

b) Naval special operations capability,

c) Ability to infiltrate, dodge, operate in hostile waters

while ability to be transported by another vehicle and low acoustic detectability in surface operations are less important to be included. Both largeness of the engine room and operating room have relatively less PC, which might be a facilitating factor to provide space for electrical and acoustic equipment. On the other hand, that the ship should sustain both high maneuverability and speed in surface operations while having low acoustic detectability in under water operations forms a difficulty since these require both the usage of high-power diesel engines in surface operations while electric propulsion in under water operations.

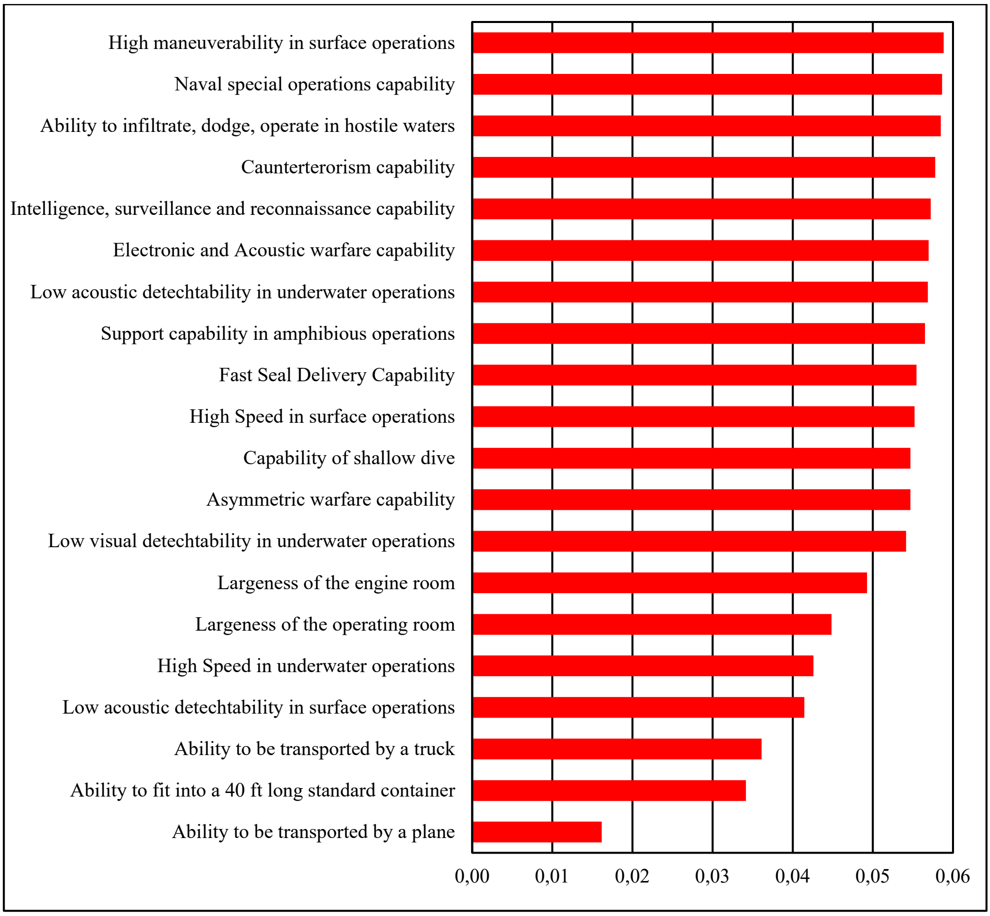

Figure 5. *Parameter Coefficients (PCs) for Different Design Parameters.*

It should be kept in mind that these parameters have implicit interrelations which means a change in any design feature might directly or indirectly affect all these parameters. Having a prioritization such as in Fig. 5 helps the designer to keep control of each parameter and avoid any undesired outcome to occur. It is also possible to group these parameters based on which feature or features of the ship they are closely related. Fig. 6 compares the importance of the design parameters which are closely related to the operational tasks of the ship. It can be deduced from the figure that Naval special operations capability is more important than the other tasks while asymmetric warfare capability is less important than all the other parameters. It should be noted however, all parameters related to the operational tasks have close parameter coefficients.

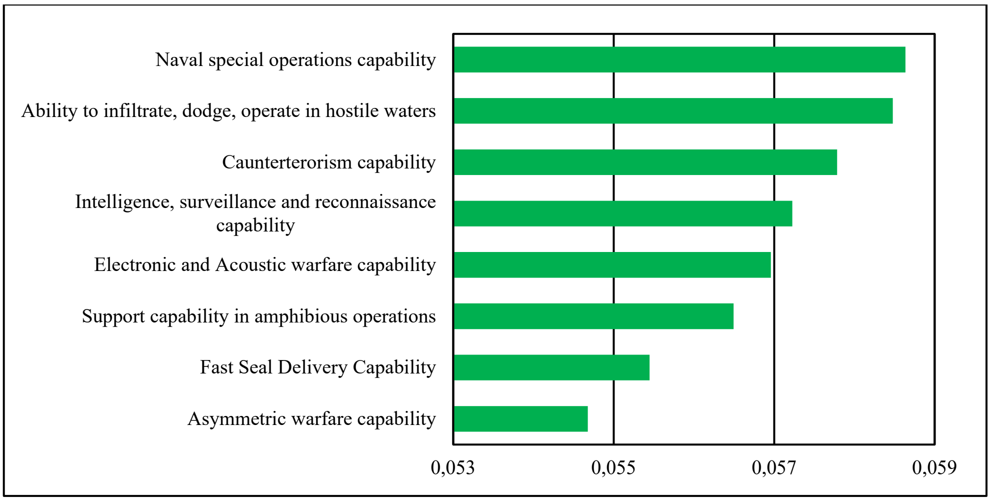

Figure 6. *Parameter Coefficients for Design Parameters Related to Operational Tasks.*

Fig. 7 compares the importance of the design parameters, which are closely related to the functional features of the ship. According to the results, high maneuverability in surface operations has the highest importance while high speed in underwater operations has the lowest importance, which is reasonable since low acoustic detectability is more important than the speed in under water operations.

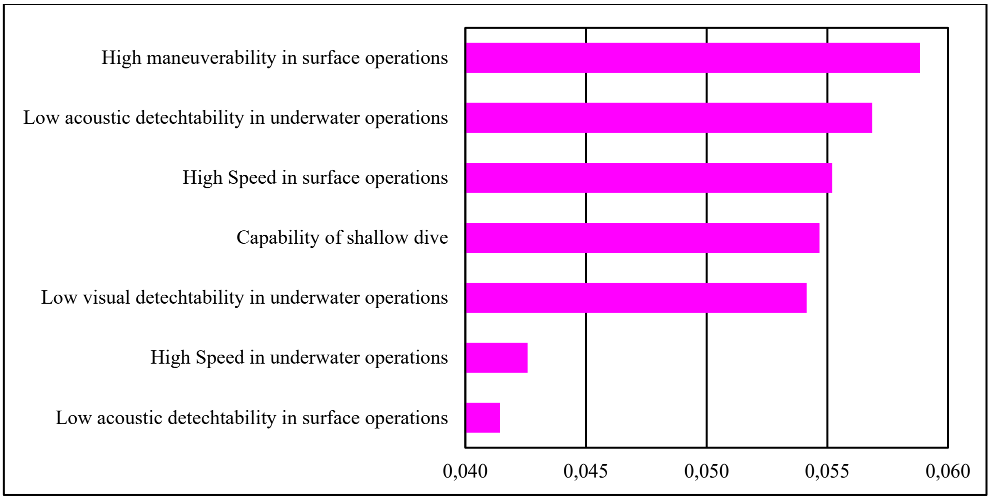

***Figure** 7. Parameter Coefficients for Design Parameters Related to Functional Features.*

5. CONCLUSION

This paper presents general features of semi-submersible naval ships and investigates which operational and functional features are important to include when designing them. Design features are prioritized by analyzing the results of a questionnaire appropriate for the FD method. Thirty-seven naval officers were surveyed. The purpose of this survey is to provide practical and convenient information on the design features and design constraints of a special type of naval ships.

A semi-submersible naval ship is a special type of warship, which can be considered as a hybrid ship which operates both on surface and under water. These ships have been used by countries since the beginning of the 20th century for several operations such as sabotage, intelligence gathering and seal delivery.

Designing a semi-submersible naval ship has several difficulties since the ship should include functional and operational features of both a surface ship and a submarine. It is observed that both high maneuvering capabilities and achieving high service speed in surface operations are essential for these ships while low observability and infiltration capabilities are profoundly important to include. One possible solution to these requirements would be including two water jets for high maneuverability and two high-powered diesel engines for high speed while additional electrical propulsion units for acoustic performance in underwater operations. Additionally, shallow diving can be achieved by a suitable water ballast system while diving angle can be controlled by additional fins located at either side of the shell.

An engineer should consider all requirements and restrictions as a whole while designing a product. It is useful at first stage to carry out a prioritization study to gain better understanding of the problem while seeing all design parameters in one graph. Results of this study can be used as a starting point of conceptual design of a semi-submersible. Authors are intended to make conceptual design of a semi-submersible naval ship and investigate its hydrodynamic performance in both surface and underwater operations.

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The authors declare no conflict of interest.

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APPENDIX

Table: Expert Questionnaire for Design Parameters

	Importance				
Design Parameter	**1**	**2**	**3**	**4**	**5**
Intelligence, surveillance and reconnaissance capability					
Ability to infiltrate, dodge, operate in hostile waters					
Electronic and Acoustic warfare capability					
Fast Seal Delivery Capability					
Naval special operations capability					
Support capability in amphibious operations					
Counterterrorism capability					
Asymmetric warfare capability					
High Speed in surface operations					
Capability of shallow dive					
High manoeuvrability in surface operations					

	Importance				
Design Parameters	**1**	**2**	**3**	**4**	**5**
High Speed in underwater operations					
Low acoustic detectability in underwater operations					
Low visual detectability in underwater operations					
Low acoustic detectability in surface operations					
Ability to be transported by a truck					
Ability to be transported by a plane					
Ability to fit into a 40 ft. long standard container					
Largeness of the operating room					
Largeness of the engine room					

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RESEARCH ARTICLE

**An ethical committee approval and/or legal/special permission has not been required within the scope of this study.*

AN EVALUATION OF WAVE ENERGY GENERATION AND COST OF ENERGY IN THE BLACK SEA

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ABSTRACT

The performance of several axisymmetric wave energy converters is studied by evaluating the yearly energy capture and the expense of energy in two sites in the Black Sea. The added mass, hydrodynamic damping, and wave forces exerted on the floats are calculated by a 3D panel method based on potential flow theory. The oscillations of the floats are calculated in the time domain by employing a family of Runge-Kutta Methods at various levels of accuracy and the yearly energy generated is calculated by taking into account the occurrence of sea states in a year. The expense of energy captured by each wave energy converter is evaluated by calculating the Levelized Cost of Energy. The results show that the WECs with Berkeley Wedge-Shaped floats generate the maximum amount of energy in Sinop and Hopa. The most economical wave energy converters are those with a cone float and with a Berkeley Wedge-Shaped float in Sinop and Hopa, respectively.

Keywords: *Wave Energy Generation, The Black Sea, Annual Energy Production, Cost Analysis*

KARADENİZ'DE DALGA ENERJİSİ ÜRETİMİ VE ENERJİ MALİYETİNİN DEĞERLENDİRİLMESİ

ÖZ

Eksenel simetrik dalga enerjisi dönüştürücülerinin Karadeniz'de iki bölgede gösterecekleri performans, yıllık enerji üretim miktarının ve enerjinin maliyetinin hesaplanmasıyla değerlendirilmiştir. Dalga enerjisi dönüştürücülerinin şamandıralarının ek su kütlesi, hidrodinamik sönüm katsayısı ve şamandıralara etki eden dalga kuvvetleri potansiyel akım teorisine dayalı 3 boyutlu bir panel yöntemi ile hesaplanmıştır. Şamandıraların yapmış olduğu salınım hareketlerinin hesabı ise farklı hassasiyet seviyelerindeki Runge-Kutta yöntemleri kullanılarak zamanın bağlısı olarak yapılmış ve yıllık enerji üretimi de bahse konu bölgelerde görülen deniz durumlarının bir yılda görülme süreleri ele alınarak yapılmıştır. Her bir dalga enerjisi dönüştürücüsü tarafından üretilen enerjinin birim maliyeti, sistemin ömrü boyunca karşılaşılacak tüm giderlerin maliyetinin göz önüne alınmasıyla hesaplanmıştır. Hesaplama sonuçları Berkeley Kama şeklindeki şamandıralara sahip dalga enerjisi dönüştürücülerinin Sinop ve Hopa'da en yüksek miktarda enerjiyi üretebileceklerini göstermektedir. Sinop ve Hopa'da en maliyet etkin dalga enerjisi dönüştürücüleri ise sırasıyla koni ve Berkeley Kama şeklinde şamandıralara sahip olan dalga enerjisi dönüştürücüleridir.

Anahtar Kelimeler: *Dalgalardan Enerji Üretimi, Karadeniz, Yıllık Enerji Üretimi, Maliyet Analizi*

1. INTRODUCTION

The necessity for generating energy for a long time without damaging the natural environment has led to the consideration of natural resources that were not adequately utilized before. The vast amount of energy contained by the waves on the surface of the oceans is a promising but challenging candidate. Many wave energy converter (WEC) designs have been proposed, some of them were even tested at sea under real conditions, but none of the devices have been successful in producing great amounts of energy economically. The efficiency of the wave energy converter arrays should be higher than that of the current level to add wave energy to the energy mix. Technological advancements in the design and control of the WECs allow them to produce energy more economically, which brings the WECs closer to commercial viability every day.

The expense of energy generation by an array of wave energy converters is a key factor for a project's economic competitiveness. Thus, the price of the unit energy must be evaluated during the design of WECs and necessary changes in the design should be applied to increase the power capture and to reduce the costs. The Levelized Cost of Energy (LCOE) is commonly considered the primary metric for assessing the economic performance of wave energy converters(Tetu & Chozas, 2021). Capital expenditures (CAPEX), operation and maintenance expenditures (OPEX), and decommissioning costs are the main elements of the total cost of an array of WECs considered in the early stages of design. The capital costs generally comprise the cost of the structure, the power take-off (PTO) system, moorings, installation, and project management. Different breakdowns of the CAPEX and OPEX are considered in various studies to calculate the costs and the LCOE of wave energy converter arrays. The cost of each element can be calculated by first estimating the cost of the material that the structure of the WEC will be manufactured and then utilizing the corresponding cost ratio of each element. The operation and maintenance costs which comprise planned and unplanned repairs and maintenance, and possibly a mid-life refit, can be estimated as a ratio of the capital costs of a project. However, a more accurate estimate would require determining factors such as whether the maintenance will be carried out on-site or by towing the devices to the shore, and the frequency of routine repair and maintenance. Finally, the decommissioning costs are also an important part of the total expenditures of a wave energy project. Predicting the cost of decommissioning at the beginning of a project may be challenging since this cost is a result of activities that will take place at the end of the life of a wave energy converter array. The devices may be dismantled and recycled as raw material or they may be left on site and sunk to the bottom of the ocean to serve as shelter for marine life. Various research is carried out to assess the economics of wave energy projects. A method to analyze the economics of wave energy generation that can also be utilized to support the investment decisions for developing wave energy converters and arrays is presented (Teillant et al., 2012). The proposed method comprises the calculation of both the energy generated by the devices and several economic indicators. Operational costs are evaluated by carrying out detailed operational scenarios. The method is tested by simulating a WEC array with 100 devices deployed near the Irish West Coast. The performance analysis of two wave energy converters is carried out by taking into account both the energy capture and the costs (O’Connor et al., 2013). The form of WECs, wave climate at different locations, and use of scaled versions of the devices are considered for comparison. The cost factors that affect the economics of wave energy are reviewed and the preliminary costs, operation and maintenance costs, and decommissioning costs are described and their reference values and ratios of total or capital costs are given (Astariz & Iglesias, 2015). Additionally, formulas to calculate levelized cost and initial cost are also presented. Finally, the performances of different wave energy converters are compared based on the levelized cost of energy and their economic competitiveness is discussed. The economic modeling of wave energy is studied by carrying out a spatial analysis of the Levelized Cost of Energy through a Geographical Information System (GIS) (Castro-Santos et al., 2015). Initial costs and operation and maintenance costs are considered and the sensitivity of the analysis is evaluated by utilizing different discount rates. Several physical restrictions are also considered and the method is tested for an oscillating water column (OWC) off the Portuguese coast. The levelized cost of wave energy is analyzed by taking different values of each cost and by considering different capacity factors and discount rates. The results are compared to those of other renewable and non-renewable energy sources, and it's concluded that wave energy is more expensive than all others since it is still an immature technology. The influence of variable operation and maintenance costs, learning curve, and externalities are also considered by carrying out a sensitivity analysis (Astariz & Iglesias, 2016). The levelized cost of energy of different wave energy converters is evaluated for different locations and cost reduction methods are studied to achieve economic competitiveness by reaching a target price (Chang et al., 2018). The feasibility of deploying wave energy farms off the coast of Portugal is studied by taking into account the geographical features such as wave climate, distances between the wave energy farm and shore facilities, the bathymetry of the ocean sites, the energy capture performance of the wave energy farm, the cost of energy, and the restrictions that could affect the wave energy projects. The amount of energy captured and economic performance of the three WECs are evaluated and the best area to install wave energy converter arrays is determined (Castro-Santos et al., 2018). The expense of wave energy is generally calculated by estimating the cost of one component of a WEC and then utilizing a cost breakdown for the other components of the device. As a result, the accuracy of this approach depends on the available cost data. An alternative method is proposed by (Giglio et al., 2023) that the cost of energy is calculated by breaking the system into its all components and by estimating the cost of each component. This method is expected to reduce the uncertainties in the cost estimations. Detailed equations are given to calculate the cost of each component and a cost analysis is carried out for a WEC and the results are compared to other methods.

The performances of axisymmetric wave energy converters with several different float shapes and masses are evaluated by studying the energy captured in a year and the Levelized Cost of Energy in two sites in the Black Sea in this study. The combination of a large number of floats and power take-off system parameters resulted in many candidate WEC designs. First, the energy capture of each WEC design is calculated by considering all the sea states occurring in the considered sites. Then, the highest annual energy absorption achieved in two locations by all the floats considered is evaluated. Finally, the cost of energy is calculated by taking into account the CAPEX, OPEX, the decommissioning costs, and the annual energy produced.

This paper has four sections including the 'Introduction' section. The second section describes the methods that are utilized to compute the hydrodynamic parameters of the floats, the wave excitation forces, the motions of the floats, the energy captured by the WECs, and the cost of energy. The energy captured by the WECs in two locations along with a cost analysis are presented in the third section. The final section concludes the results of this study.

2. THE COMPUTATIONAL METHOD

The problem associated with wind-generated surface gravity waves is presented briefly as the following. The velocity potential of the uni-directional waves that propagate in the free surface of infinitely deep water is evaluated by satisfying the continuity equation, the linear free surface boundary condition, and the bottom boundary condition given in Eqs. (1)-(3), respectively, and thus, the potential function of the waves can be obtained in the complex form as given in Eq.(4) (Newman, 1989).

$$\nabla^2 \emptyset = 0 \tag{1}$$

$$\frac{\partial^2 \emptyset}{\partial t^2} + g\frac{\partial \emptyset}{\partial z} = 0, on\ z = 0 \tag{2}$$

$$\lim_{z \to -\infty} \frac{\partial \emptyset}{\partial z} \to 0 \tag{3}$$

$$\emptyset_I = \Re\left[\frac{igA}{\omega} e^{kz} e^{-i(kx-\omega t)}\right] \tag{4}$$

The wave excitation forces acting on the float of a WEC can be written as the sum of forces under the Froude-Krylov hypothesis and forces taking into account diffraction effects as given in Eq.(5), where m_i is the generalized unit normal vector as given in Eq. (6). The diffraction potential can be obtained by satisfying the body boundary condition as given in Eq.(7).

$$F_i = -\rho \iint_{S_B} \frac{\partial(\emptyset_I + \emptyset_D)}{\partial t} m_i dS, i = 1,2,\dots,6 \tag{5}$$

$$m_i = \begin{cases} n_i, i = 1,2,3 \\ (r \times n)_{i-3}, i = 4,5,6 \end{cases} \tag{6}$$

$$\frac{\partial \emptyset_I}{\partial n} = \frac{-\partial \emptyset_D}{\partial n}, on\ S_B \tag{7}$$

The motions of a body in the free surface of the water generate waves that radiate outwards. The hydrodynamic force exerted on a body due to its oscillatory motions can be calculated by solving the radiation problem. The radiation problem is evaluated by employing a 3D panel method based on discretizing the body surface into triangular elements and distributing pulsating sources over these surface elements, whose potential function is given in Eq.(8) (Wehausen & Laitone, 2002). The wave excitation forces and radiation forces are calculated by utilizing in-house computer programs developed by employing MATLAB and Fortran software.

$$\emptyset = \frac{-\sigma}{4\pi}\left[\frac{1}{r} + \frac{1}{r'} + 2\nu PV \int_0^\infty \frac{e^{k(z+c)} J_0(kR)}{k-\nu} dk + i2\pi\nu e^{\nu(z+c)} J_0(\nu R)\right] \tag{8}$$

The hydrodynamic force exerted on the body by the surrounding fluid can be calculated as given in Eq.(9). The body surface and the inner water plane area are discretized into a sufficient number of panels such that the numerical results converged and the irregular frequencies are suppressed. Additionally, the source strength on each panel is assumed constant throughout the calculations. The details of the evaluation of the potentials of the body motions ($\emptyset_j$) can be found in (Erselcan & Kükner, 2017) and (Erselcan & Kükner, 2020).

$$F_{ij}{}^{Rad} = -\rho \iint_{S_B} \left(\frac{\partial \emptyset_j}{\partial t}\right) \zeta_j m_i dS, i,j = 1,2,\dots,6 \tag{9}$$

The added mass can be obtained by dividing the real part of the force calculated by Eq.(9) when the amplitude of the motions is unitary by the square of angular frequency (ω^2) and the hydrodynamic damping can be computed by dividing the imaginary part by ($-\omega$).

The heave displacement of the float of an axisymmetric WEC is computed by solving the equation given in Eq.(10) in the time domain (Bruzzone & Grasso, 2007). This equation is solved by employing 4th order Runge-Kutta method and a family of Runge-Kutta-Nyström methods with 5th, 6th, and 7th orders of accuracy (Fehlberg, 1974). The evaluation of the equation is carried out by employing different time steps and random wave phase angles and the results obtained by each method are compared to each other and the differences between them are presented in detail (Erselcan & Kükner, 2020).

$$(M + A_{33}{}^{\infty})\ddot{x}_3(t) + \rho g S x_3(t) + \int_{-\infty}^{t} h_{33}(t-\tau)\ddot{x}_3(t)d\tau = F_3{}^{FK}(t) + F_3{}^{D}(t) + F_{PTO}(t) \tag{10}$$

The energy captured by the WECs in a year (AEP) is computed by taking the sea states occurring off the coasts of Sinop and Hopa into account. A total of five sea states at each location, one of which is a fully developed sea state while the others are developing sea states are considered in this study. The spectral functions, the mean values of the parameters corresponding to each sea state, and the occurrence rates of these sea states are given in (Yılmaz, 2007) and (Yılmaz & Özhan, 2014). The energy captured by each WEC in a given sea state is calculated by integrating the instantaneous power over time as given in Eq.(11) and the AEP is the sum of the total energy captured in all sea states occurring during a year as given in Eq.(12),

$$E = \int_0^T P(t)dt \tag{11}$$

$$AEP = \sum_{i=1}^{N_{SS}} E_{i,1H} C_i \tag{12}$$

where $E_{i,\,1H}$ is the average energy captured by a WEC in 1 hour in a given sea state, Ci is the total hours that a sea state occurs in a year, and N_{SS} represents the number of sea states occurring in the considered sites.

The wave energy converters analyzed in this study are considered to have a hydraulic power take-off system. The power take-off system comprises a double-acting hydraulic cylinder, a group of check valves, high and low-pressure hydraulic accumulators, a flow control valve, and a hydraulic motor that runs a generator. The hydraulic cylinder is rigidly connected to the float and it pumps the hydraulic fluid by the heave motion of the float. The hydraulic fluid is first pumped into the high-pressure (HP) accumulator. The high-pressure accumulator is discharged after it is fully charged. A flow control valve regulates the flow of the fluid, such that the HP accumulator is discharged at a constant flow rate. The flow of hydraulic fluid and the pressure differential between the accumulators runs the motor and the electric generator generates electricity. A detailed schematic of the power take-off (PTO) system is shown in Figure 1 and the modeling of the PTO system can be found in (Erselcan & Kükner, 2017) and (Erselcan & Kükner, 2020).

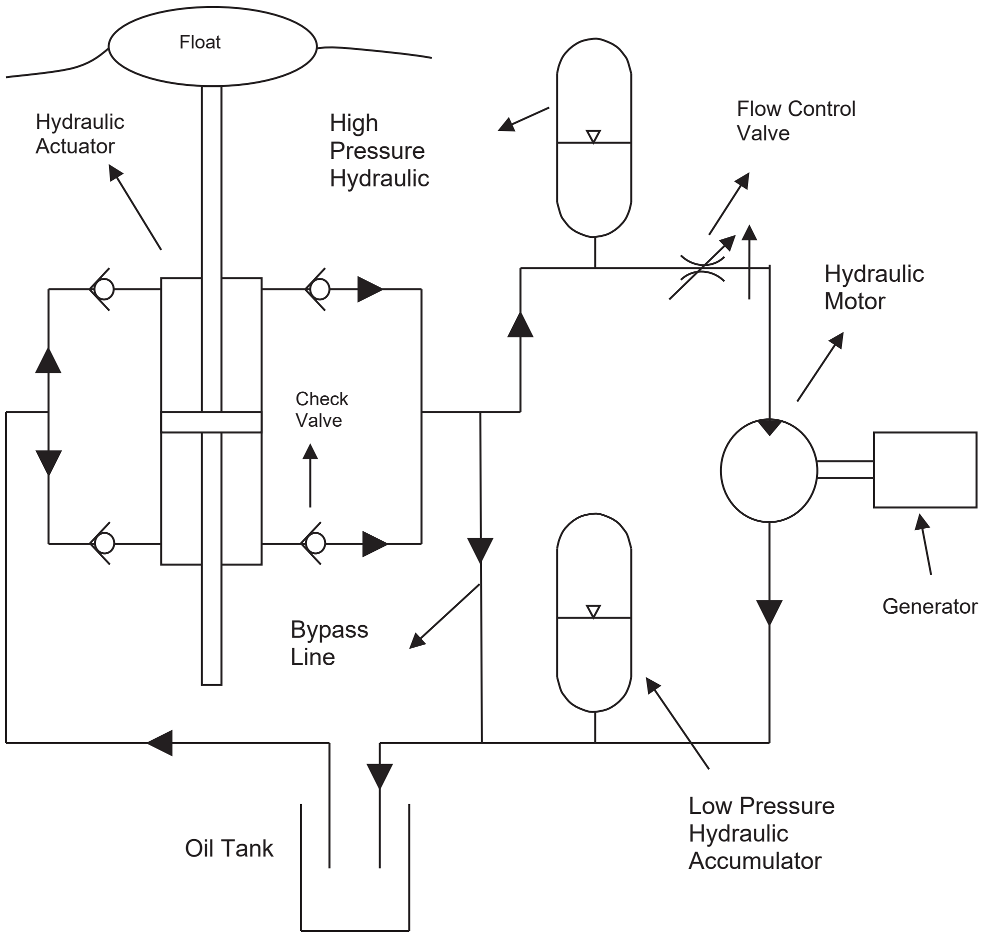

Figure 1. Hydraulic Power Take-Off (PTO) System.

The expense of the energy is evaluated by calculating the Levelized Cost of Energy (LCOE) of each WEC. The LCOE is computed by evaluating Eq.(13) as given in (SI Ocean, 2013).

$$LCOE = \frac{SCI + SLD}{87.6 \cdot LF} \cdot \frac{r \cdot (1+r)^n}{(1+r)^n - 1} + \frac{OM}{87.6 \cdot LF} \quad (13)$$

The capital costs (SCI), the decommissioning costs (SLD), the discount rate (r), the lifetime of the array (n), and the yearly operating and maintenance costs are considered to evaluate the LCOE of a wave energy converter array. The capital costs mainly comprise the cost of the project, the costs of manufacturing the devices, foundations, and moorings, the cost of installation, and the cost of decommissioning. The operating costs are comprised of the costs of operation, maintenance, insurance, and transmission charges. The calculation of capital costs depends on calculating the cost of material used to manufacture the devices. Thus, the amount of material used to manufacture the components of a WEC such as the float, mooring lines, and the body of the device should be estimated. Several cost breakdowns of wave energy converters as a ratio of either capital cost or the total costs are shown in Table 1 and are given in (Bosserelle et al., 2015; Guo et al., 2023; Piscopo et al., 2017; SI Ocean, 2013). Finally, all the steps of the analyses are visualized by a flowchart as seen in Figure 2.

	Cost Division 1 (CD-1)	Cost Division 2 (CD-2)	Cost Division 3 (CD-3)	Cost Division 4 (CD-4)
Structure	31%	27%	53.1%	38.2%
PTO	22%	49%	13.2%	24.2%
Infrastructure	5%	4%	3.6%	8.3%
Installation	18%	13%	10.2%	10.2%
Mooring	6%	5%	5.4%	19.1%
Project Management/Permits	---	2%	14.5%	---
O&M	7%	4%	6.3%	5%

Table 1. Wave energy converters cost breakdowns.

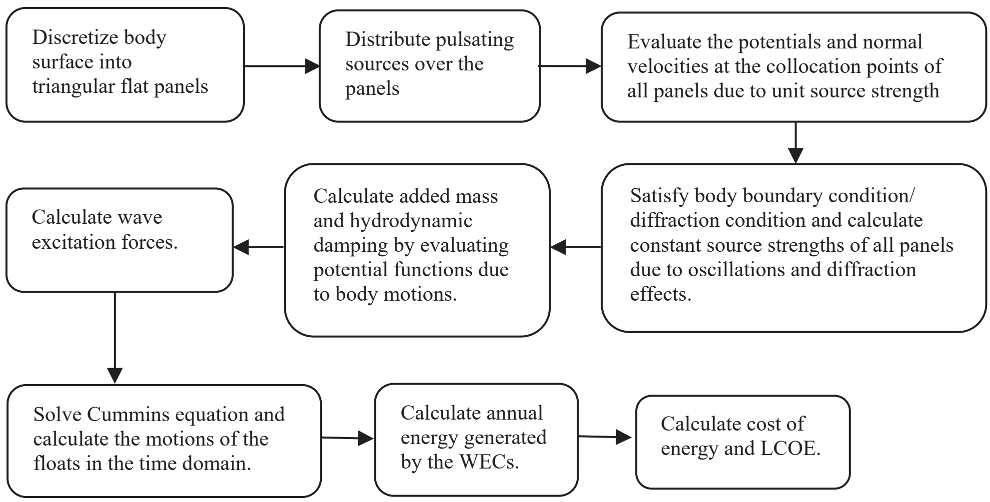

Figure 2. Flowchart of the analysis method.

3. RESULTS

The research aims to design an axisymmetric WEC and to optimize it for the best operation under the action of irregular waves observed in the target areas throughout the year. Thus, 5 different axisymmetric bodies, a half-immersed ellipsoid (SE), a half-immersed elliptic paraboloid (SEP), a cylinder (CYL), a cone (CONE), and a Berkeley Wedge (BW) which can be seen in Figures 3-7, are chosen as the floats of the point absorber WEC. Additionally, 3 different displacement masses in seawater are determined for each float type and each float is designed to have 5 different draft-to-radius ratios. The floats weigh the same as semi-spheres (M4, M5, and M6) whose radii are 4, 5, and 6 meters, respectively. A total of five ratios of draft to radius range equally from 0.2 to 1. As a result, a total of 75 different float geometries are considered for the analyses to design the most suitable WEC in each location. Moreover, 4 different power take-off system parameters, the hydraulic piston’s cross-sectional area, the greatest working pressure of the HP accumulator, flow rate while discharging, and the discharge duration, are also considered for the design and the optimization of the WEC. The values of the hydraulic piston’s cross-sectional area, the highest gas pressure of the HP accumulator, the flow rate while discharging, and the discharge duration range from 0.01 m^2 to 0.2 m^2, from 50 Bars to 150 Bars, from 0.01 m^3/s to 0.5 m^3/s, and from 10 seconds to 100 seconds, with increments of 0.01 m^2, 10 Bars, 0.01 m^3/s, and 10 seconds, respectively. The optimization of the power take-off system is carried out simultaneously along with the optimization of the floats.

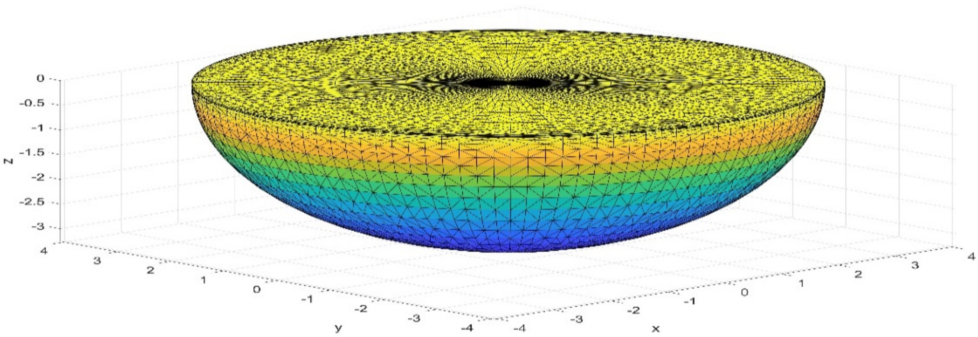

Fig. 3. Semi Ellipsoid (SE) Float.

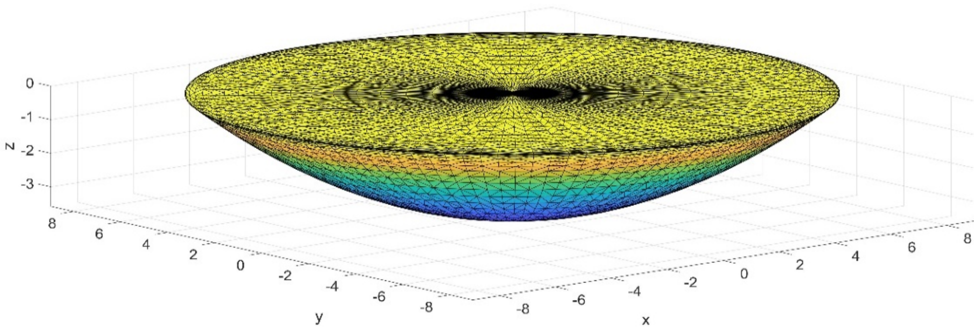

Figure 4. Semi Elliptic Paraboloid (SEP) Float.

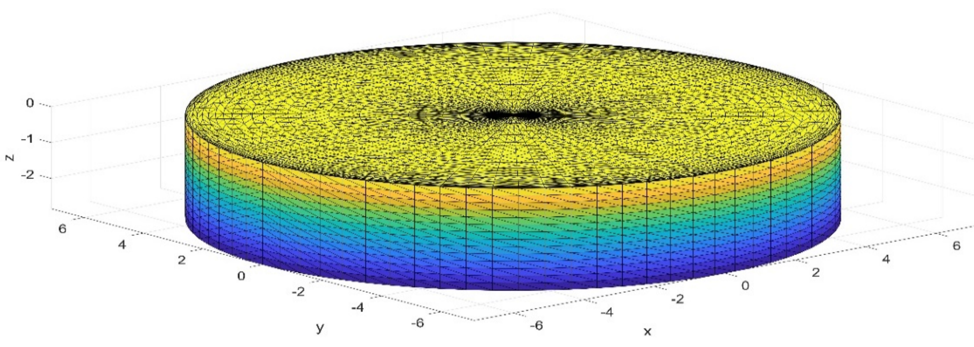

Figure 5. Cylinder (CYL) Float.

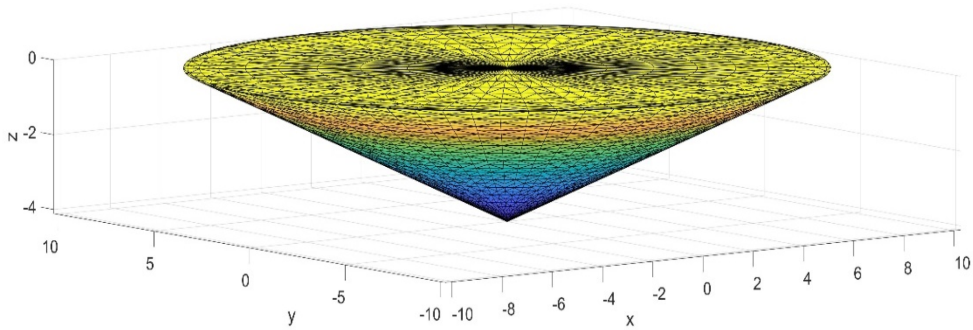

Figure 6. Cone Float.

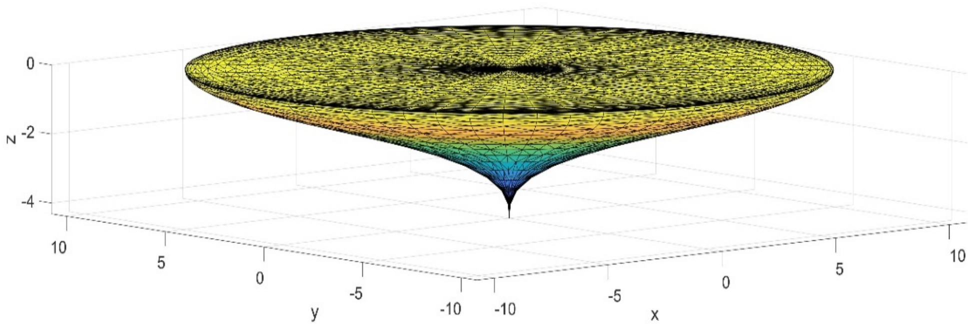

Figure 7. Berkeley Wedge-Shaped (BW) Float.

The coupling of every float with a set of PTO working parameters resulted in a point absorber WEC design and the energy captured by each WEC is computed by evaluating the oscillatory motion of the float in the time domain. The comparisons of the energy captured in a year by the WECs at each location are presented in Figure 8 and Figure 9. The results are presented in a non-dimensional form such that the energy captured in a year by each WEC is divided by the maximum energy captured in a year in each location. The results indicate that the maximum energy is captured when the ratio of the draft to the radius of each float is the smallest in both locations. In addition, all WEC designs with different float geometries show a similar trend that when the ratio of draft to radius increases, the energy captured decreases. Moreover, the Berkeley Wedge-shaped float (M6) can absorb the highest energy from the waves both in Sinop and Hopa. These results may indicate that designing a WEC with an oblate and a heavy float ensures absorbing the highest energy. However, an analysis of the cost of the energy is essential to be carried out and the least unit energy cost should be determined. As a result, the cost of the energy captured is evaluated and the results are presented in Figure 10 and Figure 11 in non-dimensional form that the energy cost achieved by each WEC is divided by the highest cost. The results show that the least unit energy cost is not achieved by the WECs that generate the greatest energy. The least unit energy cost is achieved when each WEC with a different float geometry has a different draft-to-radius ratio in both locations. Additionally, it can also be concluded that a light WEC can be more economical than that of a heavy one.

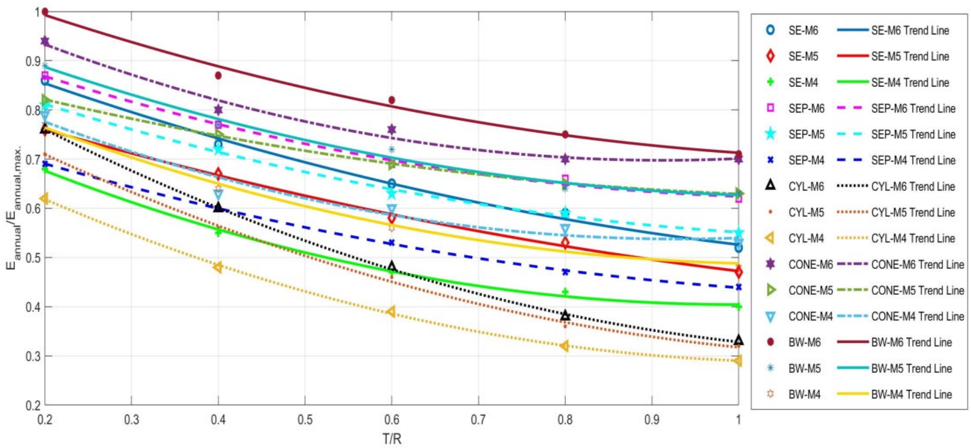

Figure 8. The comparison of the energy captured in a year by all WECs in Sinop.

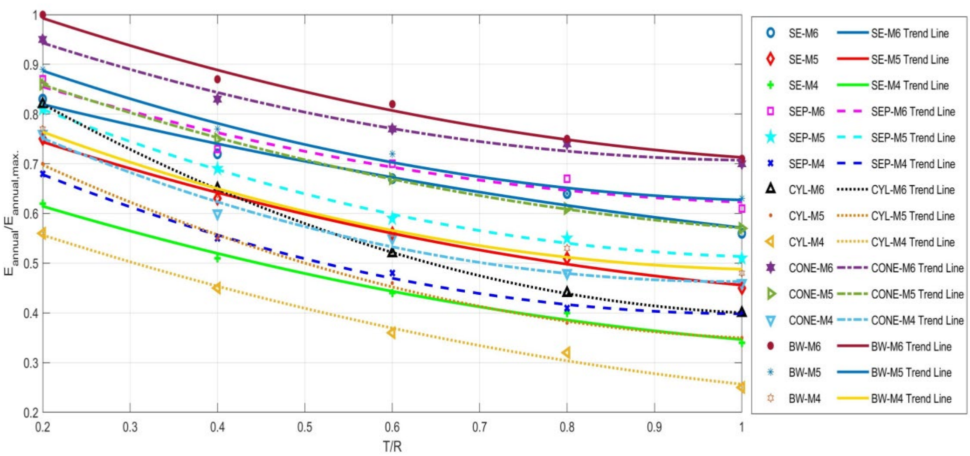

Figure 9. Comparison of the energy captured in a year by all WECs in Hopa.

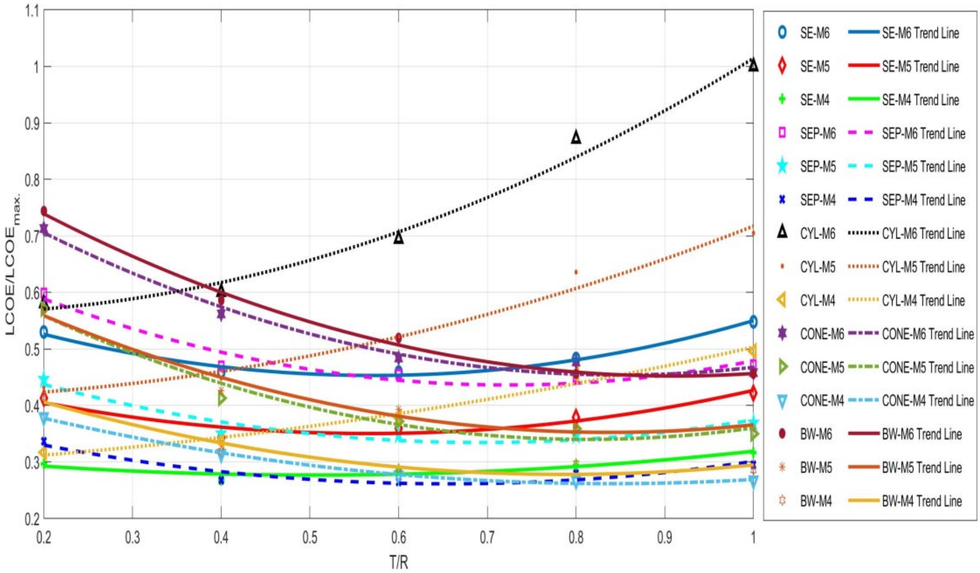

Figure 10. Comparison of the LCOE of all WECs in Sinop.

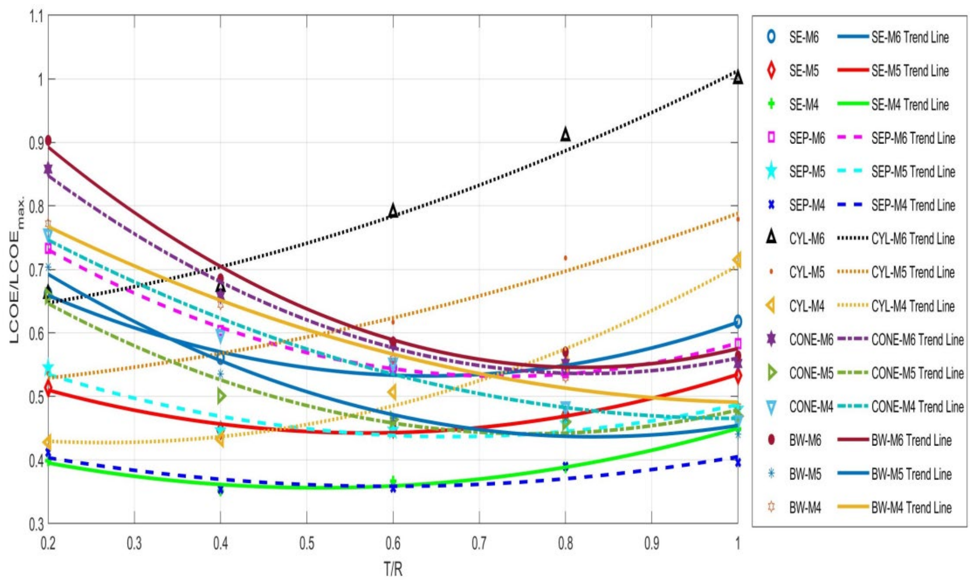

Figure 11. Comparison of the LCOE of different WECs in Hopa.

The sensitivity of the cost analysis is carried out by utilizing different cost breakdowns, device lifetimes, and discount factors. The cost breakdowns presented in Table 1 are utilized in the cost analyses of the WECs designed in the current study. The device lifetime is taken between 20 and 30 years and increased by 1 year for each analysis. The discount factor is taken between 1% and 25%. The analyses showed that the LCOE changed significantly when different cost breakdowns were used in the cost analyses. Additionally, increasing the discount factor resulted in an increase in the LCOE for any given device lifetime. The rate of increase in LCOE due to increasing discount factor differs for different cost breakdowns, which changes approximately between 3% and 13% for every increase of the discount factor by 1% at any given lifetime of the device as shown in Figure 12. Similar results showing that the LCOE increases with an increasing discount factor are presented by (Chang et al., 2018). Moreover, the LCOE increases significantly when the discount factor increases substantially. Figure 13 shows that if the discount factor is increased from 1% to 25%, the LCOE increases approximately by 150-300% when the device lifetime is taken 20 years and approximately by 190-460% when the device lifetime is taken 30 years. However, LCOE decreases with increasing lifetime for any given discount factor as shown in Figure 14. The decrease in LCOE is evaluated by comparing the LCOEs indicating that if the financial risks are low and the devices can be operational for long periods, then the cost of energy can be reduced. Finally, the most significant result is that the ratio of the LCOE of the devices to the maximum LCOE at each location remained the same as shown in Figures 10-11, despite the changes in the cost breakdown, device lifetime, and discount factor.

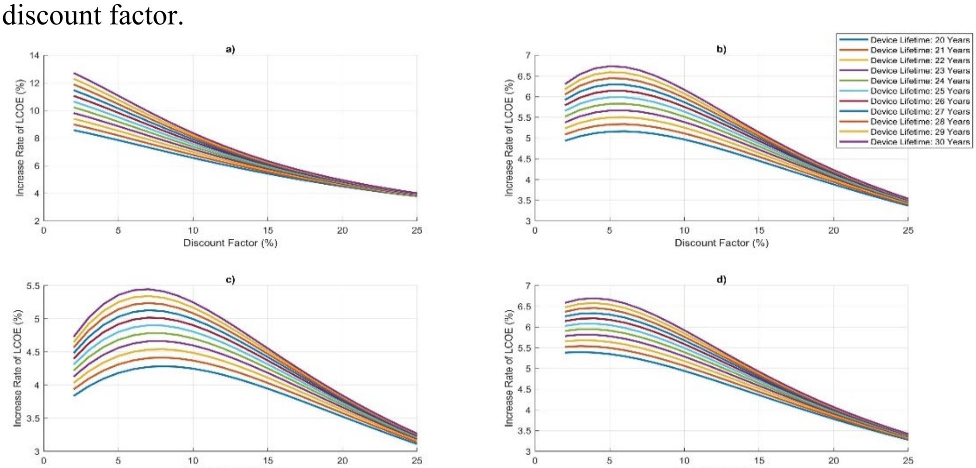

Figure 12. Increase rate of LCOE by 1% increase of discount factor, a) CD-1, b) CD-2, c) CD-3, d) CD- 4.

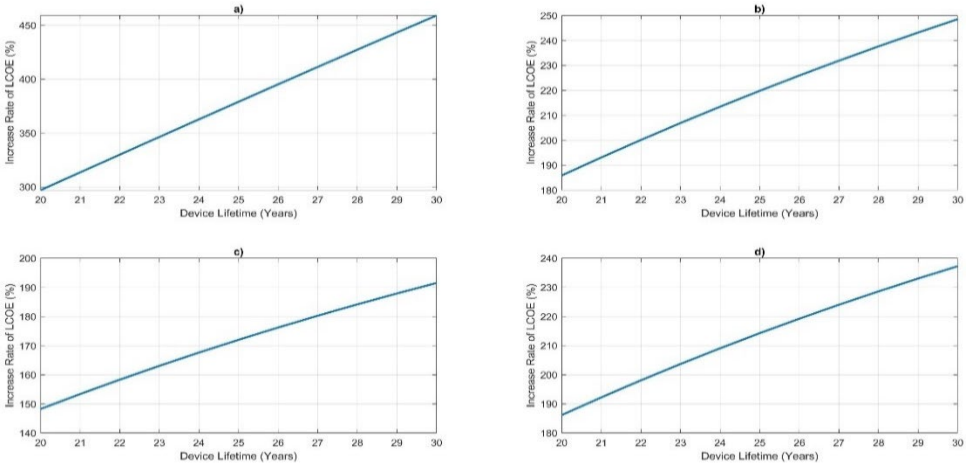

Fig. 13. Increase rate of LCOE due to the change of discount factor from 1% to 25% at different device lifetimes, a) CD-1, b) CD-2, c) CD-3, d) CD-4.

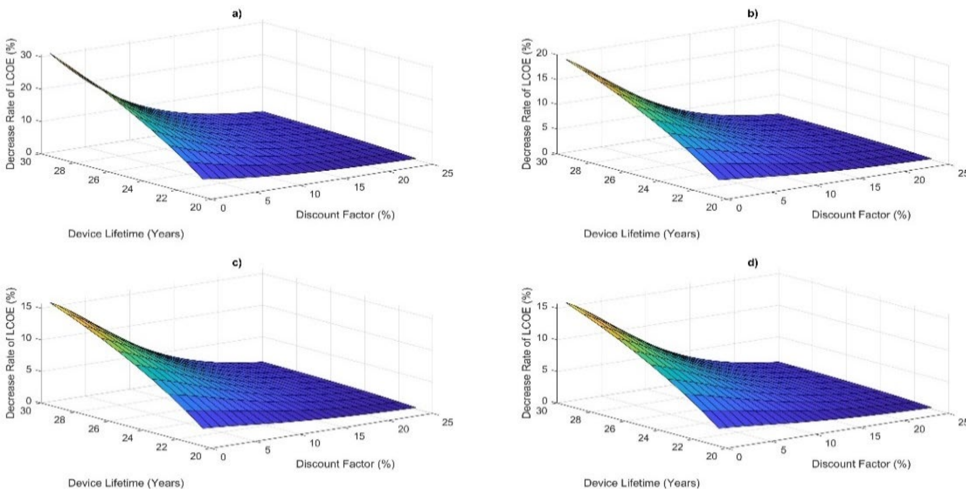

Figure 14. Decrease of LCOE at different device lifetimes for a given discount factor, a) CD-1, b) CD-2, c) CD-3, d) CD-4.

The results presented in Figures 3-6 are obtained by analyzing wave energy converters assuming they stand alone. However, wave energy converter arrays will be needed to generate utility-scale energy to power many living and working spaces.

The energy capture and cost analyses show that there may be more than one optimum wave energy converter design that is suitable for constructing an array. While some of these designs can capture more power than others, their cost of unit energy can be higher than those whose energy capture is low. Thus, it should be determined that an array would either consist of a large number of wave energy converters with low energy cost or a small number of devices with high energy cost for a given total energy capture.

Constructing a WEC array requires the evaluation of the influences of array layout, the number of WECs, the gap width, and the incident wave angle with respect to the fundamental orientation of the array on the energy capture. Each of these factors affects the wave forces acting on each WEC, so the energy capture of the devices within the array differs from that of a single isolated device. As a result, the total energy absorption of an array will be different than that of the same number of single isolated wave energy converters due to the constructive or destructive hydrodynamic interactions between the waves and the WECs. Consequently, the total efficiency of an array can be measured by evaluating a q-factor (Babarit, 2013) based on the yearly energy production of the array and that of a single standing wave energy converter as given in Eq.(14),

$$q_{Array} = \frac{E_{Annual}}{N_{WEC} E_{Annual,Isolated}} \tag{14}$$

where E_{Annual} is the energy produced in a year by an array, N_{WEC} is the number of WECs in the array, and $E_{Annual,\ Isolated}$ is the annual energy production of a single standing WEC.

4. CONCLUSION

The energy captured by different WECs that are considered for deploying in two locations near the Turkish coast of the Black Sea and the unit energy expense is evaluated by taking into account various floats, float masses, PTO parameters, sea states, cost breakdowns, discount factors, and device lifetime. It is determined that the energy captured can be increased by increasing the mass of the float. Additionally, if the ratio of the draft to the radius of the floats reduces, then the energy captured by all the WECs increases. As a result, it can be concluded that more energy can be captured by increasing a float’s mass and by making it more oblate.
The LCOE of each WEC design considered in the current research is calculated to evaluate the energy expenses. The results indicate that the most economical WECs are not able to absorb the highest amount of energy. The LCOEs of all the WECs except with cylinder-shaped floats reach their minimum values at a ratio of draft to

radius within the considered range. However, the WECs with cylinder-shaped floats have minimum LCOE values while their draft-to-radius ratios are 0.2. Moreover, the results show that the LCOE decreases with decreasing mass of the float, which indicates that manufacturing smaller WECs by using less material may help reduce the cost of energy. Furthermore, the effects of different cost breakdowns, discount factors, and device lifetime on the LCOE are studied. Using different cost breakdowns that are proposed in different studies results in different initial, operation and maintenance, decommissioning, and total costs. The main reason for such a differentiation in the costs is that the cost of each component and the rate of the cost of each component to the total cost in different WEC designs differ from each other. Thus, using a cost breakdown of a similar type of WEC to estimate the cost of energy of a particular type of wave energy converter may result in more accurate cost estimates. On the other hand, although different cost breakdowns result in different LCOEs, it is determined that the ratios of the LCOEs of different WECs to the highest LCOE remain the same.

The effect of the discount factor and the device lifetime applied in the calculation of the LCOE are also studied and the results indicate that an increase in discount factor causes the LCOE to increase for any given device lifetime. However, the LCOE decreases with increasing device lifetime for any given discount factor.

Consequently, the results and conclusions obtained in this study reflect the output of a single-standing wave energy converter. However, many devices will be installed in proximity to form arrays and hydrodynamic interactions will change the power capture of each wave energy converter in an array. Thus, further work that will take the hydrodynamic interactions among the WECs in an array into account is required to assess the energy capture and economic performances of wave energy converter arrays.

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RESEARCH ARTICLE

**An ethical committee approval and/or legal/special permission has not been required within the scope of this study.*

THE RELIABILITY EVALUATION OF THE DECK MACHINERY AND GALLEY EQUIPMENT OF A BULK CARRIER BY UTILIZING THE FAILURE RECORDS

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ABSTRACT

Among various modes of transportation, maritime transportation holds critical importance since it provides substantial carrying capacity with low unit costs. To perform seamless and efficient operations in maritime transportation plays a pivotal role in achieving sustainable development goals and the International Maritime Organization (IMO) targets. The execution of uninterrupted operations can only be carried out with the existence of reliable systems. Creating reliable systems onboard is possible through the implementation of planned and proactive maintenance strategies and leveraging experiences gained from past failures. One decade of failure records has been scrutinized within the scope of system reliability to determine critical equipment and units on bulk carriers. The failure data has been categorized into fundamental headings and sub-headings considering marine experts' opinions and literature review. Subsequently, reliability analyses have been conducted on each sub-heading. The scope of the sub-heading equipment, the navigation instrument with (1.967E-04) failure rate has the worst reliability curve. Especially, the failure occurrence in the Radio Detection and Ranging (RADAR) equipment affects officers' on-watch performance and triggers emergencies such as collisions, groundings, and more. The high failure rate of navigation instruments is followed by fire-fighting systems (1.489E-04), cargo equipment (1.218E-04), and Global Maritime Distress and Safety System (GMDSS) (9.831E-05) instruments, all of which should have high-reliability rates to ensure sustainable, smooth, and environmentally friendly operations in the maritime sector. To strengthen equipment reliability, it is recommended to keep regular failure records and implement planned and proactive maintenance strategies.

Keywords: *Reliability Analysis, Navigation Equipment, Communication Devices, Cargo Equipment, Failure Records*

BİR DÖKME YÜK GEMİSİNDE GÜVERTE MAKİNALARI VE KUZİNE EKİPMANLARININ ARIZA KAYITLARINDAN YARARLANILARAK GÜVENİLİRLİK DEĞERLENDİRMESİNİN YAPILMASI

ÖZ

Çeşitli taşıma modları arasında deniz taşımacılığı, düşük birim maliyetlerle önemli miktarda taşıma kapasitesi sağlaması nedeniyle kritik öneme sahiptir. Deniz taşımacılığında kesintisiz ve verimli operasyonlar gerçekleştirmek, sürdürülebilir kalkınma hedeflerine ve Uluslararası Denizcilik Örgütü (IMO) hedeflerine ulaşmada önemli bir rol oynamaktadır. Operasyonların kesintisiz yürütülmesi ancak güvenilir sistemlerin varlığı ile gerçekleştirilebilir. Gemide güvenilir sistemler oluşturmak, planlı ve proaktif bakım stratejilerinin uygulanması ve geçmiş arızalardan elde edilen deneyimlerden faydalanılmasıyla mümkündür. Dökme yük gemilerindeki kritik ekipman ve ünitelerin belirlenmesi için sistem güvenilirliği kapsamında on yıllık arıza kayıtları incelenmiştir. Arıza verileri, denizcilik uzman görüşleri ve literatür taraması dikkate alınarak temel başlık ve alt başlıklar halinde kategorize edilmiştir. Daha sonra, her bir alt başlık için güvenilirlik analizleri gerçekleştirilmiştir. Alt başlık ekipmanları kapsamında, (1.967E-04) arıza oranı ile seyir ekipmanları en kötü güvenilirlik eğrisine sahiptir. Özellikle radarda meydana gelen arıza, zabitlerin vardiya performansını etkilemekte ve çarpışma, karaya oturma gibi acil durumları tetiklemektedir. Seyir ekipmanlarındaki yüksek arıza oranını yangın söndürme sistemleri (1.489E-04), kargo ekipmanları (1.218E-04) ve küresel denizcilik tehlike ve güvenlik sistemi (GMDSS) (9.831E-05) cihazları takip etmektedir ve bunların tümü denizcilik sektöründe sürdürülebilir, sorunsuz ve çevre dostu operasyonlar sağlamak için yüksek güvenilirlik oranlarına sahip olmalıdır. Ekipman güvenilirliğini güçlendirmek için düzenli arıza kayıtlarının tutulması, planlı ve proaktif bakım stratejilerinin uygulanması önerilmektedir.

Anahtar Kelimeler: *Güvenilirlik Analizi, Navigasyon Ekipmanları, Haberleşme Cihazları, Kargo Ekipmanları, Arıza Kayıtları.*

1. INTRODUCTION

The techniques and protocols employed in quality assurance and reliability engineering have undergone significant advancements during the past six decades. Reliability Availability Maintainability (RAM) analysis is employed for intricate systems and equipment to mitigate faults, ensure uninterrupted operations, and decrease expenses (Eriksen et al., 2021; Alamri & Mo, 2023). Before the 1950s, an item was considered to have met quality targets if it left the producer without any instances of failure. In modern times, RAM analysis is employed to assess failures that arise in the item, equipment, or systems over the course of their operation, to achieve quality objectives (Tsarouhas, 2020). The reliability of a system refers to the likelihood of successfully executing an action within a specific timeframe and under specific environmental variables and constraints (Stapelberg, 2009). Reliability refers to the likelihood of failure and the corresponding records collected while a system is in operation (Breneman et al., 2022). Design criteria for manufacturing, testing, and reliability are crucial for effectively implementing reliability, which refers to the quality of a product or system over time (Gullo & Dixon, 2021). Reliability encompasses three crucial factors: the desired purpose, a specific duration, and the designated constraints and circumstances (Yang, 2007). Reliability is quantified through the utilization of mathematical models or statistical factors (Sürücü & Maslakçı, 2020).

Availability refers to the ratio of delivered service to the expected service of objects (Aslanpour et al., 2020). It is the level of reliability of a system, which is determined by the maintainability of the elements within the system (James, 2021). Availability depicts the state in which an object can perform a required function when used in a suitable environment, provided that maintenance is carried out at specified intervals (Bussel & Zaaijer, 2001). Assessing the availability of a system is quite challenging as it is crucial to consider factors such as reliability, maintainability, human factors, and logistical support in the calculations (Smith, 2021). Maintainability is the consideration of the length of time that a system experiences faults during maintenance (Ghosh & Rana, 2011; Tortorella, 2015). It means the capacity of an equipment or system to fulfill its intended purpose when maintenance is conducted under certain conditions, employing the appropriate processes and resources (Velasquez & Lana, 2018). Maintenance has a significant impact on the reliability and availability of the marine sector. It is critical to the life of a ship as it can reduce downtime and operating costs. Maintenance accounts for 20-30% of a ship's operating costs (Stopford, 2009). In addition, given the environmental impact of shipping and the critical need for safe ship operations, ship owners and operators are seeking to implement a maintenance plan and processes that will save costs and improve the long-term durability of the vessel. Reliability is a crucial factor in assessing the duration and degradation of a ship's operating systems under different situations and time intervals (Li et al.,2020). Implementing preventive maintenance planning before high-risk ship operations for systems or system components that have reached the minimum acceptable level of reliability, as determined by the operator or technical manager, can greatly enhance the proper system functioning of the marine vessel (Biçen & Çelik, 2023).

Ensuring the reliability, availability, and proper maintenance of ship safety equipment is crucial in maritime operations. The reliability aspect is concerned with consistent and accurate performance, while availability emphasizes operational readiness when needed. Rigorous maintenance practices, including regular inspections and preventive measures, are essential. Adherence to international regulations and continuous crew training contribute to overall maritime safety and sustainability by ensuring equipment is in top condition. The critical situation of safety equipment is that it needs to be used in rare but vital moments.

The technological aspect of the ship's navigation system evaluated under the deck machinery systems consists of a complex network of different components, subsystems, assemblies, and human-machine interfaces. The bridge team uses this equipment to perform nautical tasks such as monitoring, anticipation, and decision-making to navigate the ship safely throughout the voyage. Ship's navigation systems and their subsystems include sensors, radio navigation, communication equipment, and data sources in addition to data processing, evaluation, and visualization capabilities. The operation and performance of these components and subsystems are influenced by human configuration and control apart from their reliability levels. Ship navigation systems currently in use can therefore be classified either as technological systems, which operate without human intervention, or as socio-technical systems, which require human input. However, when prioritizing the safety and effectiveness of ship navigation, it is imperative to consider the technological system and the crew as a cohesive unit, operating in synchrony with the constantly evolving environment (Engler et al., 2019).

Deck and cargo equipment is critical to the safety of the ship and cargo. Maintenance schedules for this equipment should be prepared using appropriate materials and taking into account the manufacturer's schedule. Maintenance and repairs to the deck and cargo equipment can be carried out while the ship is underway. However, it may not be possible to repair large equipment such as anchors on board. Anchoring is an essential procedure used to maintain the position of vessels securely during periods of waiting for berthing, cargo handling, bunkering, or protection from hazardous environmental and operating circumstances. The anchor and chain facilitate the ship's ability to secure itself to the seabed using the anchor chain, allowing it to remain stationary for a desired duration (Kuzu, 2023). Anchoring equipment should be kept ready for use at all times.

Furthermore, reliable, usable, and well-maintained galley equipment is essential for the smooth running of galley operations on board ships. The proper preparation of the daily meal for the ship's personnel is essential for the smooth running of all other operations. Consistent performance of cooking appliances and refrigeration units is essential to meet the demands of food preparation on board. Availability emphasizes that these systems must be operational at all times required by galley operations. To achieve these objectives, systematic maintenance practices, including regular inspections and preventive measures, are essential. This proactive approach helps to prevent breakdowns and ensures optimum operating conditions for kitchen equipment. Adherence to industry standards, regulations, and ongoing training of kitchen staff is vital to maintaining the reliability and availability of equipment. Prioritizing the proper functioning of galley equipment not only improves the quality of meals on board but also contributes to the overall efficiency and safety of maritime operations.

Academic scholars and maintenance professionals have urged the importance of maintenance management and determining the reliability of systems, especially in marine vessels (Tan et al., 2020; Daya & Lazakis, 2023). Existed systems in the ships have been classified as engine room and deck machinery systems. The reliability of ship machinery systems has been scrutinized to keep uplevel propulsion efficiency within the scope of related sub-systems (Bayraktar & Nuran, 2022; Bahootoroody et al., 2022; Karatuğ et al., 2023; Ceylan et al., 2023). Ivanovskaya et al., (2022) have stated that failures in the deck equipment have resulted in accidents and device malfunctions that diminished the operational and economic efficiency of the ship. Kimera & Nangolo (2022) have revealed that in the deck machinery systems, deck equipment used in towing, docking, lifting, anchoring, loading, and offloading is crucial for maintaining the operation of vessels because malfunctioning of deck equipment can result in unexpected catastrophes. Deck equipment failure is more common in vessels due to the lack of regular maintenance compared to other remaining systems (Kimera & Nangolo, 2022). Zhou and Thai (2016) have used both grey theory and fuzzy theory in failure mode effect analysis (FMEA) to evaluate equipment failure modes on tankers. Navigation equipment and deck machinery have the highest risk, after the main engine both in the grey method and fuzzy method. Planned maintenance efforts of these systems must be carried out carefully considering their high priority risk. Kimera and Nangolo (2022) have employed Weibull and Gamma distributions in the reliability analysis of deck machinery systems utilizing failures and maintenance data. Among the deck machinery systems, capstans exhibit greater reliability compared to winches and cranes based on the outcomes of the analysis. Ship age and ignoring planned maintenance intervals have lowered the reliability of systems.

2. SYSTEM DESCRIPTION AND METHODOLOGY

The failure records of four sister marine vessels have been gathered and the reliability analysis of the deck machinery navigation and galley equipment has been conducted in the paper. Figure 1 illustrates the flowchart of the methodology used in the evaluation.

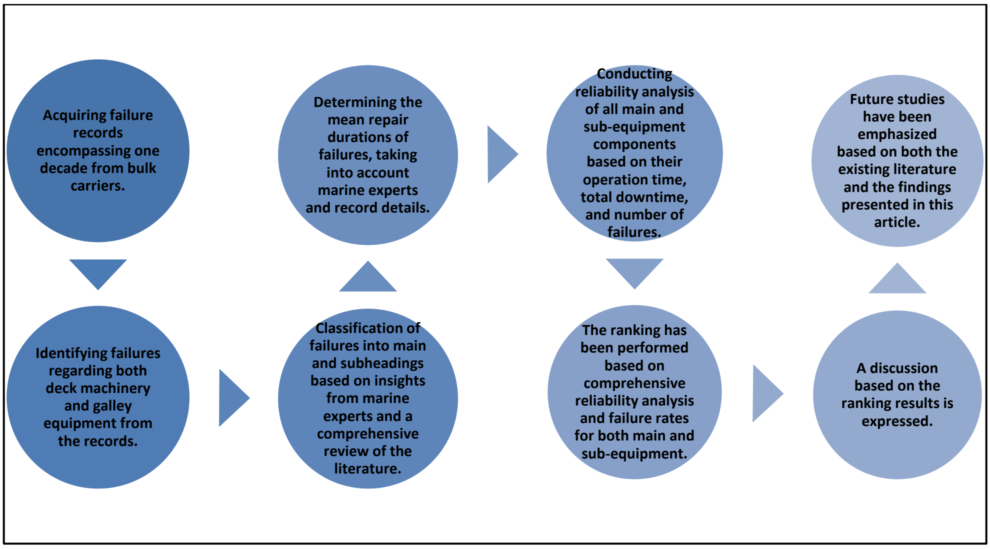

Figure 1. *The methodology flowchart.*

Information about the experts who determine mean repair durations of failures in the flow diagram is given in Table 1.

Based on expert opinions and an extensive literature review, the data has been meticulously prepared for the analysis. The reliability analysis of each system has been conducted by utilizing operating time, failure rate (λ), or Mean Time Between Failures (MTBF). The Failure Rate (λ) is determined by dividing the cumulative number of system failures by the total operational time and it has been expressed in Formula 1 (Zacks, 2012; Bayraktar & Yüksel, 2023).

Table 1. *Information about the experts*

Experts	Educational background	Length of experience	Personal background	Academic titles
Expert I	Marine Engineering	10 Years	Oceangoing Watchkeeping Engineer Academician at Marine Engineering Department	Ph.D.
Expert II	Naval Architecture and Marine Engineering	11 Years	Academician at Marine Engineering Department	Ph.D.
Expert III	Maritime Transportation and Management Engineering	12 Years	Oceangoing Watchkeeping Officer Academician at Maritime Transportation and Management Engineering	Ph.D.
Expert IV	Maritime Transportation and Management Engineering	16 Years	Oceangoing Master Marine Pilot	M.Sc.

$$Failure\ Rate\ (\lambda) = \frac{Number\ of\ Failures}{Operating\ Time} \tag{1}$$

The equation of Reliability depending on the Failure Rate (λ), total operating time, and constant has been described in Formula 2 (Zacks, 2012; Bayraktar & Yüksel, 2023).

$$Reliability = R(t) = e^{-\lambda t} \tag{2}$$

Bulk carrier records are used in the reliability analysis. The technical specifications of the ship are expressed in Table 2.

Based on the DWT classification, the vessel belongs to the Supramax category within the bulk carrier classification. The Supramax classification is widely favored thanks to its substantial cargo-carrying capacity and the inclusion of bridge-handling equipment on board. The Supramax bulk carriers have the largest share in terms of the number of vessels and they hold the second position in overall carrying capacity (United States Department of Agriculture, 2021). The continuous operational performance of Supramax bulk carriers exerts a considerable influence on maritime transportation. Therefore, forecasting the reliability values of each system onboard is quite significant in providing sustainability and applying planned maintenance.

Table 2. *Particulars of the Bulk Carriers (ClassNK, 2024)*

Parameters	Value/Descriptions	Unit
Type of Ship	Bulk Carrier	-
Gross Tonnage	29978	-
Net Tonnage	18486	t
Deadwight (DWT)	53483	t
Summer Freeboard	5.037	m
Summer Draught	12.303	m
Max. Speed	15.7	kt
Engine Power	9480	kW
Engine Revolution	127	rpm
Capacity of Generators	4 AC 1565	kVA
Length*Breath*Depth	183.06*32.26*17.3	m^3
Cargo Capacity (Bale)	65526	m^3
Cargo Capacity (Grain)	68927	m^3
Cranes	4*30.5	mt
Grabs	4*12	m^3
Number of Warehouse	5	-
Capacity of Tanks (Fuel Oil & Diesel Oil)	2317	m^3
Capacity of Tanks (Fresh Water)	408	m^3
Total Enclosed Lifeboats	2*(25)	Person
Rigid Rescue Boats	1*(6)	Person
Inflatable Life rafts	1*(6) and 2*(25)	Person
Radio Installations	GMDSS[1] A1+A2+A3, SSAS[2]	
Navigation Equipment[3]	MC, GYRO, HCS, ECDIS, GPS, RDX, RDS, ARPA, AIS, VDR, LOG, ES, STGTEL, LRIT, BNWAS	

[1] GMDSS = Global Maritime Distress and Safety System [2]SSAS = Ship Security Alert System, [3]ARPA = Automatic radar plotting aids, HCS = Heading Control System, ECDIS = Electrobinc Chart Display Information System, GPS=Global Positioning System, RDX=X Band Radar, AIS = Automatic Identification System, VDR = Voyage Data Recorder, LOG = Speed Log, ES = Ecosounder, STGTEL = Steering Telephıne, LRIT = Long Range Identification and Tracking, BNWAS = Bridge Navigational Watch & Alarm System.

The required data for the analysis have been obtained from 10-year failure records in which nearly a hundred failures have existed. Failures belonging to deck machinery and galley systems have been classified under four systems considering literature review, manufacturer reports, and marine experts. Moreover, repair and breakdown times for failures have been determined by the operating deck officer.

The limitations of this study have been described since both the analysis and the results have been evaluated within the framework of these limitations.

- Ten-year failure records of four sister ships have been utilized in this investigation.
- The failures have been obtained from the record of Bulk Carrier ships.
- Evaluation has been performed only on recorded data.

Failures that have been instantly resolved or not reported have not been included in the analysis.

3. RESULTS AND DISCUSSION

The reliability analysis results of deck machinery equipment have been discussed and shown in Figures 1 to 4 under four systems: Safety equipment; bridge equipment; deck and cargo equipment; and galley equipment respectively. The x-axis of the figures represents the operation time in hours and the y-axis depicts the reliability of the respective equipment. Figure 2 demonstrates the reliability level of the safety equipment onboard.

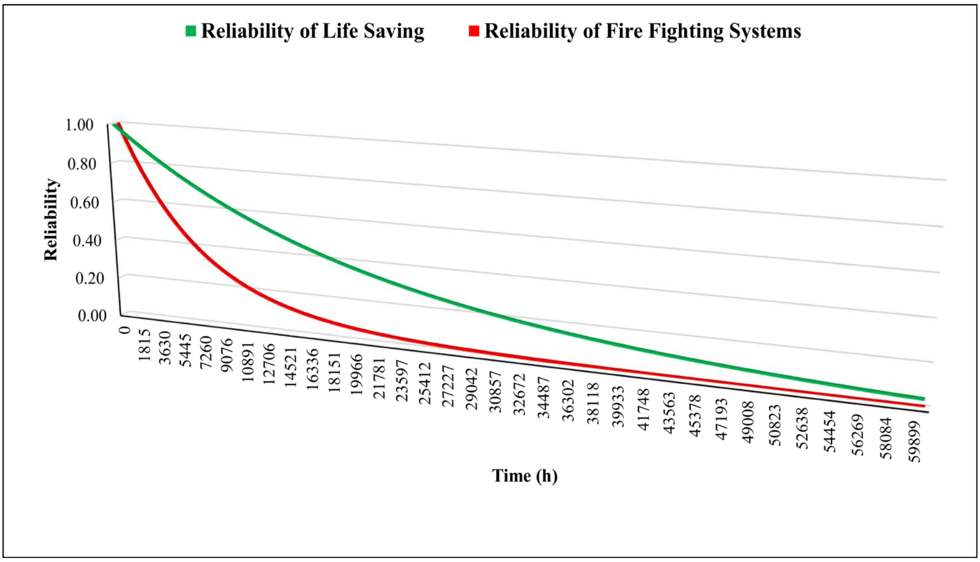

Figure 2. *Reliability of safety equipment*

The reliability analysis of the equipment included in safety systems has been conducted by assessing the failures that occurred over a cumulative operating duration of 60,504 hours. Results of safety equipment reliability have been depicted into two parts considering twelve failures: Life-saving appliances and fire-fighting systems. Their error failure rates are 0.000049596 and 0.000148864 respectively. The number of failures that occurred in life-saving appliances is three and fifteen hours have been needed to fix these malfunctions. The failures have occurred in the lifeboat engine, brake system, and battery charging system. On the other hand, the occurrences of failures in the fire-fighting systems numbered nine, and a total duration of forty-six hours was required for the fixation of these malfunctions. Fire detection systems, emergency fire pumps, and fire alarm systems are the most critical ones because the majority of malfunctions stem either directly or indirectly from these equipment components. The cumulative downtime for all safety equipment amounts to 61 hours. In addition to safety equipment, the reliability of bridge equipment has been described in Figure 3.

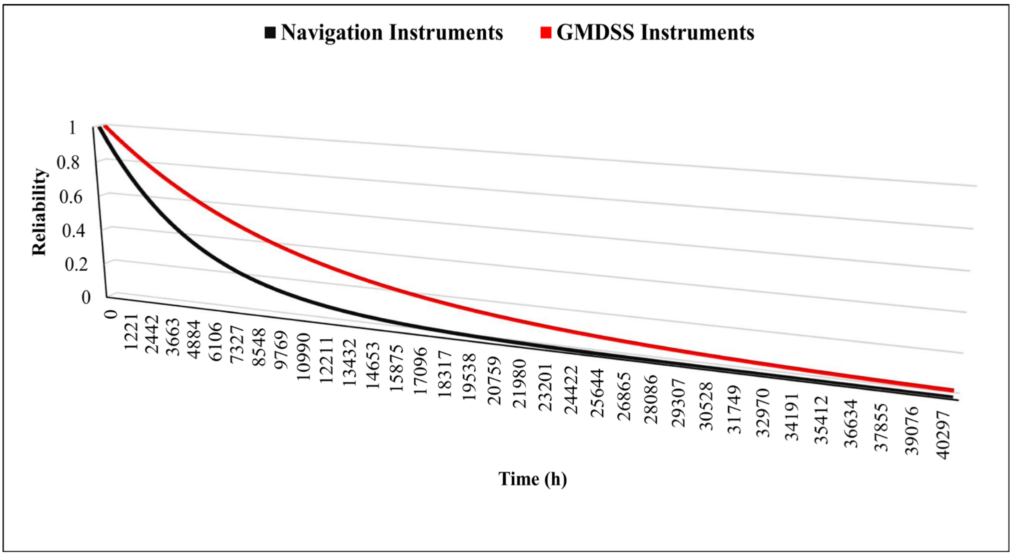

Figure 3. *Reliability of Bridge Equipment*

Bridge equipment has been classified as navigation and GMDSS instruments. A total of 12 failures have occurred in these instruments throughout the 40704 hours. Failure rates of navigation are higher than GMDSS instruments which are 0.00019673 and 0.000098311 respectively. Eight failures requiring forty hours of repair time to fix these issues have occurred in navigation instruments. Furthermore, four failures have occurred in GMDSS (Global Maritime Distress and Safety System) instruments, and forty hours have been required to repair their breakdowns. Under navigation instruments, magnetic compass, ECDIS, Radio Detection and Ranging (RADAR), GPS, and AIS devices have been broken down. On the other hand, failures of GMDSS instruments have occurred in Marine MF/HF SSB (Single Side Band), INMARSAT-C, and emergency position indicating radio beacon (EPIRB) devices. The reliability of deck and cargo equipment has been depicted in Figure 4.

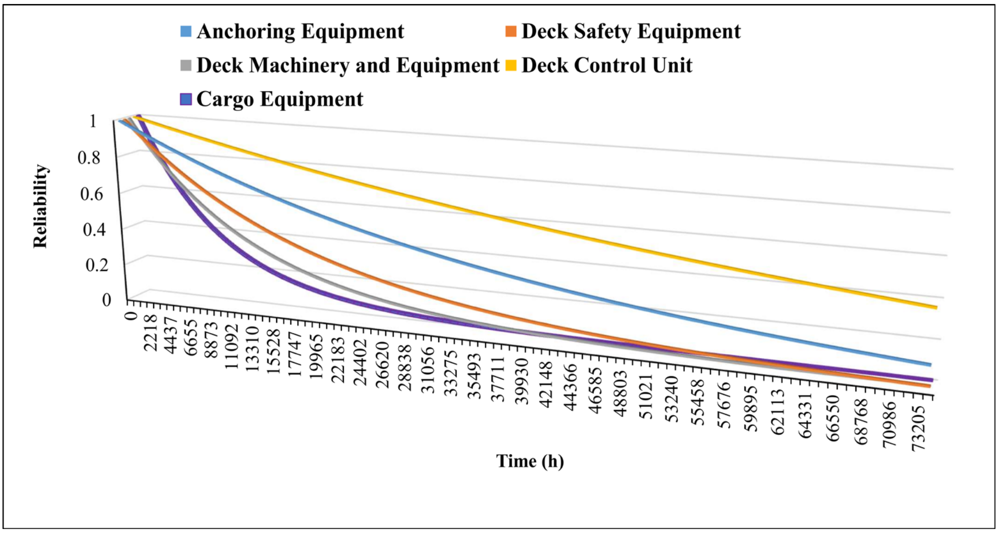

Figure 4. *The reliability of deck and cargo equipment*

The deck and cargo equipment have been divided into five sub-equipment and units. The number of twenty-two failures have occurred in these systems during 73944 hours. Among the sub-equipment and units, the most failures have occurred in cargo equipment with nine failures which were fixed in fifty-three hours. In the realm of deck machinery and equipment, six failures have transpired, resulting in a cumulative breakdown duration of 53 hours. The remaining failures have manifested in anchoring equipment, deck safety equipment, and the deck control unit, totaling six failures and necessitating a collective repair time of 60 hours. At the remaining stage, the reliability of galley equipment has been calculated and placed in Figure 5.

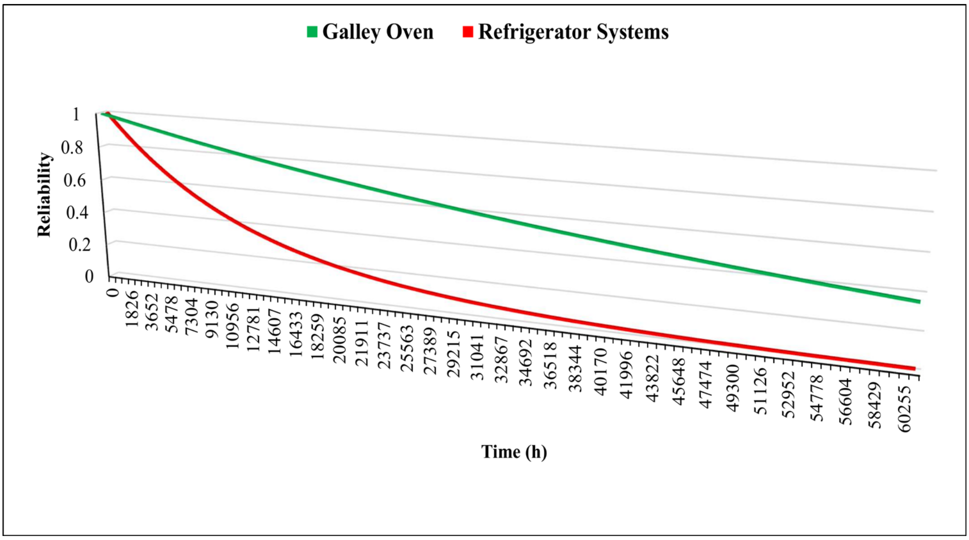

Figure 5. *The reliability of galley equipment*

The number of one and five failures have been realized in the galley oven and refrigerator systems respectively considering 60864 operation hours. The failure sourcing from the transformer fire that occurred in the galley oven has been fixed within 10 hours. The remaining failures have led to a breakdown lasting 44 hours in the refrigerator systems. Failure rates of all subsystems have been expressed in Figure 6.

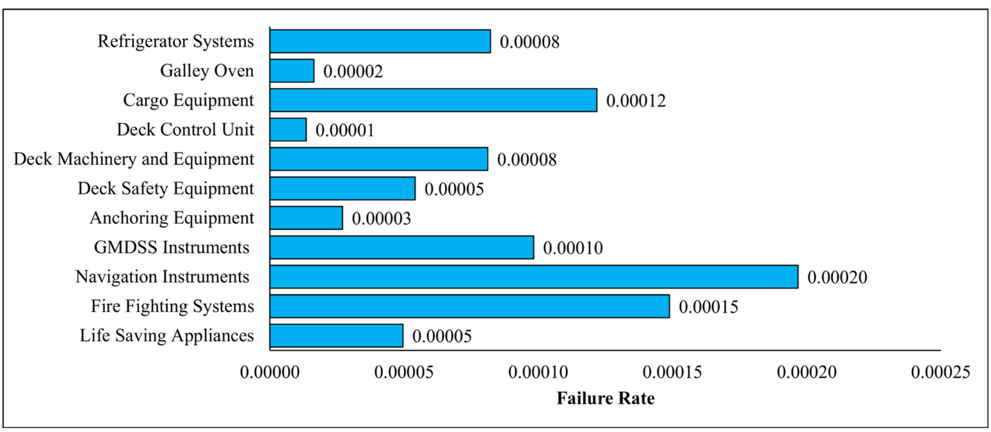

Figure 6. *Failure rates of all subsystems*

Navigation instruments, fire-fighting systems, cargo equipment, and GMDSS instruments have exhibited the highest rates of failure when examining records. The error rate for these systems surpasses that of the remaining systems by more than two times. While there is a lack of empirical studies on the failure rates and reliability analyses of specified equipment, the detailed information provided in the warranty periods and user manuals of products has been considered in the evaluation. Under the navigation instrument, warranty periods of the magnetic compass, ECDIS, ARPA, GPS, and AIS have been varied between one to ten years (SperryMarine, 2022; BlueLine, 2024; Furuno, 2024; Simrad, 2024; AIS, 2018). Apart from these, some companies offer a never-expiring warranty on some instruments such as ECDIS (ChartWorld, 2024) because the Electronic Chart Display and Information System (ECDIS), provides substantial benefits in maritime navigation, safety, and commerce, and it is a critical and mandatory navigation aid (Xiaoxia & Chaohua, 2002). Regular and planned maintenance is very significant for lifetime warranties. 3-monthly, 6-monthly, and annual maintenance have been recommended for ARPA (Furuno, 2024), which is an important step in preventing collisions at sea (Wärtsilä, 2024). A roundly up to 10-year warranty is provided for malfunctions in electronic components of AIS units (AIS, 2018). Fire-fighting systems can have warranties of up to 3 years with regular maintenance (United Safety, 2024). Warranty periods for cargo equipment are shorter roundly one year (Marine Deck Crane, 2024) since they are used in handling operations. GMDSS instruments warranty periods are similar to navigation instruments, provided that planned maintenance is carried out. The failure rates and reliability outcomes are notably consistent with the warranty durations and user manuals of the products.

Perera et al. (2013) have expressed that failures that occur in ship navigation can cause collision and Zhou and Thai (2016) have highlighted that Navigation equipment is one of the riskiest equipment. For this reason, the reliability level of the system should be kept as high as possible. Perera (2018) has also highlighted that it is especially critical for autonomous ships to perform smooth operations because the advanced systems used in them rely heavily on data from navigation devices.

Therefore, navigation devices must be manufactured and operated with the highest level of reliability for marine vessels.

The firefighting systems hold the utmost eminence in ensuring the operational sustainability and viability of ships. System factors constitute one of the various factors in the application of the firefighting system. Among the system factors, fire ability and misinformation are the most critical ones (Zhang et al., 2013). To prevent the fire ability from being interrupted, the equipment of the fire system must be suitable and highly reliable for operation at all times.

Cargo handling equipment on bulk ships has an important share in the realization of maritime transportation. Failures occurring in this equipment disrupt loading/unloading operations in the ports and cause increased waiting times for ships at the port and congestion. Reliability analysis to be carried out on handling equipment ease periodic maintenance planning management that minimizes equipment failures (Sayareh and Ahouei, 2013). The presence of reliable cargo handling equipment provides both environmental and financial benefits for ship owners, operators, and stakeholders.

The presence of reliable communication systems on ships holds paramount significance in carrying out ship operations, especially in emergency responses. Radio communication failures are the highest frequent ones on the ship and it is followed by GMDSS Operation, EPIRB, and HF/MF failures respectively. Selecting highly reliable equipment for communications prevents excessive delays in getting help in any emergencies (Karahalios, 2018). Therefore, knowing the periodic failures and reliability rates of the devices enables the implementation of a planned and proactive maintenance strategy and ensures smooth ship operations. Bicen et al. (2022) have also highlighted that in addition to maximizing system reliability, it is necessary to provide a comprehensive training program for the ship's crew to enhance their familiarity with the existing systems because numerous errors can be attributed to human factors.

4. CONCLUSION

The comprehensive reliability analysis undertaken on both deck machinery and galley systems has yielded invaluable insights into their intricate operational intricacies and inherent susceptibilities. Through meticulous examination, pivotal revelations have come to light, underscoring the paramount importance of fostering heightened reliability within these domains. Foremost among the discerned insights is the criticality of ensuring robust reliability standards, particularly within pivotal facets such as navigation, firefighting, cargo handling, and communication systems. These subsystems have been identified as focal points warranting heightened attention due to their propensity for elevated failure rates in comparison to other equipment within the maritime infrastructure. Consequently, the imperative for stringent maintenance protocols and proactive interventions aimed at fortifying the operational resilience of these systems is unequivocally underscored. By meticulously attending to the reliability dynamics of these pivotal subsystems, stakeholders can proactively mitigate risks, enhance operational efficiencies, and ultimately bolster the safety and efficacy of maritime endeavors. Such strategic imperatives are pivotal for navigating the dynamic complexities inherent in maritime operations and engendering sustainable advancements within this multifaceted domain.

Additionally, failures within these maritime systems not only pose inherent safety hazards but also engender operational impediments, thereby disrupting the seamless flow of maritime transportation. The elucidated article underscores the imperative of implementing meticulously devised and proactive maintenance protocols. Such protocols are formulated through a comprehensive analysis of the reliability and potential failures of both overarching systems and their constituent sub-systems. This strategic approach is fundamental for ensuring the sustained efficacy of maritime operations amidst the dynamic challenges inherent in this domain.

The conclusions drawn and the subsequent discourse arising from the analytical investigation are poised to yield significant implications for a diverse array of stakeholders within the maritime domain. Principally, shipowners, operators, and regulatory bodies stand to benefit from the insights gleaned, as they offer invaluable guidance for enhancing both operational resilience and safety standards across the maritime sector. Implementing thorough crew training programs is crucial to improving the crew's understanding of onboard systems and reducing errors caused by human factors. Enhancing operational efficiency, safety, and environmental sustainability in maritime transportation can be achieved by optimizing system reliability and investing in crew training. This reliability analysis emphasizes the importance of upholding high equipment dependability standards and promoting a proactive maintenance culture to guarantee the safety, efficiency, and sustainability of marine operations in a changing maritime environment.

Moreover, as we chart a course into the future, it becomes increasingly imperative to perpetuate research endeavors and foster collaborative initiatives aimed at advancing the field of reliability assessment about ship systems. Sustaining such efforts is essential not only for surmounting existing barriers but also for ensuring the seamless operation of vessels in alignment with the targets delineated by the IMO and the overarching aspirations encapsulated within the Sustainable Development Goals. By steadfastly pursuing this trajectory of research and collaboration, stakeholders can collectively navigate the intricate complexities of maritime operations while simultaneously striving toward the attainment of broader environmental and societal objectives on a global scale.

In addition to bulk carriers, oil tankers, container ships and other types of ships also hold significant share in maritime transportation and the interruption of operational continuity in these types of ships results in economic, social, and environmental losses. Therefore, reliability analyzes should be conducted on these ship types as part of future research efforts to fulfill IMO and United Nations objectives.

CONFLICT OF INTEREST STATEMENT

The author(s) declare(s) no conflict of interest.

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RESEARCH ARTICLE

**An ethical committee approval and/or legal/special permission has not been required within the scope of this study.*

A WORKLOAD DEPENDENT RESOURCE CONSTRAINED SCHEDULING PROBLEM FOR NAVY HELICOPTER PILOTS

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ABSTRACT

In this paper, we consider a problem inspired by a real-life problem, which aims to schedule high multiplicity jobs on a single machine by taking into account the organization-specific constraints in a different schedule structure. The schedule is daily with daytime and nighttime periods. The operator is considered as an additional resource that varies in terms of consumption and scheduling depending on the period. There are specific rest periods before and after night-period jobs, and night-period jobs affect both the daily working time and number of the jobs in the daytime- period. In addition, the operator's daily workload is divided into two categories: normal and heavy. If the workload is heavy on consecutive days, specific rest periods must be scheduled. The integer programming model of the problem is presented. The feasible solutions obtained in a short time with greedy constructive heuristic algorithms are used in the exact solution approach as both upper bound and warm-start point. Finally, the effectiveness of the solution approaches is compared and evaluated through numerical experiments carried out for a variety of problem instances of different sizes.

Keywords: *Scheduling, Additional Resources, High-Multiplicity, Integer Programming, Greedy Constructive Heuristic.*

DENİZ HELİKOPTER PİLOTLARI İÇİN İŞ YÜKÜNE BAĞLI KAYNAK KISITLI BİR ÇİZELGELEME PROBLEMİ

ÖZ

Bu çalışmada; az çeşit yüksek sayıdaki (yüksek multiplisite) işlerin, organizasyona özgü çalışma düzeni ve kısıtlar eşliğinde farklı bir çizelge yapısı altında tek makinede çizelgelenmesini amaçlayan, gerçek yaşam probleminden kurgulanan bir problem ele alınmıştır. Gündüz ve gece olarak ikiye ayrılan çizelge yapısında, işlerin yapıldığı periyoda göre operatör ek kaynağının tüketilmesi ve çizelgelenmesi açısından farklı kısıtlar dikkate alınmaktadır. Gece periyodunda yapılan işler öncesi ve sonrasında operatöre yönelik özel dinlenme süreleri kısıtları bulunmakta, gece periyodunda yapılan işlerin hem süre hem de sayı olarak gündüz periyodundaki iş çizelgelemesine etkileri bulunmaktadır. Ayrıca, operatörün günlük iş yükü normal ve ağır olarak iki kategoriye ayrılmaktadır. Ardışık günlerde ağır kategori iş yükü oluştuğunda özel dinlenme sürelerinin çizelgelenmesi gerekmektedir. Problemin tam sayılı programlama modeli sunulmuştur. Açgözlü kurucu sezgisel algoritmalar ile kısa sürede elde edilen uygun çözümler hem üst sınır hem de sıcak başlangıç olarak tam çözüm yaklaşımında kullanılmıştır. Son olarak, çözüm yaklaşımlarının etkinliği farklı büyüklükteki örnek test problemleri kullanılarak karşılaştırılmış ve değerlendirilmiştir.

Anahtar Kelimeler: *Çizelgeleme, Ek Kaynaklar, Yüksek Multiplisite, Tam Sayılı Programlama, Açgözlü Kurucu Sezgisel.*

1. INTRODUCTION

Personnel scheduling has been studied extensively in the scheduling literature. The main reason for this is economic considerations, but another important reason is the inevitable changes in job characteristics and working rules over time. Organizations and companies must obey all the regulations on working time enforced by the authorities, as well as the direct or indirect costs of scheduling workforce. Therefore, all the restrictions enforced by government regulations, union agreements and company-specific rules must be taken into account in personnel scheduling.

There are different work regulations for different industries. The aviation industry probably has the most stringent policies and regulations regarding working hours due to the risks involved. Regulations on working hours and rest periods for pilots and flight crews are constantly monitored, particularly to reduce fatigue-related incidents. On the other hand, military aviation differs from civil aviation because of the different types of aircraft and the different purposes for which they are used. Thus, military pilots are subject to specific work and rest regulations. In this paper, we study the helicopter pilot scheduling problem with organization-specific work and rest regulations adapted from the Turkish Naval Air Force.

The study is organized as follows: Section 2 provides a brief literature review of the personnel scheduling problem, focusing on work and rest regulations. Section 3 presents the problem definition and integer programming model of the problem. Section 4 describes solution approaches including greedy heuristics and exact solution. Numerical experiments are performed in Section 5 to compare the solution approaches. Finally, Section 6 concludes the paper.

2. LITERATURE REVIEW

The personnel scheduling, or rostering, problem introduced by Dantzig in the 1950s has evolved over time (Dantzig, 1954; Bergh et al., 2013). The personnel scheduling problem is very diverse and can be classified according to different methods. Bergh et al. (2012) organized the personnel scheduling problem into 4 classification fields as follows: "personnel characteristics, decision delineation and shifts definitions", "constraints, performance measures and flexibility", "solution method and uncertainty incorporation" and "application area and applicability of research". Ozder et al. (2020) categorize the personnel scheduling problem according to the characteristics: "Days-off scheduling problem", "Shift scheduling problem", "The cyclic staffing problem", "Crew scheduling problem", "Operator scheduling problem". The constraints and solution methods of the operator scheduling problem are of primary interest in this paper.

The Nurse Scheduling Problem (also known as the Nurse Rostering Problem - NRP) is the problem of finding an optimal way to assign nurses to shifts takes the first place in the literature of personnel scheduling problem (Ozder et al., 2020). Burke et al. (2004) categorized NRP papers according to solution methods, constraints and performance measures. There are many different types of time-related constraints in the NRP. In addition to the time related constraints are enforced by government regulations and union agreements, there are also hospital-specific working rules. This gives some hospital administrators the flexibility to set and define the structure of the time related constraints.

The Driver Scheduling Problem (DSP) is another large area of research in the personnel scheduling. DSP consists of selecting a set of duties for the drivers or pilots of vehicles, (e.g., buses, trains, boats, or planes) for the transportation of passengers or goods (Portugal et al., 2009). The DSP can also be divided into sub-categories such as Bus Driver Scheduling Problem (BDSP), Truck Driver Scheduling Problem (TDSP).

Driver planning in road freight transportation is different from transportation in other areas -airlines, railways, mass transit and buses (Goel et al., 2012). All tasks to be performed by employees in regular shifts are determined from a given timetable (either flight, train, subway or bus) in which arrival times are fixed (Ernst et al., 2004), however, there is no regular shift in road freight transportation and arrival times are typically not fixed but can even be scheduled with some degree of freedom (Ernst et al., 2004). Even some of the studies combine Vehicle Routing Problem (VRP) and TDSP (Goel, 2009; Kok et al., 2010). Driving periods, breaks, and rest periods must be scheduled in TDSP according to the regulations. Regulations may vary country to country. The two most widely studied regulations in the literature are the US-TDSP for the United States of America (Goel & Kok, 2012) and the EU-TDSP for the European Union (Goel, 2009; Goel, 2010). For example, a driver cannot accumulate more than 11 hours of driving in the U.S. and 9 hours of driving in Europe between two consecutive daily rests. In addition, there may also be different company-specific rules that do not violate the rules of higher regulatory bodies in the same country.

The Crew Scheduling Problem (CSP) is another type of personnel scheduling problem which model is relatively different from the other personnel scheduling models. CSP and DSP are related problems. CSP appears in a number of transportation contexts such bus and rail transit, truck and rail freight transport, and freight and passenger air transportation similar to DSP. CSP particularly important in the transport sector in the airline industry and has received the most attention from both the industry and from the academic community (Ozder et al., 2020; Barnhart et al., 2003). The Airline Crew Scheduling Problem (ACSP) is one of the most comprehensive of crew scheduling applications in terms of economic size and impact. A large number of restrictive rules mandated by governing agencies (FAA in the US, EASA in the EU, DGCA in Türkiye), labor organizations and the airlines themselves make ACSP one of the hardest CSPs.

ACSP can be defined as the assignment of flight crew (cockpit and cabin) to scheduled flights, so as to ensure that the crew needed for all flights are covered. Due to the difficulty of solving the ACSP as one integrated problem, it is divided into two sub-problems: Crew Pairing Problem (CPP) and Crew Rostering Problem.

It is possible to give examples of personnel scheduling problem involving restrictions on working hours in other sectors. These constraints usually vary significantly between different organizations and these differences give rise to a wide variety of scheduling problems and models (Ernst et al., 2004). However, the impact of these constraints on the complexity has barely been studied (Bergh et al., 2013; Ozder et al., 2020). Brucker et al. (2011) underpin the theory of personnel scheduling, which unlike in traditional scheduling, needs theoretical studies on models and complexity.

On the other hand, in the vast majority of scheduling problems, only machines are considered as resources and limited additional resources, such as operators, tools, pallets and industrial robots are not taken into account (Pinedo, 1995; Ventura et al., 2003). An extensive amount of research has been done on pure personnel scheduling (independent of machine scheduling), but little research has been done on models that combine personnel scheduling with machine scheduling. Some more theoretical research has been done in other areas related to these types of problems, namely resource constrained scheduling (i.e., a limited number of personnel may be equivalent to a constraining resource) (Pinedo, 2022).

The Resource Constrained Scheduling Problem (RCSP) is a subclass of scheduling problems and is mostly related to the Project Scheduling domain. In other words, scheduling problems that deal with personnel or workforce constraints are referred to as Resource Constrained Project Scheduling Problems (RCPSP) (Pinedo, 2007; Artigues et al., 2008). Details of RCPSP are beyond the scope of this paper and the interested reader is referred to Brucker et al. (1999) and Hartmann and Briskorn (2010).

Considering operators as additional resources in machine or project scheduling problems is a variant of the personnel scheduling problem. The working hours of operators can be considered as *doubly constrained* additional resource (both renewable and non-renewable) according to the regulations. In EU-TDSP, the daily driving time shall not exceed 9 hours and the weekly driving time shall not exceed 56 hours (The harmonization of certain social legislation relating to road transport and amending Council Regulations (EEC) No 3821/85 and (EC) No 2135/98 and repealing Council Regulation (EEC) No 3820/85, Regulation 561/2006). Thus, the driver's working hours are renewable on a daily basis without violating break and rest period rules but not on a weekly basis. Similarly, in ACSP, the maximum daily flight time shall not exceed 6 hours and the maximum monthly flight time shall not exceed 110 hours for rotary wing aircrafts according to DGCA (SHT-6A.50, 2014). The flight planning department may prepare flight plans on a daily basis without exceeding the monthly flight limit considering rest periods.

Although similar in some aspects to the personnel scheduling problems mentioned above, the problem considered in this paper is related to helicopter pilot scheduling and has a new and different constraint structure from them. The working hours of pilots are considered as doubly constrained resource. The processing times of the jobs vary depending on the day period (daytime and nighttime), the fatigue coefficient is taken into account in the workload calculation and the workload is categorized as normal and heavy based on total daily working hours. Consecutive days of heavy category work and night work require special rest periods. We are not aware of any study that includes this constraint structure at the same time.

Scheduling problems tend to be NP-hard structure. There are many solution methods in the personnel scheduling literature. These are classified into mathematical programming categories such as integer programming, linear programming, dynamic programming and goal programming, or as constructive or improvement heuristics. Other categories are simulation, constraint programming and queuing (Bergh et al., 2013). The solution methods can also be combined to increase the efficiency of the approaches. The personnel scheduling problem can be modeled as a linear, integer or mixed integer programming model. Many of the studies are modeled as integer and mixed integer programming (Ozder et al., 2020). Unfortunately, linear integer programming often requires a large number of variables and it is difficult to find the optimal or feasible solution in a reasonable time.

Our problem is formulated as an integer programming model and we propose the exact solution approach using commercial solver (CPLEX) in this paper. To obtain faster solutions and improve the solution performance, greedy constructive algorithms are implemented which both set upper bounds and generate warm-start points for the exact solution.

3. PROBLEM DEFINITION

Our problem is a variant of the personnel scheduling problem with organization-specific constraints inspired by a real-life problem. The aim is to schedule the flights of helicopter pilots on a warship under specific work and rest regulations.

Navy planning is a comprehensive process and critical at every level -strategic, operational, and tactical. Navy planning can be applied whether conditions permit a lengthy, deliberate process or if the situation forces a compressed timeline (Navy Planning NWP 5-01, 2013). Navy planning staff has to consider several factors. These include the disposition and number of platforms such as ships, aircraft, weapons, and supplies. These platforms have different capabilities. While warships can operate at sea for long periods, helicopters (also known as rotary-wing aircraft) can operate for relatively short periods.

Maritime helicopters can embark on ships that have flight decks for shipboard helicopter operations such as patrol, surveillance, search and rescue (SAR), humanitarian support, transportation, anti-submarine warfare, anti-surface warfare. Warships can carry different numbers and types of helicopters depending on their size and capacity. Additionally, when flight crews using helicopters are taken into account, the problem arises in different configurations. For example; one helicopter one flight crew, one helicopter two flight crews, two helicopters three flight crews. Since the number of helicopters in fleets is limited, it is not an easy task to assign helicopters and flight crews to each warship. To make planning easier, it is assumed that each ship will have a helicopter and a crew where possible.

'*One helicopter one flight crew*' configuration is studied. For the sake of generalization, it is assumed that helicopters are machines, pilots are operators and missions are jobs. Since the helicopters can fly for about 2,5-5 hours due to their fuel capacity, the processing times of jobs are also limited. It is assumed that jobs are divided into a small number of sets and the processing time of all jobs in the same class is identical. In other words, jobs have a high multiplicity structure. The objective is to minimize the makespan. This problem can be denoted by $1/NR/C_{max}$ using the three field notation of Graham et al.(1979) where NR stands for "non-renewable resource". It is NP-hard in the strong sense (Gafarov et. al, 2011).

The problem has similarities to NRP, TDSP and ACSP but introduces new types of constraints. To the best of our knowledge, this is the first personnel scheduling problem that includes the following constraints at the same time.

- Categorization of total working hours per day
- Consecutive working and rest periods depending on the category of total working hours per day
- Fatigue coefficient for night-period work
- Effects of night-period work on daytime-period

3.1. Problem Formulation

Let n be the total number of jobs and let g be the number of job types. Each job type k has n_k jobs for $k = 1, 2, \dots, g$ with $\sum_{k=1}^{g} n_k = n$.

Indices and Sets:

$k \in K$: Set of job types
$j \in J$: Set of jobs
$J_k \subset J$: Subset of job type $k \in K$
$t, t' \in T$: Set of time periods
$d, d' \in \mathrm{D}$: Set of days
$T_d \subset \mathrm{T}$: Set of day periods $d \in D$
$T_d^{daytime} \subset \mathrm{T}$: Set of daytime-periods $d \in D$
$T_d^{night} \subset \mathrm{T}$: Set of nighttime periods $d \in D$

Parameters:

p_j : Processing time of job $\boldsymbol{j}$ $\left(p_j \in \mathbb{Z} \middle| 1 \leq p_j \leq 3\right)$
α : Fatigue coefficient for night-period work $(a \in \mathbb{R} \mid a \geq 1)$
L^{month} : Maximum total working hour per month
L^{day} : Maximum total working hour per day
L^{normal} : Maximum total working hour per day for normal category
L^{night} : Maximum total working hour per night
N^{night} : Maximum total number of jobs per night
$L^{daytime}$: Maximum total working hour per daytime if night job is done
N^{day} : Maximum total number of jobs per day
$N^{daytime}$: Maximum total number of jobs per daytime if night job is done
R^{night} : Uninterrupted rest period before night job
$R^{night'}$: Uninterrupted rest period after the last night job
R^{heavy} : Uninterrupted rest period after consecutive heavy category workload

β : Maximum number of consecutive days of heavy category workload

γ : Maximum number of repetition of consecutiveness of heavy category workload cycle

M : A large number

LB : Lower bound

UB : Upper bound

Decision Variables:

$$x_{jt} = \begin{cases} 1, & \text{if job } j \text{ starts at time } t, \\ 0, & \text{otherwise.} \end{cases}$$

$$y_{t} = \begin{cases} 1, & \text{if job } j \text{ starts at time } t, \\ 0, & \text{otherwise.} \end{cases}$$

$$c_{d} = \begin{cases} 1, & \text{if job } j \text{ starts at time } t, \\ 0, & \text{otherwise.} \end{cases}$$

$$q_{d} = \begin{cases} 1, & \text{if uninterrupted rest period starts on day } d \text{ after consecutive heavy workload,} \\ 0, & \text{otherwise.} \end{cases}$$

C_{max} = Makespan of the schedule (Completion time of the last job)

Integer Programming Model (IP):

$$Minimize \ C_{max} \tag{1}$$

Subject to

$$\sum_{t \in T} x_{jt} = 1 \qquad \forall j \in J \tag{2}$$

$$\sum_{t'=t}^{t+p_j-1} y_{t'} \geq p_j x_{jt} \qquad \forall j \in J, t \in \{1,2,\cdots,(|T| - p_j + 1)\} \tag{3}$$

$$\sum_{t\in T} y_t = \sum_{j\in J} p_j \tag{4}$$

$$\sum_{j\in J}\sum_{t'=t-p_j}^{t-1} x_{jt'} \leq 1 \qquad \forall j\in J, t\in\{1,2,\cdots,(|T|-p_j+1)\} \tag{5}$$

$$\sum_{t\in T_d^{night}} y_t \leq L^{night} \qquad \forall d\in D \tag{6}$$

$$\sum_{j\in J}\sum_{t\in T_d^{night}} x_{jt} \leq N^{night} \qquad \forall d\in D \tag{7}$$

$$\sum_{t\in T_d^{daytime}} y_t \leq L^{daytime} + (1-y_{t'})\left(L^{day}-L^{daytime}\right) \quad \forall d\in D,\ t'\in T_d^{night} \tag{8}$$

$$\sum_{j\in J}\sum_{t\in T_d^{daytime}} x_{jt} \leq N^{daytime} + \left(1-\sum_{j\in J} x_{jt'}\right)\left(N^{day}-N^{daytime}\right) \quad t'\in T_d^{night},\ \forall d\in D \tag{9}$$

$$R^{night}\left(1-x_{jt}\right) \geq \sum_{t'=t-R^{night}}^{t-1} y_{t'} \qquad j\in J, t\in T_d^{night}, \forall d\in D \tag{10}$$

$$R^{night'} y_t \leq \sum_{t'=t+1}^{t+R^{night'}} (1-y_{t'}) + \sum_{t'=t+1}^{d*24} y_{t'} \qquad \forall t\in T_d^{night}, \forall d\in D \tag{11}$$

$$\sum_{t\in T_d^{daytime}} y_t + \alpha \sum_{t\in T_d^{night}} y_t \leq L^{normal} + \left(L^{day}-L^{normal}\right) c_d \quad \forall d\in D \tag{12.a}$$

$$\sum_{t\in T_d^{daytime}} y_t + \alpha \sum_{t\in T_d^{night}} y_t \geq L^{normal}\ c_d + \varepsilon \qquad \forall d\in D \tag{12.b}$$

$$\sum_{d'=d-\beta+1}^{d} c_{d'} - \sum_{d'=d-\beta+1}^{d-1} q_{d'} \geq (\beta - 1) + q_d \quad \forall d \in \{\beta, \beta+1, \cdots, |D|\} \quad (13.a)$$

$$M(1-q_d) + M\left\{1 - \left(y_t - \sum_{t'=t+1}^{d*24} y_{t'}\right)\right\} \geq \sum_{t'=t+1}^{t+R^{heavy}} y_{t'} \quad (13.b)$$

$$t_d \in \{24(d-1) + L^{normal} + 1, 24(d-1) + L^{normal} + 2, \cdots, 24d\}, \forall d \in D$$

$$q_d = 0 \quad \forall d \in \{1, \cdots, \beta - 1\} \quad (13.c)$$

$$q_d \leq c_{d'} \quad \forall d \in \{\beta, \beta+1, \cdots, |D|\}, d' \in \{d-\beta+1, d-\beta+2, \cdots, d\} \quad (13.d)$$

$$\sum_{d'=d}^{d+\beta-1} q_{d'} \leq 1 \quad \forall d \in \{1,2,3, \cdots, |D| - \beta + 1\} \quad (13.e)$$

$$\sum_{d \in D} q_d \leq \gamma \quad (14)$$

$$\sum_{t \in T_d^{daytime}} y_t + \alpha \sum_{t \in T_d^{night}} y_t \leq L^{month} \quad \forall d \in D \quad (15)$$

$$(p_j + t)\, x_{jt} \leq C_{max} \quad \forall j \in J, \forall t \in \{1,2, \cdots, |T| - p_j + 1\} \quad (16)$$

$$LB \leq C_{max} \leq UB \quad (17)$$

$$C_{max} \in \mathbb{Z}^+ \quad (18)$$

$$x_{jt} \in \{0,1\} \quad \forall j \in J, \forall t \in T \quad (19)$$

$$y_t \in \{0,1\} \quad \forall t \in T \quad (20)$$

$$c_d \in \{0,1\} \quad \forall d \in D \quad (21)$$

$$q_d \in \{0,1\} \quad \forall d \in D \quad (22)$$

As seen from the mathematical model our problem is formulated as an integer linear programming model. The objective function (1) minimizes the makespan, in other words, completion time of the last job. Constraint (2) requires that all jobs must be scheduled. Constraint (3) ensures that the operator is busy during the processing time. Constraint (4) imposes that the operator cannot be busy more than total processing time of jobs. Constraint (5) ensures that at most one job can be processed at any point in time. Constraint (6) limits total processing time of night jobs and Constraint (7) limits the total number of night jobs. Constraint (8) defines the maximum total working hour per daytime and Constraint (9) defines the maximum total number of jobs per daytime if night job is done. Constraint (10) enforces the minimum uninterrupted rest period before night job and Constraint (11) enforces the minimum uninterrupted rest period after the last night job. Constraints (12.a) and (12.b) determine the daily workload (normal or heavy) while defining the daily maximum total working hour. Constraint (13) enforces the minimum uninterrupted rest period after the consecutive heavy category workload. Constraint (13.a) determines the day that uninterrupted rest period starts after the consecutive heavy category workload while Constraint (13.b) determines the hour. Constraints (13.c), (13.d) and (13.e) are the technical constraints related to heavy category workload days and their consecutiveness. Constraint (14) limits the maximum number of repetition of consecutiveness of heavy category workload cycle. Constraint (15) defines the monthly maximum total working hour. Constraint (16) is used to compute the makespan within the lower bound and upper bound specified in Constraint (17). The calculation of the lower bound and upper bound values will be explained in detail in the next section. Constraints (18) - (22) declare decision variable domains. All of the decision variables except C_{max} are binary variables.

Assumptions:

The time unit is one hour and the scheduling horizon is up to one month. One month has 30 days and one day has 24 hours. Day is the period from sunrise to sunrise the next day. Daytime is the period between sunrise and sunset, night is the period between sunset and sunrise. Daytime and night equal 12 hours every day for simplicity. All of the parameter values except from fatigue coefficient α are positive integers. Due to operating restrictions of the machine, there are three job type according to deterministic processing times (1, 2 and 3 hour). The schedule is empty and all the jobs are available at time zero. There are no *machine non-availability* (MNA) and *operator non-availability* (ONA) intervals. The machine and the operator are available throughout the scheduling period without violating work and rest regulations. The machine can process only one job at a time. No preemption is allowed. A job, once taken up, is fully completed before the next is taken.

4. SOLUTION APPROACHES

Basically, we propose exact solution approach using commercial solver (CPLEX) to our integer programming problem. As a result of discretizing time, the model creates huge number of variables depending on size of the problem. So determining cardinality of time set $(|T|)$ is a critical step. Two greedy constructive heuristics that adapted from Offline Bin Packing Problem (BPP) algorithms have been used for this step. As it is known, computationally BBP is NP-hard and for this reason many approximation algorithms developed for getting faster solutions. Solutions from the heuristic approaches set both the upper bound and warm-start point for exact solution approach.

4.1. Greedy Constructive Heuristics

Days can be considered as bins and the capacities of the bins can be defined as working hours. *First-fit-decreasing (FFD)* and *First-fit-increasing (FFI)* algorithms are adapted for constructing feasible solution without violating work and rest regulations.

4.1.1. Greedy Constructive Heuristic (GR1)

In $GR1$ the capacity of bins is the maximum total working hour per day for normal category (L^{normal}). If operator works for normal category each day, constraints related to heavy workload category become redundant, just as the constraints related to consecutiveness become redundant. Certainly, this increases the planning horizon and provides bad objective function value (C_{max}). The reason for overestimating the planning horizon is to investigate whether it has an impact on warm-start approach. The pseudocode of the $GR1$ is given in Algorithm 1.

List of jobs can be sorted according to the two different ordering criteria: descending and ascending. So, two upper bound values $(UB[GR1^{dec}], UB[GR1^{inc}])$ and two solution sets $(sol[GR1^{dec}], sol[GR1^{inc}])$ can be obtained. Minimum of the upper bounds and its associated solution is chosen C_{max} for $GR1$ using Equation (23).

$$GR1_{Cmax} = min(UB[GR1^{dec}], UB[GR1^{inc}]) \tag{23}$$

4.1.2. Greedy Constructive Heuristic (GR2)

In $GR2$ the capacity of bins is the maximum total working hour per day for heavy category (L^{heavy}). But for this time, constraints related to night jobs and heavy workload category step in. Algorithm 1 is modified to check solution feasibility as each job is scheduled. The modified algorithm also produces two upper bound values $(UB[GR2^{dec}], UB[GR2^{inc}])$ and two solution sets $(sol[GR2^{dec}], sol[GR2^{inc}])$ according to the ordering criteria. Minimum of the upper bounds and its associated solution is chosen C_{max} for $GR2$ using Equation (24).

$$GR2_{Cmax} = min(UB[GR2^{dec}], UB[GR2^{inc}]) \tag{24}$$

$GR2$ mostly has better objective function values than $GR1$ and provides tighter upper bounds. In exceptional problem instances, $GR2$ cannot find a feasible solution in a monthly planning horizon. This is one of the already known side effects of the greedy approach.

Algorithm 1: $FFD_{L^{normal}}$. Pseudocode of $GR1$ for determining upper bound and solution for warm-start.

Input: List of jobs sorted in *decreasing* order according p_j, L^{normal}
Output: $|T|, sol$

```
1  sol ← ∅
2  d ← 1
3  workload(d) ← 0
4  for each job j ∈ J do
5      for each d ∈ D do
6          if workload(d) ≤ L^normal
7              for each t ∈ T^d do
8                  if Σ_t^{t+p_j−1} y_t = 0 and t + p_j − 1 < d * 24 then
9                      if p_j + workload(d) ≤ L^normal then
10                         x_jt = 1
11                         sol.insert(x_jt)
12                         workload(d) ← p_j + workload(d)
13                         break
14                     end if
15                 end if
16             end for
17         end if
18         if |sol| = j then
19             break
20         end if
21     end for
22     if |sol| < j then
23         |D| ← |D| + 1      //add new day
24         goto line 5
25     end if
26 end for
```

4.2. Exact Solution Approach

The exact solution approach (IP) is applied in four configurations using the output of the greedy constructive heuristics $GR1$ and $GR2$ as shown in Table 1.

Table 1. *Exact Solution Configurations.*

Name	Description
$IP1$	$GR1_{Cmax}$ is used for *Upper Bound* value
$IP2$	$GR2_{Cmax}$ is used for *Upper Bound* value
$WS1$	$sol(GR1_{Cmax})$ is used as solution set for *Warm-Start* point
$WS2$	$sol(GR2_{Cmax})$ is used as solution set for *Warm-Start* point

It is observed that the solver cannot reach a feasible solution for large-size problem instances in reasonable computational times. It spends much time on presolving the model and solving the root node linear programming (LP) relaxation. To overcome this problem, lower bound (LB) and upper bound (UB) values are calculated and the warm-start technique is applied to the exact solution approach. As known, warm-start may sometimes improve the performance of the solver even though it is not guaranteed. The performance comparison of the exact solution configurations is presented in the computational experiments section.

Assuming that no rest period is allowed and operator can work heavy category every day, a safe lower bound (LB) has been formulated in Equation (25).

$$LB = \left\lfloor \left(\left\lceil \frac{\sum p_j}{L^{day}} \right\rceil - 1 \right) * 24 + \left\{ \sum p_j - \left[\left(\left\lceil \frac{\sum p_j}{L^{day}} \right\rceil - 1 \right) * L^{day} \right] \right\} \right\rfloor \tag{25}$$

5. COMPUTATIONAL EXPERIMENTS

We have performed computational experiments to compare the performance of the solution approaches. Since the problem is organization-specific and involves custom constraints, there are no available datasets in the literature for benchmarking purposes. Therefore, test instances are simply generated by randomly selecting a number of jobs for each job type. The naming convention for the test instances is shown in Figure 1.

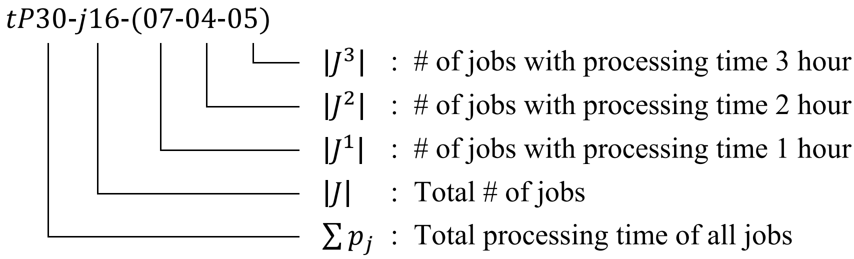

Figure 1. *Test instance naming convention.*

Depending on the number of jobs in each job type, there may be test instances with the same total processing time but different total number of jobs, and test instances with the same total number of jobs but different total processing time. $tP30$-$j10$-(00-00-10) have the same total processing time but different total number of jobs with $tP30$-$j16$-(07-04-05). $tP40$-$j16$-(02-04-10) have different total processing time but the same total number of jobs with $tP30$-$j16$-(07-04-05). The values of the parameters used in the experiments are given in Table 2.

Table 2. *Parameter values for experiments.*

α	=	1.5	N^{day}	=	8	R^{heavy}	=	24
L^{month}	=	60	$N^{daytime}$	=	3	β	=	2
L^{day}	=	8	N^{night}	=	2	γ	=	2
L^{normal}	=	5	R^{night}	=	2			
L^{night}	=	3	$R^{night'}$	=	8			

Greedy constructive heuristic algorithms are coded using the C# programming language in the Visual Studio 2022 platform. All of the IP models are coded and solved using IBM ILOG CPLEX 22.1 with default optimality gap settings of (0.01%) and a CPU time limit of one hour. Each test instance was solved in 4 configurations; $IP1$ and $IP2$ with the same lower bound but different upper bounds, $WS1$ and $WS2$ with different warm-start points. Both the greedy heuristic algorithms and CPLEX are run on an Intel i7 2.2 GHz 8 GB RAM computer.

Computational results are shown in Table 3. The table is divided into eight main columns. The first main column is the name of the test instance. The second main column is the LB value. The third and fourth main columns show the solutions (UB) and the computation time of the greedy constructive algorithms $GR1$ and $GR2$. The remaining four columns show the solution (C_{max}), computation time (t) and gap (g) values for the exact solution configurations $IP1$, $IP2$, $WS1$ and $WS2$, respectively. The solution values are in hours, the computation time values are in seconds and the gap values are in percent. The star symbol near C_{max} values indicates optimal solutions. The dagger symbol in the computation time columns indicates that the solver was interrupted and no optimal solution was found within the time limit. Lastly, the double dagger symbol in C_{max} columns means that no solution was found within the time limit.

The computation times of $GR1$ and $GR2$ are less than one second. For small-size problems, all exact solution approaches show almost similar performance in finding the optimal solution in a relatively short time. For long total processing time problems consisting of long processing time jobs, although the total number of jobs is relatively small, the optimal solution is not found within the time limit. As the total processing time of the jobs increases the solver fails to find an optimal solution. As expected, in large-size problems, the constraints related to consecutive heavy category workload and rest periods start to activate.

$IP2$ shows relatively better performance than $IP1$. Tight upper bounds obtained by $GR2$ seem to help improve the solution. However, sometimes, as in problem instance $tP48\text{-}j16(00\text{-}00\text{-}16)$, $IP2$ cannot find a solution while $IP1$ finds a solution with a looser upper bound. When tight upper bounds are set for problem instances consisting of all or most of the jobs with the longest processing time, the solver has difficulty finding a feasible solution.

$WS1$ and $WS2$ show similar performance. So, the warm-start technique does not seem to provide a very significant improvement in computational efficiency. However, it at least provides a feasible solution where no solution can be found in a reasonable time.

Table 3. *Computational results.*

Instance	LB	$GR1$		$GR2$		$IP1$			$IP2$			$WS1$			$WS2$		
		UB	t	UB	t	c_{max}	t	g	c_{max}	t	g	c_{max}	t	g	c_{max}	t	g
tP40-j40(40-00-00)	104	173	0.003	**132**	0.016	**126***	542	0.00	**126***	653	0.00	**126***	**444**	0.00	**126***	1188	0.00
tP40-j20(00-20-00)	104	220	0.003	**124**	0.013	**124***	1418	0.00	**124***	**525**	0.00	**124***	1175	0.00	**124***	2400	0.00
tP40-j14(01-00-13)	104	291	0.003	**150**	0.014	171	†	26.90	‡	†	-	**150**	†	18.00	**150**	†	14.00
tP40-j20(05-10-05)	104	173	0.003	**125**	0.015	**124**	†	0.81	125	†	0.80	**124**	†	0.81	**124**	†	0.81
tP40-j22(10-06-06)	104	173	0.003	**145**	0.017	125	†	1.61	125	†	5.67	**124**	†	2.42	**124**	†	2.42
tP48-j48(48-00-00)	128	219	0.003	**152**	0.018	**151**	†	0.66	**151***	2149	0.00	**151***	**649**	0.00	**151***	1592	0.00
tP48-j24(00-24-00)	128	268	0.003	**152**	0.014	**152**	†	1.97	**152***	1900	0.00	**152**	†	1.97	**152**	†	1.97
tP48-j16(00-00-16)	128	363	0.003	**198**	0.014	**198**	†	22.73	‡	†	-	**198**	†	22.22	**198**	†	23.74
tP48-j24(08-08-08)	128	219	0.003	**169**	0.017	**151**	†	2.65	**151**	†	1.99	**151**	†	2.65	**151**	†	2.65
tP60-j60(60-00-00)	172	269	0.003	**199**	0.021	**198**	†	1.01	**198***	**1724**	0.00	**198**	†	0.51	**198***	2870	0.00
tP60-j20(00-00-20)	172	459	0.003	**723**	0.017	**267**	†	7.12	723	†	76.21	**267***	**520**	32.99	723	†	76.21
tP60-j30(00-30-00)	172	**340**	0.003	722	0.016	220	†	20.45	243	†	29.22	**200**	†	2.00	218	†	21.10
tP60-j30(10-10-10)	172	269	0.003	**218**	0.022	**198**	†	2.02	**198**	†	2.02	200	†	3.00	200	†	3.00

* Optimal. † Run terminated after 1 hour. ‡ No solution found in 1 hour.

6. CONCLUSION

In this paper, we consider workload dependent resource constrained scheduling problem with organization-specific work and rest regulations. The problem has custom constraints different from other personnel scheduling problems.

Exact solution approach using the commercial solver (CPLEX) is proposed to solve the problem. Due to its NP-hardness of the problem, the solver could not yield an optimal solution within a reasonable solution time, especially for large-size problem instances. In order to obtain faster solutions, we implemented modified versions of the greedy constructive heuristic algorithms for the BPP. The solutions obtained from the heuristics are used as upper bounds as well as warm-start points for the exact solution approach. Heuristic algorithms are able to find feasible solutions in a very short time. The warm-start technique does not significantly improve the performance, but may provide a feasible solution for some of the problem instances where the solver cannot.

The performance of the exact solution is affected by the distribution of high multiplicity. Although problem instances have the same total processing time, the solver cannot find a feasible solution for some of them. This is also the case for the problem instances that have the same number of jobs with different total processing times. When real data is available and the high multiplicity distribution is known, the effectiveness of the solution approaches can be evaluated more realistically by running the problem instances with real data.

Planners can use this study to determine how the schedule will be affected by changing parameter values, such as increasing workload category limits or reducing rest periods. Further studies can be addressed to investigate other solution approaches (metaheuristics, constraint programming, etc.) for this problem and to consider other machine-operator configurations such as 'one machine n operator', 'm machine n operator'.

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YAZIM KURALLARI

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Etik İlkeler ve Yayın Politikası

Deniz Bilimleri ve Mühendisliği Dergisi (Bundan sonra DBMD olarak anılacaktır.); uluslararası düzeyde, hakemli, çok disiplinli, 2003 yılından bu yana yılda iki kez yayınlanan, bilim ve teknoloji dergisidir. DBMD yayın etiğinde en yüksek standartların, editoryal ve hakemlik süreçlerinin kilit unsuru olarak değerlendirildiği bir platform sunmayı taahhüt etmektedir.

DBMD'ne gönderilen her bir makale için değerlendirme sürecinde çift-kör hakemlik sistemi uygulanmaktadır. Buna göre, değerlendirme süreci boyunca hakem ve yazarlar birbirlerinin bilgilerini görememektedir. Dergiye gönderilen çalışmaların yazar-hakem ve hakem-yazar açısından süreçlerinde gizlilik esastır. DBMD'ne gönderilen makalelerin değerlendirme sürecindeki inceleme aşamasında kabul edilmeleri halinde, ilgili makaleler için düzenleme aşamasına geçilmektedir. Düzenleme aşamasında, ilgili makaleler yazım formatı ve dilbilgisel yönlerden incelenir. Makalelerin sayfalar üzerindeki biçimi ve yerleşimleri kontrol edilip düzenlenir. Ayrıca referans kontrolü yapılır. DBMD'nde kontrol edilen ve düzenlenen makaleler gizli tutulmaktadır.

DBMD'ne gönderilen makaleler, Yayın Kuralları sayfasında belirtilen kriterlere ilişkin, intihal tespit programı aracılığıyla kontrol edilir. Editörler, kanıtlanmış bir bilimsel kötü kullanımdan ya da usulsüzlükten haberdar olurlarsa bu konuda gerekli adımları atabilirler. Bu anlamda, Editörler gerekli durumlarda DBMD'ne gönderilen ya da DBMD'nde yayınlanmış makaleleri geri çekme hakkına sahiptir.

Düzenleme aşamasının başarılı olarak sonuçlanmasını takiben, ilgili makaleler DBMD'nin bir sayısında yayınlanmak üzere saklı tutulur ve kayıt altına alınır. DBMD'ne yayınlanmak üzere gönderilen makaleler; yazılı materyal gönderme, işleme ve yayınlama süreçlerindeki tüm ücretlerden muaf tutulmaktadır. DBMD'nde yayınlanmak üzere kabul edilen makaleler, derginin internet sitesinden çevrimiçi olarak ücretsiz bir şekilde yayınlanır ve basılır. Dergide yayınlanması kabul edilen çalışmalar, derginin web sitesinden açık erişim ile erişilebilir kılınmıştır. Dergi ayrıca, Milli Savunma Üniversitesi, Deniz Harp Okulu Matbaası tarafından basılmaktadır.

DBMD; editörü ve en az beş değişik üniversitenin öğretim üyelerinden oluşmuş danışman grubu ile açık erişim politikasını benimsemektedir. Buna göre, tüm içerikler ücretsiz olarak kullanıcılar veya kurumlar için ulaşılabilirdir. Kullanıcıların DBMD bünyesindeki makalelerin tam metinlerini okuma, indirme, kopyalama, dağıtma, yazdırma, arama veya bunlara bağlantı verme ve diğer yasal araştırma amaçları için kullanma hakları saklı tutulmaktadır.

DBMD'nin yayın etiği, temel olarak Yayın Etiği Komitesi (COPE), Dünya Mühendislik Kuruluşları Federasyonu (WFEO), Bilim Kurulu Editörleri (CSE) ve Elsevier'in Editörler için Yayın Etiği açıklamaları kapsamında yayınlanmış yönergelere ve önerilere dayanmaktadır.

Editörler, yazarlar ve diğer taraflar da dâhil edilebilecek şekilde yayın sürecindeki görev ve sorumluluklar aşağıdaki gibi tanımlanmıştır.

Yazarların Sorumlulukları:

-Yazarlar, dergide yayınlanan makalelerinin bilimsel, bağlamsal ve dilsel yönlerinden sorumlu tutulmaktadır. Dergide ifade edilen veya ima edilen görüşler, aksi belirtilmediği sürece, Enstitünün resmi görüşü olarak yorumlanamaz ve yansıtılamaz.

-Yazarlar çalışmalarında, DBMD'nin DergiPark internet sayfasında yer alan "Yazım Kuralları"nı dikkate almalıdır.

-Yazarlar araştırmalarını etik ve sorumlu bir şekilde yürütmeli ve ilgili tüm mevzuatları takip etmelidir.

-Yazarlar çalışmaları ve yayınlarının içeriği için ortak sorumluluk almalıdır.

-Yazarlar, yöntemlerin ve bulguların doğru bir şekilde raporlandığından emin olmak için yayınlarını her aşamada dikkatlice kontrol etmelidir.

-Yazarlar, başkalarına ait çalışmaları dolaylı alıntı, doğrudan alıntı ve referanslar ile doğru bir şekilde göstermelidir. Yazarlar, makalelerindeki fikirlerin şekillendirilmesinde etkili ya da bilgilendirici olmuş her türlü kaynağa referans vermelidir.

-Yazarlar çalışmalarındaki hesaplamaları, ispatları, veri sunumlarını ve yazı tiplerini dikkatlice kontrol etmelidir.

-Yazarlar çalışmalarının sonuçlarını dürüstçe; uydurma, çarpıtma, tahrifat veya uygunsuz manipülasyona yer vermeden sunmalıdır. Çalışmalardaki görsel kaynaklar yanıltıcı bir şekilde değiştirilmemelidir.

-Yazarlar, çalışmalarındaki bulguları açık ve net bir şekilde sunmak için araştırma yöntemlerini tanımlamalı ve paylaşmalıdır.

-Yazarlar, yayınlanmış makalelerinin telif haklarını DBMD yayıncısına devrettiklerini kabul etmektedir.

-Yazarlar çalışmalarına çeşitli görsel kaynakları, figürleri, şekilleri vb. dahil etmek için gerekli izinleri almakla yükümlüdür. İlgili çalışmada yer alması gereken resim, şekil vb. anlatımı destekleyici materyaller için gerekli kişilerden ya da kurumlardan izin alınması yazarın sorumluluğundadır.

-Çok yazarlı yayınlarda -aksi belirtilmedikçe- yazar sıralamaları sunulan katkılara göre yapılmalıdır.

-Yazarlar gönderdikleri çalışmada herhangi bir hata tespit ederlerse bu konuda derhal editörü uyarmalıdır.

-Yazarlar dergiye gönderdikleri makalelerin başka bir yerde yayımlanmamış ya da yayımlanmak üzere gönderilmemiş olmaları ile ilgili DBMD'nin DergiPark internet sayfasında yer alan "Yayın Kuralları"nı dikkate almalıdır.

-Yazarlar, ilgili çalışmaları DBMD'nde yayınlandıktan sonra hata tespit ederlerse bu konuda gerekli düzeltmelerin yapılabilmesi amacıyla derhal editör veya yayıncı ile iletişime geçip onlar ile birlikte çalışmalıdır.

-İlgili çalışmada, doğası gereği kullanımlarında olağandışı tehlikeler barındıran çeşitli kimyasallar veya ekipmanlardan yararlanılmış ise yazarların tüm bunları çalışmasında açıkça belirtmesi ve tanımlaması gerekmektedir.

-İnsanlar ve hayvanların katılımını gerektiren çalışmalar için, yazarlar tüm sürecin ilgili yasalara ve kurumsal yönergelere uygun olarak gerçekleştirildiğinden emin olmalıdır ve ilgili komitelerden etik onay alındığını çalışmalarında açık bir şekilde ifade edip belgelendirmelidir.

-İnsanların katılımını gerektiren çalışmalar için, yazarlar kurumsal etik kurul onayı almakla yükümlüdürler. Yazarlar, katılımcıların süreç ile ilgili olarak bilgilendirildiklerini ve bu anlamda, katılımcılardan gerekli izinlerin alındığını bildirmek ve belgelemek zorundadır. Yazarlar, katılımcıların haklarının gözetildiğini açıklayan açık bir bildirim sunmalıdır. Ayrıca bu süreçte, katılımcıların gizlilik hakları her zaman korunmalıdır.

-Yazarlar, hakemlerin değerlendirmelerini, yorumlarını ve eleştirilerini zamanında ve işbirliği içerisinde dikkate almalıdır ve bu konuda, gerekli güncellemeleri yapmalıdır.

Hakemlerin Sorumlulukları:

-Hakem değerlendirme sürecinin iki temel amacı vardır: İlk amaç, ilgili makalenin DBMD'nde yayınlanıp yayınlanamayacağına karar vermektir ve ikinci amaç, yayından önce ilgili makalenin eksik yönlerinin geliştirilmesine katkıda bulunmaktır.

-DBMD'ne gönderilen her bir makale için değerlendirme sürecinde çift-kör hakemlik sistemi uygulanmaktadır. Buna göre, değerlendirme süreci boyunca hakem ve yazarlar birbirlerinin bilgilerini görememektedir. Dergiye gönderilen çalışmaların yazar-hakem ve hakem-yazar açısından süreçlerinde gizlilik esastır.

-Hakemler, değerlendirme sürecinin gizliliğine saygı göstermelidir.

-Hakemler, değerlendirme sürecinde elde ettikleri bilgileri kendilerinin veya başkalarının çıkarları için kullanmaktan kaçınmalıdır.

-Hakemler, değerlendirme sürecinde yazar(lar)ın kimliğinden şüphe etmeleri ve bu bilginin herhangi bir potansiyel rekabet veya çıkar çatışması yaratacağını düşünmeleri halinde mutlaka DBMD ile iletişime geçmelidir.

-Hakemler, değerlendirme sürecinde şüphe ettikleri potansiyel rekabet veya çıkar çatışması durumlarını DBMD'ne bildirmelidir.

-Hakemler, uygun bir değerlendirme yapabilmek için gereken uzmanlığa sahip oldukları, çift-kör hakemlik sisteminin gizliliğine riayet edebilecekleri ve değerlendirme süreci ile ilgili detayları gizli tutabilecekleri çalışmaların hakemliğini kabul etmelidir.

-Hakemler makaleyi, ek dosyaları ve yardımcı materyalleri incelemelerini takiben bazı eksik belgelere ihtiyaç duymaları halinde bunları talep etmek üzere DBMD ile iletişime geçmelidir.

-Hakemler dergide yayınlanacak makalelerin akademik kalitesinin en temel tespit edicisi olduklarının bilinciyle davranmalı ve akademik kaliteyi arttırma sorumluluğuyla inceleme yapmalıdır.

-Hakemler, Etik İlkeler ve Yayın Politikası ile ilgili herhangi bir usulsüzlük tespit etmeleri halinde DBMD editörleri ile irtibata geçmelidir.

-Hakemler, kendilerine tanınan süre içerisinde makaleleri değerlendirmelidir. Şayet uygun bir zaman içerisinde değerlendirme yapamayacaklarsa, bu durumu en kısa zamanda DBMD'ne bildirmelidirler.

-Hakemler, değerlendirme sürecindeki çalışma için kabul etme / yeniden gözden geçirme / reddetme şeklindeki önerilerini DBMD tarafından sağlanan Hakem Değerlendirme Formu aracılığıyla bildirmelidir.

-Sonucu reddetme şeklinde olan değerlendirmeler için hakemler, ilgili çalışmaya dair eksik ve kusurlu hususları Hakem Değerlendirme Formu'nda açık ve somut bir şekilde ortaya koymalıdır.

-Hakem değerlendirme raporlarının, DBMD tarafından sağlanan Hakem Değerlendirme Formu'na uygun biçimde ve içerikte hazırlanması ve gönderilmesi gerekmektedir.

-Hakem değerlendirme raporları adil, objektif, özgün ve ölçülü olmalıdır.

-Hakem değerlendirme raporları, ilgili makale ile ilgili yapıcı eleştiriler ve tavsiyeler içermelidir.

Editörlerin Sorumlulukları:

-Editörler, derginin bilimsel kalitesini arttırmak ve yazarları bilimsel kalitesi yüksek araştırmalar üretmek için desteklemek ile sorumludur. Hiçbir koşulda, intihal ya da bilimsel kötüye kullanıma izin verilmemektedir.

-Editörler, dergiye gönderilen her çalışmanın çift-kör hakemlik sürecine ve diğer editoryal süreçlere tabi olmasını sağlamaktadır. DBMD'ne gönderilen her çalışma, çift-kör hakemlik sürecine ve nesnel değerlendirmeye dayalı editör kararına bağlı tutulmaktadır.

-DBMD'ne gönderilen her bir çalışma, uygunlukları açısından editör tarafından değerlendirilir ve daha sonrasında, incelenmesi ve değerlendirilmesi amacıyla en az iki uzman hakeme gönderilir.

-Editörler, yazarlar ile çıkar çatışması olmayan hakemleri, çalışmayı değerlendirmek üzere atamakla sorumludur. Çift-kör hakemlik süreci, editör için değerlendirme ve düzenleme aşamalarında katkı sağlamaktadır.

-Editörler, DBMD'ne gönderilen tüm çalışmaların ön kontrol, tarama, intihal kontrolü, değerlendirme ve düzenleme aşamalarından geçmesini sağlar. Editörler iddia edilen veya kanıtlanmış bilimsel kötü kullanımdan haberdar olurlarsa makaleyi geri çekebilirler. Editörler, gerekli durumlarda gönderilen çalışmayı düzeltme, geri çekme veya çalışma hakkında özür yayınlama hakkına sahiptir.

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