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GREEN LINER SHIP ROUTING AND SCHEDULING OPTIMIZATION WITH TIME WINDOWS UNDER ADDED RESISTANCE EFFECTS OF SEVERAL WEATHER CONDITIONS

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(ZAMAN PENCERELERİ VE ÇEŞİTLİ HAVA ŞARTLARININ EK DİRENÇLERİ ETKİSİNDE YEŞİL SABİT HAT GEMİ ROTALARININ VE ÇİZELGELERİNİN OPTİMİZASYONU)

by

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LIST OF SYMBOLS

CO_2	: Carbon dioxide
COG	: Course Over Ground
ECA	: Emission Control Area
EEDI	: Energy Efficiency Design Index
EEOI	: Energy Efficiency Operational Indicator
GHG	: Greenhouse gases
GSRSP	: Green Ship Routing and Scheduling Problem
HFO	: Heavy Fuel Oil
IMO	: International Maritime Organization
MARPOL	: International Convention for the Prevention of Pollution from Ships
MGO	: Marine Gas Oil
MILP	: Mixed Integer Linear Programming
MTZ	: Miller-Tucker-Zemlin Subtour Elimination Constraints
NO_x	: Nitrogen Oxide
PM	: Particulate Matter
RQ	: Research Question
SCI-E	: Science Citation Index-Expanded
SEC	: Subtour Elimination Constraints
SFOC	: Specific Fuel Oil Consumption
SEEMP	: Ship Energy Efficiency Management Plan
SO_x	: Sulphur Oxides
SOG	: Speed Over Ground
STW	: Speed Through Water
TEU	: Twenty-foot Equivalent Unit
TSP	: Traveling Salesman Problem
UN	: United Nations
UNCTAD	: United Nations Conference on Trade and Development
VLSFO	: Very Low Sulphur Fuel Oil
VRP	: Vehicle Routeing Problem
WoSCC	: Web of Science Core Collection

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ABSTRACT

Maritime transportation is the most preferable method for shipping large volumes of commodities even though it is slower compared to other modes of transportation. Globalizing trade resulted in maritime transportation to become one of the foundational pillars of international trade. Technological advances in ship building and introduction of containers standardized cargo carriage reduced cost and increased efficiency and, hence competition among shipping companies. Gaining competitive advantage requires minimum transportation time, hence, container ships are also designed for speed, at the cost of environmental damage, meanwhile not conforming with the environmental regulations. Fuel consumption of ships and greenhouse gas (GHG) emissions increases each year, thus new concepts such as green vehicle routing surface to mitigate or more conveniently adapt to the decarbonization policies. This study aims to propose a methodology for liner shipping companies adopting short sea shipping that revises shipping routes to minimize fleet fuel consumption and Carbon Dioxide (CO_2) emissions. A mixed integer linear programming model has been developed including port time windows and cargo demand. The proposed methodology considers involuntary speed loss caused by added resistance of winds and waves. As a case study, Black Sea has been chosen. Static weather grids have been applied on to Black Sea for efficiently calculating involuntary speed loss in detail for estimating average speed over ground throughout the voyage depending on the seasons. Numerical experiments have been carried out for evaluating viability and reliability of the proposed MILP model. Proposed model's optimum values and routes have been compared to the original system CO_2 emissions derived from a container shipping company's routes. Significant improvements have been observed regarding CO_2 emissions and fuel consumption, while effect of added resistances causes differences on seasonal routes. Significant efforts have been performed for decarbonization over the years. Accurate modelling of ship routes with green approaches will yield both financial and environmental benefits in the near future.

ÖZET

Deniz taşımacılığı, diğer yöntemlere göre göre daha yavaş olmasına rağmen, büyük hacimli malların taşınması için en çok tercih edilen yöntem olarak kabul edilmektedir. Küreselleşen ticaret, deniz taşımacılığının uluslararası ticaretin temel direklerinden biri haline gelmesini sağladı. Gemi inşasındaki teknolojik gelişmeler ve konteynerlerin standartlaştırılmış kargo taşımacılığının tanıtılması maliyeti azaltmış, verimliliği ve denizcilik şirketleri arasındaki rekabeti artırmıştır. Avantaj elde etmek süreye bağlı olduğundan konteyner gemileri de hız için tasarlanırken, aynı zamanda çevresel zarara sebep olmakta, çevre düzenlemelerine de uymamaktadır. Gemilerin yakıt tüketimi ve sera gazı (GHG) emisyonları her yıl artmaktadır. Bu nedenle, dekarbonizasyon politikalarına uyum sağlamak için yeşil araç rotalama gibi yeni kavramlar ortaya çıkmaktadır. Bu çalışmada, filo yakıt tüketimini ve Karbon Dioksit (CO2) emisyonlarını en aza indirmek için denizcilik rotalarını revize eden kısa deniz taşımacılığını benimseyen denizyolu taşımacılığı şirketleri için bir metodoloji önermek amaçlanmaktadır. Liman zaman pencerelerini ve kargo talebini içeren bir karma tamsayılı doğrusal programlama modeli geliştirilmiştir. Önerilen metodoloji, rüzgâr ve dalgaların ilave direncinin neden olduğu istemsiz hız kaybını dikkate almaktadır. Vaka çalışması olarak Karadeniz seçilmiştir. Mevsimlere bağlı olarak seyir boyunca karaya göre ortalama hızı tahmin etmek ve istem dışı hız kaybını verimli bir şekilde ayrıntılı olarak hesaplamak için Karadeniz'e statik hava etkisi hücreleri uygulanmıştır. Önerilen modelin uygulanabilirliğini ve güvenilirliğini değerlendirmek için sayısal deneyler yapılmıştır. Önerilen modelin optimum değerleri ve rotaları, bir konteyner nakliye şirketinin rotalarından elde edilen orijinal sistem CO_2 emisyonları ile karşılaştırılmıştır. CO_2 emisyonları ve yakıt tüketiminde önemli iyileşme gözlenirken, eklenen dirençlerin etkisi mevsimsel rotalarda farklılıklara neden olduğu tespit edilmiştir. Yıllar boyunca dekarbonizasyon için önemli çabalar sarf edilmiştir. Yeşil yaklaşımlarla gemi rotalarının doğru bir şekilde modellenmesi, yakın gelecekte hem finansal hem de çevresel faydalar sağlayacaktır.

1. INTRODUCTION

The maritime transportation has always played a crucial role in the international trade. According to United Nations Conference on Trade and Development (UNCTAD, 2021), approximately 83% of the global trade volume has been carried out by international shipping carriers. According to Stopford (2008), maritime transportation is considered as the most productive transportation method and thus it is one of the main pillars of world commerce.

Maritime transportation is considered the most preferable method for shipping large volumes of commodities even though it is slower compared to other means of transportation (Chang & Thai, 2017). Technological advances in naval architecture and shipbuilding, and subsequent economies of scale conveyed into bigger vessels, have lowered the cost of transportation of goods, thus encouraging trade by enabling the freight accessible across greater distances (Talley, 2000). Moreover, globally, seaborne transportation has seen an immense increase, nearing to 300% since 1970 (Dulebenets et al., 2021).

Generally speaking, shipping industry consists of two unique markets: i) the bulk carrying sector, which is mainly related to the transportation of ores and energy commodities and ii) the liner shipping, which focuses on transportation of final products (Stopford, 2008; Haralambides, 2019). Haralambides (2019) states that these bulk carrying sector and liner shipping sector differentiates from each other in many ways such as types of ships, volume of ships, charter party contracts, packaging etc.

Lawrance (1972) on the other hand defines the maritime transportation as per the modes of operation based on freight, which are industrial shipping, liner shipping and tramp shipping. In industrial shipping, cargo owners are the main controller of the vessel. In liner shipping, operation of the vessel is based on fixed routes, freight rates (although these rates may fluctuate depending on the market tendency) and schedules. In these fixed routes and schedules, vessels sail between ports of call in a rotation based on their cargo loading and discharging (unloading) sequences. In tramp shipping, unlike liner shipping, do not have any fixed schedule or route to follow. In this form of operation, the services offered based on negotiable freight rates and spot contracts of transportation. Haralambides (2019) supports this differentiation by stating that, tramp shipping is a form of operation based on spot market and liner shipping is a form of operation based on timetables and regular services and do not relate to any form of ship type, considering bulk carrying is often mentioned as tramp shipping.

With the introduction of containers in the commercial interactions between United States and Europe, the transportation of goods has been revolutionized and standardized in dimensions most commonly 20 feet in length, 8 feet in width and height containers which is known as Twenty-foot Equivalent Unit (TEU) (Bissel, 1970). Due to the rise of containerization, economic globalization and the rapid development of foreign trade, container ships have become more and more common, and they have a widespread utilization for transportation of commodities between ports (Qi et al. 2013). Expensive cargoes with lower volumes became easier to transport globally and reduced costs of transportation while minimizing the shipping time and time spent at berth (Haralambides, 2019). Apart from containerization, international shipping has been shifting from industrial shipping to voyage chartering (tramp shipping), with single voyage freight contracts (Christiansen et al, 2013; Pache, 2019).

The nature of container shipping is in line with the liner shipping freight transportation method considering previously mentioned definitions by Lawrance (1972) and Haralambides (2019). In the competitive environment of seaborne trade, shipping companies are required to consider their cost of transportation in order to maximize their profit. Liner shipping is a capital sensitive way of transporting commodities while comprising of complex parameters (Lim, 1998). Regarding this, containerships are usually designed with capacities to achieve economies of scale, carrying thousands of containers, in an efficient manner (UNCTAD, 2021). In container shipping, economies of scale refer to minimizing the cost by increasing transportation volume. Conventionally, this is achieved by increasing the ship size (Lim, 1998), while the decline is based on the parameters such as cost of ship building, bunker, and management, although bigger ships do not always lead to maximized profit.

Optimized container transportation relies on port costs, voyage costs, cargo handling rate and fuel consumption (that is a function of speed) (Haralambides, 2019). Efficiently transporting commodities enhances logistics performance and enables shipping companies to become competitively advantageous (Salehi et al., 2017) and speed is considered as a major variable in reaching economies of scale in container shipping or liner shipping in general (Doudnikoff & Lacoste, 2014; Haralambides, 2019; Lim, 1998). Hence, container ships are also designed for speed, meanwhile conforming with the constantly updated environmental regulations.

Recently, environmental sustainability has become a concern politically and environmental regulations have been affecting dynamics in global maritime transportation (UNCTAD, 2019). Larger ships have an immense load capacity and consume huge amount of bunker (fossil fuels) to operate.

International Maritime Organization (IMO), which is an agency under United Nations (UN) is aims to promote safety, security, sustainability and environmentally efficient international shipping (IMO, 2017) and was established after IMO Convention entering into force in 1958, aims to reduce greenhouse gas emissions by 40% until 2030 and by 70% 2050 compared to the baseline 2008 (IMO, 2018). According to Fourth IMO GHG Study (Faber et al., 2021), it is projected that the emissions will increase 90 - 130% of emissions level in 2008 by 2050. In the reports of the study, CO_2 was observed as the main source of impact of seaborne trade to climate, which is consistent with previous GHG study carried out in 2014 (Faber et al., 2021).

Since IMO's formation, the biggest regulation related to environmental protection and pollution was MARPOL 73/78, stated as the primary international convention for prevention of pollution sourced from ship on the marine environment. After being adopted in 1973, 1978 protocol was adopted as a corrective action for the tanker ship accidents in 1976-1977. The combined regulation entered into force in 1983. Since then, MARPOL 73/78 has been updated by amendments, resulting in six annexes.

MARPOL 73/78 Annex IV: Regulations for the Prevention of Air Pollution from Ships is amended into the MARPOL by the 1997 Protocol, which set boundaries for NO_x (Nitrogen Oxide) and SO_x (Sulphur Oxides) emissions sourced from vessels' exhausts and prohibited knowingly release of ozone depleting substance containing emissions (IMO, 2018). MARPOL amendments for Annex VI was adopted in 2008 introducing, revised fuel quality requirements. Tier II and Tier III NO_x emission limits for recent engines, and Tier I NO_x requirements for engines that was built before 2000 was set. Since October 2008, 53 countries chose to ratify Annex VI, which is equal to 81.88% of tonnage.

In Annex IV emission and fuel quality requirements was determined under two categories: global requirements, and Emission Control Areas (ECA) requirements. ECAs are designated areas for SO_x and PM (Particulate Matter), or NO_x, or all three types of emissions sourced from ships.

2011 MARPOL Annex VI amendments has presented compulsory precautions to control and decrease total greenhouse gas (GHG) emissions (IMO, 2018). As the new addition to Annex VI, Chapter 4 brought regulations for ships' energy efficiency. Two new concepts have been presented to the industry which are, Energy Efficiency Design Index (EEDI) that is a performance tool that needs a specific minimum energy efficiency in recent vessels and Ship Energy Efficiency Management Plan (SEEMP), Setting up a system for managers to boost ships' energy efficiency. Ship designers can freely select technologies best suitable for the EEDI requirements in a particular vessel design. The regulations include to all ships with a gross tonnage greater than 400 gross tonnage and entered into force in 2013. (IMO, 2018)

For recently built ships, the EEDI provides encouragement for the usage of energy efficient equipment and engines. For various vessel types and sizes, the EEDI requirements, minimum energy efficiency level per capacity mile. The EEDI is indicated in grams of carbon dioxide per vessels' capacity-mile. The formula is based on technical design aspects of each specific vessel. (IMO, 2018)

Reduction levels for grams of CO_2 per ton-mile on the first step was set to 10% and was expected to restrict every following five years to keep up with new technologies on efficiency and reduction measures. The regulation required new ships starting from 2015 to be more efficient, starting from 10% and continuing the efficiency level to be increased 10% each following 5-year period and the baseline is set to the average efficiency for ships built between 2000 and 2010. (IMO, 2018)

The aim of the SEEMP is to promote vessels' energy efficiency in a cost-effective manner while providing methods for ship managers to focus on ship and fleet efficiency. The Energy Efficiency Operational Indicator (EEOI) is among the most utilized tools for monitoring energy efficiency. The EEOI enables owners and operators to evaluate the fuel efficiency of a vessels during ship operations and to calculate results of any input, such as better passage planning or increase in propeller cleaning frequency, by doing so, across the maritime transportation sector, EEOI have been utilized as a key indicator of sustainable and green shipping operations (Sun et al., 2019).

As a huge ingredient of the ship's operational costs, the expense of the bunker accounts for a substantial percentage of the ship's operational cost ranging from 20% to 60% (Ronen, 1993; Notteboom, 2006; Golias et al., 2009). Besides, bunker consumption has been shown to be a key factor for both shipping costs and emissions. IMO Fourth IMO GHG Study shows that container ships have the highest heavy fuel oil (HFO) consumption among other ship types (Faber et al., 2021). Even though for decarbonization of maritime transportation, alternative energy sources are researched for common utilization (Mallouppas & Yfantis, 2021), conventional fuels still thrive. Ronen (1982) and Doudnikoff, (2013) have stated that container ships are some of the leading fuel-consumers and air polluters, because of their high service speed. Although, in Fourth IMO GHG Study, high service speed is not mentioned specifically for the main cause of container ship emissions, slow transit and normal cruising proportionally have the higher percentage for contributing CO_2 emissions (Faber et al., 2021).

To reduce ship sourced emissions in line with the IMO's projections and aims, it is pivotal to optimize operational phases of maritime transportation, mainly voyage based processes. Finding the optimal relation for total distances and speed of ships are two main and basic ways of reducing emissions (Kontovas, 2014; Xin et al., 2019; Ma et al., 2021), but there is a trade-off for green ship routing. This trade off can be stated as the conflict between money and environment, or simply conflicting objectives of green ship routing and scheduling. Meanwhile, recommended measures may cause an increase on total cost, for example, by ships' not meeting time windows, loss of market competitivity caused by slower transportation of commodities, additional hardware installments and additional conflicts such as increased usage of costly marine gas oil (MGO) in ECAs. Hence, optimizing ship schedules and environmental effects of ships becomes a very complex problem. There are various studies trying to provide an effective method on optimizing route and speed while minimizing emissions (Kontovas, 2014; Psaraftis & Kontovas, 2014; Dulebenets et al., 2021; Ma et al., 2021; Yu et al., 2021) but the problem of green ship routing has not been provided a common solution that fits all situations.

1.1. Purpose of The Study

Maritime transportation is one of the main pillars of international trade. Although it is widely utilized for transporting commodities in a financially acceptable way, it is also a pillar among the sources for environmental damage lead by container shipping.

It is important to note that, there is a vast literature comprise of journal articles, technical reports from international organizations, news, conferences etc. about mitigation of decarbonization. Although it can be seen that decarbonization is a concerning issue that needs to be solved, it is also can be noted that, there is no one-size-fits-all solution to the problem. Until there are environmentally safe energy sources for maritime transportation, or maybe an unconventional way of solving global logistics problems that is safe for environment, adapting to the decarbonization is a more important task prior to the mitigation. Hence, an optimization for adaptation to the decarbonization was considered regarding maritime transportation during the composition of this research and methodological proposal.

In this study, a green vehicle routing approach has been introduced to minimize the CO_2 emission generated by small scale liner container shipping. In order to find out the inadequacies and deficits in the recent literature, a systematic literature review has been carried out. Accordingly, from the findings of the systematic literature review, a methodology has been constructed for the green ship routing and scheduling problem for short sea container shipping that would compensate for the lacking areas.

The aim of the study is to develop a reliable estimation tool for short sea liner shipping companies regarding decision making on route planning. This approach enables pre-planning of shipping lines to be presented for a given period of time. Proposed methodology considers both added resistances caused by weather effects between departure and destination ports on each voyage as well as time window restrictions and cargo demand in each port. This approach provides flexibility for liner shipping companies to update their liner routes depending on the fuel consumption and produced CO_2 emission based on the dynamic effects. Considering weather conditions enables a more realistic approach for determining shipping lines by including the dynamic nature of maritime transportation to the calculations and with the proposed methodology, it is also aimed to lower the complexity of resistance calculations while still providing a reliable and practical linear programming model for managerial insight regarding planning of liner shipping routes.

The remainder of this study consists of five sections. In chapter two, GSRSP concept has been explained and a systematic literature review method has been detailed. Results of systematic literature review presented regarding GSRSP in the recent literature. Following section defines the problem and presents the methodologies that have been utilized during this study. Here a mixed integer linear programming (MILP) model and method of calculating involuntary speed loss due to weather effects have been detailed. Fourth chapter explains the numerical experiments that was carried out and discusses the findings as well as reliability and utility of the proposed methodology. Final chapter summarizes and concludes this study, while discussing future research opportunities regarding GSRSP and its solution methods.

2. LITERATURE REVIEW

In this section, firstly, the concept of green ship routing and scheduling has been defined by presenting a detailed literature review on the subject as well as discussing approaches in the related literature by referencing the foundations and recent studies.

Secondly, a systematic literature review has been presented based on the guidelines of Kitchenham (2004). The systematic literature review provides a representation of the recent literature about green ship routing and scheduling problems for showcasing the must-have constraints, solving methods and objective functions as well as finding out what is lacking for green ship routing and scheduling problems. After the systematic literature review, presented results have been discussed regarding the research questions of the systematic literature review.

2.1 Green Ship Routing and Scheduling

In the competitive environment of shipping companies, cost reduction has become one of the major strategies for sustainable ship operations (Ng, 2019). Broadly speaking, maritime routing problems are in strong relation with both the well-known Traveling Salesman Problem (TSP) (Applegate et al., 2011) and the Vehicle Routing Problems (VRP) (Toth & Vigo, 2002). The VRPs are generalized versions of the TSP which is based on the routing of a number of vehicles with fixed capacities, visiting all client destinations in order to collect or distribute commodities and then returning to the initial departure point without revisiting the same client (Öncan et al., 2009). Regarding the maritime vehicle routing problem, the main goal is to deliver or to receive all the cargo with minimum cost or maximum profit under certain assumptions specific to the dynamic nature of the shipping business (Ando and Taniguchi, 2006).

There is a vast body of literature on the ship routing. Among several models and algorithms which have been proposed to optimize the encountered real-life problems. Ronen (1983) has performed one of seminal works on the ship routing and scheduling problems. Since then, many viable solution methods have been presented. Notice that the ship routing problems are NP-Hard problems (Brouer et al., 2014; (Dithmer et al., 2017)) since they are extensions of the VRP. In other words, due to the complexity of maritime routing problems, reasonable solution times may not be attained for large scale instances. Therefore, complicated solution methods are required.

Mostly, objective functions of previous studies minimize cost of shipping while considering environmental effects in the form of externalities. In Christiansen et al. (2013), it was stated that the increase in bunker costs diverted focus to ship routing and scheduling as well as speed and consequently emissions. In Wang et al. (2013), a literature survey presenting methodologies for optimizing container shipping routes and ship schedules. Accordingly, in liner shipping network studies, main focus for optimization was minimization of fuel consumption and running cost as well as maximization of profit, which are subject to capacity, speed, time windows and fleet size constraints (Agarwal and Ergun, 2008; Thun et al., 2017; Christiansen et al., 2020; Ameln et al., 2021; Surury et al., 2021).

Kontovas (2014) adresses the green ship routing and scheduling problem (GSRSP). The author states optimizing bunker costs and environmental costs relay into optimum ship speed. In Psaraftis & Kontovas (2014) and Bektaş et al. (2019) separate literature surveys on green freight transportation were carried out. In Psaraftis and Kontovas (2016), purpose of greening of maritime transportation established as achieving acceptable environmental performance and answering economic criteria of maritime business. Recent studies show that (Fagerholt et al., 2015; Dithmer et al., 2017; Dulebenets, 2018; 20, Cariou et al., 2018; Zhen et al., 2020; Maneengam and Udomsakdigool, 2021; Ma et al., 2021), various models for optimizing shipping routes while sailing in Emission Control Areas for minimizing emissions have been designed.

2.2 Systematic Literature Review on GSRSPs

A systematic literature review defined by Kitchenham (2004) as the method for identification, evaluation, and interpretation of all available research about specific research questions, topics etc. Accordingly, all studies included in the systematic literature review are defined as “primary studies” and a systematic literature review is considered as a “secondary study”.

Systematic literature reviews have been utilized to;

- summarize existing literature,
- identify gaps in the current literature and shed light on the possible research fields,
- provide a viable and reliable background information as well as framework for research activities on a topic area,
- examine theoretical hypotheses as well as contributing to them by generating new hypotheses.
- Present different views, approaches, and results on a topic area (Kitchenham, 2004; Kitchenham et al., 2009; Elbert et al., 2020; Dede et al., 2021).

The importance of carrying out systematic literature review lies on thorough and fair examination of existing literature while applying certain restrictions to present concentrated results based on research questions of the study. By establishing a predefined research strategy, a complete assessment is enabled while the probability of biased examination decreases or is completely eliminated (Dede et al., 2021).

In this study, a systematic literature review based on but not limited to the guidelines set by Kitchenham (2004) has been carried out in order to rigorously review the recent literature on green ship routing and scheduling problem. The aims of this systematic literature review are to present a background for the topic area, examine previous methodologies while presenting different approaches and lay the foundation for proposing a novel methodology that covers the lacking areas of the green ship routing and scheduling problem literature.

Although a systematic literature review provides major advantages such as providing information on the impact of methodologies and subject areas as well as trends in the research field, it also requires substantial amounts of effort than conventional literature reviews (Dede et al., 2021; Kitchenham, 2004; Kitchenham et al., 2009). Additionally, considering quantitative studies, a systematic literature review enables utilizing various meta-analytic techniques for combining data extracted for observing more far-reaching impact of the studies that are otherwise harder to detect with conventional literature review applications.

Based on Kitchenham (2004), the review process for this systematic literature review comprises of the following stages:

- Identifying the requirements for a review
- Establishing a review protocol
- Selecting primary studies
- Extracting relevant data
- Synthesizing extracted data
- Reporting the obtained results

2.2.1. Search Process and Data Collection

Considering ship routing optimization, the literature comprises of variety of studies that has been carried out and models and algorithms with a wide spectrum has been utilized to optimize encountered problems. Evidently, restricting this topic area to green ship routing and scheduling narrows the studies, but in order to carry out an improved literature review, the following research questions (RQ) have been established:

- *RQ1:* What are the researched objective functions in green ship routing and scheduling studies?
- *RQ2:* Which solution methods have been utilized in green ship routing and scheduling studies?

- *RQ3:* Have time windows and cargo demand constraints been included in green ship routing and scheduling studies?
- *RQ4:* Have added resistances due to weather effects (or weather effects in general) been included in green ship routing and scheduling studies?
- *RQ5:* Which ship types have green ship routing and scheduling studies been focused on?
- *RQ6:* Which voyage types have green ship routing and scheduling studies been focused on?

RQ1 intends to analyze objective functions that are most utilized in GSRSPs. In the conducted conventional literature review in section 2.1, it is observed that objective function in a GSRSP can vary depending on the case and problem description. The objectives of the proposed algorithms are either minimization or maximization but the objective in the problem can fit in to either of them, such as maximization of profit and minimization of cost depending on fuel consumption considers the same parameters while the execution is completely different. By researching the objective functions in the literature, it is aimed to provide a detailed representation of the recent trends and approaches in the GSRSPs.

Time windows and cargo demand are essential constraints in seaborne trade (Cóccola & Méndez, 2015). Arriving to berth earlier does not mean it is more profitable than arriving on time. Waiting adrift or at anchor may cause a shipping company more, considering ships at anchor although do not burn HFO, auxiliary machinery is utilized for onboard operations and living, hence marine diesel oil is burned. Meanwhile, late arrival causes a shipping company to fall into demurrage. Time windows allow ships to transport optimum cargo, i.e. arriving early to a port may mean that a ship is able to reach a specific cargo, where otherwise she would not be able to reach, or may miss the cargo if the time windows are not managed appropriately, resulting in the ship's carrying less cargo (in case of containers) because urgent cargo was transported by other ships. Cargo demand also relates to ships' capacities. Having capacity and cargo demand constraints restricts the optimization algorithms for optimum utilization of vessels while carrying maximum amount of cargo, which often relays into maximization of profit (Vad Karsten et al., 2017). Vessel capacity and time windows are common and integral constraints for VRPs (Bektaş et al., 2015; Bettinelli et al., 2011; Fazi et al., 2020; Yuan et al., 2021). Possibilities and dynamic nature of shipping business forces to reliable algorithms to be constructed with time windows (Cóccola & Méndez, 2015; Jiang, Mao, & Zhang, 2020; S. Wang et al., 2014). In RQ2 and RQ3, time window and cargo demand constraint utilization are researched. These analyses, enable extraction of different approaches for time windows and cargo demand constraints.

With RQ4, it is aimed to search for weather effect utilization in GSRSPs. Although there are studies on weather routing in maritime transportation literature, RQ4 refers to the utilization of added resistance effects on ships' vector as constraints or additional parameters (Du et al., 2021; Gkerekos & Lazakis, 2020; Kepaptsoglou et al., 2015; Kwon, 1981; Szlapczynska & Szlapczynski, 2019; Taskar & Andersen, 2020; H. B. Wang et al., 2018). In the literature about added resistances, there have not been a consensus on a commonly acknowledged empirical calculation method (M. Kim et al., 2017; H. Yu et al., 2021). RQ4 is also aimed at finding widely accepted empirical formula that can be employed in GSRSPs, while avoiding overly complicating the optimization algorithm and increasing the solving duration.

RQ5 and RQ6 have been established to analyze the tendency of authors on researching GSRSP optimization algorithms regarding types of ship and types of shipping. Depending on the ship type, the methodologies would change considering ship capacity, transported commodity, ship size, ship machinery etc., meanwhile traveled waters would also affect the methodologies since distances vary and liner or tramp voyages plays a crucial role on constructing the problem (Ančić et al., 2020; Cóccola & Méndez, 2015; Elgesem et al., 2018; S. Wang & Wang, 2016; Wu et al., 2021; Zheng et al., 2019).

In the search process, an electronic database search utilizing Web of Science Core Collection (WoSCC) has been carried out. The studies were extracted from the WoSCC by using domain defining keywords "maritime transp*", "maritime logist*", "ship*" and "maritime", in combination with keywords for routing optimization; "routing*", "optim*", "model*" and for environmental approach; "green*", "sustain*", "fuel consump*" and emission*) in the titles, abstracts and keywords. In the search codes, asterisk allows for enhancement of the research by including suffix and spelling variations.

Initially, without allocating any timespan filters, 5185 studies were found and after removal of duplicates, 4430 studies were extracted. Afterwards, for the systematic literature review, timespan for the studies were established from January 1st, 2016 to May 1st, 2022. Established timespan enables researching more recent approaches in the GSRSP literature. After introducing the timespan criteria to the research 2778 studies were extracted. For creating a reliable research procedure, only studies that had been listed under Web of Science, Science Citation Index-Expanded (SCI-E) citation index was introduced as a commonly accepted reliability criterion. After citation index criterion, total number of results was reduced to 2380. Extracted 2380 studies were thoroughly and rigorously evaluated for relevancy and remaining 77 studies were determined for the systematic analysis on GSRSP. From the studies, abstracts, full references, methodologies, and objectives have been extracted.

2.2.2. Inclusion and Exclusion Criteria

The main purpose of this systematic literature review is to evaluate methodological approaches to GSRSPs in order to accumulate a generalized and reliable methodology proposal. Accordingly, certain exclusion criteria were established for keeping the focus on GSRSPs. The exclusion criteria that were established are:

- Studies that do not solely focus on maritime transportation or are not relevant to maritime transportation.
- Studies that focus on marine engineering
- Studies which concentrate on naval architecture
- Studies that do not propose a methodology for green ship routing or ship scheduling

Furthermore, certain studies were included depending on their context. The criteria for inclusion are:

- Studies that primarily focus on fuel consumption and emission while providing a methodology for ship routing or ship scheduling
- Studies on speed optimization with a routing approach
- Maritime network studies with green ship routing or ship scheduling approach.
- Conjectural studies that provide a methodology for green ship routing or ship scheduling

2.2.3. Systematic Literature Review Results

In this section the results for systematic literature review on GSRSPs have been presented. Table 2.1, 2.2 and 2.3 showcases the tabulated results for the 77 selected GSRSP studies that are identified as relevant to detailed systematic literature review criteria. For each study, an article number has been assigned.

Table 2.1 presents general information about the primary studies collected. In Table 2.1, author information, publication years, source titles and citations to the studies are presented. The citation information has been obtained from Google Scholar for a wider representation as of 1st of May 2022.

Table 2.1 General Information on Systematic Literature Review Studies

Article Number	References	Source Title	Citation Count
JA1	(S. Wang & Wang, 2016)	Transp. Res. Part B-Methodological	27
JA2	(De et al., 2016)	Computers & Industrial Engineering	102
JA3	(Wen et al., 2016)	Computers & Operations Research	40
JA4	(J. G. Kim et al., 2016)	Mathematical Problems in Engineering	13
JA5	(Reinhardt et al., 2016)	Transp. Res. Part E-Logistics and Transportation Review	38

JA6	(Wen et al., 2017)	Transp. Res. Part D-Transport and Environment	87
JA7	(S. Wang, 2017)	Optimization Letters	1
JA8	(Veneti et al., 2017)	Computers & Operations Research	31
JA9	(Aydin et al., 2017)	European Journal of Operational Research	84
JA10	(He et al., 2017)	Transp. Res. Part B-Methodological	32
JA11	(De et al., 2017)	Engineering Applications of Artificial Intelligence	97
JA12	(S. Yu et al., 2017)	Advances In Mechanical Engineering	4
JA13	(B. Kim & Kim, 2017)	Applied Ocean Research	15
JA14	(Dulebenets, 2018a)	International Journal of Production Economics	105
JA15	(H. Lee et al., 2018)	Computers & Operations Research	84
JA16	(Cariou et al., 2018)	Transp. Res. Part D-Transport and Environment	28
JA17	(S. M. Lee et al., 2018)	Ocean Engineering	46
JA18	(Li et al., 2018)	Ocean Engineering	23
JA19	(Zaccone et al., 2018)	Ocean Engineering	82
JA20	(Dulebenets, 2018b)	Alexandria Engineering Journal	42
JA21	(Lin, 2018)	Marine Structures	11
JA22	(Gürel & Shadmand, 2019)	Central European Journal of Operations Research	13
JA23	(Tanaka & Kobayashi, 2019)	International Transactions in Operational Research	4
JA24	(H. Wang et al., 2019)	Ocean Engineering	44
JA25	(Abioye et al., 2019)	Energies	40
JA26	(Zheng et al., 2019)	Journal of Cleaner Production	46
JA27	(Cheaitou & Cariou, 2019)	Annals of Operations Research	37
JA28	(M. Liu et al., 2020)	Computational & Applied Mathematics	1
JA29	(Koza, 2019)	European Journal of Operational Research	16
JA30	(De et al., 2019)	IEEE Transactions on Engineering Management	62

JA31	(Topaj et al., 2019)	Applied Ocean Research	36
JA32	(Xing et al., 2019)	Transport	7
JA33	(Rabbani et al., 2019)	Scientia Iranica	2
JA34	(Giovannini & Psaraftis, 2019)	Flexible Services and Manufacturing Journal	24
JA35	(H. Fan et al., 2019)	Sustainability	5
JA36	(K. Wang et al., 2020)	Ocean Engineering	8
JA37	(Gkerekos & Lazakis, 2020)	Ocean Engineering	23
JA38	(Zhen, Wu, et al., 2020)	Transp. Res. Part B-Methodological	40
JA39	(De et al., 2020)	IEEE Transactions on Intelligent Transportation Systems	43
JA40	(Martínez-López & Chica, 2020)	Sustainability	1
JA41	(Christiansen et al., 2020)	European Journal of Operational Research	41
JA42	(Jiang, Mao, Wang, et al., 2020)	Sustainability	3
JA43	(Eide et al., 2020)	Computers & Operations Research	8
JA44	(D. Ma et al., 2020)	Ocean Engineering	35
JA45	(Zhen, Hu, et al., 2020)	Transp. Res. Part C-Emerging Technologies	30
JA46	(Y. Zhao et al., 2020)	Journal of Advanced Transportation	6
JA47	(Zhuge et al., 2020)	Naval Research Logistics	11
JA48	(Yang et al., 2020)	Sustainability	14
JA49	(Li et al., 2020)	Applied Ocean Research	30
JA50	(Reinhardt et al., 2020)	European Journal of Operational Research	19
JA51	(Tzortzis & Sakalis, 2021)	Ocean Engineering	1
JA52	(Zhuge et al., 2021)	Transp. Res. Part B-Methodological	8
JA53	(Lashgari et al., 2021)	Applied Ocean Research	3
JA54	(Maneengam & Udomsakdigool, 2021)	Applied Sciences-Basel	0
JA55	(Z. Wang et al., 2021)	Regional Studies in Marine Science	2

JA56	(Pasha et al., 2021)	Advanced Engineering Informatics	39
JA57	(Zhang et al., 2021)	Journal of Ocean University of China	9
JA58	(Maskooki et al., 2021)	International Transactions in Operational Research	3
JA59	(Y. Wang & Wang, 2021)	Transp. Res. Part E-Logistics and Transportation Review	9
JA60	(Ritari et al., 2021)	Journal of Marine Science and Engineering	1
JA61	(Du et al., 2021)	Ocean Engineering	3
JA62	(Y. Yu et al., 2021)	Mathematical Problems in Engineering	2
JA63	(Zhu et al., 2021)	Advanced Engineering Informatics	0
JA64	(W. Ma, Ma, et al., 2021b)	Journal of Cleaner Production	4
JA65	(Y. Liu et al., 2021)	Ocean & Coastal Management	11
JA66	(S. Wang et al., 2021)	Transportation Science	10
JA67	(W. Zhao et al., 2021)	Journal of Marine Science and Engineering	8
JA68	(A. Fan et al., 2021)	Proceedings of the Institution of Mechanical Engineers Part M-Journal of Engineering for The Maritime Environment	5
JA69	(Chen et al., 2021)	Mathematical Problems in Engineering	4
JA70	(W. Ma, Hao, et al., 2021)	Applied Ocean Research	13
JA71	(Nzualo et al., 2021)	Applied Ocean Research	1
JA72	(Sasa et al., 2021)	Ocean Engineering	6
JA73	(Gao & Hu, 2021)	Sustainability	2
JA74	(H. Wang et al., 2021)	Transp. Res. Part D-Transport and Environment	10
JA75	(Herrera Rodriguez et al., 2022)	International Journal of Production Economics	2
JA76	(T. Zhao et al., 2022)	IEEE Transactions on Industry Applications	1
JA77	(W. Zhao et al., 2022)	Journal of Ocean University of China	2

In Table 2.2, conceptual contents of the primary studies are presented in accordance with the research questions specified in section 2.2.1. Referring to RQ1, RQ2, RQ5 and RQ6, ship types, voyage types, presented objective functions and utilized solution methods are detailed in Table 2.2. Ship types are categorized depending on the common ship types while situational ships such as tugboats are categorized under "other". Voyage types are categorized depending on the navigation area researched in the studies, which are trans-oceanic and short sea shipping. Short sea shipping refers to the small distances such as Mediterranean Sea or Black Sea. It is important to note that, short sea shipping does not refer to coastal shipping but, coastal shipping is a part of short sea shipping. Trans-oceanic on the other hand only refers to long distance voyages, mainly ocean-going ships. Furthermore, objective functions and solution methods are presented as detailed in the extracted studies. Instead of specifically writing down each individual objective function of the studies, they are categorized as general objectives. As an example, "cost" sometimes relates to just fuel consumption cost, while in some studies it also includes costs such as crewing, time spend at berth, early and late coming to ports etc. Categorization provides eliminating redundancy of stating each objective as stated in the studies, while also enabling extracting statistical data regarding the objectives. This categorization also utilized for solution methods, although it had to be done with more detail since general concepts such as heuristics would not explain the authors methodologies correctly. It is important to note that various studies utilized multiple methods, while some of them for comparison and some of them are complementary. The categorization, although, was done according to all the solution methods utilized since all mentioned methods in Table 2.2 were able to solve the problem stated in each study.

Table 2.3 showcases the constraints in GSRSPs referring to RQ3 and RQ4. These constraints, as detailed in section 2.2.1, are time windows, cargo demand and weather effects. In RQ3 and RQ4, instead of the formulation of these constraints, what is researched is that whether these constraints were, in a way, embedded to the mathematical formulation or solution methodology or considered for ship routing and scheduling. Hence, in the tabulated form, the results are presented as considered (✓) or not available (-).

Table 2.2: Conceptual Contents of the Systematic Literature Review Studies

Article Number	Ship Type	Voyage Type	Objective Function	Solution Method
JA1	Container	N/A	Cost	Polynomial-Time Algorithm
JA2	N/A	N/A	Cost	Particle Swarm Optimization; Genetic Algorithm
JA3	Chemical Tanker	N/A	Profit	Branch-And-Price; Column Generation
JA4	N/A	N/A	Fuel Consumption	Recursive Partitioning Algorithm
JA5	Container	N/A	Cost	Branch and Bound, Mixed Integer Linear Programming (MILP)
JA6	N/A	N/A	Cost	Branch-And-Price; Constraint Programming Model
JA7	N/A	N/A	Fuel Consumption	Dynamic Programming
JA8	N/A	Short Sea	Fuel Consumption, Risk	Mixed Integer Non-Linear Programming (MINLP); Shortest Path
JA9	N/A	Short Sea	Cost	Dynamic Programming
JA10	Bulk	Trans-oceanic	Cost	Convex Optimization
JA11	Container	N/A	Cost	Particle Swarm Optimization; Genetic Algorithm
JA12	Container	Trans-oceanic	Profit	Bat Algorithm
JA13	Other	Short Sea	Towing tension, Distance	Genetic Algorithm
JA14	Container	N/A	Cost	Global Multi-Objective Optimization Algorithm
JA15	N/A	N/A	Fuel Consumption, Service Level	Particle Swarm Optimization
JA16	Container	Trans-oceanic	Profit	MILP; Genetic Algorithm
JA17	Container	Short Sea and Trans-oceanic	Fuel Consumption	NSGA-II
JA18	CO Tanker	Trans-oceanic	Fuel Consumption, Cost	MINLP
JA19	Bulk	Trans-oceanic	Fuel Consumption	Dynamic Programming
JA20	Container	Trans-oceanic	Cost	MINLP
JA21	Container	Trans-oceanic	Fuel Consumption	Particle Swarm Optimization

JA22	Container	Short Sea and Trans-oceanic	Cost	MINLP
JA23	Bulk and Tanker	Short Sea	Fuel Consumption	MINLP
JA24	Container	Trans-oceanic	Cost	3D Dijkstra
JA25	Container	Trans-oceanic	Profit	MINLP
JA26	Cruise	Short Sea	Fuel Consumption	Particle Swarm Optimization
JA27	Container	Trans-oceanic	Profit, Emission	Multi-Objective Optimization Algorithm
JA28	Container	Trans-oceanic	Cost	Two Stage Stochastic Programming
JA29	Container	Short Sea	Cost	Branch-And-Price; MILP
JA30	Container	N/A	Emission, Profit	Particle Swarm Optimization; Genetic Algorithm
JA31	CO Tanker	Short Sea	Cost	Graph Theory
JA32	Container	Trans-oceanic	Cost	Simulated Annealing
JA33	CO Tanker	Short Sea	Cost, Social Benefit Emission	Multi-Objective Optimization Algorithm
JA34	Container	Trans-oceanic	Profit	MINLP
JA35	Bulk	Short Sea	Cost	Genetic Simulated Annealing Algorithm with Variable Neighborhood Search
JA36	Bulk	Short Sea	Fuel Consumption	Particle Swarm Optimization
JA37	CO Tanker	Trans-oceanic	Distance	A* Dijkstra
JA38	Container	Trans-oceanic	Cost	Dynamic Programming
JA39	Container	Short Sea	Cost	Particle Swarm Optimization; Variable Neighborhood Search
JA40	Container	Short Sea	Cost, sailing time	Genetic Algorithm
JA41	Container	Short Sea and Trans-oceanic	Cost	Backbone Flow, Two-Phase, Heuristic Column Generation, Tabu Search, Two-Phase, Metaheuristic, Subset of Services
JA42	Container	Trans-oceanic	Cost	MINLP
JA43	Bulk	N/A	Cost	MINLP
JA44	Bulk	Short Sea and Trans-oceanic	Cost	A* Dijkstra; MILP

JA45	Container	Short Sea and Trans-oceanic	Cost	Bi-Objective Mixed Integer Linear Programming
JA46	Container	Short Sea	Profit	Genetic Algorithm
JA47	Container	Trans-oceanic	Cost	Enumerative Algorithms, Piecewise-Linear Approximation
JA48	Chemical Tanker	Trans-oceanic	Fuel Consumption	Genetic Algorithm
JA49	Container	Trans-oceanic	Cost	MILP
JA50	Container	Trans-oceanic	Cost	Variable Neighborhood Search
JA51	Container	Trans-oceanic	Fuel Consumption	Particle Swarm Optimization
JA52	Container	Trans-oceanic	Cost	Dynamic Programming
JA53	Container	Trans-oceanic	Cost	Stochastic Linear Integer Programming Model
JA54	Bulk	Short Sea	Emission, sailing time	Set Covering
JA55	Bulk	Short Sea	Fuel Consumption	Genetic Algorithm
JA56	Container	Trans-oceanic	Profit	Recursive Route Decomposition Heuristic
JA57	Ferry	Short Sea	Fuel Consumption, navigation safety, sailing time	Multi-Objective Ant Colony Optimization Algorithm
JA58	Other	Short Sea	Distance, Visited Ports	K-Nearest-Neighbors; MILP
JA59	Container	Trans-oceanic	Cost	Tailored MILP and Lower Bound Model
JA60	Container	Short Sea	Cost	Mixed-Integer Quadratically Constrained Programs
JA61	CO Tanker	Trans-oceanic	Fuel Consumption, sailing time	MINLP
JA62	Container	Trans-oceanic	Profit	MILP
JA63	Other	Short Sea	Emission	Variable Neighborhood Search
JA64	Bulk	Short Sea	Cost	NSGA-II
JA65	Container	Trans-oceanic	Profit	Genetic Algorithm
JA66	Container	Trans-oceanic	Cost	Dynamic Programming
JA67	Container	Trans-oceanic	Fuel Consumption, Risk, sailing time	Particle Swarm Optimization; Genetic Algorithm
JA68	Cruise	Short Sea	Fuel Consumption	Dynamic Programming
JA69	N/A	Trans-oceanic	Distance	A* Dijkstra

JA70	Cruise	Trans-oceanic	Cost	Genetic Algorithm
JA71	Bulk	Trans-oceanic	Cost	MILP
JA72	Bulk	Trans-oceanic	Speed	Modified Isochrone Method
JA73	Container	Trans-oceanic	Cost	MINLP
JA74	Chemical Tanker	Trans-oceanic	Fuel Consumption, sailing time	Genetic Algorithm
JA75	Container	Trans-oceanic	Cost, Service Level	MINLP
JA76	Cruise	Short Sea	Cost, Emission	Particle Swarm Optimization; NSGA-II
JA77	Container	Trans-oceanic	Fuel Consumption, Risk, sailing time	Particle Swarm Optimization; NSGA-II

Table 2.3: Time Window, Cargo Demand and Weather Effect Constraints of the Systematic Literature Review Studies

Article Number	Time Window Constraints	Cargo/ Demand Constraints	Weather Effect / Added Resistance Constraints
JA1	✓	-	-
JA2	✓	✓	-
JA3	✓	✓	-
JA4	✓	-	-
JA5	✓	✓	-
JA6	✓	✓	-
JA7	-	-	-
JA8	✓	-	✓
JA9	✓	-	✓
JA10	✓	✓	-
JA11	✓	✓	-
JA12	✓	✓	-
JA13	-	-	-
JA14	✓	✓	-
JA15	✓	-	✓
JA16	✓	✓	-
JA17	✓	-	-
JA18	✓	-	✓
JA19	-	-	✓
JA20	✓	✓	-
JA21	-	-	✓
JA22	✓	-	-
JA23	-	-	✓
JA24	-	-	✓
JA25	✓	-	-
JA26	✓	✓	-
JA27	-	✓	-
JA28	-	✓	-
JA29	✓	✓	-
JA30	✓	✓	-
JA31	-	-	✓
JA32	-	✓	-
JA33	✓	✓	-
JA34	✓	✓	-
JA35	✓	✓	-
JA36	-	-	✓
JA37	-	-	✓
JA38	✓	-	-
JA39	✓	-	-
JA40	-	✓	-
JA41	✓	✓	-
JA42	✓	✓	-
JA43	✓	✓	-

JA44	-	✓	✓
JA45	✓	-	-
JA46	-	-	-
JA47	✓	-	-
JA48	✓	-	✓
JA49	✓	-	✓
JA50	✓	✓	-
JA51	✓	-	✓
JA52	✓	-	-
JA53	✓	-	-
JA54	✓	✓	-
JA55	-	-	✓
JA56	✓	-	-
JA57	-	-	✓
JA58	✓	-	-
JA59	✓	✓	-
JA60	-	-	-
JA61	-	-	✓
JA62	-	✓	-
JA63	✓	-	-
JA64	-	-	✓
JA65	-	✓	-
JA66	✓	-	-
JA67	-	-	✓
JA68	✓	-	-
JA69	-	-	✓
JA70	✓	-	-
JA71	✓	-	✓
JA72	-	-	✓
JA73	-	✓	-
JA74	-	-	✓
JA75	-	✓	-
JA76	-	-	-
JA77	-	-	✓

Systematic literature review results presented in tables above are summarized in graphical representation. Figure 2.1 shows the ship types utilized in extracted studies. Some of the studies had not mentioned any types of ship, hence they are represented as “N/A”. Ship types diverting from the conventional merchant navy ships were grouped under “other”. These ships include types such as tugs and river boats. Interestingly, a trend has been observed that would support the reproach mentioned in Haralambides (2019), which is assuming liner shipping as container shipping. As detailed in the introduction section of this study, liner shipping includes container shipping but not limited to it. Note that chemical tanker, gas tanker lines, Ro-Ro shipping all fall into liner shipping categorization. Container shipping was observed to be the dominant shipping type in GSRSP domain with 41 studies while bulk carrying is the second most discussed shipping type with 11 studies. Ro-Ro shipping have not been utilized in any of the studies. This may be the result of fixed tour routing of the Ro-Ro shipping in short seas. These results show that, more studies need to be carried out on other ship types rather than focusing on container shipping. Since container shipping is predictable compared to other general voyage planning of other ship types, regarding they are under tramp shipping (Doudnikoff & Lacoste, 2014; Haralambides, 2019), it is convenient to focus on it.

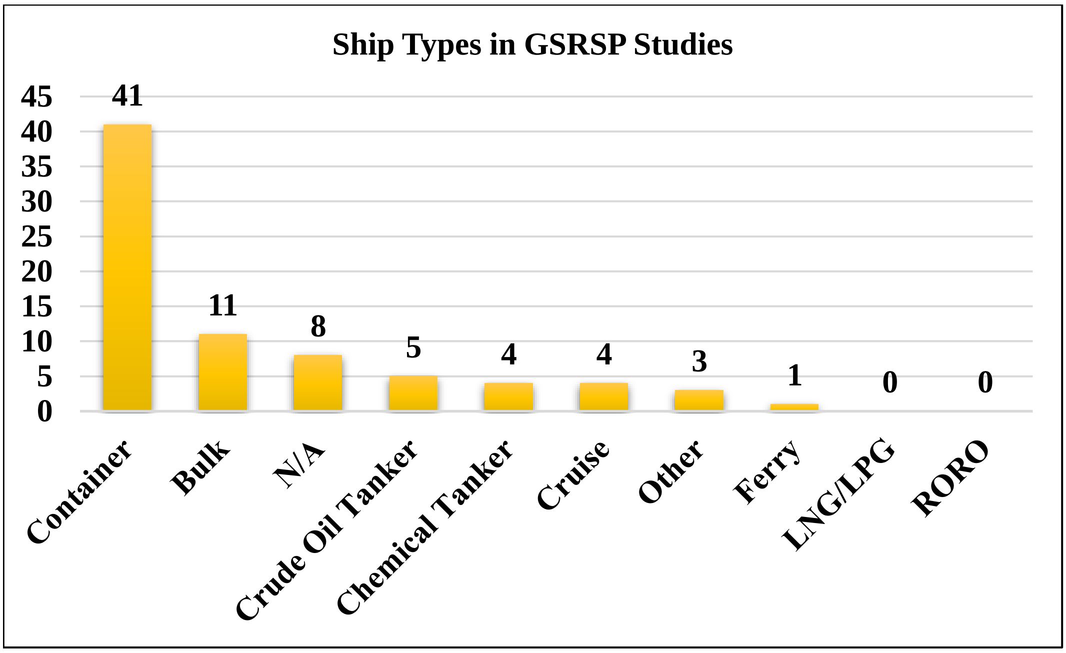

Figure 2.1: Ship Types in GSRSP Studies

Number of studies depending on the voyage types are listed in Figure 2.2. It has been observed that trans-oceanic shipping is the most researched voyage type in GSRSP research area with 38 studies. Most of the studies presented their methodologies on big maritime logistic networks or utilized one trans-oceanic route for weather routing. Short sea shipping on the other hand was a subject to 22 studies. Combined with 5 studies that had researched both trans-oceanic and short sea shipping, short sea shipping represents nearly 35% of the studies. This result show that, although short sea shipping is an easier voyage type to collect data with higher precision implementation compared to trans-oceanic shipping considering the nature of maritime transportation, the research trend was on trans-oceanic routes.

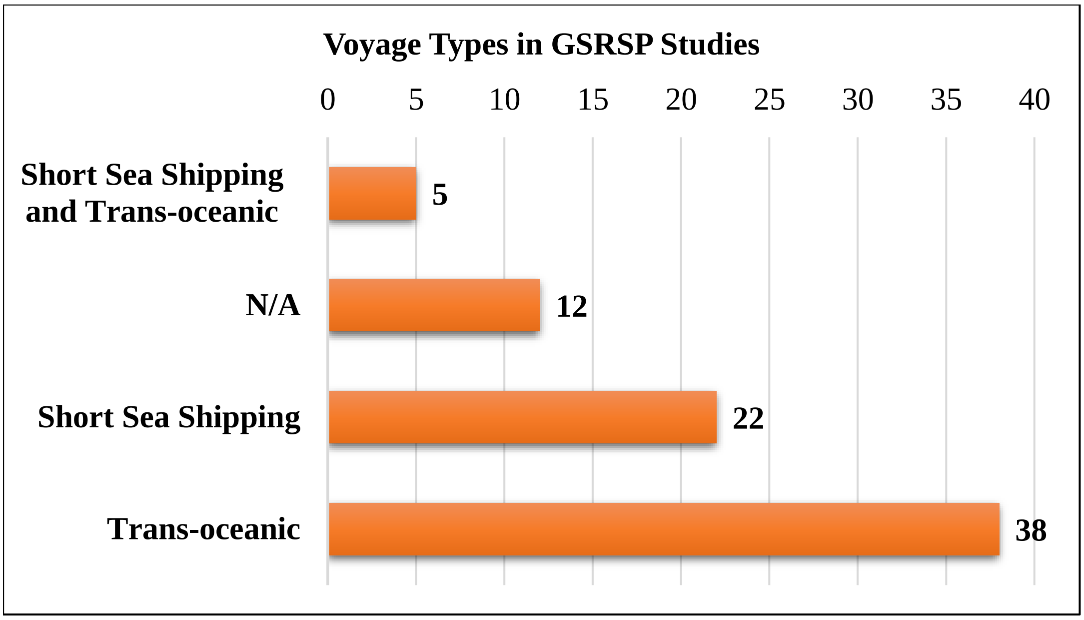

Figure 2.2: Voyage Types in GSRSP Studies

Figure 2.3 summarizes utilized objective functions in GSRSP studies. Cost has been observed to be the most common objective function with 40 GSRSP studies utilizing it. Cost is followed by fuel consumption which has been observed in 20 GSRSP studies while profit had been utilized in 11 studies. Note that, profit functions also include cost but since the objective function types were maximization, the categorization have been done accordingly. Interestingly, in extracted GSRSP studies, emission had been utilized only 6 times in the objective functions. Although some studies had used emissions as constraints for restricting their methodologies, it has also been observed that emissions utilized as externalities, which then added as another type of cost to the objective function. Sailing time is another objective function that has been observed multiple times with 7 studies using it. Sailing time directly affects fuel consumption and emissions. Sailing time also is a directly affected functional parameter that has a strong relation with time windows for ports or commodities depending on the problem. In close relation with sailing time, sailing distance also utilized in 4 studies. Overall, 17 studies had utilized multi objective methodologies, as can be seen in Table 2.2, which have utilized cost or fuel consumption with additional objective functions.

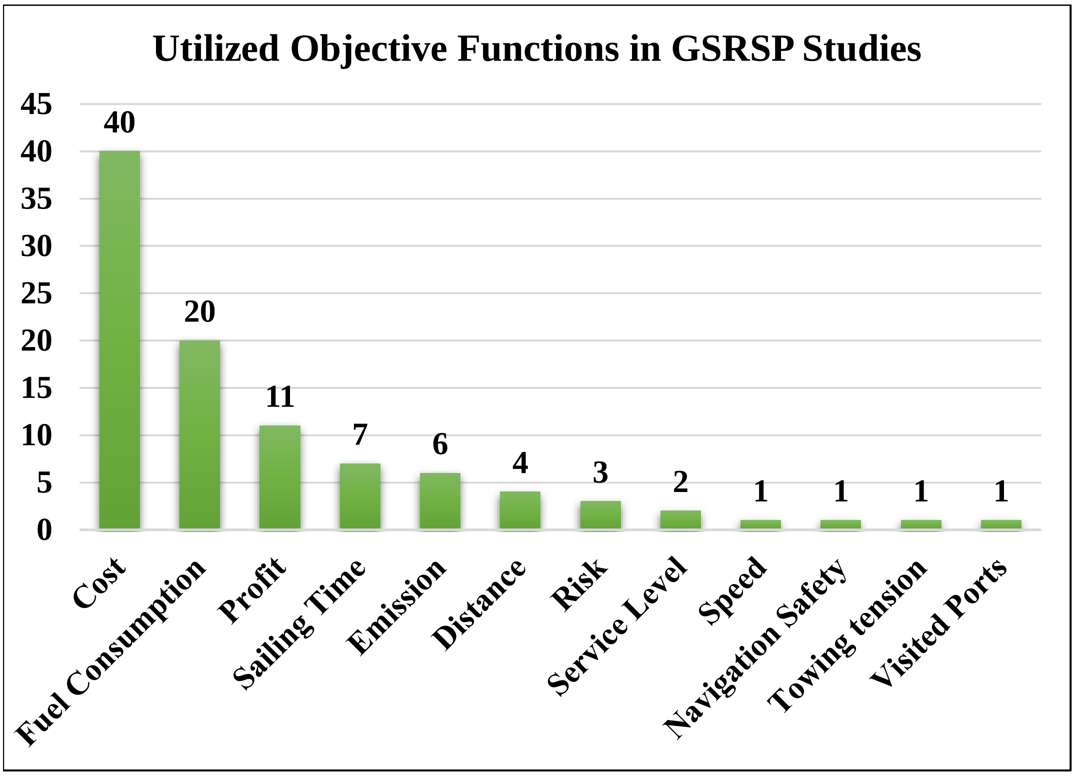

Figure 2.3: Utilized Objective Functions in GSRSP Studies

Results given in Table 2.3 have been summarized in pie charts as given in Figures 2.4-2.6. Conveniently, time window constraints have been observed to be utilized in 61% of the extracted studies, further proving that, they are indeed an integral part of maritime transportation. Especially for network designs. Cargo or demand constraints on the other hand, unexpectedly occurred only 40% of the GSRSP studies. This phenomenon may have occurred due to inability to obtain reliable cargo or demand data from shipping companies, since these data can be considered as trade secrets.

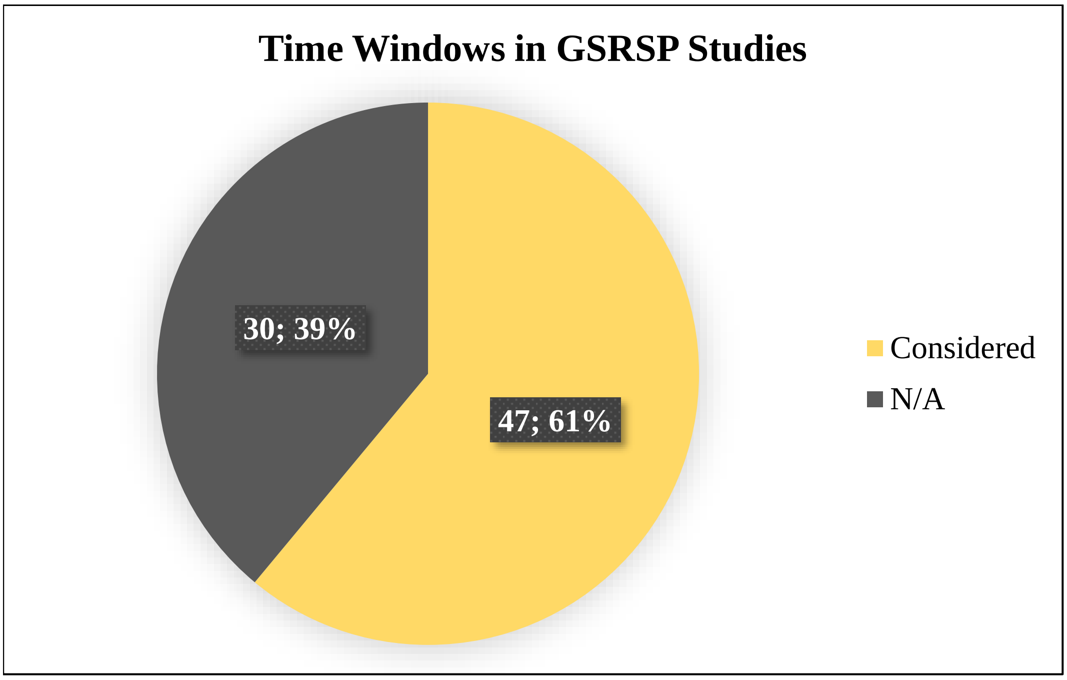

Figure 2.4: Time Windows in GSRSP Studies

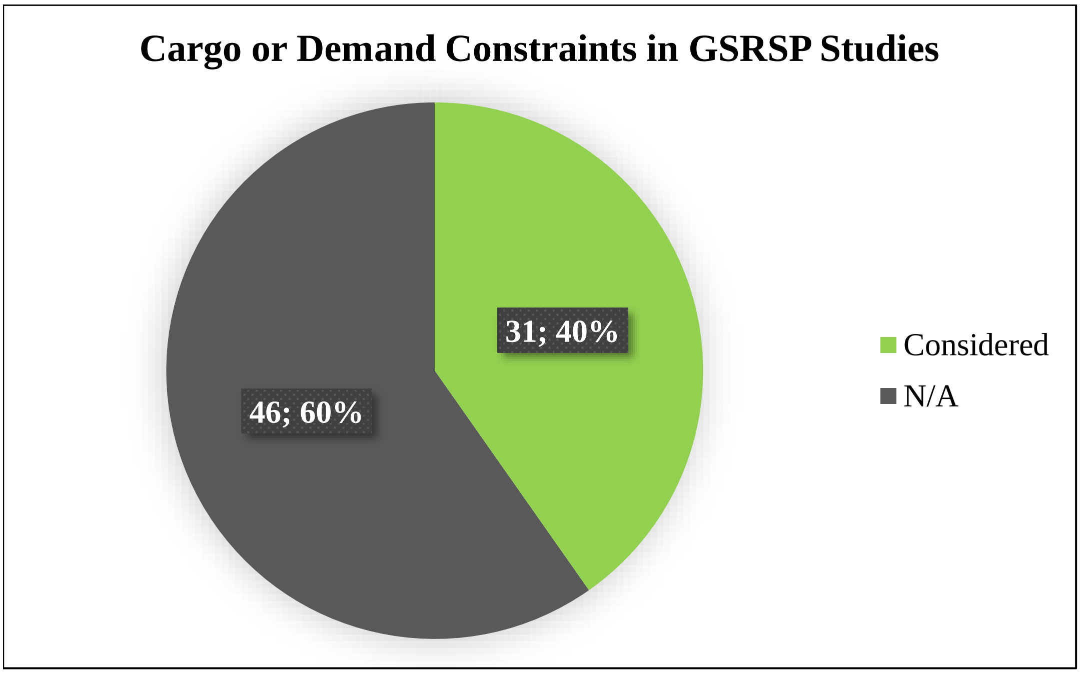

Figure 2.5: Cargo or Demand Constraints in GSRSP Studies

Weather effect has been observed in 32% of the reviewed studies. Granting some of the studies were weather routing studies, only a few studies incorporated weather effect as added resistances to the ship motion trough water, impacting speed of the vessel. Various methodologies have been observed regarding weather effect applications in GSRSP studies. Accordingly, weather effect addition has been stated in studies to cause non-linearization of the mathematical formulation, further complicating already NP-Hard problem type. Added resistances calculations include non-linear calculations using ship displacement, speed, angular wave effect etc., ergo, directly utilizing these parameters in methodologies causes complex formulations.

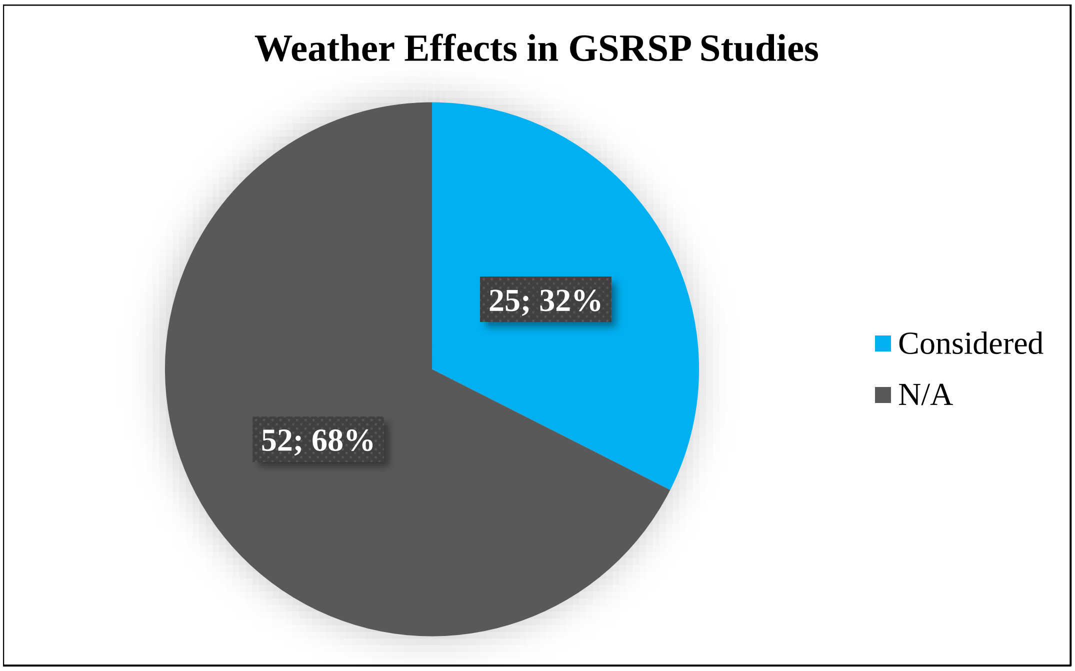

Figure 2.6: Weather Effects in GSRSP Studies

The results of the systematic literature review show that, time windows are an integral part of GSRSP studies, while cargo or demand constraints have been fairly utilized when deemed necessary. Hence, in this study, time windows and cargo demand have been incorporated into the optimization algorithm. The literature focuses on cost as objective function, this provides an opportunity for researching incorporation of fuel consumption and emissions since these objectives lacking in the results. Directly using fuel consumption and emission in the objective function enables utilizing benchmarks such as EEOI while still optimizing routing of the ships. Therefore, this study focuses on fuel consumption and emissions as objectives. The equations for each of these parameters are presented in chapter 3.

Furthermore, since there is a gap in short sea shipping GSRSP studies, in order to contribute to the literature, this study focuses on short sea shipping routing problem. In order to test the reliability and validity of the problem, container shipping has been selected.

Although weather effects rely on certain assumptions, they enable more realistic calculations to some regard. Given that the unpredictability of weather conditions, which method to utilize is a crucial question regarding reliability. This study employs a validated calculation methodology for wind and wave sourced added resistance effect on ship speed in short seas. Implementing added resistances to ship routing mathematical formulation for evaluating and minimizing fuel consumption have been considered to provide a realistic approach to decision making while routing scheme planning in liner container shipping. Weather effect and added resistance methodology and its implementation have been detailed in chapter 3.2 of this study.

3. METHODOLOGY

In this chapter, problem description, weather effect methodology and a MILP model for GSRSP have been presented. We tackle the GSRSP considering time window, demand, and capacity constraints as well as weather effects on ship speed. For the green approach, we suggest a modification of the objective function of the VRP model. Namely, instead of minimizing the total distance of the routes we concentrate on the minimization of the CO_2 emission of the ship routes. Reducing emission (and consuming less fuel) is the main goal of GSRSPs. The proposed methodology in this study aims to provide a reliable solution approach to reduce emission of a liner container fleet in short sea shipping.

3.1 Problem Description

In tramp shipping, ships carry cargo from a loading port to port a discharging port, then proceed to another loading port (or waiting area) in ballast condition. Liner shipping differs in that manner since the cargo carried in each leg differs and in container shipping, being in ballast conditions is a rare occasion for ships considering there is always a cargo to be transported to a port in one of the scheduled legs. Also, ships used in liner shipping is more restricted with time windows, causing liner ships to consume more fuel to reach their destinations in time, with high speed.

In this study, a sample problem has been derived from a liner container shipping company that operates in Black Sea Region (Arkas, 2022). The derived problem has been constructed as a seasonal pre-planning of a small-scale liner container shipping company that the concern for routing is the green approach, therefore minimizing emissions. Accordingly, the ports in the derived problem comprise of Odessa, Yuzhnyy, Novorossiysk, Constanta, Samsun, Poti, Varna and Burgas and northern exit of the Istanbul Strait. Istanbul Strait acts as the depot, which is utilized as node “0” in conventional VRP problem, describing start and return node for vehicles. Hence, in this derived problem, each ship starts and finish their tours at Istanbul Strait entrance. Usually, these ships visit some ports in Marmara Sea but due to waiting time for Istanbul Strait Passage and additional operations such as bunkering, provisioning or crew exchange at the southern exit of Istanbul Strait, routing for the Marmara Sea and beyond has not been included. The active routes are described with Figure 3.1. Additionally, narrow channel such as Istanbul Strait requires high amount of maneuvering (Birpinar et al., 2009).

During maneuvering, ships fuel consumptions cannot be estimated with precision (Sofia et al., 2020). This is due to using lots of engine commands, which then causes irregular burning. Irregular burning affect precision on estimated fuel consumption and emitted GHGs. This is also considerable during berthing, unberthing and approaching phases of the voyage (Zis et al., 2014; Sofia et al., 2020). During these phases, ships burn MGO instead of HFO most of the time, causing even more imprecise estimation. Thus, only distances considered in this problem are the distances between pilot embarkation/disembarkation points of the ports.

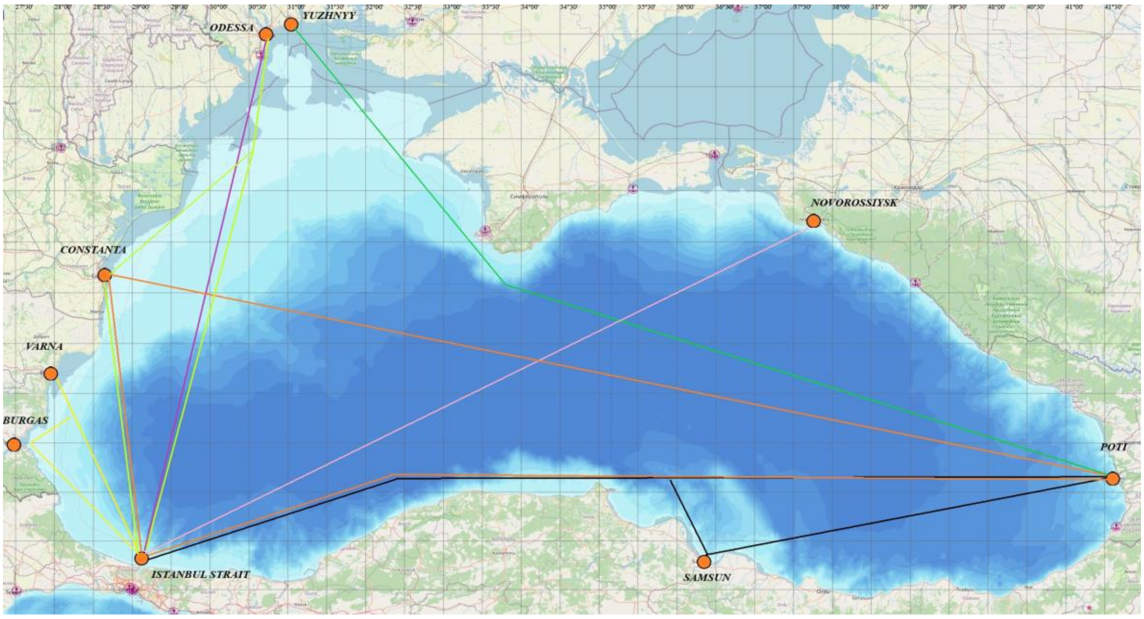

Figure 3.1 General Representation of Derived Black Sea Shipping Lines (Arkas, 2022)

3.2 Mathematical Model

The GSRSP has been approached with a MILP methodology that minimizes fleet CO_2 emission while generating a green routing and scheduling scheme. Time windows and cargo demand in ports have been included as constraints. Their incorporation to the solution methodology has been in the form of subtour elimination constraints (Miller et al., 1960; Toth & Vigo, 2002; Yuan et al., 2021). The notations used for the mathematical model is summarized in Table 1.

Table 3.1: Notations for GSRSP MILP Model

Notations	Definitions
V	Set of ports to be visited
K	Set of available ships
N	Set of static weather grids
c_{ijk}	CO_2 emission generated by ship *k* sailing from port *i* to port *j*
F_{ijk}	Fuel consumption of ship *k* sailing from port *i* to port *j*
P_k	Main engine power of ship *k*
EL_k	Main engine load of ship k
t_{ijk}	Sailing time for ship *k* from port *i* to port *j*
V_{ijk}^{sog}	Average speed over ground of ship *k* sailing from port *i* to port *j*
d_{ij}	Distance between port *i* to port *j*
x_{ijk}	Equals to 1 if and only if ship *k* visits port *j* immediately after port *i*
y_{ik}	Equals to 1 if port *i* is served by ship *k*
Q_k	Capacity of each ship
q_i	Cargo demand at port *i*
u_{ik}	Amount of cargo loaded onboard ship *k* after visiting port *i*
w_{ik}	Departure time of ship *k* from port *i*
$[a_i, b_i]$	Time windows for port *i*
$[E, L]$	Early and late departure times from *the depot*
SFOC	Specific fuel oil consumption constant (g/kW.h)
M	A sufficiently large number

In the literature, there are various methods for estimated calculation of fuel consumption (Yu et al., 2021). In the Second IMO GHG Study (Buhaug et al., 2009), the main methodology for calculating fuel consumption stated as the product of main engine power in kilowatts (kW), operating time in hours (h), main engine load factor and specific fuel oil consumption constant that is applicable to the main engine of the vessel in grams (g) per kWh. Although this process is the basis for fuel oil consumption estimation, in Yu et al. (2021), variables such as sailing speed, displacement, resistance, and distances have all been included.

In Kontovas (2014), fuel consumption has been calculated as a function of ship speed and displacement as given in Equation 3.1, including wetted surface of the ship. This formulation, as defined in Barrass (2004) includes three constant values (h, l and θ) defining ship specific constant that is a function of load condition and engine characteristics and cargo load. Mostly this function assumed as a cubic function where *k* is a known constant, $\theta = 3$ and $l = 0$. There are drawbacks of this cubic function starting with non-linearity and inaccuracy in lower speed values (Kontovas, 2014). The function solely utilizes propulsion speed and weather effect cannot be integrated precisely.

$$Fuel\ Consumption = h(l + v^{\theta})(displacement)^{2/3} \quad (3.1)$$

In fact, many of the estimated fuel consumption formulation in Yu et al. (2021) utilizes non-linear functions with exponential speed parameters. Hence, in this study, to incorporate estimated fuel consumption to the objective function, the main methodology stated in Second IMO GHG Study (Buhaug et al., 2009), has been employed as given in Equation 3.2. For each ship available, a fuel consumption value needs to be calculated for each voyage between ports *i* and *j*. CO_2 emission generated for each voyage between ports *i* and *j* by each ship *k*, emission factor of CO_2 is multiplied with the fuel consumption value of the same voyage of same ship. Emission factor values changes over the years based on international organizations' calculation methods and improved data. The emission factor of CO_2 has been considered as 3,1144 g CO_2 per g consumed fuel oil which is the recommended value in Fourth IMO GHG Study for ships using gas turbines (Faber et al., 2021) as given in Equation 3.3. Since emission factors are constant values, depending on the unit of calculated fuel consumption, total emitted CO_2 can be directly found by simple multiplication on the same unit (i.e., 1 kg of consumed fuel oil generates 3,1144 kg of CO_2).

$$F_{ijk} = P_k * EL_k * SFOC * t_{ijk} \tag{3.2}$$

$$c_{ijk} = F_{ijk} * 3{,}1144 \tag{3.3}$$

Sailing time t_{ijk} has been calculated by dividing the distance between port *i* to port *j*, represented by d_{ij} to the average speed over ground of the vessel *k* between port *i* to port *j*, represented by V_{ijk}^{sog}. Speed over ground of the vessel is the speed affected by various weather conditions in the form of added resistances and current. These added resistances and current effects cause involuntary speed loss or increase depending on the direction of effect in the area. Weather effects have been detailed in section 3.3. Sailing time calculation has been given in Equation 3.4.

$$t_{ijk} = \frac{d_{ij}}{V_{ijk}^{sog}} \tag{3.4}$$

Following these preliminary calculations, the MILP model has been structured as in Equations 3.5-3.15:

$$minimize \sum_{i,j \in V} \sum_{k \in K} c_{ijk} * x_{ijk} \tag{3.5}$$

Subject to:

$$\sum_{k \in K} y_{ik} = 1, \qquad \forall i \in V \backslash \{0\} \tag{3.6}$$

$$\sum_{k \in K} y_{0k} = K \tag{3.7}$$

$$\sum_{j\in V} x_{ijk} = \sum_{j\in V} x_{jik} = y_{ik}\,, \qquad \forall i \in V\setminus\{0\},\ i \neq j, k \in K \tag{3.8}$$

$$q_i * y_{ik} \leq Q_k\,, \qquad \forall i \in V\setminus\{0\}, k \in K \tag{3.9}$$

$$u_{ik} - u_{jk} + Q_k * x_{ijk} \leq Q_k - q_j\,, \qquad \forall i,j \in V\setminus\{0\}, i \neq j, k \in K \tag{3.10}$$

$$q_i \leq u_{ik} \leq Q_k\,, \qquad \forall i \in V\setminus\{0\}, k \in K \tag{3.11}$$

$$w_{ik} - w_{jk} + t_{ijk} \leq \left(1 - x_{jik}\right) * M\,, \qquad \forall i,j \in V\setminus\{0\}, i \neq j, k \in K \tag{3.12}$$

$$a_i * y_{ik} \leq w_{ik} \leq b_i * y_{ik}\,, \qquad \forall i \in V\setminus\{0\}, k \in K \tag{3.13}$$

$$E \leq w_{0k} \leq L\,, \qquad k \in K \tag{3.14}$$

$$x_{ijk} \in \{0,1\}, \qquad \forall i,j \in V\setminus\{0\}, i \neq j, k \in K \tag{3.15}$$

$$y_{ik} \in \{0,1\}, \qquad \forall i \in V\setminus\{0\}, k \in K \tag{3.16}$$

The objective function 3.5 minimizes total CO_2 emission generated by the ships in the system. Note that the unit of emissions generated can change depending on the unit of fuel consumption. Constraints (3.6)-(3.8) ensure that each port each port is visited exactly once, K ships leave and return the Istanbul Strait, while each individual ship *k* enters and leaves a port. Constraints 3.9 define the capacity restriction for ship *k*.

VRPs faces with subtours if they are not obviated in the mathematical formulae. With the inclusion of capacitated vehicle routing problems (CVRP) into the literature, designed systems with demands and fixed capacities enabled different methods to obviate subtours (Bazrafshan et al., 2021). In this study, the subtour elimination constraints (SECs) originally proposed in Miller et al. (1960) have been employed in constraints (3.10) and (3.12) for cargo and time windows respectively. These SECs are so-called Miller-Tucker-

Zemlin SECs (MTZ). Note that these constraints utilize continuous auxiliary variables u_{ik} and w_{ik}. u_{ik} is defined as the amount of cargo loaded onboard ship k after visiting port i and w_{ik} d is defined as the departure time of ship k from port i. These auxiliary variables in MTZ SECs define the order for visiting each node *i* on a given tour. Although MTZ formulation is not the most recent, it is one of the most flexible ones compared to other conventional SECs (Öncan et al., 2009). MTZ formulation conveniently enables integration of time windows and cargo demand into the mathematical formulation without additional requirements with acceptable solution times (Toth & Vigo, 2002; Öncan et al., 2009).

In constraints 3.10, when $x_{ijk} = 1$, $u_{ik} + \ q_j \leq u_{jk}$ holds, evidencing the cargo demand in port *j* and cargo onboard ship *k* after she left port *i* is less than or equal to the cargo onboard ship k after she left port j. Constraint (3.11) impose bounds on the auxiliary variables u_{ik}. For time window incorporation to the proposed methodology, constraints (3.12) have been utilized. Here, M, which states a sufficiently large number, ensures the voyage feasibility together with constraints (3.12) regarding the time windows for each port. In constraints (3.13), w_{ik} is restricted to ensure time windows are not exceeded for each visited port. With the inclusion of y_{ik}, in constraints (3.13), time windows are guaranteed to be imposed whenever ship *k* visits port *i*. Constraints (3.14) enforce that the ships start their tour from İstanbul Strait Northern Exit, in which *E* and *L* represents early and late departure options. Constraints (3.15) and (3.16) are for the domain definitions of decision variables namely x_{ijk} and y_{ik} , respectively.

3.3 Weather Effect and Added Resistances

Ships are exposed to weather effects during their voyages, mainly winds, waves and currents (Bowditch, 2019). Weather effects are vectoral forces with respect to ships' motion. These forces impact the ships' vector, which comprise of ships' speed and heading on water, causes changes in ships' direction and speed with respect to land observers.

Ships' direction and speed on water without any effect is called speed through water (STW) and ships' affected direction and speed (or vectoral speed) are described as course over ground (COG) and speed over ground (SOG), respectively (Bowditch, 2019). In equation 3.17, this vectoral calculation have been summarized, where $\overrightarrow{v_{ship}}$ denotes ship's own speed vector (service speed in this case), $\overrightarrow{v_{wind,wave}}$ and $\overrightarrow{v_{current}}$ represents relative wind and wave effect and current vector (or set and drift) and $\overrightarrow{v_{sog}}$ represents ship's speed over ground. The effects of these vectors are depicted with Figure 3.2.

$$\overrightarrow{v_{sog}} = \overrightarrow{v_{ship}} + \overrightarrow{v_{wind,wave}} + \overrightarrow{v_{current}} \tag{3.17}$$

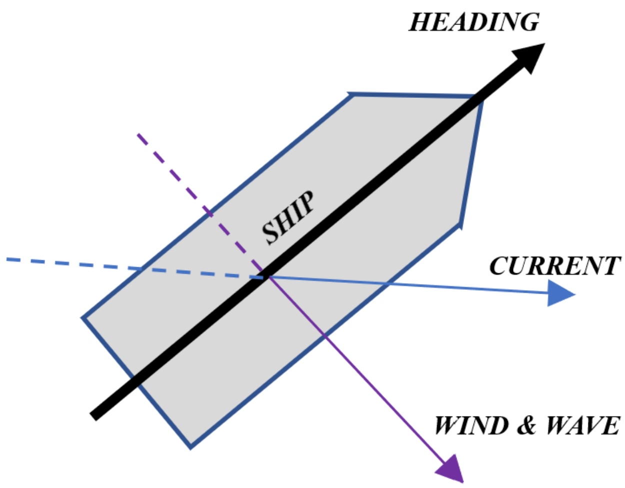

Figure 3.2 Vectoral forces affecting the ship speed (Bowditch, 2019).

The magnitude of $\overrightarrow{v_{sog}}$ has been considered as the main speed parameter for the ships, providing a more realistic approach. The speed parameter determines the sailing time which affects both the time windows and the fuel consumption of the ships (Li et al., 2020; Yu et al., 2021).

Added resistance effect sourced from winds and waves can be calculated by considering wind resistance on ships' freeboards and wave resistance on ships' wetted surfaces (Prpić-Oršić et al., 2016; Kim et al., 2017). Generally, winds and waves have to affect the ship for a long period of time in a given area with considerable magnitude for them to have an impact on ships' surfaces (Bowditch, 2019). As the wind speed and/or duration increases, sea disturbance also increases. Although weather effects are an estimation, since the calculation requires resistances on ships' surfaces, complex methodologies required to be carried out. Usually, in order to measure the wind and wave effect on ships as added resistances, computational fluid dynamics is utilized (Prpić-Oršić & Faltinsen, 2012; Kim et al., 2017)

Various methodologies have been proposed for calculating added resistance effect on ships (Luo et al., 2016; Kim et al., 2017; Szelangiewicz & Żelazny, 2018; Martić et al., 2020; Yu et al., 2021). In Second IMO GHG Study (Buhaug et al., 2009), this situation was addressed, and the methodology proposed in Kwon (1981) further improved in Kwon & Dai (2005) and finalized in Kwon (2008), that utilizes a semi-empirical approach based on effects of added resistances caused by weather on ships for calculation of involuntary speed loss was recommended. One of the benefits of this method was stated as its ability to provide consistent results without the requirement of complex added resistance calculations (Buhaug et al., 2009; Li et al., 2020). Another benefit is that Kwon's method considers both wind and wave resistances while in methodologies such as the one given in Prpić-Oršić & Faltinsen (2012), only wave effect had been considered. One other advantage of Kwon's method is its equations takes wind and wave in the form of Beaufort Numbers. This eliminates the need of precisely calculating wind speed and wave height, considering it is impossible to generalize such effects without wide assumptions. One disadvantage of Kwon's method is that in Kwon (1981), which is the original dissertation, this method was stated to be utilized in short sea voyages and not for trans-oceanic voyages. It was also stated that, the method holds its reliability until 8 Beaufort. Lastly, there is a general assumption of winds and waves are always in the same direction, but winds and waves may come from different directions (Bowditch, 2019).

It is a painstaking task to incorporate involuntary speed loss caused by added resistances considering complex calculations and exponential parameters disables the ability to use linear programming methods. Therefore, for its non-complex calculation methodology, and as per IMO's recommendation, involuntary speed loss due to added resistances methodology presented in Kwon (2008) has been employed in this study. Although Kwon's method also comprise of exponential parameters. Therefore, for incorporating Kwon's method for involuntary speed loss, static weather grids have been utilized on the described problem area.

As mentioned in section 3.1, Black Sea have been chosen as the research area. Weather routines in Black Sea has been taken from Black Sea Meteorological Atlas by Seyir Hidrografi ve Oşinografi Dairesi (1991) (SHOD) (Navigation, Hydrography and Oceanography Department of Türkiye). Static weather grids on Black Sea have been structured in accordance with the observation areas presented in Black Sea Meteorological Atlas but they are narrowed down for more precision regarding routes between ports. Black Sea has been divided into Static weather grids of 1° latitudes and 1° longitudes for application of the extracted data from in Black Sea Meteorological Atlas. In these static weather grids, seasonal averages of observation areas regarding wind direction, wind speed in knots and currents in knots have been entered as data. Figures 3.3-3.6 shows the static weather grids for Winter, Spring, Summer and Fall seasons, while Figure 3.7 shows the current routine in static weather grids.

Considering *N* is the set of static weather grids for the route from port *i* to port *j* and $V_{ijk,n}^{sog}$ is the speed over ground for each static weather grid *n* for each vessel *k* in knots, Equation 3.18 calculates the average speed over ground on a route from port *i* to port *j* for vessel *k*.

$$V_{ijk}^{sog} = \sum_{n=1}^{N} v_{ijk,n}^{sog} \Big/ N \,, \qquad \forall i, j \in V, i \neq j, k \in K \tag{3.18}$$

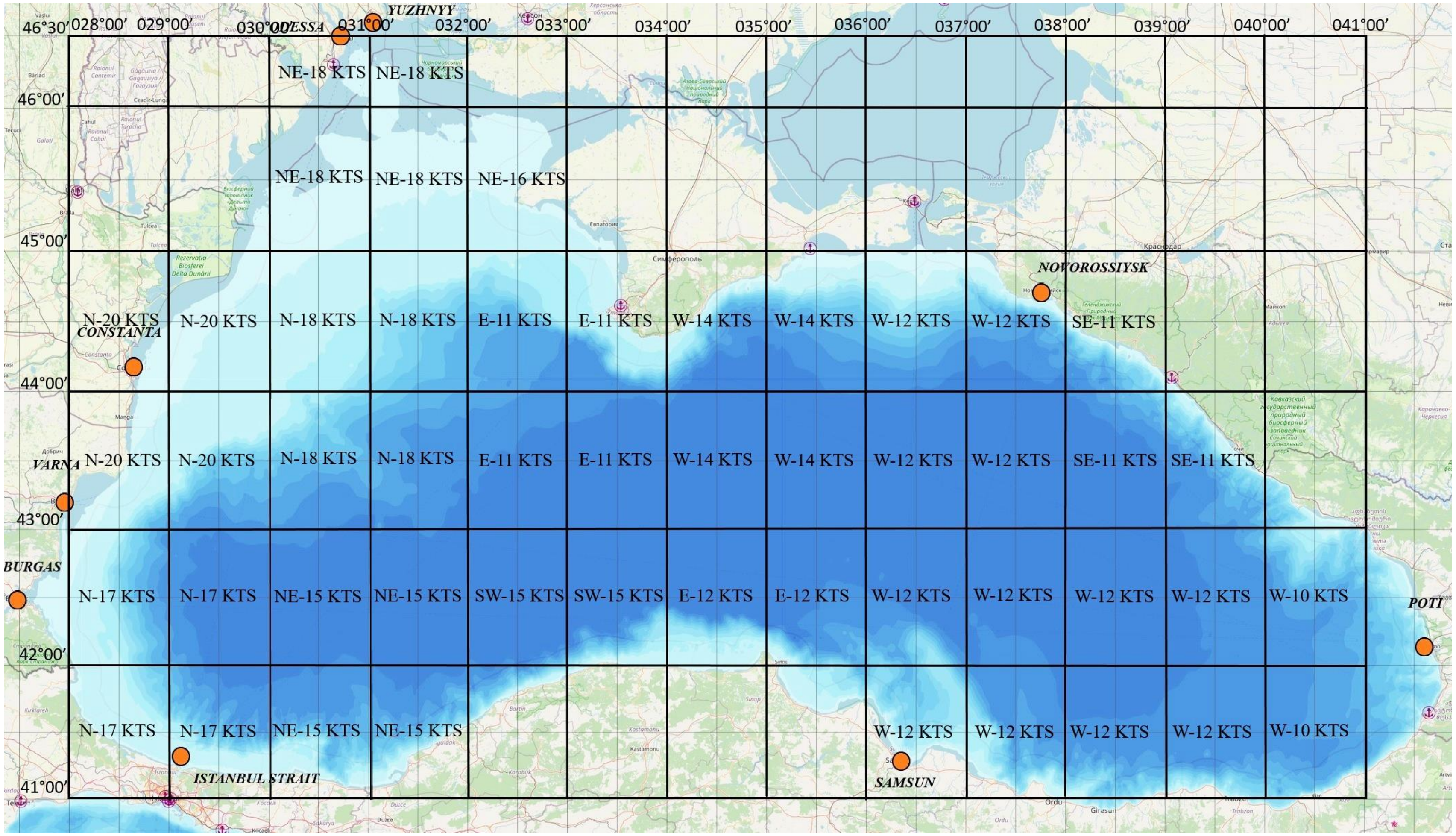

Figure 3.3: Black Sea wind direction and speed in knots for Winter (SHOD, 1991).

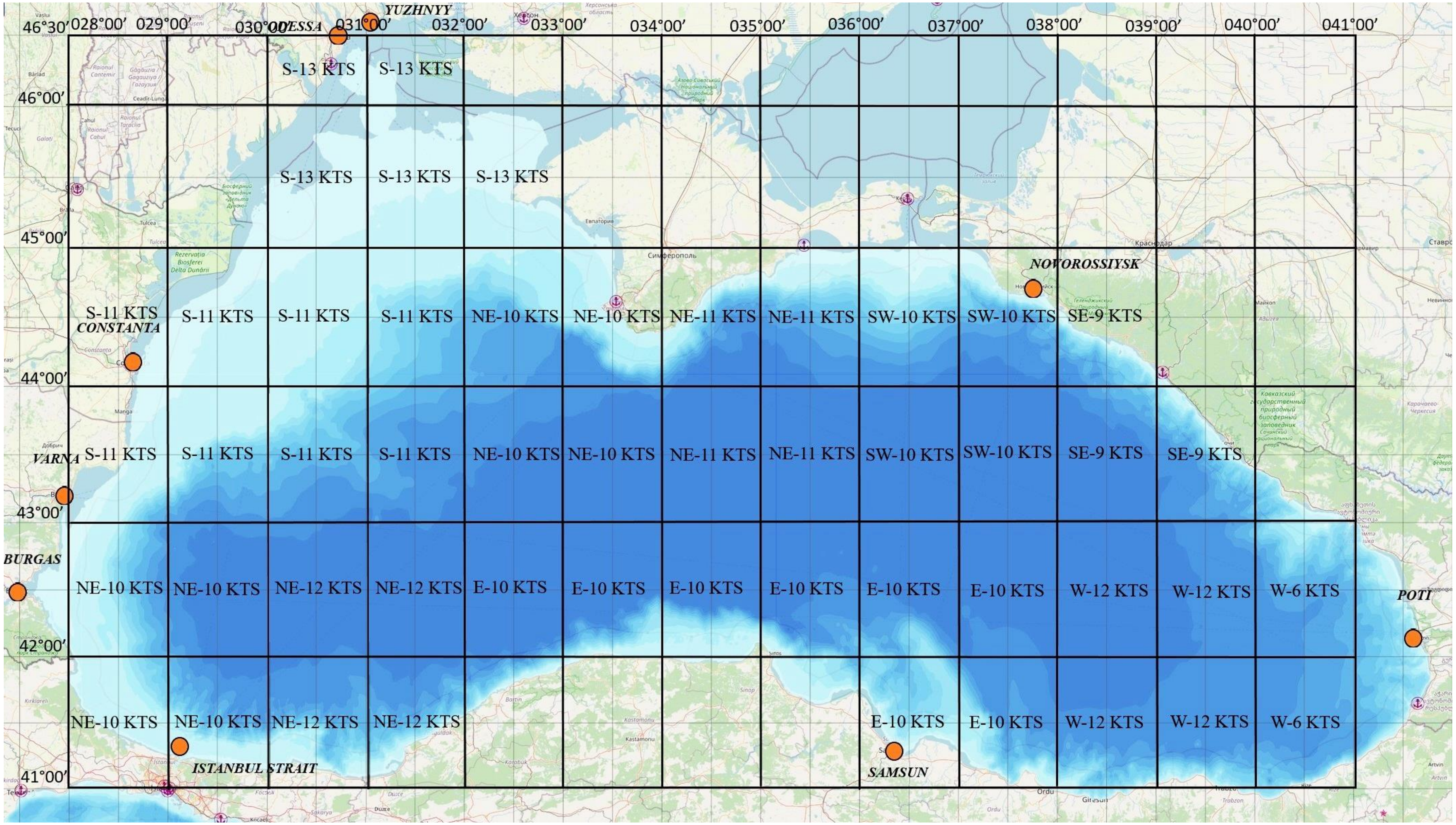

Figure 3.4: Black Sea wind direction and speed in knots for Spring (SHOD, 1991).

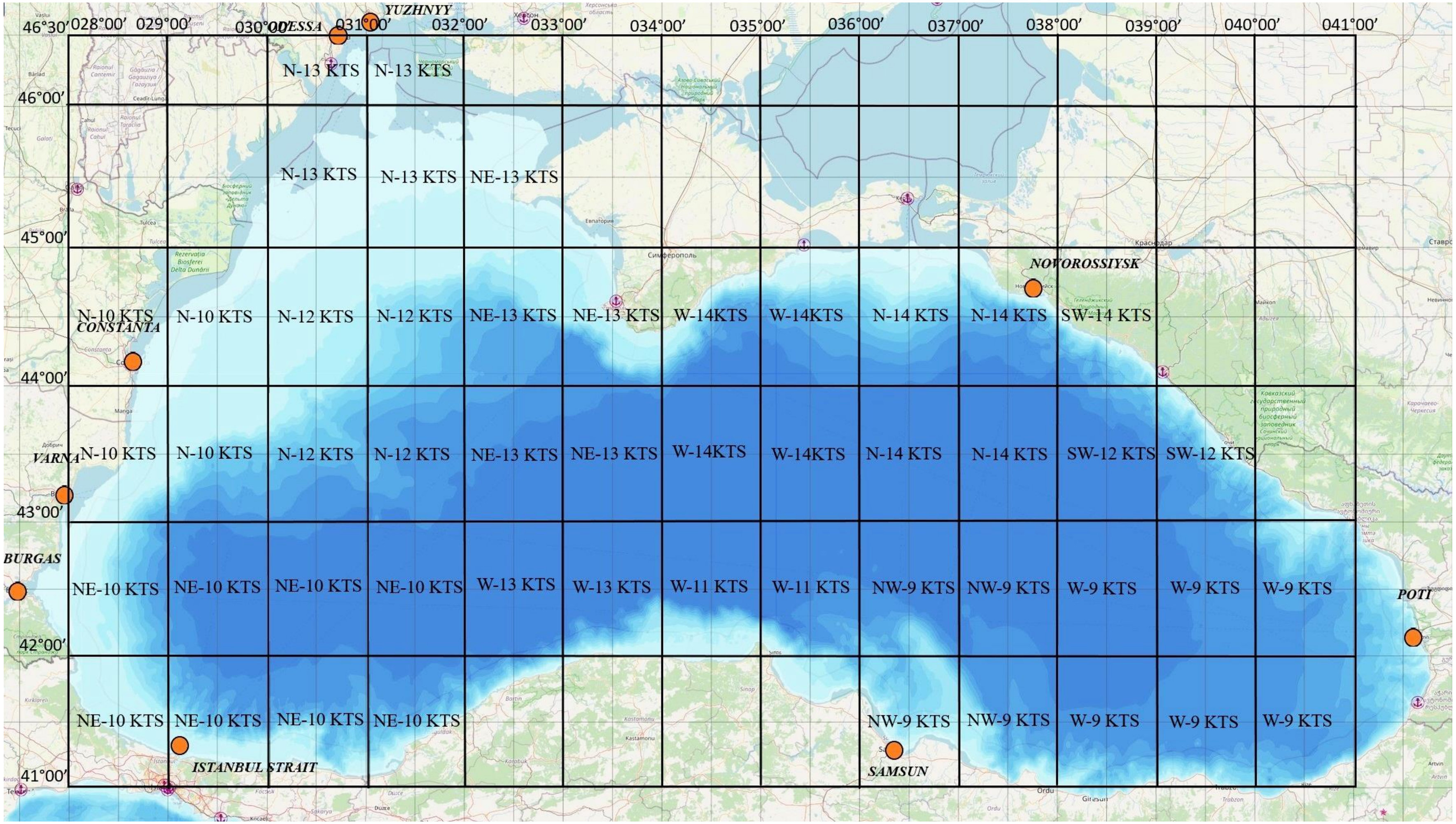

Figure 3.5: Black Sea Wind Direction and Speed in Knots for Summer (SHOD, 1991).

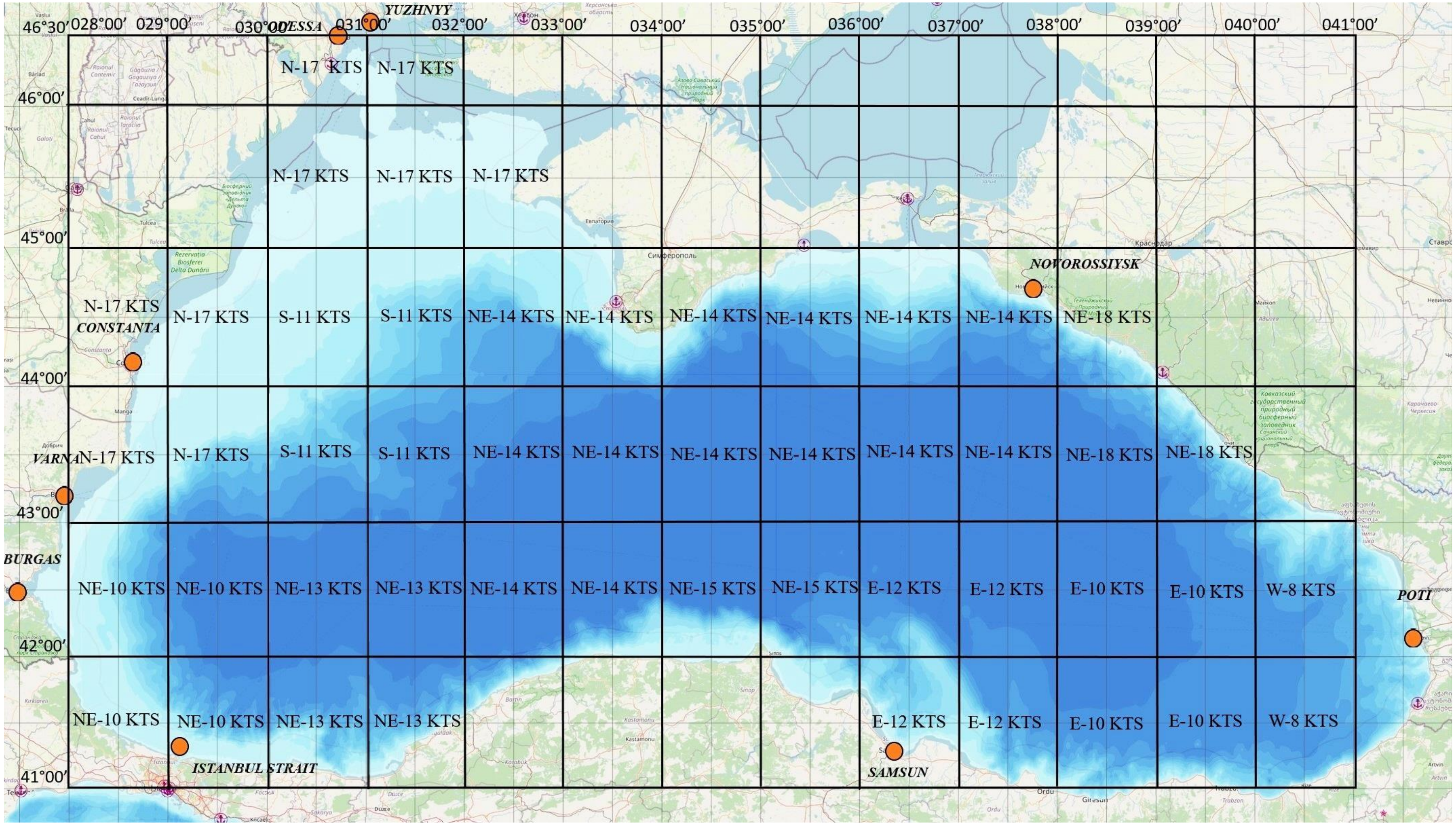

Figure 3.6: Black Sea Wind Direction and Speed in Knots for Fall (SHOD, 1991).

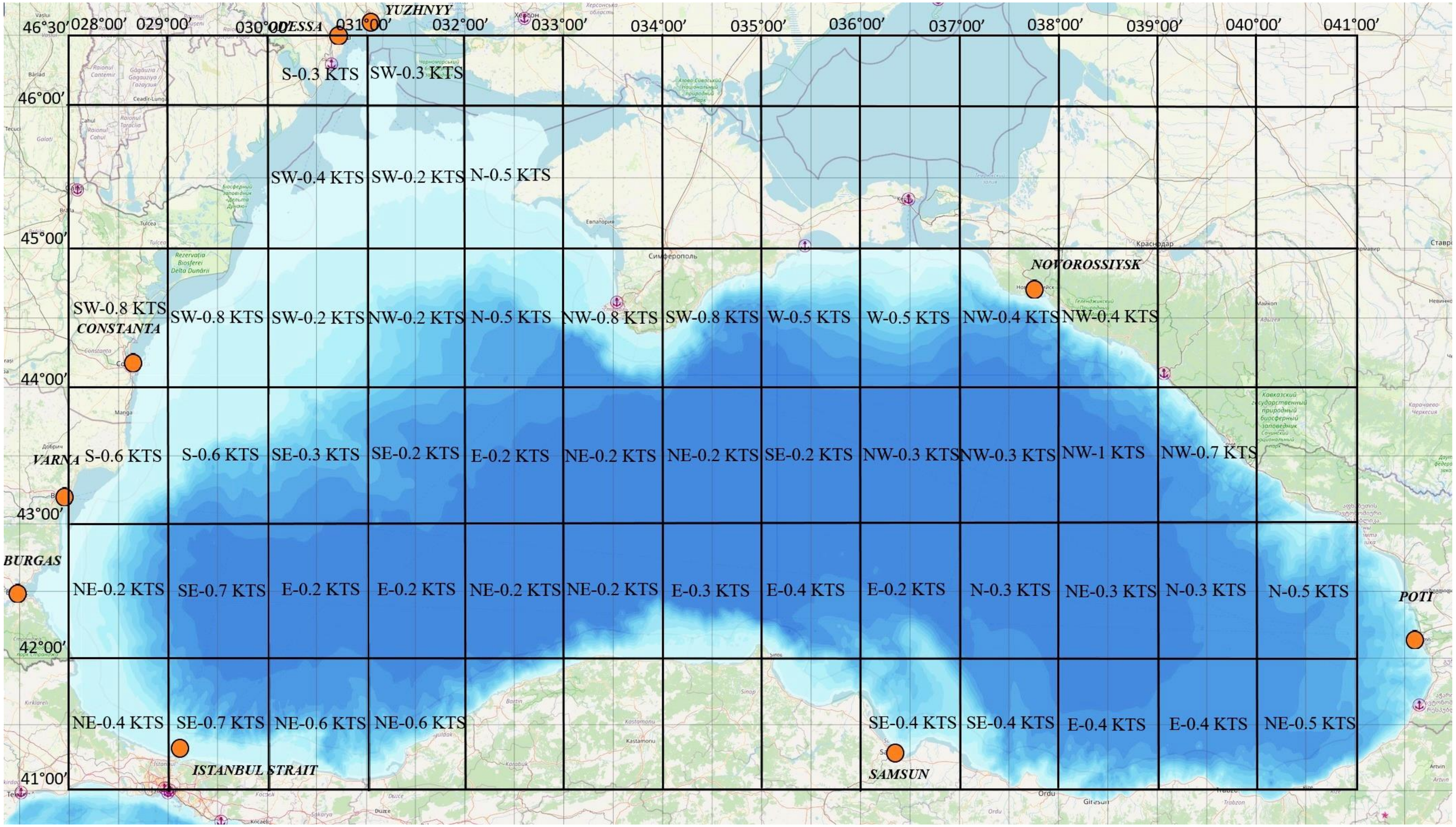

Figure 3.7: Black Sea Currents' Sets and Drifts (SHOD, 1991).

Weather effect on each static weather grid has been stated as W_{ijk}^{n}. Kwon's method utilizes Froude Number (Fn) in its equations, which requires speed unit of m/s. In Equation 3.19 Fn_k is the Froude Number for the ship k, L_{pp} is the length between perpendiculars and g is the gravitational acceleration (9,80665 m/s^2). Froude number is utilized in this empirical methodology to provide ratio of the flow inertia depending on the load condition of the ship to find out speed reduction based on underwater hull area (Kwon, 2008). Hence, W_{ijk}^{n} can also be stated as the speed change for vessel *k* in grid *n* for the route from port *i* to port *j* in m/s. Equation 3.20 represents the final speed on grid *n*, with the assumption of vessel *k* sails with her service speed v_k^{ss} in m/s.

$$Fn_k = \frac{v_k^{ss}}{\sqrt{L_{pp} * g}}, \qquad k \in K \tag{3.20}$$

$$v_{ijk,n}^{sog} = v_k^{ss} - W_{ijk}^{n}, \qquad \forall i,j \in A, k \in K, n \in N \tag{3.20}$$

In Equations 3.21-3.23, Kwon's method of calculating the effect of weather on ships' involuntary speed loss in closed seas or during short sea waves is given (Kwon, 1981; Kwon & Dai, 2005; Kwon, 2008). ΔV_{ijk}^{n} is the change in speed in a static weather grid *n* and v_k^{ss} is the service speed of a ship *k*. Equation 3.21 utilized for calculating the percentage involuntary speed loss due to added resistances sourced from winds and waves.

$$W_{ijk}^{n} = \Delta V_{ijk}^{n} = v_k^{ss} - v_{ijk,n}^{sog}, \qquad \forall i,j \in A, k \in K, n \in N \tag{3.21}$$

$$\frac{\Delta V_{ijk}^{n}}{v_k^{ss}} * 100 = S_{ijk}^{n,\propto} * S_{ijk}^{n,\beta} * S_{ijk}^{n,\gamma}, \qquad i,j \in A, k \in K, n \in N \tag{3.22}$$

$$\Delta V_{ijk}^{n} = \left(S_{ijk}^{n,\propto} * S_{ijk}^{n,\beta} * S_{ijk}^{n,\gamma}\right) * v_k^{ss}/100, \qquad i,j \in A, k \in K, n \in N \tag{3.23}$$

$S_{ijk}^{n,\propto}$ is the coefficient for reduction based on wind and wave direction. Equations 3.24-3.27, given in Table 3.2, considers directional effect of winds and waves and provides a speed reduction coefficient $S_{ijk}^{n,\propto}$ with the aforementioned assumption of all winds and waves comes from the same direction. Note that the wind and wave angles given in the tables defines a specific formula for $S_{ijk}^{n,\propto}$, where the directions are relative to ship. Although, in the static weather grids, these directions have been given as true directions. In order to find which formula to utilize, all routes between the ports in the set *V* should be known and $S_{ijk}^{n,\propto}$ should be calculated for each static weather grid *n* that the ships pass through during their voyage from port *i* and port *j*.

Table 3.2: Wind and Wave Directional Speed Reduction Coefficient Formulae (Kwon, 1981; Kwon, 2008; Li et al., 2020)

Wind and Wave Direction	**Wind and Wave Angle**	**Wind and Wave Directional Speed Reduction Coefficient ($S_{ijk}^{n,\propto}$)**	
From Head	$0° - 30°$	$S_{ijk}^{n,\propto}=1$	(3.24)
From Port or Starboard Bow	$30° - 60°$	$S_{ijk}^{n,\propto} = \frac{(1{,}7 - 0{,}03(BN_n - 4)^2)}{2}$	(3.25)
From Beam	$60° - 150°$	$S_{ijk}^{n,\propto} = \frac{(0{,}9 - 0{,}06(BN_n - 6)^2)}{2}$	(3.26)
From Aft	$150° - 180°$	$S_{ijk}^{n,\propto} = \frac{(0{,}4 - 0{,}03(BN_n - 8)^2)}{2}$	(3.27)

$S_{ijk}^{n,\beta}$ is the coefficient for speed reduction based on block coefficient (Cb_k). Equations 3.28-3.37, given in Table 3.3, presents speed reduction coefficient $S_{ijk}^{n,\beta}$ based on ships load condition and Cb_k. Here, Cb_k relays into the wetted surface area of the ship. Formulation with Fn provides the speed reduction based on the added resistances sourced from ships wetted surface or simple water resistance considering underwater hull area, with the inclusion of service speed from Fn formula. Note that $S_{ijk}^{n,\beta}$ calculation changes depending on the ship load conditions. Ships in ballast conditions usually have less wetted surfaces than ships in laden condition. Depending on the ships' Cb_k and load condition, $S_{ijk}^{n,\beta}$ can be determined.

Table 3.3: Load Condition Speed Reduction Coefficient Formulae (Kwon, 1981; Kwon, 2008; Li et al., 2020)

Block Coefficient (Cb_k)	**Ship Load Condition**	**Load Condition Speed Reduction Coefficient ($S_{ijk}^{n,\beta}$)**	
0.55	Laden	$S_{ijk}^{n,\beta} = 1{,}7 - 1{,}4Fn_k - 7{,}4Fn_k^2$	(3.28)
0.60	Laden	$S_{ijk}^{n,\beta} = 2{,}2 - 2{,}5Fn_k - 9{,}7Fn_k^2$	(3.29)
0.65	Laden	$S_{ijk}^{n,\beta} = 2{,}6 - 3{,}7Fn_k - 11{,}6Fn_k^2$	(3.30)
0.70	Laden	$S_{ijk}^{n,\beta} = 3{,}1 - 5{,}3Fn_k - 12{,}4Fn_k^2$	(3.31)
0.75	Laden	$S_{ijk}^{n,\beta} = 2{,}4 - 10{,}6Fn_k - 9{,}5Fn_k^2$	(3.32)
0.80	Laden	$S_{ijk}^{n,\beta} = 2{,}6 - 13{,}1Fn_k - 15{,}1Fn_k^2$	(3.33)
0.85	Laden	$S_{ijk}^{n,\beta} = 3{,}1 - 18{,}7Fn_k + 28Fn_k^2$	(3.34)
0.75	Ballast	$S_{ijk}^{n,\beta} = 2{,}6 - 12{,}5Fn_k - 13{,}5Fn_k^2$	(3.35)
0.80	Ballast	$S_{ijk}^{n,\beta} = 3 - 16{,}3Fn_k - 21{,}6Fn_k^2$	(3.36)
0.85	Ballast	$S_{ijk}^{n,\beta} = 3{,}4 - 20{,}9Fn_k + 31{,}8Fn_k^2$	(3.37)

$S_{ijk}^{n,\gamma}$ is the coefficient for ship type and loaded condition where displacement of the ship and Beaufort Number contributes to percentage involuntary speed loss as given in Equations 3.38-3.40 in Table 3.4. Beaufort Number BN_n states the weather condition in static weather grid *n*, ∇_{ijk} represents the displacement of the ship *k* sailing from port *i* to port *j* in tons. Displacement is the amount of water "displaced" by ships underwater volume, representing cargo onboard ships with a unit of cubic meters (Bowditch, 2019). In order to find displacement with a unit of tons, simple density formula can be utilized depending on the density of sea water ship is sailing through. Note that this is the second set of formula that changes depending on the ship load conditions. Kwon's method considers tankers and bulk carriers under the same category while for containers a different formulation was presented.

Table 3.4: Ship Type Coefficient Formulae (Kwon, 1981; Kwon, 2008; Li et al., 2020)

Ship Type	**Ship Load Condition**	**Ship Type Speed Reduction Coefficient ($S_{ijk}^{n,\beta}$)**	
Tanker and Bulk	Laden	$S_{ijk}^{n,\gamma} = 0{,}5BN_n + \frac{BN_n^{6,5}}{2.7 * \nabla_{ijk}^{2/3}}$	(3.38)
Tanker and Bulk	Ballast	$S_{ijk}^{n,\gamma} = 0{,}7BN_n + \frac{BN_n^{6,5}}{2.7 * \nabla_{ijk}^{2/3}}$	(3.39)
Container	Laden	$S_{ijk}^{n,\gamma} = 0{,}7BN_n + \frac{BN_n^{6,5}}{22 * \nabla_{ijk}^{2/3}}$	(3.40)

In maritime transportation, in order to correctly and universally evaluate wind and wave conditions Beaufort Scale is utilized. In the Beaufort Scale, wind speeds ranging between two values are assigned a Beaufort Number, representing the sea state with explanations given on the scale such as how the waves should be looking, wave height, wind speed in knots etc. These numbers start from 0 representing calm water up to 12 which means hurricane. 12 is the highest Beaufort Number and wind speeds exceeding 64 knots are all considered as 12 Beaufort. Accordingly, Kwon's method is advised to be utilized up to 8 Beaufort, which states gale, with wind speed ranging from 34 knots to 40 knots. In Table 3.5, Beaufort Scale with corresponding wind speeds in knots has been presented.

Table 3.5: Beaufort Numbers with Corresponding Wind Speeds in Knots.

Minimum Wind Speed in knots	Maximum Wind Speed in knots	Beaufort Number
0	1	0
1	3	1
4	6	2
7	10	3
11	16	4
17	21	5
22	27	6
28	33	7
34	40	8
41	47	9
48	55	10
56	63	11
64	71	12

3.4 Problem Assumptions

The aim of this proposed methodology is enabling pre-planning of liner shipping routes with incorporation of weather effects depending on the seasons with a green approach. Proposed MILP model minimizes CO_2 emissions while an increased precision to ship speed has been implemented with involuntary speed loss calculations in static weather grids. This methodology focuses on short sea shipping as it employs Kwon's method (Kwon, 2008) for calculation of involuntary speed loss caused by added resistances of winds and waves. Certain assumptions had to be made in order to utilize aforementioned methodologies:

- All ships are well maintained and fully operational.
- Pilot-to-pilot routing has been considered for routes between ports.
- Ships use very low Sulphur fuel oil (VLSFO).
- Only main engine fuel consumption has been considered, ergo, only CO_2 emissions sourced from main engine has been included.
- Ships use service speed with 85% main engine load.
- Specific fuel oil consumption (SFOC) is 0,305 kg/kWh, as recommended (Faber et al., 2021).

- All ports in the system are operationally capable for cargo operations.
- All ports in the system have available and suitable berths for each ship.
- Winds and waves come from the same direction, thus rouge winds and waves, swells and other unregular weather effects have been excluded.
- Ships will start the system in laden condition.
- The fleet is homogenous and comprise of the ships in the set *K*.
- The fleet can meet the total cargo demands in ports. Ships can take cargo as their capacity allows. All ships are considered fully loaded with maximum displacement (t).
- Ships go directly to berth, hence anchorage assumed to be unnecessary.

With consideration of these assumptions, numerical experiments have been carried out to test the reliability of the proposed methodology based on four different scenarios regarding time windows and cargo demand in ports. The scenarios and results have been presented in chapter four of this study.

4. RESULTS AND DISCUSSION

Numerical experiments have been performed for examination of the proposed methodology's reliability. The experiments have been structured as a comparison of original Black Sea routes with obtained routes from the developed MILP model. The comparison has been done regarding fuel consumption and CO_2 emissions generated in the system.

For the purpose of comparison, the values of fuel consumption and CO_2 emissions have been calculated with the same formulation using Equations 3.2-3.4. For Equation 3.4, ship's service speed has been used. Accordingly, information about the ship used in numerical experiments is given in Table 4.1. Here, for calculating displacement in cubic meters, density of Black Sea was considered as 1,017 g/m^3.

Table 4.1: Particulars for Homogeneous Ships in Numerical Experiments.

Ship Particulars	
Length Overall (m)	184
Length Between Perpendiculars (m)	177,75
Breadth (m)	24.5
Summer and Winter Draught (m)	9.00
Displacement (t)	29783
Displacement (m^3)	29285,15
Fn	0,246435537
Block Coefficient	0,7
Main Engine Power (kW.h)	13280
Service Speed (Knots)	20

Estimated fuel consumption and CO_2 emission values of the original Black Sea routing network are given in Table 4.2 below. These routes have been altered accordingly with problem description, meaning that although some of these routes extend beyond the İstanbul Strait, distances between ports have been calculated with same assumptions and method. Emission factor for CO_2 used accordingly with the recommended value of 3,1144 kg CO_2 per kg fuel consumed.

Table 4.2: Estimated Fuel Consumption and CO2 Emission Values of the Original Black Sea Routing Network.

Routes	**Fuel Consumption (Kg)**	**Emission Values (Kg CO_2 per kg VLSFO)**
Istanbul-Poti-Constanta-Istanbul	227091,91	707255,04
Istanbul-Constanta-Odessa-Istanbul	117050,85	364543,17
Istanbul-Novorossiysk-Istanbul	149608,25	465939,93
Istanbul-Burgas-Varna-Istanbul	50325,00	156732,18
Istanbul-Poti-Samsun-Istanbul	200556,50	624613,16
Yuzhnyy-Poti-Yuzhnyy	191301,40	595789,08
Network Total	935933,91	2914872,57

For numerical experiments four different scenarios have been created for each season regarding time windows and cargo demand. All routes between ports, time windows and cargo demand in ports have been determined in consultation with a group of experts comprise of ship captains, academicians, and logistics experts. Tight and loose time windows have been set including berthing, unberthing and cargo operations while anchorage assumed to be non-applicable. High and low demand values have been set for each port respectively, while total fleet cargo capacity meets these set demand values. Seasons incorporates into weather effects in accordance with the methodology detailed in section 3.3 of this study.

Numerical experiments have been carried out on a laptop with 2.30GHz 11th Gen Intel (R) Core (TM) i7-11800H processor and 16 GB RAM. Solution of the MILP problems have been performed using CPLEX Studio 20.1.0, which is called within C++ code running in Microsoft Visual Studio 2022 platform. Routes between ports have been drawn by hand and approved by experts. Weather effect calculations using static weather grids have been carried out on MS Excel, where each static weather grid have been represented. For each static weather grid routes pass through, relative wind and wave direction have been entered to the MS Excel sheet, where $v_{ijk,n}^{sog}$ is calculated using Equation 3.1, followed by Equation 3.18 for finding V_{ijk}^{sog}. Results obtained from solution of the MILP model is given in Tables 4.3-4.7. Table 4.3 presents fleet fuel consumption and CO_2 emissions for each scenario.

Table 4.3: Emission Values for Numerical Experiments.

Weather Period	Demand	Time Windows	Fleet Fuel Consumption (Kg)	Fleet Emission Values (kg CO2 per kg fuel)
Winter	High	Loose	399369,44	1243796,18
	Low	Loose	340841,16	1061515,71
	High	Tight	423469,32	1318852,85
	Low	Tight	440683,52	1372464,75
Summer	High	Loose	395926,60	1233073,80
	Low	Loose	337398,32	1050793,33
	High	Tight	416583,64	1297408,09
	Low	Tight	437240,68	1361742,37
Fall	High	Loose	395926,60	1233073,80
	Low	Loose	337398,32	1050793,33
	High	Tight	416583,64	1297408,09
	Low	Tight	430355,00	1340297,61
Spring	High	Loose	392483,76	1222351,42
	Low	Loose	333955,48	1040070,95
	High	Tight	413140,00	1286683,22
	Low	Tight	430355,00	1340297,61

From the obtained routes, a significant difference regarding the fuel consumption and emissions have been observed. Figure 4.1 showcases the comparison between obtained GSRSP routes and original routes of the system. Depending on the season, emitted CO_2 values changes. With a simple minimum-maximum value comparison, highest emission value has been obtained during winter and lowest value have been observed in spring. Based on scenarios, highest emission values have been observed in tight time window scenarios, depicting that time windows are a more integral part of evaluating and improving emissions generated in a routing network. Interestingly, second highest emission value observed in summer. This can be discussed as a result of wind direction effect, although wind speed is not high, ships facing head winds (including bow direction) causes involuntary speed loss as opposed to taking the wind from aft, which provides small but a positive effect on ship speed. Generally, an improvement varying between 1874801,62 kg to 1542407,82 kg CO_2 emission difference have been observed. This represents a 52,9% to 64,3% improvement with the proposed methodology. Highest differences have been noted during low cargo demand and loose time window conditions of each season and lowest differences, as stated before, noted for low cargo demand and tight time window scenarios of each season.

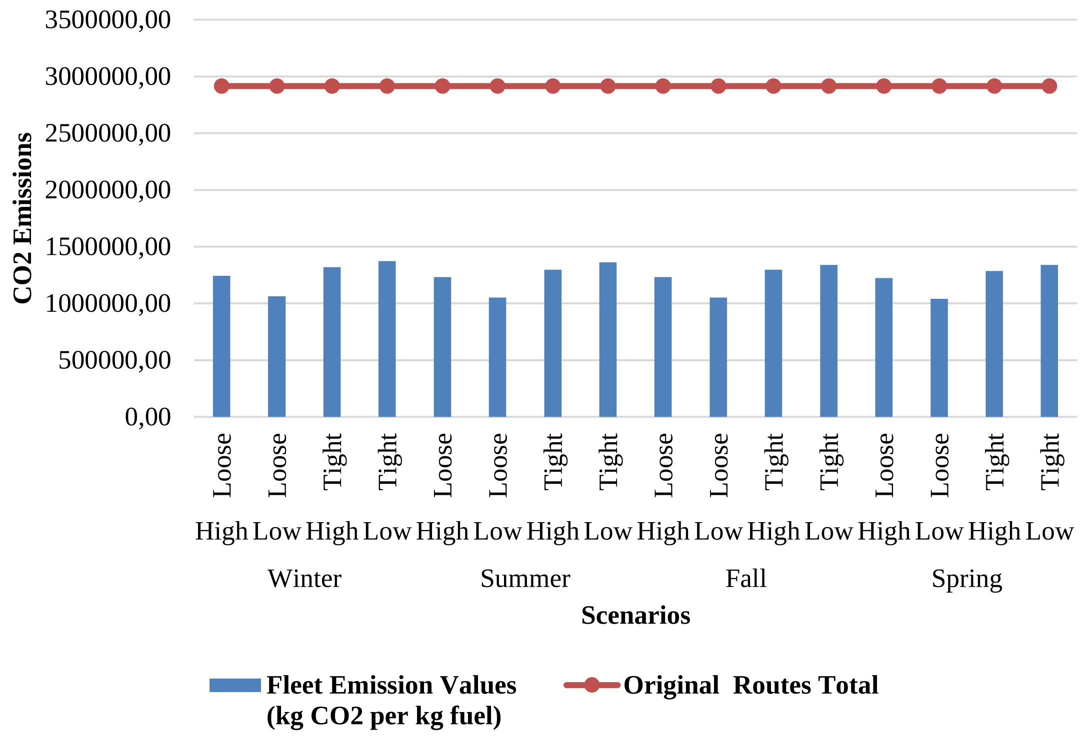

Figure 4.1: Comparison of CO_2 Emission Values Between Original Routes and GSRSP Solution

Moreover, Tables 4.4-4.7 shows the routes obtained from MILP solution. The route each ship assigned to complete have been given in accordance with the scenarios.

Table 4.4: Optimal Routes for Numerical Experiments in Winter.

Weather Period	Demand	Time Windows	Routes	
Winter	High	Loose	Ship 1:	İstanbul-Yuzhnyy-Odessa-İstanbul
			Ship 2:	İstanbul-Novorossiysk-Poti-Samsun-İstanbul
			Ship 3:	İstanbul-Burgas-Varna-Constanta-İstanbul
	Low	Loose	Ship 1:	İstanbul-Burgas-İstanbul
			Ship 2:	İstanbul-Varna-İstanbul
			Ship 3:	İstanbul-Constanta-Yuzhnyy-Odessa-Novorossiysk-Poti-Samsun-İstanbul
	High	Tight	Ship 1:	İstanbul-Yuzhnyy-Odessa-İstanbul
			Ship 2:	İstanbul-Samsun-Novorossiysk-Poti-İstanbul
			Ship 3:	İstanbul-Varna-Constanta-Burgas-İstanbul
	Low	Tight	Ship 1:	İstanbul-Varna-Constanta-Odessa-Yuzhnyy-Novorossiysk-İstanbul
			Ship 2:	İstanbul-Burgas-İstanbul
			Ship 3:	İstanbul-Samsun-Poti-İstanbul

Table 4.5: Optimal Routes for Numerical Experiments in Summer.

Weather Period	Demand	Time Windows	Routes	
Summer	High	Loose	Ship 1:	İstanbul-Odessa-Yuzhnyy-İstanbul
			Ship 2:	İstanbul-Novorossiysk-Poti-Samsun-İstanbul
			Ship 3:	İstanbul-Constanta-Varna-Burgas-İstanbul
	Low	Loose	Ship 1:	İstanbul-Varna-İstanbul
			Ship 2:	İstanbul-Constanta-Odessa-Yuzhnyy-Novorossiysk-Poti-Samsun-İstanbul
			Ship 3:	İstanbul-Burgas-İstanbul
	High	Tight	Ship 1:	İstanbul-Yuzhnyy-Odessa-İstanbul
			Ship 2:	İstanbul-Samsun-Novorossiysk-Poti-İstanbul
			Ship 3:	İstanbul-Burgas-Varna-Constanta-İstanbul
	Low	Tight	Ship 1:	İstanbul-Varna-Constanta-Yuzhnyy-Odessa-Novorossiysk-İstanbul
			Ship 2:	İstanbul-Samsun-Poti-İstanbul
			Ship 3:	İstanbul-Burgas-İstanbul

Table 4.6: Optimal Routes for Numerical Experiments in Fall.

Weather Period	Demand	Time Windows	Routes	
Fall	High	Loose	Ship 1:	İstanbul-Novorossiysk-Poti-Samsun-İstanbul
			Ship 2:	İstanbul-Yuzhnyy-Odessa-İstanbul
			Ship 3:	İstanbul-Burgas-Varna-Constanta-İstanbul
	Low	Loose	Ship 1:	İstanbul-Constanta-Odessa-Yuzhnyy-Novorossiysk-Poti-Samsun-İstanbul
			Ship 2:	İstanbul-Burgas-İstanbul
			Ship 3:	İstanbul-Varna-İstanbul
	High	Tight	Ship 1:	İstanbul-Samsun-Novorossiysk-Poti-İstanbul
			Ship 2:	İstanbul-Burgas-Varna-Constanta-İstanbul
			Ship 3:	İstanbul-Yuzhnyy-Odessa-İstanbul
	Low	Tight	Ship 1:	İstanbul-Samsun-Poti-İstanbul
			Ship 2:	İstanbul-Varna-Constanta-Odessa-Yuzhnyy-Novorossiysk-İstanbul
			Ship 3:	İstanbul-Burgas-İstanbul

Table 4.7: Optimal Routes for Numerical Experiments in Spring.

Weather Period	Demand	Time Windows	Routes	
Spring	High	Loose	Ship 1:	İstanbul-Odessa-Yuzhnyy-İstanbul
			Ship 2:	İstanbul-Burgas-Varna-Constanta-İstanbul
			Ship 3:	İstanbul-Novorossiysk-Poti-Sansum-İstanbul
	Low	Loose	Ship 1:	İstanbul-Varna-İstanbul
			Ship 2:	İstanbul-Burgas-İstanbul
			Ship 3:	İstanbul-Constanta-Odessa-Yuzhnyy-Novorossiysk-Poti-Samsun-İstanbul
	High	Tight	Ship 1:	İstanbul-Yuzhnyy-Odessa-İstanbul
			Ship 2:	İstanbul-Constanta-Varna-Burgas-İstanbul
			Ship 3:	İstanbul-Samsun-Novorossiysk-Poti-İstanbul
	Low	Tight	Ship 1:	İstanbul-Samsun-Poti-İstanbul
			Ship 2:	İstanbul-Varna-Constanta-Yuzhnyy-Odessa-Novorossiysk-İstanbul
			Ship 3:	İstanbul-Burgas-İstanbul

Routes mostly differ from the original network, although Istanbul-Poti-Samsun-Istanbul route and its variations have been acquired in low demand and tight time window scenarios of each season. It can be discussed that, most of the time weather effect on ship during this route is direct, meaning that the ship is either affected from head, losing speed or from aft, increasing her speed.

Results show that there is a high similarity between fall and summer routes, which relays into generated emissions. For 3 out of 4 scenarios, summer and fall values are the same, while some changes can be observed regarding port arrangements.

Another important note is that, although routes are similar between seasons depending on each scenario, the arrangement of visited ports varies. This occurs due to involuntary speed loss sourced from added resistances of winds and waves. Since wind direction and sea state changes on each season, as aimed in this study, decision making regarding routing and scheduling of the ships can be carried out with a better estimation of the generated emissions and fuel consumption, which reduces cost if optimized.

In general, a significant deviation can be observed from the original system on each scenario. Although real data was not used for the scenarios, with expert opinion and certain assumptions, it can be stated that the proposed methodology provides value regarding its efficiency in route generation.

The limitations of this methodology sources from obtaining reliable weather data. For the sake of carrying out numerical experiments of this study, wind and wave data have been extracted from Black Sea Meteorological Atlas (Seyir Hidrografi ve Oşinografi Dairesi, 1991). Although with a method of calculation, it is not difficult to calculate involuntary speed loss, as the number of ports increase, hand driven routes and calculating weather effect in each individual grid may take its toll in the form of time. This enables a room for improvement regarding the proposed methodology for further studies. Finally, as the size of the problem grows, MTZ subtour elimination constraints may cause increase in solution time, hence additional methodologies maybe need to be applied.

5. CONCLUSION

Maritime transportation has always been one of the main pillars of international trade. Maritime transportation is considered the most preferable method for shipping large volumes of commodities even though it is slower compared to other means of transportation. As technological feasibility increases day by day, ships become a more prominent way of transporting goods that enables economies of scale. Increasing vessels' capacities while lowering the cost of transportation of goods, encourages trade and enables freight accessibility across greater distances.

Introduction of containers to the global trade revolutionized and standardized in dimensions. Due to the rise of containerization, economic globalization and the rapid development of foreign trade, container ships have become more and more common, and they have a widespread utilization for transportation of commodities between ports, providing mainly liner shipping services. Ability to transport expensive cargoes with low hold occupation became easier and transportation of goods in containers with smaller amounts instead of bulks became preferable instead of waiting to ship big volumes. Globally standardized cargo carrying "boxes" increased efficiency on all legs of logistic processes, thus, transporting such cargoes globally with reduced cost and increased efficiency and consequently competition among shipping companies.

In the competitive environment of seaborne trade, shipping companies are required to consider their cost of transportation in order to maximize their profit. Liner shipping is a capital sensitive way of transporting commodities while comprising of complex parameters. Optimized container transportation usually relies on port costs, voyage costs, cargo handling rate and fuel consumption. Gaining competitive advantage requires minimum transportation time, hence, container ships are also designed for speed, at the cost of environmental damage in the form of emitted GHGs, meanwhile conforming with the constantly updated environmental regulations.

To reduce ship sourced emissions in line with the IMO's projections and aims, it is pivotal to optimize operational phases of maritime transportation, mainly voyage based processes. Finding the optimal relation for total distances and speed of ships are two main and basic ways of reducing emissions. This trade off can be stated as the conflict between money and environment, or simply conflicting objectives of green ship routing and scheduling. This causes optimizing ship routes and schedules considering environmental effects of ships becomes a very complex problem, namely green ship routing and scheduling problem (GSRSP).

Until there are environmentally safe energy sources for maritime transportation, or maybe an unconventional way of solving global logistics problems that is safe for environment, adapting to the decarbonization is a more important task prior to the mitigation. Therefore, an optimization for adaptation to the decarbonization was considered regarding maritime transportation during the composition of this research and methodological proposal.

In order to find out the inadequacies and deficits in the recent literature, a systematic literature review on GSRSP has been carried out regarding ship types, voyage types, objective functions, solution methods, time window constraints, cargo demand constraints and weather effect. Results of the systematic literature shows that vast majority of the studies was observed to be about container shipping and trans-oceanic voyages. Cost has been observed to be the most common objective function followed by fuel consumption. Interestingly, emission was not a common objective function, although some studies had used emissions as constraints for restricting their methodologies. Time windows observed to be an integral part of GSRSP studies, while cargo or demand constraints have been fairly utilized when deemed necessary.

In this study, a green vehicle routing approach has been introduced to minimize the CO_2 emission generated by small scale liner container shipping network. The aim of this study is to provide a reliable estimation tool for short sea liner shipping companies regarding decision making on route planning. This approach enables pre-planning of shipping lines to be presented for a given period of time. In accordance with the results of the systematic literature review, this study contributes to the gap observed for short sea shipping GSRSPs. For evaluating the reliability and validity of the proposed methodology, container shipping has been selected. Time windows and cargo demand have been incorporated into the methodology, considering their integrality in maritime transportation. Incorporating weather effects is another contribution of this study to enable more realistic estimations, which provides flexibility for liner shipping companies to update their liner routes depending on the fuel consumption and produced CO_2 emission based on the dynamic effects.

A MILP model has been developed for the GSRSP. A sample problem has been derived from a liner container shipping company that operates in Black Sea Region. The derived problem has been constructed as a seasonal pre-planning of a small-scale liner container shipping company that the concern for routing is the green approach, thus, minimizing fleet CO_2 emissions while generating a green routing and scheduling scheme. Time windows and cargo demand in ports have been included as constraints. Their incorporation to the solution methodology has been in the form of MTZ subtour elimination constraints.

Weather effects has been added to the MILP methodology in the form of added resistances concept. Added resistance effect sourced from winds and waves can be calculated by considering wind resistance on ships' freeboards and wave resistance on ships' wetted surfaces. Kwon's method, a validated a semi-empirical method of calculating estimated involuntary speed loss due to added resistances in short sea shipping, has been employed. For incorporating Kwon's method for involuntary speed loss, static weather grids have been utilized on the described problem area. In these static weather grids, seasonal averages of observation areas regarding wind direction, wind speed in knots and currents in knots have been entered as data, then Kwon's method have been applied to each individual static weather grid. For each static weather grid routes pass through, relative wind and wave direction have been calculated. Then using Kwon's method, involuntary speed loss has been found. Then average speed over ground of each ship for each route between ports have been calculated. Vessel speed over ground directly impacts fuel consumption and emission, since fuel consumption is a function of sailing time, hence, ship speed.

Numerical experiments have been performed for examination of the proposed methodology’s reliability. Four different scenarios have been created for each season regarding time windows and cargo demand. Tight and loose time windows and high and low demand values have been set for each port respectively. The experiments have been structured as a comparison of original Black Sea routes with obtained routes from the developed MILP model.

Numerical experiment results show significant improvement in overall fuel consumption while inclusion of weather effects changes routes depending on the seasons for each scenario. Obtained routes shows a decrease in fuel consumption and emission varying between 51-62% depending on the season and scenario.

It can be discussed that appropriate modelling regarding ship routes, a greener maritime transportation can be achieved. Although mitigating emissions seems to be an impossible task, adaptation to greener services may be the key for financial and environmental improvement for seaborne trade.

There are some limitations observed during the application of the proposed methodology. Firstly, obtaining reliable weather data, since weather effect is a crucial part of the methodology, can be a tolling experience. There are various meteorological research trying to extract trends in long term weather prediction, but simply, it may not seem possible in the near future. Hence, the only way to utilize weather data is by looking for previous weather reports for an estimation. Note that, this methodology utilizes seasonal averages, consequently, daily precise weather data is not required. Additionally, calculating involuntary speed loss for each static weather grid is a time-consuming task. Finally, we observe that the MTZ subtour elimination constraints requires excessive CPU time as the problem size grows.

As a further research avenue, it is planned to address these limitations. Reducing the time to calculate involuntary speed loss on each grid requires room for improvement. Instead of using MS Excel, a software specifically designed for regional involuntary speed loss calculation can be considered to be developed, while noting that it may by costly since a generalized solution cannot be obtained for all seas.

Last but not least, in order to alleviate the limitations regarding MTZ subtour elimination constraints, it is possible to devise tailor-made branch-and-cut algorithm for solving medium to large size real-life instances.

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