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Small-scale LNG supply chain optimization for LNG bunkering in Turkey

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ABSTRACT

LNG (Liquefied Natural Gas) provides a viable option to comply with emission control measures as an alternative marine fuel. Supply chain optimization is critical for LNG bunkering development in the maritime context as it requires high capital-expenditure. This study proposes a model for optimizing the ship-to-ship LNG bunkering supply chain. The related problem is defined as a Multiple Period Maritime Fleet Size and Routing Problem. The proposed mathematical model has been solved for various demand scenarios obtained by multiple regression and forecasting as a case study of ship-to-ship LNG bunker deliveries in Turkey. The model presents an optimal solution as a tactical and strategic decision-making tool, finds the number and size of the LNG bunker barges and the optimum allocation of the barges and the distribution network within a ship-to-ship bunkering framework. Moreover, it provides a commercial framework for shipowners and suppliers by determining the breakeven point for investment decisions.

1. Introduction

According to the UN National Determined Conditions Global Outlook Report (2019), human-caused GHG (Greenhouse Gas) emissions have reached historic highs this century, reaching 50.8 billion tonnes in 2016, increasing 48% since 1990 (UNNDC, 2019). Energy supply is the source of the most GHGs, accounting for 34% of global emissions in 2016, followed by industry (22%) and transportation (14%). Shipping is responsible for a significant amount of air pollution, mainly sourced from fossil fuels. According to the Fourth International Maritime Organization (IMO) GHG Study (2020), shipping-related GHG emissions grew from 977 million tonnes in 2012 to 1076 million tonnes in 2018. Hence, the share of global anthropogenic GHG emissions attributed to shipping has increased from 2.76% in 2012 to 2.89% in 2018 (IMO, 2020). In dealing with the air pollution caused by shipping, measures such as Emission Control Areas, a global sulphur cap, and NOx Tier I-III criteria have been implemented. Compliance with sulfur emission restrictions is subject to the fuel use policy for owners and operators. The owners and operators of the fuel-use policy are responsible for adhering to sulphur emission regulations. Fuel prices, environmental implications, and investment payback periods affect selecting emission reduction strategies (Acciaro, 2014). LNG provides a viable option amongst other alternatives such as low sulphur distillates, scrubbers, or other alternative fuels such as ammonia, LPG (Liquid Petroleum Gas), hydrogen, batteries, and fuel cells. LNG has a significant positive effect on air pollution as it provides complete removal of SO_x and PM (Particular Matters); moreover, it reduces NO_x emission up to 85% and contributes to mitigation of CO_2 emission at least 20% (DNV-GL, 2015).

According to Shell LNG's 2019 projection, gas and renewables will meet more than 70% of future energy demand growth, with gas providing more than 40% of the increased demand (Shell, 2019). The research also notes that LNG usage in transportation is rapidly increasing, particularly in heavy-duty trucks and buses and marine LNG, with 143 LNG-fuelled ships now in service (Shell, 2019). Despite obstacles such as a lack of infrastructure, high investment costs, or LNG pricing, environmental consciousness is a key driver for LNG and LNG as a ship fuel (Fevre, 2018; Wang and Notteboom, 2014).

Consumer characteristics shape the supply chain, location, consumption profile, cost, etc. Distance for LNG distribution and LNG transshipment scale are essential elements that affect the overall supply chain (EMSA, 2017). The scale of LNG to be treated affects the distribution channels in operation and costs and technical issues such as Boil-off gas (EMSA, 2017). While defining the scale of LNG handling, there are no exact criteria (EMSA, 2017); how-

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ever, generally accepted industry definitions are onshore terminals of less than 10 000 cbm and ships of less than 10,000 cbm LNG are defined as small-scale LNG (DMA, 2012).

This paper studies the strategic and tactical decisions that must be given in Turkey's LNG Bunker supply chain optimization. There is a limited number of studies on small-scale LNG bunkering supply chain optimization field, and they are not mainly focused on ship-to-ship deliveries that are the predominant bunkering option in maritime (Alvarez et al., 2020; Bittante et al., 2017a, 2018; Deluster et al., 2018; Jokinen et al., 2015). This paper focuses on the small-scale LNG supply chain and ship-to-ship LNG bunker deliveries that constitute the most common bunkering practices in the maritime industry. The developed model provides a decision-making tool concerning the minimum quantity to be transferred from the loading ports to the discharging locations and banning the barges from travelling until the last planning period if requested deliveries are insufficient. Since it is not practical to perform operations such as mooring, hose connection, lining-up, safety precautions, or safety meetings in less than a specified time, discharging and loading times are included in the model considering the minimum time requirement. The decisions taken are the optimum number and size of barges, the optimum allocation of barges to distribution plans, and the routing of distribution plans. Therefore, our study differentiates from other studies by providing a strategic and tactical level decision support system, considering ship-to-ship operational level features.

Turkey is an important country in shipping with a large fleet, the construction and repair industry, the supply and storage of bunkers, the considerable economic volume, various sorts of ports, and having two worthwhile straits such as Çanakkale and Istanbul. This study also aims to explore Turkey's bunkering dynamics as a case. Technical reports and time-series data from various sources are used, and Turkey's bunker demand projections are carried out through a multiple regression model. Demand forecast provides ground for the mathematical model and evaluates Turkey's LNG bunkering case under different scenarios.

The paper is organized as follows: Section 2 reviews the LNG bunkering supply chain. Section 3 gives the problem description; Section 4 describes the proposed MILP model, objective function, constraints, and Turkey case. This section also includes Turkey's bunker delivery forecast. Computational results are discussed in Section 5, followed by the conclusion and recommendations.

2. LNG bunkering supply chain

Bunkering is the refuelling of the bunker, which is referred to as marine fuel (Vilhelmsen et al., 2013). It is an operation that involves supplying the fuel required to keep the ship's main and auxiliary engines running. It is a vital energy market for the shipping industry. Bunkering operations can take place at ports or in anchorage locations. Although bunkers are available worldwide, the business is concentrated along key maritime routes, with six countries accounting for 60% of the market. The IMO (2020) standards and impending additional restrictions force shipowners to seek alternative fuels. LNG is a promising alternative due to environmental benefits and availability (Notteboom et al., 2021). European Maritime Safety Agency defines LNG bunkering as an LNG fuel transfer to an LNG fuelled ship through a distribution source. As a ship-side, different stakeholders involved in this process are LNG suppliers, ports, safety personnel, administrations, and policy-makers (EMSA, 2017).

There are different stakeholders and aspects in a small-scale supply chain for LNG as a marine fuel. Different stakeholders have different priorities in the supply chain mechanism. However, several aspects need to be considered while designing supply chains, such as reliability, safety, security of supply, flexibility, capacity, operational cost, and investment cost (IMO, 2016). Shipowners will not take LNG as a primary fuel source unless they are not convinced of its sufficient availability in the market. The stipulation of LNG as a marine fuel is subject to supply chain development (Sharples, 2019). Small scale LNG supply chain can be produced from pipeline via liquefaction terminal or extended from LNG receiving terminal by ship, truck, or pipeline. Bunkering operation takes place at the last step; LNG-powered ships can receive the fuel either by bunker barge, truck, or direct piping connection in port (EMSA, 2017). The final stage of the delivery follows the same options as conventional fuel supply: Truck to Ship, Ship to Ship, Pipeline to Ship, and Container to Ship.

Bunker supply cost has two main parts: 1- the price of the LNG marine fuel at the import hub, 2-infrastructure cost of storage and transhipment from a hub to the ship. The bunkering method has a significant effect on the infrastructure cost. While investment costs include LNG bunkering equipment, bunkering vessel, license cost, safety measures, training, and installation of a quay in some cases, operational costs include bunker vessel's operation costs and transhipment costs from import terminal (Faber et al., 2015). Since building an LNG bunker vessel is highly costly, the ship-to-ship LNG bunkering option requires high capital expenditure. Operational expenditures are also much higher than the truck option. However, the ship-to-ship option provides flexibility for suppliers, and bunker can be delivered either at port or anchorage area, in large quantity and much faster (Faber et al., 2015). LNG bunker price for end-users is subject to these costs associated with these investments and operational costs. Inevitably, high CAPEX requirement is to be reflected for end-users. Therefore, LNG bunker fuel advantage is subject to another variable in the equation, LNG market price. Relation of LNG price and MGO (Marine Gasoil) or VLSFO (Very Low Sulphur Fuel Oil) prices are important criteria for LNG marine fuel option.

LNG bunkering supply chain problem is a relatively new subject in the literature. Current literature on small and medium-scale LNG and LNG Bunkering supply chains is limited. Only a few articles in the literature investigate the supply chain viewpoint of LNG bunkering. Aymelek et al. (2015) cover LNG bunkering challenges and propose a deep-sea liner shipping network model. Jafarzadeh et al. (2017) system engineering approach explores the technical aspects of LNG fuelled systems, significantly contributing to the decision-making process while considering an operation, safety, and economic perspective. However, the study is limited to fishing vessels and the Norway case. Calderón et al. (2016) explore the LNG bunkering development by port perspective and investigate safety standards, logistics, and financial aspects. Gucma et al. (2019) propose a model of the LNG distribution concept based on the location-routing problem (LRP). Jokinen et al. (2015) present small-scale LNG supply chain optimization at Finland coasts. The study has two dimensions: maritime routing problem and capacitated vehicle routing problem. Its objective is to minimize the cost, and the research provides an optimum solution for satellite port location and fleet size. The research also explores small-scale LNG supply chain models under different LNG price scenarios while considering ship and truck utilization. It is assumed that the current FO demand would be replaced by LNG. A MILP model solved the problem with a thirty-day time horizon. Artana et al. (2013) investigate Indonesia's small-scale supply chain problem. The first objective is to find the best location for a satellite terminal sorted by the Analytic Hierarchy Process (AHP) method considering four main qualitative and fourteen sub-criteria. As the second step, a non-linear programming model is developed whose objective function minimizes cost while considering storage tank capacity, vessels size, the number of trips, receiving, and regasification capacity by Gradually Reduced Gradient Method. Strantzali et al. (2018) present a small-scale LNG supply chain for electricity generation on four populated LNG-exploited islands.The authors develop an additive value model to examine small-scale alternatives for LNG supply using the PROMETHEE method and provide a ranking of alternatives. Current electricity demand is taken as a reference to calculate LNG demand at each island. Bittante et al. (2017a) propose a small-scale LNG supply chain optimization model at tactical and strategic aspects. The model solves the LNG distribution problem, including selecting convenient ports, the size of satellite terminals, the optimal fleet, and routing for shipping and truck deployment to offset domestic demand for LNG. Bittante et al. (2017b) model provides multi-period decision support at strategic and tactical aspects. The objective function was formulated to minimize investment and operational costs simultaneously. The model proposes the optimum location of satellite terminals, number and size of the ships to be deployed, number of trucks per port, maritime routing, and road connections. However, some operational factors such as boil-off gas, terminal time windows have not been included in the model. Bittante et al. (2018) aim to propose a solution at the strategic level. The model presents an optimal solution for size and number of fleet, maritime routes, the number of the voyages for each ship while considering the uncertainty of demand, price of LNG in the Caribbean Region. On the other hand, Deluster et al. (2018) evaluate small-scale LNG supply chain at operational and strategic levels as a location routing problem, considering truck deliveries. Alvarez et al. (2020) investigate LNG fuel delivery networks in Europe with bunker barges, trucks, and satellite terminals. It has been observed that all articles, except Strantzali et al. (2018), use mathematical modelling, in particular, Mixed-Integer Linear Programming (MILP); only Artana et al. (2013) solves the problem with non-linear formulation and uses Generalized Reduced Gradient. Artana et al. (2013) also differentiate from the other articles as they use the AHP method to determine the best locations for satellite terminals. Jokinen et al. (2015) approach claim that incorporating 'shipping strategy' frees the model from scheduling variables and keeps it more simple to solve. Bittante et al. (2017a,b; 2016), Jokinen et al. (2015), and Ahn (2018) take into account both the sea and shore side of the supply chains. On the other hand, Bittante et al. (2018), Artana et al. (2013), Strantzali et al. (2018) just optimize maritime transportation. These researches are based on a case study that proposes a model for local small-scale supply chain problems. The objective functions are formulated to calculate the minimum total cost in all papers. There is a limited number of studies in the small-scale LNG supply chain. Besides, five articles out of eight belong to the same working group. The problems are solved with a deterministic approach and MILP formulation. MILP enables solving realistic problems within a reasonable time period if operational issues such as boil-off loss and scheduling are neglected (Bittante et al., 2017b). LNG Bunkering at mid/small scale LNG capacity has different dynamics than large scale LNG supply chain; it requires extended utilization, capacity control, infrastructure, and high capital expenditure for investment. Small-scale LNG supply chain optimization literature is summarized in Table 1. The related literature was narrowed to nine articles. The problems and objectives in these researches are highlighted, and the methodologies used to solve these problems are defined.

The planning horizon in maritime transportation literature is classified into strategic, tactical, and operational problems (Christiansen et al., 2007). The problems under the strategic planning horizon are related to the network and transportation systems design, fleet size, type, number of the vessels and capacity, port-terminal location, size and design, and shipping market selection. Tactical problems involve adjusting fleet size and capacity, fleet deployment for specific routes, ship routing and scheduling, berth and crane scheduling, ship management, and container management. Operational level problems include speed selection, ship loading/discharging, and weather routing (Christiansen et al., 2007).

Long-term strategic policy decisions usually involve tactical and operational information as well. Designing an optimum fleet is one of the strategic decisions for shipowners or charterers. The decision includes the number, size, and capacity of the ships. Minimizing variable and fixed costs of fleet size is the objective function of a strategic problem; however, the decision also involves tactical and operational level planning decisions such as routing and scheduling. The maritime industry has many uncertain factors: derived demand from economic activities, time lag between demand and corresponding available supply, and operational uncertainties. Therefore, it is essential to consider robustness in optimization models to encourage trust. Uncertainty and robustness are handled with different approaches such as simulation, re-optimization for different scenarios using deterministic models with penalties, and stochastic optimization models. In small-scale LNG supply chain literature, deterministic models with different scenarios are the most commonly used solution methods. MILP provides a rigorous approach to supply chain analysis. The models accurately capture important decision options, constraints, and objectives of the supply chain problem, eventually providing an optimal solution for the problem (Shapiro, 2001). MILP has been employed in the literature as the primary method in order to solve supply chain optimization problems (Alvarez et al., 2020; Bittante et al., 2017a; Deluster et al., 2018; Gao and You, 2019; Jokinen et al., 2015; Mikolajková et al., 2018; Sangaiah et al., 2020; Ye et al., 2017; Zarei and Amin-Naseri, 2019). Real-world problems often consist of integer variables, while non-integer variables are not always suitable. MILP allows the use of both types of variables and overcomes the limitations of linear programming. It provides strategic, tactical, and operational level decision support (Shapiro, 2001).

MILP is widely used in supply chain optimization. It provides a solution for strategic, tactical, and operational level supply chain problems. This study aims to find optimum solutions for a small-scale LNG supply chain for bunkering purposes in Turkey while considering sizing, timing, quantity and capacity considerations, and distribution planning issues. The MILP method is employed to solve the problem.

3. Problem description

This study aims at determining the optimal number of barges and their capacity, the number of voyages, and deliveries planned for each voyage, using a mathematical model within a monthly planning horizon. The model is developed based on Turkey's current bunkering dynamics, demand points, and predicted demand by the year 2025. The focus point of the study is ship-to-ship maritime bunker supply. Ship-to-ship bunker deliveries are conventional bunker supply options and practices in shipping. The vast majority of the bunker deliveries globally and in Turkey are performed by ship-to-ship option. Truck loading is an option for smaller vessels. Ship-to-ship operations meet a greater demand as their supply capacity is much higher and more efficient than truck loadings. Therefore, this study has taken the focus point as potential ship-to-ship LNG deliveries in Turkey.

As mentioned before, this study involves making strategic decisions as in the maritime multiple-period mixed fleet size problems; it determines the number of the barges and sizes of the small-scale LNG bunker carriers. Tactical and operational decisions are also made within our problem, such as planned voyage routing plans for each ship and LNG delivery quantities.

According to present bunker sales at subject locations, LNG bunker supply is planned from import terminals to potential demand points. TURKEY'S two LNG import terminals, Marmara

Table 1
Summary of small-scale LNG supply chain optimization literature.

Author	Problem and Objective	Methodology	Variables
Jokinen et al. (2015)	Regional supply from a large-scale regasification terminal to end-users can be carried out by a combination of ship and truck transports utilizing satellite terminals along a coastline. Minimizing fuel procurement cost. Finland case study.	MILP	Number of ships, amount of alternative fuel, total cost, transport costs, fuel demand of the customers, amount of LNG shipped
Bittante et al. (2016)	The multi-vehicle multi-visit LNG supply chain problem for the Gulf of Bothnia at the tactical and strategic levels. Minimizing total cost associated with fuel procurement.	MILP	Amount of alternative fuels, number of travels between ports, number of ships, the total amount of LNG to be transported, number of trucks allocated, the total number of trips between ports and customers
Bittante et al. (2017b)	Designing supply chain from supply terminal to satellite terminal at the coast of Finland and Sweden by ship and truck. Minimizing overall cost considering operational cost, investment, and fuel price.	MILP	Number of LNG loads transported, ship types, number of trucks and number of trips, satellite terminal activation, supply of alternative fuels
Bittante et al. (2017a)	Regional supply of LNG to satellite terminals across Bothnia Gulf, including ships and trucks. Demand is fixed for a certain time horizon at the receiving side, and split delivery is allowed. Determining the location of satellite terminals, fleet capacity, and routing is required to minimize fuel operation and investment cost. A multi-period formulation is used.	MILP	Size of storage tanks, number of trucks, number of ships, number of truck trips, amount of energy from alternative fuels, amount of energy from LNG trucked
Bittante et al. (2018)	Fleet Size and Mix Vehicle Problem with multiple depots and split delivery is considered.Minimizing fuel procurement cost in Caribbean Region.	MILP	Number of ships, number of travels between ports, the quantity of LNG to be transported, ships capacity
Deluster et al. (2018)	Small-scale LNG supply chain in Europe, two-echelon capacitated location routing problem. The objectives are to minimize facilities' construction, upgrade, and operating costs; minimizing vehicles' upgrade and operating costs.	MIP	The capacity of facility type, vehicle types, volume to be delivered, inventory at the satellite, the fleet size of vehicle type
Alvarez et al. (2020)	Two-echelon capacitated location routing problem with split deliveries. The European supply chain for LNG as fuel.	MIP	Facility type, volume to be delivered, the load of the vehicles, number of module upgrades, inventory at the satellites, the facility's capacity, and the fleet size of each vehicle type
Prause and Prause (2021)	Inventory Routing Problem, distribution of LNG from the new LNG hub- Brunsbüttel to the other German ports.	MIP	Quantity of LNG to be distributed, linkages used between the ports, the inventory at the port, max capacity of LNG storage at the port, operation costs of the time period of the vessel, storage costs of the considered time period, voyage costs of the considered time period
Mikolajková et al. (2018)	Regional gas supply chain optimization, considering the combination of pipeline and truck delivery.	MILP	Number of trucks, pipeline installation, storage capacity
Mikolajková-Alifov et al. (2019)	Local gas distribution problem in Finland, optimizing the supply chain of LNG, compressed natural gas, biogas via truck, pipeline, and storage tank utilization.	MILP	Number of trucks, mass flow rate, supply of natural gas, temperature, pressure, fuel cost, the investment cost of pipelines, LNG storages, trucks

Ereğlisi BOTAS LNG Terminal and EgeGaz Aliağa LNG Terminals, are considered bunker barges' loading ports. EMRA (Energy Market Regulatory Authority) data provides the delivery points as city, not port; Istanbul, Tekirdağ, Kocaeli, Izmir, Mersin, and Hatay. In order to make the delivery locations more specific, the biggest port in that region is taken, and the distance table is calculated as pilot-to-pilot distances. Distance from pilot points to berth is ignored for two reasons; firstly, the specific berth is unclear, and secondly, pilot-to-berth distances are negligible compared to the overall distance. As the routes are not predefined, the model is based on the arc-flow formulation. The barges travel from port i to port j while keeping track of travel time and load on the barges (Christiansen et al., 2007). Fig. 1 illustrates the distribution of LNG from the loading terminal to potential bunkering locations, as in our case. The bunker barges are allowed to distribute from the loading port to bunkering locations in any order, and the barges can travel between each bunkering location.

LNG bunker barge designs are new concepts as conventional LNG carriers that work in long hauls and large sizes. Wartsila is one of the leading technology-based companies in the maritime field and provides significant numbers of all dual-fuel engines globally. Therefore, to provide consistency of the bunker barges, Wartsila's LNG bunker barge design concepts were taken at five different sizes as 10,000 cbm and below capacity. They are heterogeneous fleet options used to identify barges' optimal number and capacity. Wartsila's technical data include consumption figures that calculate each barge's fuel cost per mile (Wartsila, 2020). Fixed costs, running costs, and daily charter rate figures were obtained from a consultant in the LNG industry, who also took part in the interview process. The figures also were cross-checked with an expert from the shipbuilding industry.

The study's focal point is at the strategic and tactical level; therefore, some unnecessary operational obstacles at this stage of the study were ignored to achieve reasonable computation time,

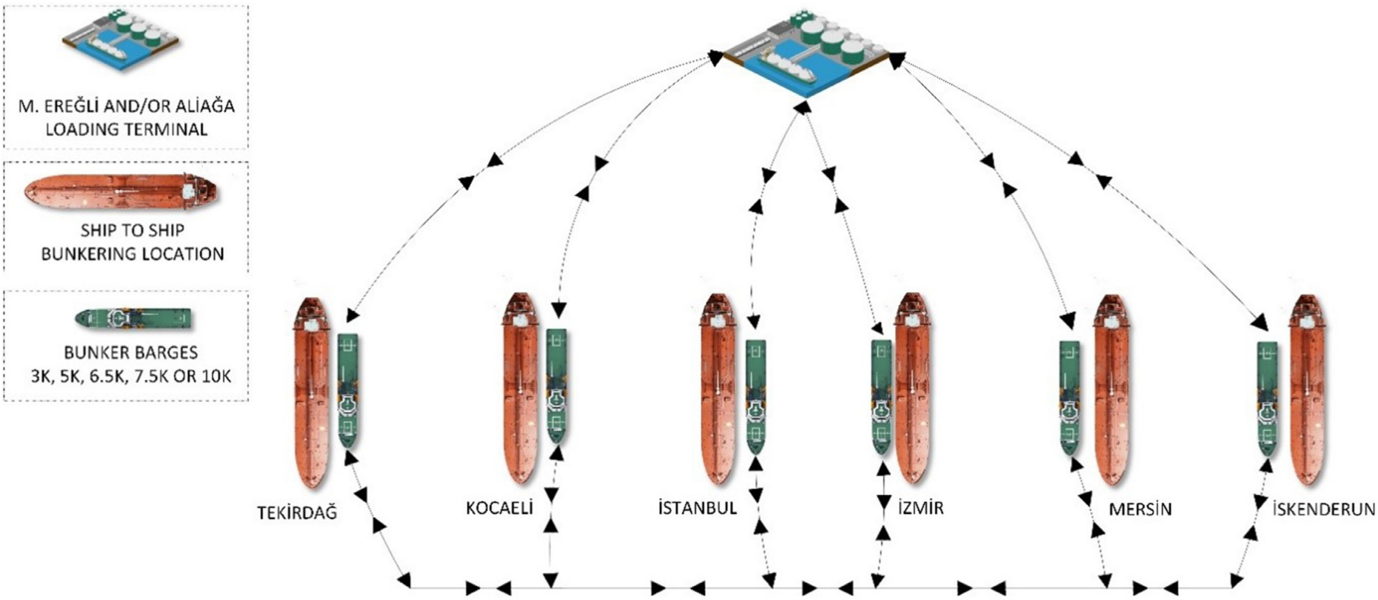

Fig. 1. Schematic representation of LNG supply chain.

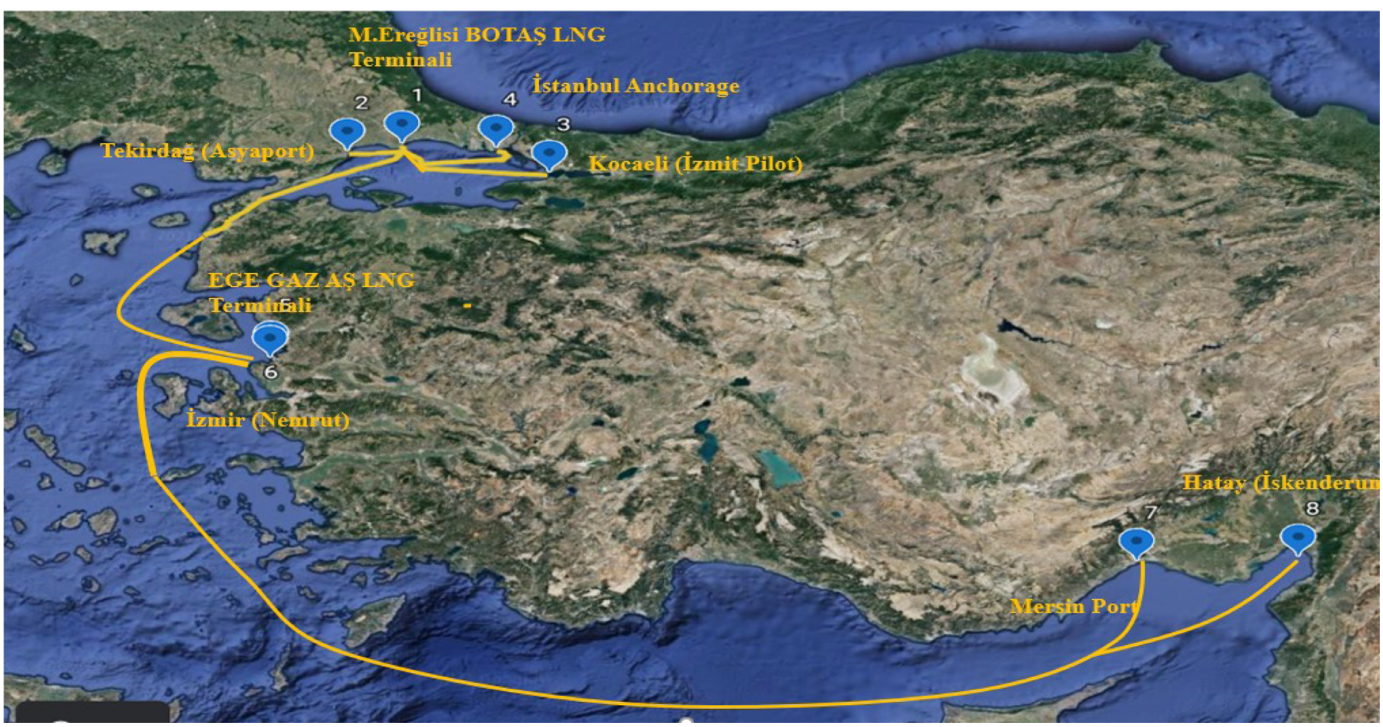

Fig. 2. Bunker delivery points and loading ports in Turkey source: (Google Earth, 2021), routes are illustrated as generic.

simplify the problem, and fulfil the study's objectives. The neglected constraints include boil-off, weather condition, current, speed reduction before arrival or time spent to increase full design speed, speed differences at laden voyage and ballast condition, light dues, port call expenses, etc. The deliveries are planned for the ship-to-ship operations; therefore, there is no storage at destination ports.

The barges are banned from travelling until the minimum ship-to-ship delivery requirement is satisfied. The proposed model is designed for a multi-period planning horizon. Because there are uncertainties in the bunker demand for the ship-to-ship delivery, the planning horizon is considered one month with weekly planning periods. Thus, fulfillment of overall monthly demand is avoided during one week or the last week, preventing LNG piling at bunkering sites, and when weekly demand is considered, LNG distribution is performed more uniformly during the planning horizon.

4. Mathematical formulation

The mathematical model includes all nodes representing supply ports and discharge locations in the set I. Two LNG import terminals of Turkey -Marmara Ereğlisi BOTAS and Aliağa EGEGAZ terminals are indicated as supply ports in the set S. The potential customers, in other words, locations where ships require LNG bunker supply, are defined as customers in the set C. These locations are Tekirdağ, Istanbul, Kocaeli, Izmir, Mersin and Iskenderun. The model aims to find the optimum number of barges and their size and the quantity of LNG delivered to a customer with each bunker barge on their constructed delivery route. Each barges' technical specifications, daily bunker consumption, speed, loading/discharging rate, and cost per nm, OPEX, CAPEX values are embedded into the model as parameters for each bunker barge. The monthly demand for each customer is divided into four weeks to ensure equal distribution and avoid meeting demand in a single voyage as quantities are too small when demand is low. Bunker barges have different discharging capacities according to their design restrictions. The developed model also considers the minimum time requirement for each discharging operation. Operational requirements such as mooring, unmooring, hose connection, and safety meetings can not be completed in less than 1.5 h; the inclusion of this requirement drives real-time operational decisions to merge with strategic and tactical decision-making processes. The model is based on linear equations and constraints involving integer variables and is defined as a mixed-integer linear programming (MILP) model. The model assumptions, notation of the model, objective function, and constraints will be explained below.

Model assumptions

In order to find optimum barge number, capacity, and distribution route, the mathematical model is formulated based on the following assumptions.

- The time horizon is taken as one month with weekly planning periods.
- The barges operate at a fixed speed at laden and ballast conditions.
- Weather, sea, current, strait passage, and other external factors affecting navigation are not considered.
- Boil-off during passage is neglected due to relatively short voyage time.
- Voyage costs such as port costs, light dues, agency fees are not considered.

Indices and Sets

i, j, m	: indices for nodes that represent the supply ports and bunkering locations (customers)
k	: index for ship type
r, t	: indices for planning period (week in our case)
I	: set of all nodes, $i \in I$
S	: set of supply ports, $i \in S$
C	: set of customers, $i, j, c \in C$ $(I - S)$
T	: set of time periods in weeks, $r, t \in T$
K	: set of different barge types, $k \in K$
A	: set of i and j pairs that link the customers to the ports $(\forall i \in C,\ j \in S$, and that show the links between the ports and customers $(\forall i \in S, j \in C)$, and the customers themselves $(\forall i \in C, j \in C)$.
n	: index for ship number
N_k	: set of ships of type k, $n \in N_k = \{1, 2, 3, \ldots, \lvert N_k \rvert\}$

Parameters

$D_{j,t}$	: LNG demand of customer j in period t
$d_{i,j}$	: Distance between nodes i and j
c_k	: Propulsion cost per nm for ship type k
r_k	: Running cost of ship type k
Q_k	: Capacity of ship type k
u_k	: Discharging rate of ship type k
v_k	: Speed of ship type k
c_k^c	: Charter cost per ship type k
t_i	: Berthing time at node i
l_t	: Available time for sailing in period t in hours (168 h in our case)
M	: Big number
Mn	: Minimum amount of LNG that must be shipped to a customer
Mt	: Minimum time required for unloading service at each customer port (1.5 h in our case)

Binary Variables

$y_{i,j,k,t,n}$	: 1 if ship type k with number n travels between nodes i and j, and 0 otherwise in period t
$z_{k,t,n}$	: 1, if ship type k with number n is used in period t, and 0 otherwise
$w_{j,t}$	: 0–1 decision variable to guarantee the minimum ship delivery to customer j in period t

Integer Variable

$x_{i,j,k,t,n}$	: Quantity of LNG as a percentage of capacity of ship type k with number n that is transferred from i to j in period t

Continuous variables

$ut_{j,k,t,n}$	: Unloading time required for the planned shipment to customer j using ship type k with number n in period t
$mut_{i,k,t,n}$	: Maximum of the durations Mt and $ut_{j,k,t,n}$
$Del_{j,t}$	: Quantity of LNG (cbm) delivered to customer j in period t

4.1. Objective function

The objective function is determined according to the minimum cost strategy. Traditionally operating shipping costs are classified under two significant expenditures: voyage costs and fixed costs (Mokia and Dinwoodie, 2002). Voyage costs are associated with related voyages and could be different according to travelling distance, port expenses, light dues, or canal passage if they are involved (Polo, 2012). The shipowner usually pays the voyage cost on a voyage charter party agreement. Charterers usually pay voyage costs under time charter or bareboat charter agreement (Stopford, 2013).

On the other hand, fixed costs are free from the voyage, and the shipowner needs to deal with these expenditures regardless of the vessel's position at sea, at the port, or anchor. Depending on vessel type, size, and specifications, these are called "running costs." Another item for fixed cost could be the charter cost that charterers need to pay with fixed intervals to the shipowner (Stopford, 2013). In other words, fixed cost is distinguished as the capital cost (CAPEX), which is derived from the property of the ship – depreciation, interests of financing credits, and running cost or fixed operation cost (OPEX), which are necessary to keep the vessel ready for the operation (Polo, 2012).

The objective function is formulated with a minimum cost strategy consisting of two sides of the shipping cost: voyage and fixed costs. Fuel cost as the major expenditure of the shipping cost is added to the objective function. Other typical voyage costs such as light dues, anchor dues, port costs were ignored as these costs are negligible compared to fuel costs. The objective function is formalized with a shipowner perspective that provides an overall picture of running the LNG bunker barge associated with voyage and fixed costs. It aims to find the optimum number of barges according to their size and travelling pattern at different demand scenarios. Finally, the objective function has been formulated as follows:

$$\min cost\ Z = voyage\ cost + fixed\ costs$$

$$\min cost\ Z = fuel\ cost + (OPEX + CAPEX)$$

$$Minimize \sum_{i \in I} \sum_{j \in I} \sum_{k \in K} \sum_{t \in T} c_k\, d_{i,j}\, y_{i,j,k,t} + \sum_{k \in K} \sum_{t \in T} \sum_{n \in N_k} r_k\, z_{k,t,n} + \sum_{k \in K} \sum_{t \in T} \sum_{n \in N_k} c_k^c z_{k,t,n} \tag{1}$$

$$Del_{j,t} = \sum_{i \in I} \sum_{k \in K} \sum_{n \in N_k} Q_k x_{i,j,k,t,n} - \sum_{m \in C \mid (j,m) \in A} \sum_{k \in K} \sum_{n \in N_k} Q_k x_{j,m,k,t,n} \quad \forall j \in C,\ t \in T,\ j \neq m, j \neq i \tag{2}$$

4.2. Constraints

Constraint (2) computes the quantity of LNG delivered to customer j in period t. The difference between the total LNG carried to customer j in period t and the total LNG transferred to other customers from customer j equals the total delivery made to customer j in the relevant period.

$$\sum_{r\leq t} Del_{j,r} \leq \sum_{r\leq t} D_{j,r} \qquad \forall j\in C, t\in T, t\neq 4 \tag{3}$$

Constraint (3) ensures that the amount of total LNG delivered to customer j for the first t weeks should be less than or equal to the total demand of customer j for those weeks. This constraint enforces that total delivery is less than or equal to the total accumulated demand of customer j up to period t and it prevents stockpiling on bunkering sites in weekly periods until the specified week. This restriction prevents the overall demand over the planning horizon from being met in earlier periods. For the last period ($t = 4$), the total planned delivery for customer j should equal the total demand of the planning horizon. For this reason, the last period should not be considered for this constraint.

$$\sum_{t\in T} Del_{j,t} = \sum_{t\in T} D_{j,t} \qquad \forall j\in C \tag{4}$$

Constraint (4) guarantees that the total amount of LNG delivered to customer j by the end of the planning horizon, in this case, four weeks, should be equal to the total demand of customer j during this planning horizon.

$$Del_{j,t} \leq Mw_{j,t} \qquad \forall j\in C, t\in T \tag{5}$$

$$Mn - Del_{j,t} \leq M(1-w_{j,t}) \qquad \forall j\in C, t\in T \tag{6}$$

Constraints (5) and (6) ensure that the amount of LNG delivered to customer j in period t must be greater or equal to the minimum amount of delivery to be shipped (Mn).

$$y_{i,j,k,t,n} \geq x_{i,j,k,t,n} \quad \forall (i,j)\in A, k\in K, t\in T,\ n\in N_k \tag{7}$$

Constraint (7) provides the relationship between the variables $y_{i,j,k,t}$ and $x_{i,j,k,t}$. LNG will not be delivered between these nodes if there are no planned voyages with ship type k and number n in period t between the ports and customers and between the customers and other customers. Since there are no shipments planned from the customers to the ports ($D_{i,t} = 0 \rightarrow x_{i,j,k,t,n} = 0,\ \forall i\in C, j\in S$), the related variable $y_{i,j,k,t,n}$ takes value one if only ship type k with number n has started a voyage in period t, considering its return to the port at the end of the voyage due to Constraint (8).

$$\sum_{i|(i,j)\in A} y_{i,j,k,t,n} = \sum_{m|(j,m)\in A} y_{j,m,k,t,n} \qquad \forall j\in I, k\in K,\ t\in T,\ n\in N_k \tag{8}$$

Constraint (8) guarantees the route continuity.

$$ut_{i,k,t,n} = \sum_{m|(m,i)\in A} x_{m,i,k,t,n}\, Q_k \frac{1}{u_k} - \sum_{j|(i,j)\in A, j\neq 1} x_{i,j,k,t,n}\, Q_k \frac{1}{u_k}$$
$$\forall\, i\in C,\ k\in K, t\in T,\ n\in N_k \tag{9}$$

Constraint (9) computes the discharging time for customer i with ship type k in period t.

$$mut_{i,k,t,n} \geq \sum_{j|(i,j)\in A} y_{i,j,k,t,n}\, Mt \quad \forall i\in C,\ k\in K, t\in T, n\in N_k \tag{10}$$

Constraint (10) provides that unloading time at customer i should be at least Mt hours for ship type k in period t, regardless of the quantity of LNG discharged.

$$mut_{i,k,t,n} \geq ut_{i,k,t,n} \qquad \forall i\in C, k\in K, t\in T, n\in N_k \tag{11}$$

Constraint (11) ensures that if unloading time at customer i is longer than Mt hours, in that case, actual unloading time should be taken, which is used in Constraint (12). Constraint (10) and constraint (11) help us to choose that maximum Mt and $ut_{i,k,t,n}$.

$$\sum_{(i,j)\in A} \frac{1}{v_k}\, d_{i,j}\, y_{i,j,k,t,n} + \sum_{j\in C} \frac{1}{u_k} Q_k x_{1,j,k,t,n} + \sum_{i\in C} mut_{i,k,t,n} \leq l_t z_{k,t,n}$$
$$\forall\, k\in K,\ t\in T, n\in N_k \tag{12}$$

Constraint (12) ensures that total time for ship type k, including loading time at the port, unloading time at the customers, and sailing times between the nodes, should not exceed the available time in each period t.

$$z_{k,t,n} - z_{k,t+1,n} = 0 \quad \forall\, k\in K, t\in T,\ t\neq 4, n\in N_k \tag{13}$$

Constraint (13) ensures that if ship type k is used in the first period, it is used for the rest of the periods.

4.3. Case study in Turkey

Turkey's LNG Bunkering case was evaluated under three different scenarios. Marmara Ereğlisi BOTAS LNG Terminal and Aliağa EGEGAZ AŞ are the two import terminals distribution centers for potential LNG marine fuel options. Therefore, scenarios were developed according to these two potential loading ports. Discharging points and potential STS transfer locations are determined according to the present bunker deliveries of Turkey; the ports of Istanbul, Kocaeli (Izmit), Tekirdağ, Izmir, Mersin, and Hatay (Iskenderun) ports have been selected.

The specific points were taken as pilot boarding positions at Mersin, Iskenderun, Asya Port (Tekirdağ) and Nemrut (Izmir) ports, and Istanbul explosive and inflammable goods anchorage areas. These positions were taken as reference distance tables because STS bunkering operations can be carried at anchor or within ports. The distances between pilot boarding position to any jetty/berth in ports are negligible compared to overall distances. All ports at the seaside and no long canal or river passage are required. While considering pilot boarding positions and potential terminals, Kocaeli (Izmit Gulf) port could be an exception. Since several ports/terminals are around the gulf, the distance could change from 3 to 25 nm. Therefore, the pilot boarding position was the reference point for consistency with other ports. The Istanbul anchorage area is the main bunkering hub for Turkey (EMRA 2019), and the tanker anchorage area is taken as a reference point since a potentially LNG-driven vessel could use this designated area if no other position is introduced. Table 2 shows the distance between the ports.

Typical LNG bunker barge specifications were taken from the Wartsila website (Wartsila, 2020). The barges' capacities range from 3000 cbm to 10,000 cbm for defined small-scale LNG carriers listed in Table 3. As LNG loading/discharging operation practices, 6% volume of the barges was calculated and determined as constant volume remaining onboard. Based on gas consumption at design speed, consumption per mile was calculated as a metric ton and eventually total fuel cost. In order to calculate cost per mile, metric ton was converted to mmBtu, and the cost for each bunker barge was calculated - based on BOTAS's official LNG price as Turkish Lira for 2020. Turkish Lira was converted to USD based on TL/USD rate as of 5 May 2020.

Table 4 indicates barges' capacity as mmBtu and DWT based on the Wartsila database. OPEX and CAPEX value of the barges have been obtained from a consultant in the LNG industry, who took part in the interview process.

Turkey's bunker delivery forecast

In order to see Turkey's marine fuel deliveries' relation with some economic indicators, correlation, ARIMA forecasting, and

Table 2
Distance table.

(nm)	Marmara Ereğlisi	Tekirdağ Pilot	Kocaeli (Izmit) Pilot	Istanbul Anchorage Area	Nemrut Pilot	Mersin Pilot	Iskenderun Pilot
M.Ereğlisi LNG	–	30	64	59	243	791	846
Tekirdağ P.	30	–	96	75	226	774	829
Kocaeli P.	64	96	–	37	314	862	917
Istanbul A.	50	75	57	–	272	819	874
Nemrut P.	243	226	290	272	–	637	692
Mersin P.	739	774	794	819	637	–	87
Iskenderun	846	829	863	874	692	87	–
Aliağa (EgeGaz)	–	220	308	266	4	639	694

Source: (SeaRoutes, 2019).

Table 3
Bunker barge.

Ship	Capacity LNG/MGO (cbm)	Deducted 6% (cbm)	Daily Consmp. (t/day)	Speed (knot)	Rate L/D (cbm)	Consmp. (t/nm)	Consmp. (mmBtu)	Cost usd/nm (ck)
1	3000/830	2820	7.5	12	600	0.0260	1.3879	9.87
2	5000/270	4700	11.9	14	800	0.0354	1.8897	13.44
3	6500/550	6110	9.8	13	1000	0.0314	1.6761	11.92
4	7500/400	7050	8.4	13.5	1000	0.0259	1.3825	9.83
5	10,000/2400	9400	12.1	14	1200	0.0360	1.9217	13.67

Source: (Wartsila, 2020).

Table 4
Barges' OPEX and CAPEX.

Ship	Capacity LNG/MGO (cbm)	mmBtu	DWT	OPEX (usd/day)	CAPEX (usd/day)
1	3000/830	67,736,4	2000	8600	11,000
2	5000/270	112,894	3000	11,000	14,000
3	6500/550	146,762,2	4200	11,400	14,600
4	7500/400	169,341	4100	11,800	15,000
5	10,000/2400	225,788	7200	12,300	15,700

Source: (Wartsila, 2020 and expert view).

multiple regression methods were used. The dependant variable is defined as total bunker deliveries of Turkey. The globalization of trade is an important driver for the world's bunker demand. World seaborne trade and maritime traffic are the consequence of global trade. Information of world GDP provides an indicator for global trade growth, and oil prices are substantial drivers of bunker prices (UNCTAD, 2020a). As the vast majority of the bunker deliveries of Turkey are performed in Istanbul, vessels traffic by number and tonnage are evaluated along with other criteria to see bunker deliveries' relation with indicators that provide a model to forecast the future trend. EViews 10 software has been used for statistical data analysis. It provides smooth data entry and analysing tools and visual features (EViews, 2019). Data to be used in the research is illustrated in Table 5. Time series data, units of series, covering years, and the data source are summarised.

Total bunker deliveries of Turkey data were obtained from EMRA's annual reports. Data provide annual deliveries between 2007 and 2018, including transit deliveries, with and without special consumption taxes, excluding marine fuel sales as cargo.

Multiple regression models were employed to see the relation of variables and how these variables influence bunkering demand in Turkey. The dependant variable as total bunker deliveries in Turkey was evaluated with independent variables as Brent oil price, bunker price, GDP per capita, world seaborne trade as miles per ton, number of passages from Istanbul and Canakkale Straits, total GT of passages from Istanbul and Canakkale Straits, world fleet as deadweight tonnage. EViews10 data analysis software was used. Different combinations of regression models, including data in Table 5, were tried to determine the convenient model that jointly influences bunker demand in Turkey. The models were compared with their R2 adjusted R2, F statistic, and Prob(f-statistics) values. However, only one model's outcome was found statistically meaningful. It was concluded that the bunker deliveries in Turkey are jointly influenced by world seaborne trade and bunker price. Before using the regression model in forecasting, the different tests were carried out, such as unit root test, multicollinearity, normality, serial correlation, and heteroskedasticity to confirm the regression model's reliability and use as a framework for forecasting.

Two time-series data -world seaborne trade and bunker price, jointly influence bunker deliveries in Turkey by multiple regression modelling. This dependant variable and explanatory variables relation could be used to forecast the future of bunker delivery quantities. In other words, the estimated equation could be used to forecast future bunker deliveries if future data of these explanatory variables are available to determine future data of the series Automatic ARIMA (Auto-Regressive Integrated Moving Average) based on historical time-series data of world seaborne trade and bunker price. At the third step, statistical data obtained through ARMA forecasting were used to forecast future bunker deliveries of Turkey until 2025. Based on the confirmed regression model, which provides significant relation between dependant variables and independent variables, Turkey's estimated bunker deliveries by 2025 were calculated as 2,291,728.402mt.

Demand was determined based on the present bunker sales share obtained through the EMRA report by cities. Yalova's share was added to Kocaeli, as some destinations of Yalova are located in Izmit Gulf and use almost the same pilot boarding position as other destinations in Izmit Gulf. 'Other' cities' share is evenly distributed selected ports, and the final share of the ports was determined. LNG demand cases were organized as 1, 5,10, and 15% of Turkey's expected total bunker sales volume. These categories also represent pessimistic, average, and optimistic demand cases. Bunker figures in EMRA reports are defined in metric tons. These metric ton units were converted to energy units as significant density and energy content differences between conventional marine

Table 5
Time series data summary.

Data	Years	Source
Annual Bunker Deliveries as metric tonnes	2007–2018	EMRA (2019)
World GDP	1980–2019	UNCTAD (2020b)
Brent Oil price as USD	1995–2018	UNCTAD (2020b)
Word Seaborne Trade as metric tonnes	1980–2018	UNCTAD (2020b)
World Fleet by Number	1980–2019	UNCTAD (2020b)
World Fleet by DWT Tonnage	1980–2019	UNCTAD (2020b)
Bunker Price HSFO 380cst as USD	1991–2020	Athennianshipbrokers (2020)
Istanbul Strait Passages by Number	2006–2019	MOTI (2020)
Istanbul Strait Passages by GT	2006–2019	MOTI (2020)
Canakkale Strait Passages by Number	2006–2019	MOTI (2020)
Çanakkale Strait Passages by GT	2006–2019	MOTI (2020)

Source: Author.

Table 6
Demand figures for each bunkering destination.

Port	Share	Monthly	1%	1%	5%	10%	15%
	(%)	Demand mmBtu	mmBtu	cbm (LNG)	cbm (LNG)	cbm (LNG)	cbm (LNG)
Tekirdağ	2,7	208,003	2080	87	433	866	1299
Kocaeli	15,6	1,193,725	11,937	497	2485	4970	7455
Istanbul	76,1	5,813,062	58,131	2420	12,100	24,201	36,301
Izmir	2,1	156,946	1569	65	327	653	980
Mersin	0,6	45,143	451	19	94	188	282
Iskenderun	2,9	222,215	2222	93	463	925	1388
TOTAL	100,0	7,639,095	76,391	3180	15,902	31,803	47,705

Source: Author, 1m^3 LNG=24.02 mmBtu, (IGU, 2012).

Table 7
Summary of reference list for the model.

Component	References	
Ship1	Wartsila/ Gas Carriers	Wartsila3k (2020)
Ship2	Wartsila/ Gas Carriers	Wartsila5k (2020)
Ship3	Wartsila/ Gas Carriers	Wartsila6.5k (2020)
Ship4	Wartsila/ Gas Carriers	Wartsila7.5k (2020)
Ship5	Wartsila/ Gas Carriers	Wartsila10k (2020)
OPEX	Expert-view	
CAPEX	Expert-view	
Distance table	Searoutes	SeaRoutes (2019)
LNG Price	Petroleum Pipeline Company (BOTAS) 2020 Tariff, 1.82 TRY/1Sm^3 (without tax)	EMRA (2020)
USD/TL Rate	The Central Bank of the Republic of Turkey 5 May 2020, 1USD=7,055TRY	TCMB (2020)
Conversion factors	International Gas Union – Natural Gas Conversion Guide	IGU (2012)

Source: Author.

fuels and LNG. Table 6 shows the distribution of demand figures for each destination.

Table 6 indicates different demand figures for each destination point as mmBtu based on Turkey's 2025 bunker demand forecast. These mmBtu figures were then converted to LNG as cbm to find each port's demand quantity as cbm. The data used to develop the model is summarised in Table 7.

Turkey's case is evaluated under three scenarios. In the first scenario, Marmara Ereğlisi BOTAS LNG Terminal is taken as the loading port for the bunker barge. LNG is distributed according to forecasted demand at all designated ports-Tekirdağ (Asyaport), Istanbul (Tanker Anchorage Area), Izmir (Nemrut), Mersin, and Hatay (Iskenderun). Various percentile increases in demand for LNG supply are assessed, such as 1, 5, 10, and 15%. The second Scenario takes Aliağa EgeGaz LNG Terminal as the loading port and distributes LNG according to different demand scenarios at all designated ports. The third scenario uses two ports for loading separately -Marmara Ereğlisi BOTAS and Aliağa Ege Gaz LNG terminals. While Marmara Ereğlisi BOTAS is serving at Marmara Sea region as a loading port, Aliağa EgeGaz LNG Terminal serves to the ports Izmir, Mersin and Iskenderun.

The MILP model was run with Intel®Core^{TM}i7–7500 U CPU @2.70GHz-2.90 GHz, 12,0GB RAM computer, and LINGO/Win64 15.0.63 software was used.

5. Computational results

The mathematical model provides insight about the optimum number of bunker barges to be utilized, the optimum capacity of the barges, minimum cost scenario, and optimum distribution patterns based on different demand cases. Three scenarios were developed under four different demand cases. The results of the model are explained in the following sections.

5.1. Scenario 1

In the first scenario, the Marmara Ereğlisi BOTAS LNG terminal is determined as the loading port, and the LNG bunker distributes according to the ports' demand quantities. The model guarantees satisfying weekly requested quantities within one month.

The MILP model consists of 1529 total variables, of which 584 are integer variables and 1313 constraints in formulating all cases of Scenario 1. It has found the optimum solution in 4.59 s for the

Table 8
Scenario 1-1% demand results.

Route	Quantity onboard (cbm)	Week No.	Barge Capacity (cbm)
M. Ereğlisi – Tekirdağ	264	4	5000
Tekirdağ – Izmir (Nemrut)	176	4	5000
Izmir – Mersin	112	4	5000
Mersin – Iskenderun	92	4	5000
Iskenderun – M.Ereğlisi	0	4	5000
M.Ereğlisi – Kocaeli	2916	4	5000
Kocaeli-Istanbul	2420	4	5000
Istanbul- M.Ereğlisi	0	4	5000

Table 9
Scenario 1–5% demand results.

Route	Quantity onboard (cbm)	Week No.	Barge Capacity (cbm)
M. Ereğlisi-Istanbul-M.Ereğlisi	4700	2	5000
M.Ereğlisi- Kocaeli- M.Ereğlisi	1863	3	5000
M. Ereğlisi-Istanbul-M.Ereğlisi	3321	3	5000
M.Ereğlisi-Tekirdağ	1316	4	5000
Tekirdağ-Izmir	884	4	5000
Izmir-Mersin	556	4	5000
Mersin-Iskenderun	464	4	5000
Iskenderun-M.Ereğlisi	0	4	5000
M.Ereğlisi-Kocaeli	4700	4	5000
Kocaeli-Istanbul	4079	4	5000
Istanbul- M.Ereğlisi	0	4	5000

1% demand case. The model results show that a barge with 5k cbm capacity is optimum, and due to low demand, distribution is carried out only in the fourth week. The first distribution pathway follows the Tekirdağ-Izmir-Mersin-Iskenderun route, and the second distribution pathway follows the Kocaeli and Istanbul route. The results are summarised in Table 8.

Secondly, the MILP model was run for the 5% demand case. It has found the optimum solution in 11.62 s in this case, and a barge with 5 k cbm capacity is found as optimum as in the 1% demand case. In this case, distribution is carried out in the second, third, and fourth weeks. The 5 k cbm barge makes its first voyage to Istanbul within the second week at fully loaded condition. Two separate voyages are planned to Istanbul and Kocaeli during the third week to fulfil their demand. The model also suggests two separate routes for fulfilling the remaining demand during the fourth week, the same as those of the 1% demand case in the fourth week; the first one follows the Tekirdağ-Izmir-Mersin-Iskenderun route, and the second one follows the Kocaeli-Istanbul route. The results are summarised in Table 9.

As the third step, the 10% demand case is investigated. The MILP model has found the optimum solution for this case in 19.79 s. The model defines the optimum bunkering capacity as a single barge with 10 k cbm capacity. The distribution routing plans and weekly timings are the same as the 5% demand case. The results are summarised in Table 10.

The model was run for the 15% demand case. It has found the optimum solution in 49.16 s. The optimum bunker barge capacity is found as two barges as 3 k and 5 k cbm. Accordingly, the two different barges provide LNG supply to Istanbul within the first week. While the 5k cbm barge visits Tekirdağ, Istanbul, and Izmir on one route during the second week, the 3 k cbm barge visits Istanbul and Kocaeli on two separate routes during the same week. 5 k barge also performs a single voyage to Istanbul during the second week. The results are summarised in Table 11.

Furthermore, these two barges provide LNG supply for Istanbul during the third week. Likewise, the two barges again provide LNG to Istanbul during the fourth week, whereas the 5 k cbm barge supplies LNG to Kocaeli. Moreover, to satisfy the remaining demand, the 5 k cbm barge follows the Tekirdağ-Istanbul-Izmir route for discharging, whereas the 3 k cbm follows the Mersin-Iskenderun route during the fourth week.

Table 10
Scenario 1–10% demand results.

Route	Quantity onboard (cbm)	Week No.	Barge Capacity (cbm)
M.Ereğlisi-Istanbul-M.Ereğlisi	7778	2	10,000
M.Ereğlisi- Kocaeli- M.Ereğlisi	2590	3	10,000
M. Ereğlisi-Istanbul-M.Ereğlisi	9400	3	10,000
M.Ereğlisi-Tekirdağ	2628	4	10,000
Tekirdağ-Izmir	1764	4	10,000
Izmir-Mersin	1112	4	10,000
Mersin-Iskenderun	924	4	10,000
Iskenderun-M.Ereğlisi	0	4	10,000
M.Ereğlisi-Kocaeli	9400	4	10,000
Kocaeli-Istanbul	7022	4	10,000
Istanbul- M.Ereğlisi	0	4	10,000

Table 11
Scenario 1–15% demand results.

Route	Quantity onboard as (cbm)	Week No.	Barge Capacity (cbm)
M.Ereğlisi-Istanbul-M.Ereğlisi	2820	1	3000
M.Ereğlisi-Istanbul-M.Ereğlisi	4700	1	5000
M.Ereğlisi-Tekirdağ	4230	2	5000
Tekirdağ-Istanbul	3600	2	5000
Istanbul-Izmir	490	2	5000
Izmir- M. Ereğlisi	0	2	5000
M.Ereğlisi-Istanbul	4700	2	5000
M.Ereğlisi-Istanbul-M.Ereğlisi	2820	2	3000
M.Ereğlisi-Kocaeli-M.Ereğlisi	2820	2	3000
M.Ereğlisi-Istanbul-M.Ereğlisi	2820	3	3000
M.Ereğlisi-Istanbul-M.Ereğlisi	4700	3	5000
M.Ereğlisi-Istanbul-M.Ereğlisi	2350	4	3000
M.Ereğlisi-Istanbul-M.Ereğlisi	4700	4	5000
M.Ereğlisi-Kocaeli-M.Ereğlisi	4636	4	5000
M.Ereğlisi-Tekirdağ	4700	4	5000
Tekirdağ-Istanbul	4070	4	5000
Istanbul-Izmir	490	4	5000
Izmir-M.Ereğlisi	0	4	5000
M.Ereğlisi-Mersin	1668	4	3000
Mersin-Iskenderun	1388	4	3000
Iskenderun – M. Ereğlisi	0	4	3000

Table 12
Summary of scenario 1 results.

LNG Demand	Optimum Number of Barge / Capacity (cbm)	Min Cost (OPEX+CAPEX+ Fuel Cost) USD
1%	1 / 5000	726,960.6
5%	1 / 5000	731,852.8
10%	1 / 10,000	816,397.9
15%	2 / 3000 and 5000	1,296,467.0

Table 12 summarises the overall results of the MILP model for Scenario 1. Three different demand cases are satisfied with one barge; however, the 15% demand case requires two barges, and optimum capacities are calculated as 3 k cbm and 5 k cbm. Parallel to the demand, the minimum cost value gradually increases due to the distance covered by the barges. As the 15% case requires two barges, the minimum cost value dramatically increases.

As indicated in Table 9, while the 10 k bunker barge provided the optimum solution in the 10% demand case, the 15% demand case was fulfilled by the 3 k and 5 k bunker barges rather than the 10k, 7.5k, or 6.5k bunker barges. Both barges (3 k and 5 k) have been employed starting from the first delivery week.

Table 13
Scenario 2-1% demand results.

Scenario 2 – 1% Demand Results - Route	Quantity onboard (cbm)	Week No.	Barge Capacity (cbm)
Aliağa – Tekirdağ	3116	4	5000
Tekirdağ - Kocaeli	3028	4	5000
Kocaeli-Istanbul	2532	4	5000
Istanbul-Mersin	112	4	5000
Mersin-Iskenderun	92	4	5000
Iskenderun-Aliağa	0	4	5000
Aliağa-Izmir	64	4	5000
Izmir-Aliağa	0	4	5000

Table 14
Scenario 2–5% demand results.

Route	Quantity onboard (cbm)	Week No.	Barge Capacity (cbm)
Aliağa – Istanbul- Aliağa	4700	2	5000
Aliağa - Istanbul- Aliağa	4375	3	5000
Aliağa - Kocaeli- Aliağa	1863	3	5000
Aliağa – Tekirdağ	4634	4	5000
Tekirdağ - Kocaeli	4202	4	5000
Kocaeli-Istanbul	3851	4	5000
Istanbul-Mersin	556	4	5000
Mersin-Iskenderun	464	4	5000
Iskenderun-Aliağa	0	4	5000
Aliağa-Izmir-Aliağa	328	4	5000

5.2. Scenario 2

In the second scenario, the Aliağa Ege Gaz LNG terminal is defined as the loading port, and the LNG fuel is distributed according to the ports' demand. The model guarantees weekly requested quantities within one month period.

The MILP model contains 1529 total variables, of which 584 are integer variables, and 1313 total constraints for all demand cases in Scenario 2. It has found an optimal solution for the 1% demand case in 5.40 s. The model results show that the 5 k cbm barge is the optimum barge capacity, and due to low demand, all distributions are carried out in the fourth week. The barge first discharges the largest quantities in the Marmara Sea following Tekirdağ, Kocaeli, Istanbul route, then discharges the remaining quantity to Mersin and Iskenderun. Izmir's demand is fulfilled with a separate voyage after that. The results are summarized in Table 13.

The second phase of Scenario 2 is based on the 5% demand case. The MILP model has found the optimum solution in 16.35 s for this case, and accordingly, the distribution plans occur in the second, third, and fourth weeks this time. The 5k cbm barge first performs the Istanbul voyage in the second week, and two separate voyages to Istanbul and Kocaeli follow it in the third week. The barge follows the route of Tekirdağ, Kocaeli, Istanbul, Mersin, Iskenderun for discharging in the fourth week and lastly makes a short voyage to Izmir. The results are summarized in Table 14.

The third phase investigates the 10% demand case for which the MILP model has found the optimum solution in 20.45 s. The optimum bunkering capacity is determined as one barge with a capacity of 10k cbm. The first delivery is done to Istanbul in the second week. The routing plan for the third and fourth weeks is the same as for the 5% case. The results are summarized in Table 15.

In the fourth phase, the 15% demand case is investigated. The proposed MILP model has found the optimum solution in 61.88 s. Hence, it suggests the optimum bunkering capacity as two barges with 3k and 5k cbm capacities. The 5000 cbm capacity barge is utilized every week. On the other hand, the 3000 cbm capacity barge is only used in the third and fourth weeks, which fulfills the Kocaeli demand in the third week and the demands of Izmir (Nemrut), Mersin, and Iskenderun in the fourth week. The results are summarized in Table 16.

Table 15
Scenario 2–10% demand results.

Route	Quantity onboard as cbm	Week No.	Barge Capacity (cbm)
Aliağa – Istanbul- Aliağa	9400	2	10,000
Aliağa - Istanbul- Aliağa	8750	3	10,000
Aliağa - Kocaeli- Aliağa	3726	3	10,000
Aliağa – Tekirdağ	9268	4	10,000
Tekirdağ - Kocaeli	8404	4	10,000
Kocaeli-Istanbul	7162	4	10,000
Istanbul-Mersin	1112	4	10,000
Mersin-Iskenderun	924	4	10,000
Aliağa-Izmir-Aliağa	652	4	10,000

Table 16
Scenario 2–15% demand results.

Route	Quantity onboard as cbm	Week No.	Barge Capacity (cbm)
Aliağa-Tekirdağ	4700	1	5000
Tekirdağ-Istanbul	4385	1	5000
Istanbul-Izmir	20	1	5000
Izmir-Aliağa	0	1	5000
Aliağa-Istanbul-Aliağa	4700	1	5000
Aliağa-Tekirdağ	4700	2	5000
Tekirdağ-Istanbul	4385	2	5000
Istanbul - Aliağa	0	2	5000
Aliağa-Istanbul-Aliağa	4700	2	5000
Aliağa - Kocaeli- Aliağa	2820	3	3000
Aliağa-Tekirdağ	4700	3	5000
Tekirdağ-Istanbul	4385	3	5000
Istanbul-Aliağa	0	3	5000
Aliağa-Istanbul-Aliağa	4680	3	5000
Aliağa-Kocaeli-Aliağa	4635	4	5000
Aliağa-Istanbul-Aliağa	4700	4	5000
Aliağa-Tekirdağ	4700	4	5000
Tekirdağ-Istanbul	4385	4	5000
Istanbul-Aliağa	0	4	5000
Aliağa - Izmir	2628	4	3000
Izmir-Mersin	1668	4	3000
Mersin-Iskenderun	1388	4	3000
Iskenderun- Aliağa	0	4	3000

Table 17
Summary of Scenario 2 results.

LNG Demand	Optimum Number of Barge / Capacity (cbm)	Min Cost (OPEX+ CAPEX+ Fuel Cost) USD
1%	1 / 5000	726,880.0
5%	1 / 5000	749,875.8
10%	1 / 10,000	834,729.4
15%	2 / 3000 and 5000	1,337,784.0

Table 17 summarises the overall results of Scenario 2 according to different LNG demand cases. The minimum costs gradually rise in parallel with the distance travelled, and the 15% case shows the high cost due to the two barges used.

In parallel to Scenario 1 results, the 15% demand case requires 3k and 5k bunker barges. However, unlike Scenario 1, 3k barge has only been used in weeks 3 and 4.

5.3. Scenario 3

The third scenario investigates two potential loading ports for LNG bunkering separately. It considers two regions separately - Marmara Ereğlisi as the loading port for the Marmara region (Scenario 3a) and Aliağa as the loading port for other destinations (Scenario 3b) Izmir, Mersin, and Iskenderun.

Table 18
Scenario 3a – M.ereğlisi centred 1% demand results .

Route	Quantity onboard (cbm)	Week No.	Barge Capacity (cbm)
M. Ereğlisi-Tekirdağ	2508	4	3000
Tekirdağ-Istanbul	1420	4	3000
Istanbul-M.Ereğlisi	0	4	3000
M.Ereğlisi- Kocaeli-M.Ereğlisi	497	4	3000

Table 19
Scenario 3a – M.ereğlisi centred 5% demand results.

Scenario 3a –%5 Demand Results - Route	Quantity onboard (cbm)	Week No.	Barge Capacity (cbm)
M. Ereğlisi-Istanbul-M.Ereğlisi	4700	2	5000
M. Ereğlisi-Istanbul-M.Ereğlisi	4700	3	5000
M.Ereğlisi-Tekirdağ	4700	4	5000
Tekirdağ-Istanbul	4268	4	5000
Istanbul-M.Ereğlisi	0	4	5000
M.Ereğlisi- Kocaeli-M.Ereğlisi	2485	4	5000

Table 20
Scenario 3a – M.ereğlisi centred 10% demand results.

Scenario 3a –%10 Demand Results - Route	Quantity onboard (cbm)	Week No.	Barge Capacity (cbm)
M. Ereğlisi-Istanbul-M.Ereğlisi	5870	1	6500
M. Ereğlisi-Istanbul-M.Ereğlisi	6110	2	6500
M. Ereğlisi-Istanbul-M.Ereğlisi	6110	3	6500
M.Ereğlisi-Tekirdağ-M.Ereğlisi	864	4	6500
M.Ereğlisi- Kocaeli-M.Ereğlisi	4968	4	6500
M. Ereğlisi-Istanbul-M.Ereğlisi	6110	4	6500

Table 21
Scenario 3a – M.ereğlisi centred 15% demand results.

Scenario 3a – 15% Demand Results - Route	Quantity onboard (cbm)	Week No.	Barge Capacity (cbm)
M. Ereğlisi-Istanbul-M.Ereğlisi	8425	1	10,000
M. Ereğlisi-Istanbul-M.Ereğlisi	9400	2	10,000
M. Ereğlisi-Istanbul-M.Ereğlisi	9400	3	10,000
M.Ereğlisi-Tekirdağ-M.Ereğlisi	1299	4	10,000
M.Ereğlisi- Kocaeli-M.Ereğlisi	7455	4	10,000
M. Ereğlisi-Istanbul-M.Ereğlisi	9075	4	10,000

The model was run for the M.Ereğlisi BOTAS loading port at the first step. The model includes 605 total variables, of which 212 are integer variables and 605 total constraints for all demand and loading port cases in Scenario 3a. The results are summarised in Tables 18–21 according to different demand cases.

The 3 k cbm barge provides all supplies during the fourth week using the Tekirdağ-Istanbul voyage and a separate voyage to Kocaeli for the 1% demand case. As the second step of Scenario 3a, the MILP model has found the optimum solution for the 5% demand case and M.Ereğlisi loading port option in 0.56 s. The 5k cbm barge carries out all supplies. The third step of Scenario 3a investigates the 10% demand case and M.Ereğlisi loading port option. The optimum solution was found in 0.8 s. The model defines optimum barge capacity as one barge at 6500 cbm capacity. As the fourth step of Scenario 3a, the model was run for the 15% demand case and M.Ereğlisi loading port option. The optimum solution was found in 0.42 s. The model defines the optimum barge capacity as 10 k cbm. The demand of Istanbul is tried to be satisfied throughout all weeks; the remaining ports' demand is provided during the fourth week.

Scenario 3a results indicate that barge capacity requirement gradually increases according to demand quantity if the distribution is planned only for potential locations at the Marmara Sea. Remarkably, the 3k bunker barge could handle all demand cases for Scenario 3b as the demand is too low at subject locations. The second part of Scenario 3 distributes EgeGaz (Aliağa) LNG to Nemrut (Izmir), Mersin and Iskenderun during the fourth week. The Aliağa-centred distribution option of Scenario 3(b) is summarised for all demand cases in Table 22. In either case, the optimum bunkering capacity is defined as a barge with a capacity of 3 k cbm. The barge also follows the same distribution route plan for all cases.

Table 23 presents the summary of Scenario 3 for the two loading port options. The choice of barge capacity to distribute from M. Ereğlisi changes with the increase in demand. On the other hand, the optimum barge capacity is 3k cbm for all cases from Aliağa. The minimum cost values of the Marmara Ereğlisi option are higher in three cases; the only exception is the 1% demand case. The minimum cost for the Aliağa (EgeGaz) centred case does not change. It can be attributed to the lower demand and the use of a single barge that carried out all shipments during the fourth week on a single distribution route. Therefore, the total cost remained below the Marmara Ereğlisi centred case.

It must be pointed out that LNG bunker demand in the world grows parallel to the size of the vessels that shift to LNG as ship fuel. The CMA CGM new order 23,000 TEU capacity container vessel has an 18,600 cbm LNG fuel tank capacity, and a 10k cbm LNG bunker barge will only be able to fill this size vessel in two trips. On the other hand, in the 15% demand case, the optimum solution was two barges with 3k and 5k cbm capacities. Both barges were utilized in different patterns covering all potential demand points. The increase in demand makes it impossible for the required capacity to be met by a single vessel. The two smaller barges give optimum results. Therefore, the optimum number of barges and their size must be evaluated according to demand and potential customers, who in our case are potential LNG fuelled ships requiring LNG.

The Aliağa EgeGaz LNG Terminal centred distribution was evaluated in Scenario 2. The Aliağa Ege Gaz LNG terminal is located on the West Coast of Turkey and in the neighbourhood of an industrial area along with other busy ports, namely Nemrut and Alsancak. Marine traffic in this port area cannot be compared to the Istanbul Strait. However, being in the vicinity of heavy marine traffic between the Marmara Sea and the Mediterranean brings advantages to the EgeGaz LNG Terminal. South of Bozcaada is an already important bunkering location that provides a bunker for those vessels waiting for passage through the Canakkale Strait. Turkey has a strong LNG infrastructure in the region. The Etki FSRU LNG terminal is also in Aliağa, and the new FSRU (Floating Storage Regasification Unit) terminal is planned for the Saros Gulf. The existing and planned LNG infrastructure provides a competitive advantage for Turkey in the region.

The mathematical results for Scenario 2 are parallel to Scenario 1. Only one bunker barge met demand cases for 1, 5, and 10%. Again, a single bunker barge with 5k cbm was the optimum barge capacity for the first two demand cases. A distribution route for the 1% demand case follows the Aliağa-Tekirdağ-Kocaeli-Istanbul-Mersin-Iskenderun-Aliağa-Izmir route during the fourth week. The 5% demand case follows the same routing plan as that of the 1% demand case in the fourth week and additionally separate voyages to Istanbul and Kocaeli in the second and third weeks. The 10% demand case was met by a 10 k bunker barge using the same distribution routing plans of the 5% demand case. Again, the most optimistic 15% demand case found that the optimum barges have 3 k and 5 k capacities. The 3 k bunker barge conducts its first delivery to Kocaeli in the third and fourth weeks, and it meets the demands of the Izmir-Mersin-Iskenderun ports on another route. On the other hand, the 5k vessel could be utilized starting from the first week to meet the demand of the Marmara region.

The third scenario considers two regions separately - Marmara Ereğlisi as the loading port for the Marmara region and Aliağa as

Table 22
Scenario 3b – aliağa centered results.

Route	Quantity onboard as cbm				Week	Barge Capacity (cbm)
	1%	5%	10%	15%		
Aliağa-Izmir	176	884	1765	2648	4	3000
Izmir-Mersin	112	557	1112	1668	4	3000
Mersin-Iskenderun	92	463	925	1388	4	3000
Iskenderun-Aliağa	0	0	0	0	4	3000

Table 23
Summary of Scenario 3 Results

LNG Demand	M. Ereğlisi		Aliağa	
	Optimum Number of Barge and Capacity (cbm)	Min Cost (OPEX+CAPEX+ Fuel Cost) USD	Optimum Number of Barge and Capacity (cbm)	Min Cost (OPEX+CAPEX+ Fuel Cost) USD
1%	1 / 3000	551682.0	1 / 3000	562835.1
5%	1 / 5000	707096.3	1 / 3000	562835.1
10%	1 / 6500	735867.2	1 / 3000	562835.1
15%	1 / 10000	793022.2	1 / 3000	562835.1

the loading port for other destinations, namely, Izmir, Mersin, and Iskenderun. As the biggest demand portfolio is sourced from the Marmara region, different barges with 3k, 5k, 6.5k, and 10k capacities were utilized parallel to the growing demand from 1% to 15%. While the 1% demand case utilizes the 3k barge only during the fourth week, the 5k barge is utilized starting from the second week for the 5% demand case, and for the 10 and 15% demand cases, the barges were employed during all weeks. The Aliağa centred distribution was carried out in the fourth week in all demand cases by a 3k barge as demand is relatively low compared to the Marmara region. Distribution of LNG bunker based on 1% demand cases for Scenario 1 (a), Scenario 2 (b), Scenario 3a (c), Scenario 3b (d) are illustrated in Fig. 3.

Fig. 4 illustrates the objective value of each scenario based on different demand scenarios. The third scenario's objective value is distinctively higher in 1, 5, and 10% demand cases. However, differences between 15% demand cases' objective values are less than 60,000 USD. Therefore, delivering the required LNG to all ports from two different loading points could be a competitive option only with a 15% demand case.

Demand forecast was carried out based on Turkey's current bunker supply view. Creating new markets and being the first adopter may change this bunker breakdown in favour of the larger ports of Turkey in the Mediterranean region. The Iskenderun Gulf consists of large ports dealing with dry bulk, containers, oil terminals, and LNG FSRU. Lifting bunker quantity per vessel is crucial for market development and fixing the optimum size of the barges.

One of the remarkable findings of the study is illustrated in Fig. 5. The objective function provides a reference point to calculate the breakeven point for LNG bunker sales. Fig. 5 illustrates the minimum cost of LNG per mt to start making a profit. Cases of 1% demand give the highest cost requirement. When the demand is the lowest, covering fuel cost, OPEX and CAPEX require the highest cost per mt of LNG in all scenarios.

Demand cases at 10 and 15% give the lowest breakeven prices, 437 and 440 USD/mt respectively for Scenario I and 438 and 442 USD/mt respectively for Scenario 2. Scenario 3 provided the lowest breakeven point – 15% demand case at 418 USD/mt, parallel to the highest demand and lowest fuel cost scenario. The LNG bunker price is crucial for shipowners to invest in LNG fuelled vessels. It is also critical for the supplier to achieve a profit margin. Bunker suppliers in Turkey work with very narrow profit margins, mainly due to the competition and the high logistics cost to deliver the bunker to the final users. A single supplier or owner does not afford the high CAPEX requirements for LNG bunker vessels.

Table 24
Objective function as time charter.

Scenario	Barge Capacity (cbm)	Scenario	Barge Capacity (cbm)
1–1%	5000	3a-1%	3000
1–5%	5000	3a-5%	5000
1–10%	10,000	3a-10%	6500
1–15%	3000 and 5000	3a-15%	10,000
2–1%	5000	3b-1%	3000
2–5%	5000	3b-5%	3000
2–10%	10,000	3b-10%	3000
2–15%	3000 and 7500	3b-15%	3000

The objective function was formulated to cover all related costs to see the overall picture; in other words, it was formulated with a shipowner perspective who wants to build and run a bunker barge. However, in the shipping business, the cost could be shared between stakeholders depending on agreements as part of Time Charter, Bareboat Charter, or Voyage Charter. The charter is responsible for voyage costs and the monthly hire rate in a time charter agreement. Therefore, the objective function is formulated with a minimum cost scenario, including fuel and capital expenditures. OPEX is neglected since it is under shipowner responsibility. The model is run for all three scenarios and 16 different cases, and the results are summarised in Table 24.

The model results for bunker barge selection are identical to those obtained by the first objective function. The second scenario's only exemption is the 15% demand case since 3k and 7.5k bunker barges provide an optimum solution rather than 3k and 5k bunker barges. As a result, the model finds that 15 cases out of 16 are identical. These findings point out that different stakeholders in the supply chain benefit from consistent investment decisions.

6. Conclusion and recommendations

This paper presents an LNG bunkering model for Turkey. The findings indicate that world seaborne trade and bunker price jointly influence bunker deliveries in Turkey. The explanatory variables, world seaborne trade, and bunker price time series were evaluated using the ARIMA EViews forecasting tool, and the time series was expanded to 2025. These findings help determine demand scenarios for the mathematical model. The developed model finds the optimum number of barges size and their size and the optimum allocation of the barges and the distribution network within a ship-to-ship bunkering framework based on the demand scenarios for 2025. The studied problem involves strategic and tac-

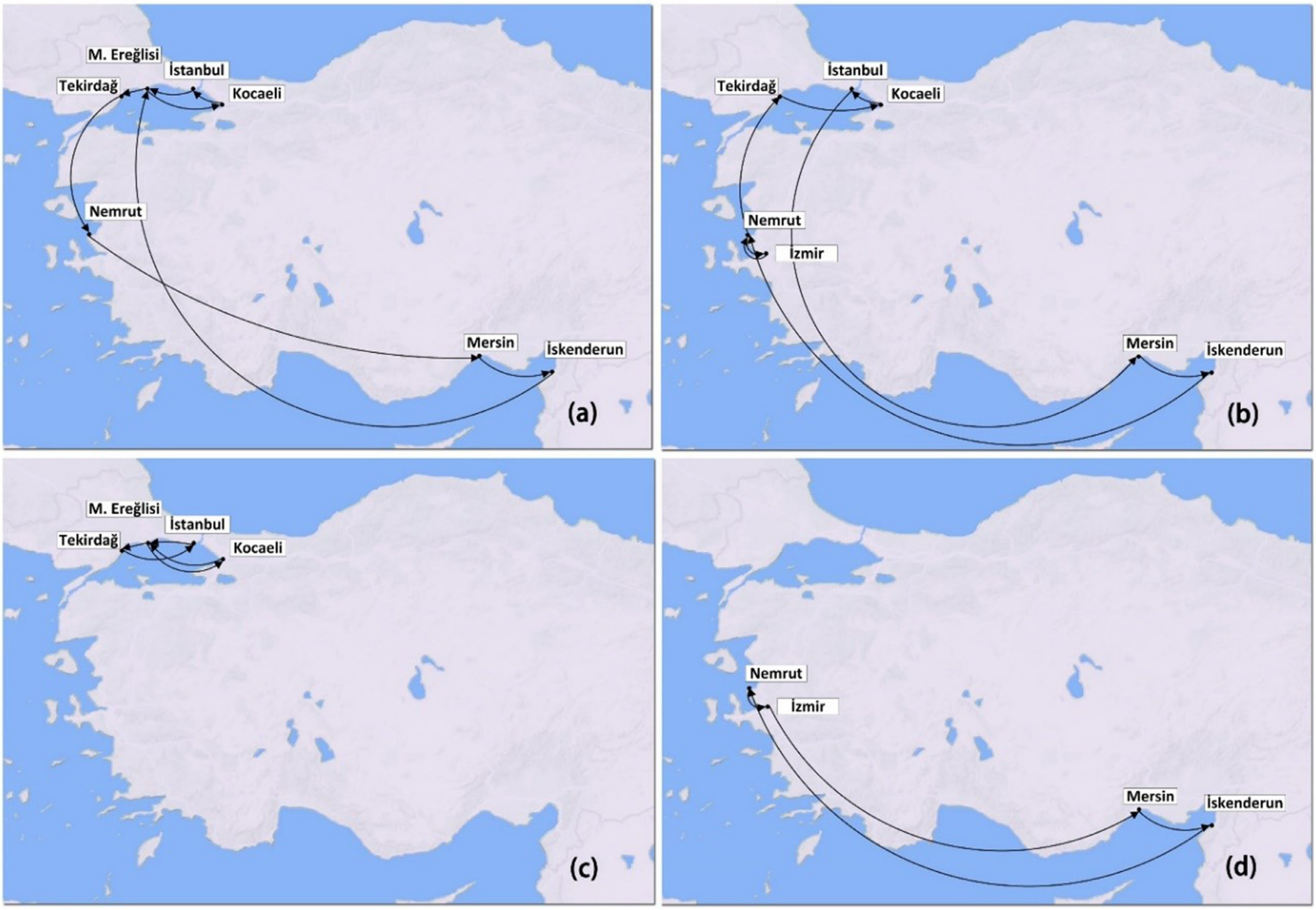

Fig. 3. 1% demand case distribution for Scenario 1, 2, 3a, and 3b.

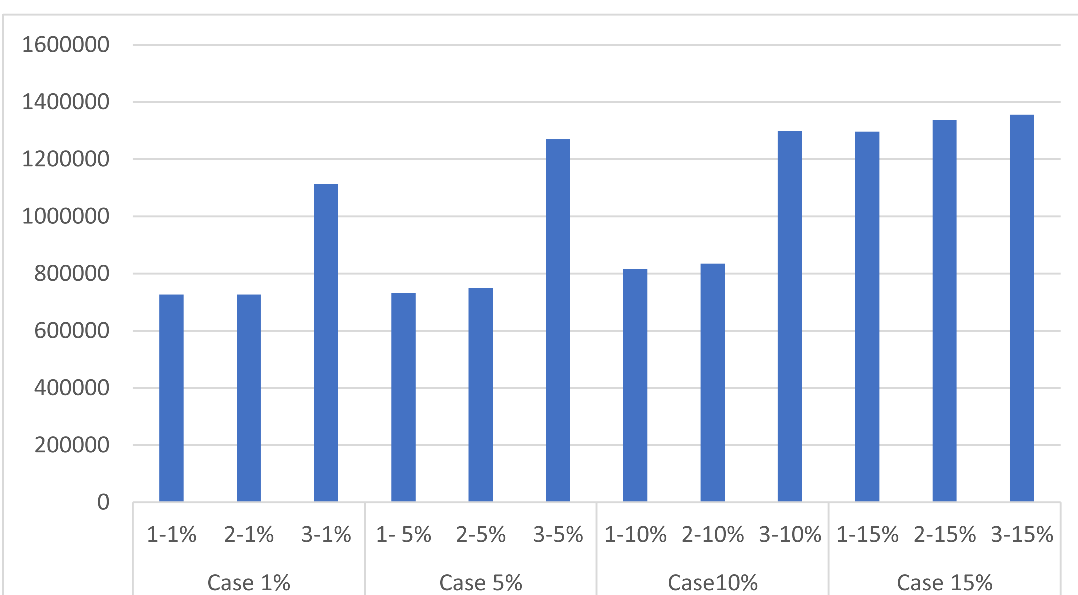

Fig. 4. Objective value for different demand cases.

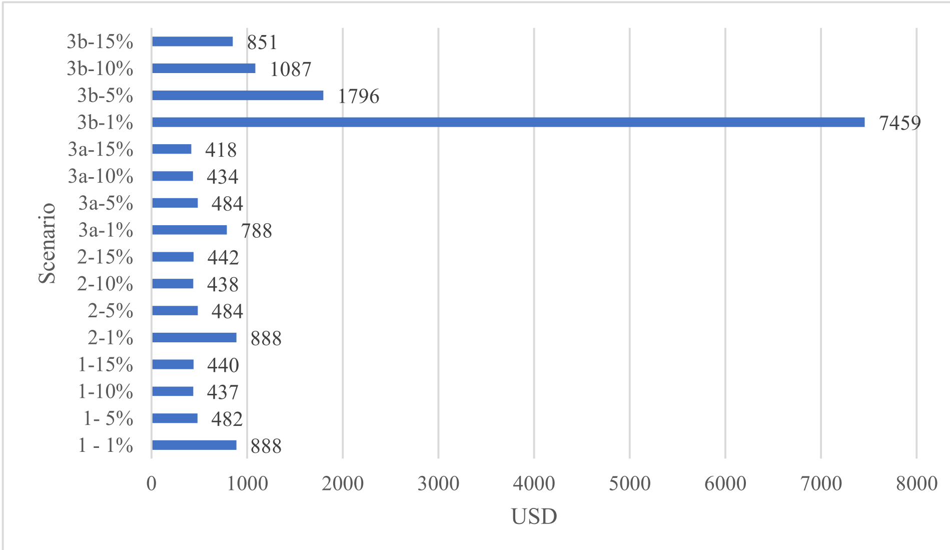

Fig. 5. Breakeven cost for LNG per MT.

tical LNG Bunker supply chain optimization decisions. This problem can be defined as a "Multiple Period Maritime Fleet Size and Routing Problem" in related literature and is formulated as a mixed-integer linear programming model. The data used in the model were acquired from industrial reports and expert views.

Two potential LNG terminals, namely, Marmara Ereğlisi BOTAS and Aliağa EGEGAZ, were defined as the loading ports, and Istanbul, Kocaeli, Tekirdağ, Izmir, Mersin, and Iskenderun were determined as the bunkering locations based on EMRA reports, which provide historical time series data concerning conventional bunkering practices in Turkey. As the routes are not predefined, the arc-flow-based distribution model was developed that uses a heterogeneous fleet. Wartsila's five different LNG bunker barges were chosen, ranging in size between 3k and 10k. The model enables split deliveries in multiple periods of the time horizon.

This study contributes to LNG bunkering investment decisions for shipowners and suppliers as it provides a model for decision support at both strategic and tactical levels. The research findings indicate that the optimum barge sizes are 3, 5, and 10 k concerning the demand scenarios. The proposed model provides a commercial framework for shipowners and suppliers by calculating the OPEX and CAPEX values of the related barges and their voyage costs. Also, it helps to determine the breakeven freight for LNG bunkering shipments under 16 different scenarios. Shipowners and suppliers should consider this crucial limit to calculate the payback time of their investment, determine profit margins, and provide a benchmark to compare the LNG option with other alternative fuels. The model presents a comprehensive tool as a feasibility study for shipowners and suppliers. It can also be generalized for global implications for any small-scale LNG supply chain fleet size and routing problem with different data sets.

Moreover, the model contributes to the decision-making literature in the maritime business. The model was developed concerning the voyage cost and fixed cost perspective in shipping. Minimum cost scenarios provide the theoretical benchmark to determine the *breakeven point* for investment decisions in the LNG Bunkering field. The regulatory framework should be standardized not only for the technical specifications of barges and LNG fuelled vessels but also for bunkering operations, bunker delivery notes, methane numbers, and the quality of the LNG and port regulations. This study guides policymakers in setting standards and updating port and custom regulations to enable LNG bunkering operations.

As a limitation of the research, the proposed model was developed based on some operational assumptions to solve the problem with MILP. Assumptions are required for using the MILP model, as the integration of all components of real-life could result in significant complexity and prolong problem solution time without providing appropriate solutions. Operational expenditures and capital expenditures were obtained from an LNG consultant. These costs may vary amongst the shipowners, the active barge areas, and the barge's shipyards.

The broader supply chain issues may need further research in this area. Additional operational parameters could be added to the base MILP model. The problem could also be designed as a two-tiered supply chain network with a solution for truck transportation. Another expansion could be through satellite terminals in the distribution network as receiving depots. A future direction for research could be to use simulation modelling to analyse the model implications in coping with the uncertainties.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Mehmet Doymus: Conceptualization, Methodology, Visualization, Formal analysis, Investigation, Writing – original draft, Data curation, Writing – review & editing. **Gul Denktas Sakar:** Supervision. **Seyda Topaloglu Yildiz:** Supervision, Methodology, Writing – review & editing, Software, Validation, Investigation. **Abdullah Acik:** Software, Methodology, Visualization.

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