

# An innovative decision support tool for liquefied natural gas supply chain planning

An innovative  
decision  
support tool

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## Abstract

**Purpose** – The purpose of this paper is to improve the tactical planning of the stakeholders of the midstream liquefied natural gas (LNG) supply chain, using an optimisation approach. The results can contribute to enhance the proactivity on significant investment decisions.

**Design/methodology/approach** – A decision support tool (DST) is proposed to minimise the operational cost of a fleet of vessels. Mixed integer linear programming (MILP) used to perform contract assignment combined with a genetic algorithm solution are the foundations of the DST. The aforementioned methods present a formulation of the maritime transportation problem from the scope of tramp shipping companies.

**Findings** – The validation of the DST through a realistic case study illustrates its potential in generating quantitative data about the cost of the midstream LNG supply chain and the annual operations schedule for a fleet of LNG vessels.

**Research limitations/implications** – The LNG transportation scenarios included assumptions, which were required for resource reasons, such as omission of stochasticity. Notwithstanding the assumptions made, it is to the authors' belief that the paper meets its objectives as described above.

**Practical implications** – Potential practitioners may exploit the results to make informed decisions on the operation of LNG vessels, charter rate quotes and/or redeployment of existing fleet.

**Originality/value** – The research has a novel approach as it combines the creation of practical management tool, with a comprehensive mathematical modelling, for the midstream LNG supply chain. Quantifying future fleet costs is an alternative approach, which may improve the planning procedure of a tramp shipping company.

**Keywords** LNG, Contract assignment, Decision support tool, LNG supply chain, MILP, Tramp shipping

**Paper type** Research paper

## 1. Introduction

Natural gas is considered to be an important alternative energy source for many countries, which is forecasted to have a global share of approximately 25 per cent among other energy sources by 2040 (BP, 2019). This share is projected to increase in the following years, when upcoming regulations aiming at the reduction of carbon emissions come to force. Liquefaction of natural gas and transportation in the form of liquefied natural gas (LNG) is proven an advantageous procedure, with regard to the feasibility and economic efficiency of its transportation. As a result, global gas demand may lead to



further LNG infrastructure projects, which may affect the future state of the LNG market. The deployment of LNG supply chains enables flexible supplies in terms of volume, destination and pricing. Already, short-term trade accounts for approximately 30 per cent of the total LNG trade (IGU, 2019), indicating that the competition will intensify, and market volatility will grow.

The LNG shipping market will be affected as well. LNG carriers (LNGC) play a key part in the overall operation of the supply chain, as they account for the transportation of LNG to regional gas markets. The cost required for building and operating such assets is significant, as the cost for a newbuild order in 2018 averaged \$1,069/m<sup>3</sup> (IGU, 2019). Consequently, the ability to plan and implement effective innovative company policies as well as managerial decisions is crucial to enable an investor make an informed decision whether to order such ships and/or how to deploy them.

The purpose of this work is to develop a decision support tool (DST) for the deployment of an LNGC fleet, which will support the decision maker on a tactical level. More specifically, the DST's objective is to optimally deploy an LNG fleet from the scope of the shipowner, assigning vessels to most favourable contracts that service cargoes for trade routes between liquefaction and regasification terminals. The fleet assignment is complemented by a schedule for each vessel that projects its utilisation throughout the time horizon. The optimization criterion is the minimisation of the fleet operating cost, co-calculating the components burdening the shipowner and the charterer. The holistic view offered to the shipowner enables him to consider the cost associated with charterer and consequently offer lower charter rates compared to the competition, while still retaining high profit margins because of the efficient fleet planning.

In the framework of the present study, a literature review on LNG supply chain planning is conducted. Researchers have previously dealt with the different aspects of the subject and a review of the published work is presented in Section 2. Having reviewed the contemporary literature on the subject, the paper emphasises on LNG shipping, to introduce realistic considerations in the developed model.

The rest of the paper is organised as follows. Section 3 elaborates on the methodological approach of the research, the assumptions and the mathematical modelling of the proposed tool. In Section 4, a case study is presented illustrating the optimisation of the midstream LNG supply chain. Finally, Section 5 summarises the conclusion of the research.

## **2. Planning within the liquefied natural gas supply chain**

### *2.1 The liquefied natural gas supply chain*

The typical high-level view of the LNG supply chain includes three stages with several types of facilities corresponding to each stage of the supply chain, namely, liquefaction (upstream), transportation (midstream) and regasification (downstream). Initially, the natural gas extracted from drilled wells are processed and purified before its liquefaction. Then, natural gas is cooled down to a temperature of approximately  $-162^{\circ}\text{C}$ , taking liquid form, which reduces its volume to about 1/600 of its volume in a gaseous state. Afterwards, LNG is transported in double-hulled LNGCs, which deliver the cargo to the receiving terminal, where LNG is stored at cryogenic storage tanks prior to regasification. This process refers to the gradual heating of LNG to vapourise, to feed it to the network and in line with regulatory and end-user requirements. Notwithstanding, the economic feasibility of storage and long-distance transportation of LNG may also remove several obstacles to countries, such as as access to natural gas or limited reserves; limited access to long-distance transmission pipelines; and security of supply because of geopolitical risks.

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The focus of the study is on LNG transportation and consequently the means that enable it, the LNG vessels. LNGCs are classified by their capacity, cargo containment and propulsion systems. LNGCs are obligated to comply with IMO Gas Codes and International Regulations, concerning operations efficiency and safety, but also pollution precautions. The examination of the special characteristics and installed technologies of designated LNG ships comply with all the relevant rules and regulations. For the present study, the classification of the various LNGC types is conducted based on the propulsion system of each vessel, i.e. steam turbine, tri fuel diesel electric (TFDE) and two stroke gas injection. Their capacity is assumed to be equal with an average value found in all newbuild LNGCs, irrespective of the specific cargo containment system.

## 2.2 Literature review

This subsection aims at presenting a brief literature review, which the current research builds upon to focus on the midstream supply chain and develop a functional LNG fleet deployment system, using MILP modelling. Significant research on the subject of optimal design and deployment of the LNG supply chain has been made.

Fodstad *et al.* (2010) developed LNGScheduler, an optimization system that covers large parts of the LNG supply chain. The study aims the profit maximization, calculating both cost and revenues of several scenarios of vessel routing, inventory management, trading and contractual obligations. The model considers trading contracts across the LNG supply chain and incorporates seasonal variations regarding inventory shipping and price arbitrage opportunities. The formulation allows the company to manage the liquefaction part onshore, deploy its own fleet and trade additional quantity of LNG for the purpose of meeting contractual terms or increasing the profitability.

Rakke *et al.* (2011) introduced a rolling horizon heuristic applied to an LNG delivery programme from the scope of an LNG producer, who manages the LNG inventories at a liquefaction terminal with berth constraints, as well as the routing and scheduling of a heterogeneous LNG fleet. The model produces an annual delivery program (ADP) based on long-term contractual distribution to the end-market by minimizing costs and maximizing profitability from selling LNG in the spot market. Initially, a mixed integer programming (MIP) solution provides a feasible set of scheduled voyages within the planning horizon. Then, to reduce complexity, the study proposes a rolling horizon heuristic that iteratively solves subproblems with shorter planning horizons. Each subproblem consists of a central and a forecasted period. The technique applied ensures a good ADP within a reasonable computational time.

Stålhane *et al.* (2012) developed an improved heuristic for a large-scale LNG ship routing and inventory management problem, from the viewpoint of an LNG producer and distributor, owning both liquefaction and regasification facilities. The problem considers multiple products, inventory and berth restrictions at the liquefaction terminal and a heterogeneous LNG fleet. Once again, the study aims at producing an ADP to meet the producer's long-term contractual requirements, simultaneously minimizing tactical and operational cost and maximizing the profits by selling LNG in the spot market. The model is handled by implementing a multi-start construction and improvement heuristic, which produces high-quality solutions to actual problems in an attractive computational time.

Halvorsen-Weare and Fagerholt (2013) published a research on routing and scheduling problem for LNG shipping with inventory and berth capacity constraints at the liquefaction port. The model is classified as an assignment problem, defining which vessel delivers which cargo and the schedule of the deliveries. The root problem is decomposed into two

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phases, where routing and scheduling are treated as separate subproblems. The solution is produced by primarily handling the scheduling for real-life problems.

Goel *et al.* (2015) introduced a constraint programming approach for the optimization of LNG ship scheduling and inventory management. More specifically, the study is based on constrained programming models, to provide optimal qualitative scheduling decisions in shorter time compared to MIP models. Additionally, the model includes an iterative heuristic search algorithm to produce a more favourable subset of solutions within the initial set of feasible solutions. Fixed storage capacities and berth restrictions are taken under consideration for both liquefaction and regasification terminals. Goals of the particular process are the delivery of the LNG to each customer and the minimization of disruptions to supply chain during the planning horizon. Such disruptions refer to loss of production because of lack of storage at the liquefaction facility and lack of stock for consumption at the receiving terminal.

Mutlu *et al.* (2016) developed a cost-effective ADP tool, which can be used by LNG suppliers. They provided an extensive and realistic description of LNG supply chain operations, contractual terms and alternative delivery options. The proposed heuristic solution calculated split-delivery schedules and resulted in substantial cost reductions.

Al-Haidous *et al.* (2016) formulated an MIP model with the objective of minimizing the vessel fleet size required to service specific long-term LNG contracts. The fleet size is directly related to the optimal ADP produced by the model, as LNGCs are assigned to specific terminals. Several constraints are considered, such as berth availability, liquefaction terminal inventory, planned maintenance and bunkering requirements.

Bittante *et al.* (2018) focused on the development of small-scale LNG supply chains, including a heterogeneous fleet, a set of export terminals and a set of import terminals with given demands, considering simultaneous load split, multiple depots and trade brackets between terminals on the same route. The model is treated as an MILP problem with the criterion of voyage cost minimization based on fuel procurement. Sensitivity analysis on LNG price in the supply ports, time horizon and berthing time as well as a preliminary computation under demand uncertainty are also carried out.

Zetos *et al.* (2018) proposed a mixed integer linear programming (MILP) model that provides strategic and tactical decisions on the deployment of an LNG fleet. The study aims at determining the optimal trade routes between predetermined sets of liquefaction and regasification terminals based on fleet cost minimization. The problem is treated from the scope of a shipping company. The MILP optimisation is distinguished into three stages: initially, the fleet assignment subproblem is solved, followed by the minimisation of fleet costs and, finally, the remaining vessels are allocated until LNG demand of each receiving terminal is met. Solutions provide the shipping company with satisfactory estimations regarding the future fleet operational expenses and voyage costs handled by the charter party.

Konstantinidis *et al.* (2019) formulated a simplified DST to evaluate the feasibility LNG supply chains. Strategic decisions regarding investment in infrastructure, such as LNG export terminals and vessels, were on the epicentre of the proposed tool. The aforementioned components have been incorporated into a mathematical model, which performed an optimisation of the supply chain for an annual time horizon based on the vehicle routing problem (VRP). LNG is loaded from a predetermined terminal and is distributed to a set of import terminals via an LNGC. The optimisation process produced a designated ship routing for minimum voyage duration, generated the inventory level at each import terminals for the year under consideration and performed an analytical calculation of the total cost for the supply chain for the midstream and downstream sections.

The focus of most studies presented above is on the upstream and midstream segments of the LNG supply chain, as the objective of the research is the planning from the scope of integrated LNG companies involved in the production and transportation of the LNG to the buyers. Considering the lack of papers dealing exclusively with the midstream supply chain and more specifically tramp shipping companies active in the LNG market, the current research is innovative in its approach.

Naturally, the objectives of the optimisation for the two perspectives differ. The optimisation models used by LNG producers aim at the minimisation of the supply chain cost, summing the shipping cost, and potential penalties associated with under deliver. Spot sales are taken into consideration, either in the form of revenues subtracted from the cost (Rakke *et al.*, 2011; Stålhane *et al.*, 2012; Halvorsen-Weare and Fagerholt, 2013) or in the form of cost deriving from lost stockout (Goel *et al.*, 2015) and spot chartering of LNGC for its delivery (Mutlu *et al.*, 2016). Al-Haidous *et al.* (2016) opt for the minimisation of the number of LNGCs required to service the annual planned production. Bittante's model (Bittante *et al.*, 2018) adopt a more versatile approach to be used by shipowners, minimising the shipping operational expenditures, the chartering cost and the LNG cargo cost.

### 3. The proposed decision support tool

#### 3.1 Problem description

The research presented in the paper focuses on the midstream section of the LNG supply chain. In the case of an integrated organisation active across the LNG supply chain, quantitative data such as shipowner and charterer costs are available for processing and planning. However, this is not the case when two independent parties operate separately, i.e. the owner of an LNG fleet, transporting the LNG, and the charterer trading the LNG. Both stakeholders have to plan their activities, each from their scope, albeit taking into consideration their counterpart's schedule. The shipping company must do so as it assesses options regarding contract options for its LNG fleet portfolio. The charterer naturally seeks the most economical plan to transport LNG cargoes and evaluates options regarding the deployment of the vessels under charter. To achieve this, both sides require insight on the planning of the other, review with relative accuracy, trends of fleet deployment on certain trade routes and delivery schedules between terminals. Such information is limited before the two parties sign a contract of services and, as a result, alternative approaches must be considered by the stakeholders to gain a global picture of the LNG supply chain and be proactive in their own planning.

The objective of the proposed DST is to provide the shipowner side with information and suggestions on:

- the deployment of the fleet on specific trade routes with minimum operating cost; and
- the fleet schedule to increase the utilisation and minimise its idle time between voyages.

The operating cost can be decomposed to the fixed costs (maintenance cost including the cost of the special surveys, crew and office personnel, as well as general expenses, such as stores and provisions) and variable costs (fuel, lubricants) calculated for each vessel sailing between specific terminals. An argument can be made that costs associated with the charterer should not be taken into consideration as the DST optimises the fleet from the scope of the shipowner. However, it is this exact innovative approach that provides the shipowner with a holistic picture of the total fleet cost, and enable him to offer lower, more competitive charter rates, without sacrificing his profit margin.

The DST incorporates more aspects of the real-world problem to its mathematical formulation, thus addressing more intricate issues of the midstream LNG supply chain. The LNG transportation via a private fleet is modelled as a generic deterministic MILP to perform the optimum deployment of the fleet on trade routes between multiple liquefaction and regasification terminals.

### 3.2 Assumptions

Assumptions are made so that the DST is aligned with the reality of the LNG midstream supply chain. To develop a functional programming tool for tactical planning, a time horizon of 365 days is considered as a reasonable period to examine the operation of an LNGC fleet. The same time period is considered by all researchers, with the exception of [Bittante et al. \(2018\)](#), who opt for monthly periods. The annual time horizon coincides with the charter duration between the ship-owner and charterer.

The voyage profile includes the departure from a liquefaction terminal, the transportation and discharging of the cargo to a regasification terminal. A standard trade route consists of three stages: the laden voyage, operations at the terminals and ballast voyage. During a laden voyage, each vessel departs fully loaded from a liquefaction terminal, operates with specific fuel consumption and berths to a regasification terminal to deliver its cargo. During the ballast voyage, the vessel returns back to the liquefaction terminal, sailing with a different fuel consumption as it has minimum LNG used:

- to keep the cargo containment system cool; and
- as a fuel for its propulsion.

In the current study, no distinction is made between different LNG types, as the shipowner is contracted by the charterer to transport specific cargo in terms of quality and quantity according to the requirements agreed between the seller and the buyer of LNG.

Fleet planning will provide information related with the departure date for each vessel on a laden voyage from an export terminal, the delivery date to the import terminal and the date of return after the ballast voyage back to the export terminal concludes. Throughout the selected time period, it is assumed that all vessels are active, service a contractual trade route without considering periods that remain idle in anchorages or drydocking periods. Moreover, refuelling, spares, stores and provision supplementation are assumed to take place during terminal operations.

Furthermore, maintenance time window is an aspect considered by [Rakke et al. \(2011\)](#), [Stålhane et al. \(2012\)](#) and [Al-Haidous et al. \(2016\)](#) underlining its impact on the planning of the LNG-integrated company. From the shipowner's perspective, it is still significant, but the in the current MILP formulation, it is modelled backwards; the produced annual sailing schedule for each vessel provides the shipowner with the time windows available for the maintenance of the vessel.

The LNG fleet consists of a set of vessels, with different technical characteristics as described in Section 2.1, which means that the fleet could be characterized as heterogeneous similar to the precedent set by most researchers referenced in the literature review ([Rakke et al., 2011](#); [Stålhane et al., 2012](#); [Halvorsen-Weare and Fagerholt, 2013](#); [Goel et al., 2015](#); [Bittante et al., 2018](#)). Each vessel of the fleet has a profile with a set of characteristics, handled as input parameters. Such parameters are used to define each LNGC and include the fuel consumption rates during sailing or terminal operations, payload capacity, propulsion system (steam turbine, dual/tri fuel diesel electric, two-stroke gas injection), average service speed and total fixed expenses per year. For improved precision, the fuel cost during ballast, laden voyages and terminal operations are calculated separately. Heavy fuel oil (HFO), marine diesel Oil (MDO)

and LNG are the available types of marine fuel for the operation of the vessels. Additionally, it is assumed that each vessel of the fleet has been scrutinised in terms of terminal compatibility by the shipowner and it is compatible with every liquefaction and regasification terminal facility, and thus no technical limitations apply. Finally, the boil-off phenomenon is taken into consideration, so the payload capacity of each vessel is reduced during the voyage by an assumed fixed percentage of 0.15 per cent per day. Boil-off rate may be altered by the user to correspond to different cargo containment technology.

Vessel capital costs are not included in the model, as the proposed DST performs fleet deployment for an existing LNGC fleet, in which the shipowner has already invested and operates. Each vessel is assigned to a unique long-term contract, matching the defined time horizon, servicing a specific trade route and delivering a predetermined quantity of LNG cargo.

The demanded quantity is assumed to be delivered in sequential discharges, equally distributed throughout the year depending on the capacity of the assigned vessel. Past research corresponds to past state of the LNG market, when it was dominated by a group of suppliers controlling the trade flows to a handful of import countries. It is crucial to address the evolving LNG market and the trade options available nowadays. Thus, three potential trading outcomes provided the set of contracts:

- A single liquefaction terminal exports LNG to a single regasification terminal.
- Several liquefaction terminals export LNG to a single regasification terminal.

In contrast with [Fodstad \*et al.\* \(2010\)](#), [Mutlu \*et al.\* \(2016\)](#) and [Bittante \*et al.\* \(2018\)](#), whose works allow partial loading and discharging, the proposed model does not consider such aspects. The shipowner's LNGC fleet services long-term contracts and deliver full cargoes between terminals.

The aspect of contracts with given attributes included in the current research is a common element with the work of [Fodstad \*et al.\* \(2010\)](#), [Rakke \*et al.\* \(2011\)](#), [Stålhane \*et al.\* \(2012\)](#), [Mutlu \*et al.\* \(2016\)](#) and [Al-Haidous \*et al.\* \(2016\)](#). The proposed model builds upon the use of contractual obligations to link available hypothetical contracts for LNG trade between specific export and import terminals. A contract is considered fulfilled once the assigned ship has delivered the total LNG quantity within the time horizon. Each contract includes certain operational attributes that are essential to the function of the model. These are:

- contract identification number;
- serviced liquefaction and regasification terminals;
- distance between two terminals expressed in nautical miles;
- delivery deadlines throughout the time horizon;
- annual LNG demand of the receiving terminal;
- loading and discharging rate of terminal equipment;
- canal of passage;
- terminal call costs at liquefaction and regasification terminals;
- total annual capacity of the regasification terminal; and
- HFO, LNG, MDO price.

### 3.3 Mathematical model

#### Sets and parameters

$TH$  = Time horizon (days);  
 $v$  = Set of vessels,  $v = \{1, \dots, V\}$ ;

$Sv_{BALLAST,v}$	= Speed of vessel $v$ for ballast voyage (knots);
$Sv_{LADEN,v}$	= Speed of vessel $v$ for laden voyage (knots);
$Cap_v$	= Cargo capacity of vessel $v$ (cubic meters of LNG);
$VFC_v$	= Fixed annual cost of vessel $v$ (\$/year);
$c$	= Set of contracts, $c = \{1, \dots, C\}$ ;
$L$	= Set of liquefaction terminals, $L = \{1, 2, \dots,  L \}$ ;
$R$	= Set of regasification terminals, $R = \{1, 2, \dots,  R \}$ ;
$D_c$	= Annual LNG demand contract $c$ serviced by vessel $v$ (cubic meters of LNG);
$R_{max,c}$	= Annual regasification capacity of terminal $R$ included in contract $c$ ;
$NV_{cv}$	= Number of required voyages for vessel $v$ to service the demand of contract $c$ (integer);
$N$	= Number of cargo deliveries for vessel $v$ (integer);
$LV_{INITIAL,L,v}$	= Distance between random initial position and liquefaction terminal $L$ (nautical miles);
$LR_c$	= Distance between liquefaction terminal $L$ and regasification terminal $R$ of contract $c$ (nautical miles);
$Dur$	= Total voyage time of vessel $v$ (days);
$Dur_{INITIAL,cv}$	= Voyage time of vessel $v$ from random initial position to liquefaction terminal $L$ included in contract $c$ (days);
$Dur_{L,cv}$	= Terminal time of vessel $v$ at liquefaction terminal $L$ (days);
$Dur_{R,cv}$	= Terminal time of vessel $v$ at regasification terminal $R$ (days);
$Dur_{VLADEN,cv}$	= Laden voyage time of vessel $v$ (days);
$Dur_{VBALLAST,cv}$	= Ballast voyage time of vessel $v$ (days);
$LQ_{cv}$	= Cargo loaded to vessel $v$ under contract $c$ (cubic meters of LNG);
$DQ_{cv}$	= Cargo discharged from vessel $v$ under contract $c$ (cubic meters of LNG);
$Du_{pt_{cv}}$	= Cargo remaining to be serviced by vessel $v$ under contract $c$ after $N$ deliveries (cubic meters of LNG);
$LNG_{RATE}$	= Loading and discharging rate of LNG (cubic meters per hour);
$BOG_{RATE}$	= Boil-off gas percentage for all vessels;
$perm$	= Cargo tank permeability percentage;
$T_{DELIVERY,c}$	= Delivery deadline under contract $c$ (days);
$TF_{Lc}$	= Fee charged by liquefaction terminal $L$ serviced by contract $c$ (\$/days);
$TF_{Rc}$	= Fee charged by regasification terminal $R$ serviced by contract $c$ (\$/days);
$C_{canal,c}$	= Canal passage fee serviced by contract $c$ (\$/per leg of voyage);
$C_{LNG}$	= Fuel price of LNG (\$/tonne);
$C_{HFO}$	= Fuel price of HFO (\$/tonne);
$C_{MDO}$	= Fuel price of MDO (\$/tonne);
$FCB_{LNG,v}$	= LNG consumption rate of vessel $v$ during a ballast voyage (tonnes/day);
$FCB_{HFO,v}$	= HFO consumption rate of vessel $v$ during a ballast voyage (tonnes/day);
$FCB_{MDO,v}$	= MDO consumption rate of vessel $v$ during a ballast voyage (tonnes/day);
$FCL_{LNG,v}$	= LNG consumption rate of vessel $v$ during a laden voyage (tonnes/day);
$FCL_{HFO,v}$	= HFO consumption rate of vessel $v$ during a laden voyage (tonnes/day);
$FCL_{MDO,v}$	= MDO consumption rate of vessel $v$ during a laden voyage (tonnes/day);
$FCP_{LNG,v}$	= LNG consumption rate of vessel $v$ during a port call (tonnes/day);
$FCP_{HFO,v}$	= HFO consumption rate of vessel $v$ during a port call (tonnes/day); and
$FCP_{MDO,v}$	= MDO consumption rate of vessel $v$ during a port call (tonnes/day).

### Variables

$x_{cv}$  = Binary decision variable equals to 1 if vessel  $v$  is assigned contract  $c$  or 0 otherwise.

The mathematical model uses MILP formulation as it is considered a suitable method for the assignment of the fleet to the trade routes with the inclusion of a binary decision variable, whilst maintaining other real-life operational variables. The MILP model is oriented to provide optimal options to a shipping company that operates LNGCs under long-term contracts, minimizing operational expenses and optimally assigning specified contracts to each vessel in the fleet. The criterion of optimization is the minimization of total cost of the LNG fleet.

Before the optimisation process, it is essential to conduct initial calculations regarding the trade routes and the LNG volumes described in each contract. These calculations are briefly provided as follows:

$$Dur_{VLADEN,cv} = \frac{LR_c}{S_{VLADEN,v}} \cdot 4 \quad (1)$$

$$Dur_{VBALLAST,cv} = \frac{LR_c}{S_{VBALLAST,v}} \cdot 24 \quad (2)$$

$$Dur_{INITIAL,Lv} = \frac{LV_{INITIAL,Lv}}{S_{VBALLAST,v}} \cdot 24 \quad (3)$$

$$Dur_{L,cv} = \sum_{v \in V} \sum_{c \in C} \frac{LQ_{cv}}{LNG_{RATE}} \cdot 24 \quad (4)$$

$$Dur_{R,cv} = \sum_{v \in V} \sum_{c \in C} \frac{DQ_{cv}}{LNG_{RATE}} \cdot 24 \quad (5)$$

Equations (1) and (2) set the duration of laden and ballast voyages for each trade route combination between the sets of liquefaction and regasification terminals. The initial transition time required for a vessel to move in place from a random point to a liquefaction terminal at the beginning of the time horizon is calculated by equation (3). Equations (4) and (5) calculate the port call time of the vessel  $v$ , under contract  $c$ , which corresponds to the berth and operations at liquefaction terminal  $L$  and regasification terminal  $R$ :

$$LQ_{cv} = perm \cdot Cap_v \quad (6)$$

$$DQ_{cv} = LQ_{cv} \cdot (1 - BOG_{RATE} \cdot Dur_{VLADEN,cv}) \quad (7)$$

$$NV_{cv} = \frac{D_{cv}}{DQ_{cv}} \quad (8)$$

The loaded cargo is equivalent to the total operational capacity of the vessel, considering full loading restrictions (cargo tank permeability 98, 5 per cent) and it is expressed by equation (5), whereas the volume discharged from the vessel to the regasification terminal considering reduction because of BOG on a daily basis is calculated in equation (7). The

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number of required voyages according to contractual specifications is given by total demanded volume divided by the volume discharged at each delivery as indicated in equation (8).

The total cost of operation for the LNG fleet to be minimised is set by the objective function (8) of the MILP model:

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$$\begin{aligned}
 \text{Min } \sum_{v \in V} \sum_{c \in C} x_{cv} \cdot \{ & VFC_v^T + [NV_{cv} \cdot Dur_{R,cv} \cdot (TF_{R,c} + TF_{L,c})] + [NV_{cv} \cdot (Dur_{L,cv} + Dur_{R,cv}) \\
 & \cdot (FCP_{LNG,v}^T \cdot C_{LNG} + FCP_{HFO,v}^T \cdot C_{HFO} + FCP_{MDO,v}^T \cdot C_{MDO})] \\
 & + [NV_{cv} \cdot (Dur_{INITIAL,cv} + Dur_{VBALLAST,cv}) \\
 & \cdot (FCB_{LNG,v}^T \cdot C_{LNG} + FCB_{HFO,v}^T \cdot C_{HFO} + FCB_{MDO,v}^T \cdot C_{MDO})] \\
 & + [NV_{cv} \cdot Dur_{VLADDEN,cv} \cdot (FCL_{LNG,v}^T \cdot C_{LNG} + FCL_{HFO,v}^T \cdot C_{HFO} \\
 & + FCL_{MDO,v}^T \cdot C_{MDO})] + 2NV_{cv} \cdot C_{canal,c} \quad (9)
 \end{aligned}$$

subject to

$$x_{cv} = \begin{cases} 0 \\ 1 \end{cases}, \forall c \in C, v \in V \quad (10)$$

$$N \cdot \sum_{c \in C} DQ_{cv} \leq \sum_{c \in C} R_{max,c} \quad (11)$$

$$N \cdot \sum_{c \in C} DQ_{cv} \geq \sum_{c \in C} D_c \quad (12)$$

$$\sum_{c \in C} (DurV_{LADEN,cv} + Dur_{L,cv} + Dur_{R,cv}) \leq \sum_{c \in C} T_{DELIVERY,c} \quad (13)$$

$$NV_{cv} \cdot \sum_{c \in C} (DurV_{LADEN,cv} + DurV_{BALLAST,cv} + Dur_{L,cv} + Dur_{R,cv}) \leq TH \quad (14)$$

All terms of the objective function are presented in the form of matrices, which are multiplied with a matrix of identical dimension that includes the decision variables for the combinations of trade routes. The first term is the fixed cost of the fleet; the second term addresses the fees charged for each port call and fuel costs for terminal operations; and the third, fourth and fifth terms represent the fuel cost for terminal operations, ballast and laden voyages, respectively. Finally, the last term corresponds to any canal charges that may

occur for the crossing of the Suez or Panama Canal when sailing on specific trades routes. Given the canal and the vessel type, the model determines the relevant cost of canal passage for each combination of contract–vessel, using the input values of canal charges.

Existing MILP modelling of similar problems includes multiple decision variables. For instance, [Bittante \*et al.\* \(2018\)](#) used three decision variables to determine the optimum number of vessels, trips and number of loaded cargoes per ship. In the present study, a single binary decision variable is included in the MILP formulation to process the assignment of the LNGC to a contract. The formulation of the problem does not require multiple decision variables, as it examines a given fleet, with a known number of vessels. The same applies for the characteristics of the voyages between the terminals, which are pre-calculated and incorporated as attributes of each contract.

The objective function is subject to several constraints for each vessel and contract. Constraint (10) limits the decision variable to take values of 0 or 1, thus being a binary variable, which indicates whether contract  $c$  is assigned to vessel  $v$ . Constraint (11) ensures the sum of LNG cargoes deliveries  $N$ , throughout the time horizon, does not exceed the annual regasification terminal capacity. Constraint (12) imposes that the total discharged quantity delivered in  $N$  sequential voyages throughout the time horizon equals the contractual demand  $D$ . Constraint (13) ensures that the duration of a laden voyage from the liquefaction to the regasification terminal does not exceed the delivery deadline, as specified by the contractual terms. Finally, constraint (14) ensures the total duration of vessel operation does not exceed the duration of planning horizon.

### 3.4 Optimisation method

The purpose of the developed model is to provide an optimal LNGC fleet deployment, given specified trade routes between LNG exporting and receiving terminals. In the case of MILP problems, a variety of optimisation methods are applicable to MILP models, such as branch-and-bound, pre-solve and parallelism, cutting planes and heuristic methods, among others. The genetic algorithm (GA) method can be applied to large MILP problems, providing a good approximation of optimal solution in short computational time. However, the generated solutions form a subset of feasible solutions, not the optimal.

In the current study, the process of determining the optimal solution follows a two-step method; initially, the GA solver, available on the MATLAB Optimisation Toolbox, finds local minima for the objective function and its constraints, and then optimal solutions are obtained using contract ranking. The GA address the complexity issue of  $c*v$  dimension matrices that can address a large number of contracts and vessels. After initial calculations are performed, the GA produces the subset of feasible solutions and finally the algorithm proceeds with the ranking of available contracts ranking, to prioritize the trade routes.

Contract ranking criteria are implemented in a priority sequence, starting with the highest priority criterion until all have been met. When a parameter between two or more contracts is equal, then the next ranking criterion is implemented to sort that particular set of contracts, without enforcing any changes to the contracts sorted before. The priority sequence follows three distinct criteria: delivery distance, delivery period and demanded volume. The selection is based on parameters with significant impact on commercial operation of LNGCs. Contracts with shorter route distance are prioritized to reduce fuel consumption during the time charter period. On the occasion two contracts service the same sailing distance, the one with an earlier delivery deadline is prioritised. If delivery deadlines are also identical, the most favorable is the one with smaller demand volume, and thus with a lower impact if it remains unassigned.

**4. Case study**

An application of the proposed DST was conducted with a twofold aim of validating the proposed solution approach, and analysing the impact of various problem parameters on the solution quality. The mathematical model was implemented using MATLAB and computations were performed on a 2.0 gigahertz dual-core processor and 8 gigabyte RAM computer running on Windows 10 environment.

The case study examined a heterogeneous fleet of five vessels available for assignment to an equal number of contracts to service pairs of liquefaction–regasification terminals. The detailed parameters used as input for each scenario are analysed below.

*4.1 Input parameters*

The terminals selected for the case study have some technical characteristics that are critical input parameters for the DST, such as nominal capacity, terminal fees and the LNG loading/ discharging rate for each of the export (liquefaction) and import (regasification) terminals, as depicted in Tables I and II, respectively.

Furthermore, the LNG vessels have specifications that are adequately described in Table III and include the capacity of each LNGC type, the nominal sailing speed and the fuel consumption for each type during a voyage and terminal operations.

The price of each bunker fuel (LNG, HFO and MDO) is different for each trade route. Fuel bunkers are assumed to take place while the LNGC is berthed in the liquefaction terminal, where the LNG export country belongs, and are presented in Table IV.

**Table I.**  
Set of import/  
liquefaction  
terminals of the case  
study

L	Liquefaction terminal	Capacity (MTPA)	$C_{visitL}$ (US\$/day)	$LNG_{RATE}$ (m <sup>3</sup> /h)
1a	Revithousa* (Greece)	5.10	50	2
1b	Qatargas IV (Ras Laffan, Qatar)	7.80	30	13
2b	Sabine Pass (Texas, USA)	18.00	25	14
3b	Ichthys LNG Terminal (W. Australia)	4.45	32	11
4b	Skikda-Azrew (Algeria)	25.30	40	9.8
5b	Egyptian LNG IDKU T1-2 (Egypt)	7.20	45	10.5

**Notes:**\*Although Revithousa LNG is not a liquefaction terminal, it is included in the relevant table as it serves as the import terminal for scenario (a)

**Source:** IGU,(2019), companies' announcements, authors' assumptions

**Table II.**  
Set of export/  
regasification  
terminals of the case  
study

L	Liquefaction terminal	Capacity (MTPA)	$C_{visitR}$ (US\$/day)	$LNG_{RATE}$ (m <sup>3</sup> /h)
1a	Samos FSRU (Greece)	0.019	0	2
2a	Chios FSRU (Greece)	0.031	0	2
3a	Lesvos FSRU (Greece)	0.046	0	2
4a	Limnos FSRU (Greece)	0.008	0	2
1b	Cartagena (Spain)	8.90	33	10.5
2b	Hitachi (Japan)	1.00	26	12
3b	PGPC (Port Qasim, Pakistan)	5.70	32	10
4b	Swinoujscie (N. Poland)	3.60	29	9.8
5b	Gwangyang (S. Korea)	2.30	28	11.8

**Source:** IGU,(2019), companies' announcements, authors' assumptions

Parameter	Small TFDE	Steam turbine	TFDE	Two-stroke-gas injection	
$C_V$	33	145,000	174,000	173,400	$m^3$
$S_V$	16	18.3	19.3	19.5	kn
$TCh$	1,460,000	4,220,000	4,440,000	4,320,000	\$/year
$FCS\_HFO$	60.48	0.85 (Laden) 0.49 (Ballast)	0.95 (Laden) 0.74 (Ballast)	0.84 (Laden) 0.47 (Ballast)	tonnes/h
$FCS\_LNG$	40.32	83.55 (Laden) 48.51 (Ballast)	94.05 (Laden) 57.02 (Ballast)	82.76 (Laden) 46.13 (Ballast)	tonnes/h
$FCT\_LNG$	1.29	3.3	3.9	3.2	tonnes/h
$FCT\_MDO$	0.3	0.2	1.8	4.1	tonnes/h

Sources: Zetos *et al.* (2018); Kissas *et al.* (2019)

**Table III.**  
LNGC data for the  
case study

C	Country – region	Liquefaction terminal	$C_{LNG}$ (US\$/tonne)	$C_{HFO}$ (US\$/tonne)	$C_{MDO}$ (US\$/tonne)
1a	Greece – Europe	Revithousa	380	372	535
1b	USA – Americas	Cove Point	333	390	595
2b	Russia – Asia	Sakhalin 2	405	410	575
3b	Qatar – Middle East	Qatargas IV	381	390	715
4b	Australia – Pacific	Ichthys LNG	405	410	575
5b	Egypt – Middle East	Egyptian LNG IDKU	381	390	715

Sources: Energy Information Administration(2019); Ship and Bunker(2019)

**Table IV.**  
LNG, HFO and MDO  
prices by relevant  
liquefaction  
terminals

For the evaluation of the distance from every single liquefaction terminal ( $L$ ), information is acquired by the *Voyage Planner* programme of the commercial site *MarineTraffic*. Based on the projected sailing plan, the trade routes that include canal passage are Cove Point (USA)–Gwangyang (S. Korea), through the Panama Canal, and Qatargas IV (Qatar)–Swinoujskie (Poland), through the Suez Canal. Finally, the contractual demanded quantities and the delivery deadlines are provided. The aforementioned parameters are summarized in [Table V](#).

#### 4.2 Results and discussion

This subsection presents the results produced by the DST for the scenario of the case study. The optimisation method described in Section 3.4 is applied to the five available vessels to trade LNG between five export/liquefaction and five import/regasification terminals. The DST performed computations with  $c^*v$  matrices (for each combination of contracts and vessels) to generate the optimum results in terms of required voyages, durations of delivery phases and initial transition and the quantitative parameters of LNG cargo loaded/discharged. As a result, all the ships of the fleet LNGCs are assigned to the examined terminals, each servicing one contract.

The optimal solution to the contract assignment problem for the heterogeneous fleet is presented with the graphical representation captured from the screen of the DST

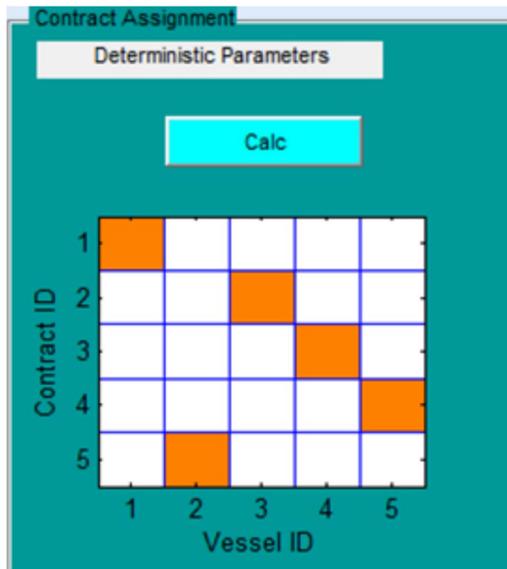
and displayed in Figure 1. Highlighted cells for which the decision variable  $x_{c,v}$  assumes the value 1 denote the contract identified by a specific number and the assigned vessel. Thus, the result of the fleet assignment is given to the user of the DST in a simple and comprehensible form. In parallel, the total operational cost of the heterogeneous fleet for the proposed deployment on the specified trade routes and under the relevant contractual terms is calculated for each vessel separately and as a total. The vector with the operational cost for each vessel (in \$ per year) is [17,507,000 | 16,788,000 | 10,793,000 | 8,417,600 | 10,276,000] and that for the whole fleet is 63,781,600.

Finally, the annual sailing schedule for each vessel also produced as a vector with the operation time for each vessel in days per year is [364 | 107 | 194 | 196 | 109]. The days refer to the total sailing and loading/discharging time for each vessel servicing the specific contractual terms. Vessels 2-5 all have periodic intervals of idle time, during which the owner can schedule maintenance works or inform the charterer beforehand to offer the

**Table V.**  
Contractual demand  
and delivery  
deadlines

c	$D(c)$ (m <sup>3</sup> LNG/year)	$T_{\text{DELIVERY}(c)}$ (days)
1a	328	30
1b	870	18
2b	825	21
3b	760	16
4b	940	24
5b	910	29

Source: Authors' assumptions



**Figure 1.**  
Optimal contract  
assignment to  
heterogeneous fleet

vessel for spot cargoes. Only Vessel 1 has a full schedule throughout the yearly time horizon. The schedule is presented to the user in the form of a bar chart as depicted in Figure 2.

## 5. Conclusion

In this paper, a real-life problem for the optimisation of LNG supply chains stimulated the formulation of a DST. The tool was designed to include as input data a variety of technical parameters regarding the export/liquefaction and import/regasification terminals and the vessels. All those components of the midstream LNG supply chain may be combined in numerous configurations under specific constraints imposed to the objective function, at the core of the mathematical model.

The case study presented in the current paper has validated the functionality of the proposed model with the use of realistic input data. As demonstrated, the DST is able to provide an optimal deployment solution to a tramp shipping company that operates LNGCs under long-term contracts, minimizing operational expenses in the form of contract assignment to each vessel in the fleet.

Specifically, the results demonstrated the deployment of the fleet on specific trade routes providing the minimum total operational cost. Thus, the DST fulfilled its ambition to support the tactical planning of midstream LNG supply chain, with its results being available to the shipowner to evaluate options for his fleet. The owner may then offer a competitive charter rate for each vessel aligned with its total cost.

For the case study scenario, a heterogeneous fleet is available to service one-year time charter contracts and transport LNG cargoes to meet contractual demand. Five contracts were available for assignment to a heterogeneous fleet of one steam turbine, two TFDE and two two-stroke gas injection vessels operating on trade routes between worldwide liquefaction and regasification terminals. The vessels differ in terms of technical and operational features, such as capacity, service speed, fuel consumption and fixed operational costs.

Except for the validity of its results, the developed DST should be evaluated with respect to the computational time required to produce them. For the case study scenario the proposed model obtained results in 37 s, whereas larger scale calculations may require significant time.

More extensions to the proposed DST are being considered for further research. One issue critical to LNG shipping is the consideration of delivery time windows and the introduction of penalty fees, which may be incorporated in the mathematical model. Additionally, a more complex simulation of the BOG phenomenon, considering BOG percentage variations provided the vessel's containment system and route's environmental conditions can be considered. Moreover, further research can be conducted on formulating the problem as a stochastic mixed integer problem, with the LNG price being a stochastic parameter. Finally, an extension of the model's mathematical formulation could include further operational considerations, such as the operational time windows for LNGCs with membrane tanks, thus enhancing further model's robustness.

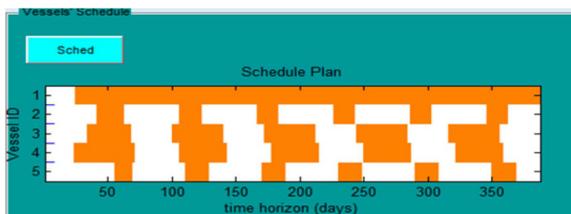


Figure 2.  
Heterogeneous fleet  
schedule plan

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