Transportation Research Part E 99 (2017) 96–114

Contents lists available at ScienceDirect

Transportation Research Part E

journal homepage: www.elsevier.com/locate/tre

The liquefied natural gas infrastructure and tanker fleet sizing problem

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A R T I C L E I N F O

Article history:
Received 9 August 2016
Received in revised form 18 November 2016
Accepted 5 January 2017

Keywords:
Maritime infrastructure planning
Tanker fleet sizing
Ship routing
Liquefied natural gas as fuel in liner shipping
Mixed integer programming

A B S T R A C T

We consider a strategic infrastructure and tanker fleet sizing problem in the liquefied natural gas business. The goal is to minimize long-term on-shore infrastructure and tanker investment cost combined with interrelated expected cost for operating the tanker fleet. A non-linear arc-based model and an exact solution method based on a set-partitioning formulation are developed. The latter approach allows very fast solution times. Computational results for a case study with a liner shipping company are presented, including an extensive sensitivity analysis to account for limited predictability of key parameter values, to analyze the solutions' robustness and to derive basic decision rules.

1. Introduction

In 2008 the International Maritime Organization (IMO), a specialized agency of the United Nations, has introduced new regulations for the prevention of pollution from ships that aim at reducing the emission of sulphur oxides, amongst others (International Maritime Organization, 2008). The regulations already apply in so-called *Emission Control Areas* (ECA) since 2015 and in late 2016 the IMO confirmed that the low-sulphur fuel oil requirements will become binding globally in 2020. Currently the majority of ships (80–85%, Chryssakis et al., 2014), including container vessels, are run on heavy fuel oil (HFO). As a consequence of the new limits on sulphur emissions, many of today's ships will no longer be able to operate as of today, because emissions due to the use of HFO exceed the limits.

In various industrial strategic papers and research studies (see e.g. Andersen et al., 2013; Rozmarynowska and Oldakowski, 2012; Chryssakis et al., 2014) three viable solutions to meet the new requirements have been identified. The first one are exhaust gas aftertreatment systems as e.g. scrubbers. The installation of scrubbers, however, is costly and requires additional space on the ship. Further, they can increase the fuel consumption of a vessel by 2–3% (Chryssakis et al., 2014). The second and most straightforward solution is the use of cleaner marine diesel oil (MDO) or marine gas oil (MGO), as these can usually be used without the need of any modification to the vessels. MDO and MGO are, however, about 1.5–2.0 times more expensive than HFO, with prices expected to increase even further once the sulphur emission limits apply globally. The third solution is the one that motivates our study and considers liquefied natural gas (LNG) as an alter-

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http://dx.doi.org/10.1016/j.tre.2017.01.003
1366-5545/

native fuel. LNG is natural gas that is converted to liquid form by cooling it down to approximately $-162\,^{\circ}C$ ($-260\,^{\circ}F$). It is the cleanest form of fossil fuels and if used to fuel ships, no further measures are needed to satisfy the new regulations concerning the emission of pollutants. As prices are expected to be lower than those for other low-sulfur fuels in the future, LNG is considered a realistic option for deep sea trades in the long term, particularly for liner trades (Lloyd's Register, 2012). However, it requires newbuild vessels as well as additional LNG infrastructure at the ports.

Liner shipping networks consist of cyclic shipping routes, called *services*, that are operated periodically. Fig. 1 shows an example liner shipping service that connects Asia and Europe. The individual services are connected through ports, where cargo can be transshipped between different services, and thus provide an extensive, wide-ranging transportation network. Typically each port on a service will be visited once per week and the container liner company publishes the weekly berthing time for each port. As a single round trip can take several weeks, each service is operated by a corresponding number of container vessels. The structure and way of operating container shipping networks is very similar to that of buses in public transport, with the containers being the equivalent of passengers. For an introduction to liner shipping see e.g. Stopford (2009).

The current lack of LNG infrastructure for marine bunkering and the uncertainty about future availability is a major drawback of using LNG as a fuel for liner shipping companies. This work is motivated by and based on a case study with a major liner shipping company that considers filling that gap by building up and operating the needed infrastructure by themselves. The study forms the basis of a future scenario in which the company uses LNG fueled container vessels on some of their services.

The liner shipping company is responsible for the transport of LNG to predetermined ports where container vessels will refuel. The transport is done via sea using special purpose LNG tankers. The tanker fleet needs to be ordered or long-term chartered by the company. Furthermore, the infrastructure at the majority of the ports of demand will be built and run by the liner shipping company. The problem is of strategic nature with a time horizon of 2–15 years and combines strategic infrastructure and tanker investment decisions with tactical tanker routing and inventory management decisions. The lack of existing infrastructure allows to simultaneously optimize strategic investment decisions and interdependent tactical decisions.

Strategic infrastructure planning and tactical planning of operations have traditionally been looked at separately in the maritime sector. For tactical and operational problems, the infrastructure and the fleet of vehicles is usually fixed to a large extent. Furthermore, strategic decisions often do not solely depend on quantifiable parameters but are subject to many qualitative arguments (legal issues, local regulations, political decisions, etc). This work aims at providing decision rules of thumb and identifying important relationships between operational/tactical and strategic decisions for the problem studied. The presented models also allow to evaluate manually developed solutions and their sensitivity to changes in input parameters. Hence, an important requirement of our industrial collaborator towards the solution method are fast running times that allow to evaluate large numbers of different scenarios within reasonable time. A second challenge was the requirement towards the solution approach to handle non-linear cost functions that can easily be replaced when better cost estimating functions are obtained during the planning phase.

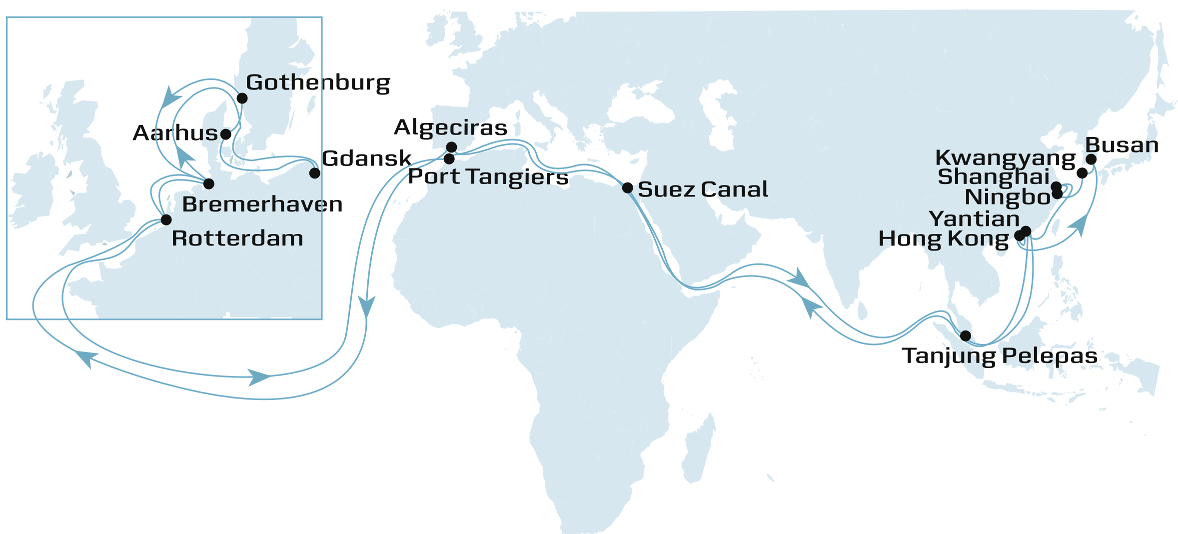

Fig. 1. Example of a liner shipping service between Asia and Europe. The whole round trip takes 12 weeks and hence 12 vessels are operating on the service to ensure a weekly frequency.