Transportation Research Part C 69 (2016) 79–90

Contents lists available at ScienceDirect

Transportation Research Part C

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

Optimal planning of liquefied natural gas deliveries

Sara Al-Haidous, Mohamed Kais Msakni, Mohamed Haouari *

Mechanical and Industrial Engineering Department, Qatar University, Doha, Qatar

ARTICLE INFO

Article history:
Received 8 February 2016
Received in revised form 23 May 2016
Accepted 23 May 2016
Available online 3 June 2016

Keywords:
Maritime transportation
LNG supply chain
Annual delivery plan
Arc-flow models

ABSTRACT

We investigate the problem of designing an optimal annual delivery plan for Liquefied Natural Gas (LNG). This problem requires determining the long-term cargo delivery dates and the assignment of vessels to the cargoes while accommodating several constraints, including berth availability, liquefaction terminal inventory, planned maintenance, and bunkering requirements. We describe a novel mixed-integer programming formulation that captures important industry requirements and constraints with the objective of minimizing the vessel fleet size. A peculiar property of the proposed formulation is that it includes a polynomial number of variables and constraints and is, in our experience, computationally tractable for large problem instances using a commercial solver. Extensive computational runs demonstrate the efficacy of the proposed model for real instances provided by a major energy company that involve up to 118 cargoes and a 373-day planning horizon.

1. Introduction

As the world energy demand is steadily increasing, mainly boosted by the emerging economies in BRICS and other fast growing markets, the quest for new sources of energy has become more crucial than ever. In this context, natural gas (NG) has emerged as an attractive source of energy. Actually, its share of the total energy market is growing at an impressive pace. Indeed, during the last three decades, the ratio of the world demand of NG to the world demand of oil grew from 45% to 70% (Yergin, 2012, p. 343). One of the main reasons of this impressive growth is that NG exhibits the property to be cleaner than other fossil energy such as oil and coal. As a matter-of-fact, natural gas is half as polluting as coal for power generation (Total, 2015), thus making it an attractive source of energy in the current context of increasing concern about serious global warming issues. However, although NG has been used as a combustible for many centuries (in Szechuan, China, natural gas was extracted before 400 B.C. and the start of the Han Dynasty (Orsay et al., 2008)), its global widespread had long been crippled by several technical, economical, and political issues related to its transportation and distribution over long-distance pipelines. Actually, the emergence of NG as a new supply source is mainly due to the rapid development of the so-called liquefied natural gas (LNG) that is obtained by condensing natural gas by cooling it to approximately −162 °C (−260 °F). In so doing, LNG takes up about 0.16% the volume of natural gas in the gaseous state and therefore becomes cost efficient to transport over long distances using specially designed cryogenic double-hulled ships. These ships use spherical tanks and are designed to prevent leakage in case of an accident. Hence, the development of the LNG technology made it possible to easily supply natural gas to remote markets worldwide. To match the supply with a rapid growing demand, the LNG industry has developed complex supply chains that include plants, storage facilities, specialized berth facilities, as well as large LNG vessel fleets. The efficient design and management of these supply chains poses many challenging optimization issues. The importance of these issues is largely motivated by the huge investment and operating costs that are typical of this industry.

* Corresponding author.
E-mail address: mohamed.haouari@qu.edu.qa (M. Haouari).

http://dx.doi.org/10.1016/j.trc.2016.05.017

This paper aims at describing a novel model for optimizing the LNG delivery process which is a specific case of maritime transportation planning. The interest in maritime transportation planning has witnessed an impressive growth since the publication in 1983 of the first review paper dedicated to this topic (Ronen, 1983). We refer to the state-of-the-art survey by Christiansen et al. (2007) for a comprehensive description of OR models and approaches for planning problems arising in maritime transportation. In this excellent survey, 119 papers dealing with strategic, tactical, and operational models are thoroughly analyzed. Recently, an updated survey was published by Christiansen et al. (2013) in which the authors analyzed over a hundred papers dealing with ship routing and scheduling that were mostly published during the last decade. In addition to these general surveys, and prompted by the ever-increasing interest for optimization models for maritime transportation, several more focused survey papers were recently published. In particular, Pantuso et al. (2014) analyzed the body of literature pertaining to ship fleet size and mix issues. Furthermore, many authors investigated maritime transportation problems that are related to the LNG supply chain decisions. In this regard, Andersson et al. (2010) studied the LNG supply chain from the natural gas extraction stage until the end-customers stage. The authors investigated two problems: the former arises for a producer, and the latter for a vertically integrated company. They mainly focused on making shipping decisions while integrating inventory management decisions at the loading and unloading terminals. For each problem, they proposed a mathematical programming model and briefly sketched solution methods. However, no computational results were provided. Grønhaug and Christiansen (2009) considered the LNG Inventory Routing Problem (LNG-IRP) where there are multiple loading ports, and where it is possible for one vessel to visit multiple unloading ports during one voyage. They described both arc- and path-flow models. This latter was subsequently used in Grønhaug et al. (2010) to develop a branch-and-price algorithm. Computational results of both studies were reported for small-sized instances with restricted number of vessels, ports and planning horizon. Recently, Andersson et al. (2015) proposed a new formulation for the LNG-IRP initially studied by Grønhaug and Christiansen (2009). This formulation was solved using a new decomposition scheme within a branch-and-cut framework. The authors presented the results of computational experiments showing that the proposed approach provides optimal or near-optimal solutions within 10-h CPU time limit and outperforms the previous methods. Goel et al. (2012) developed an arc-flow formulation for the LNG-IRP where the objective is to optimize ship schedule decisions. They also proposed both construction and improvement heuristics. Later, Goel et al. (2015) developed a constraint programming model and an iterative search heuristic that was found to outperform the results in Goel et al. (2012). In addition, Shao et al. (2015) studied a similar problem and developed a set of heuristics.

An important tactical problem that is faced by LNG producers requires designing an optimal Annual Delivery Plan (ADP). This problem requires to determine the long-term cargo delivery dates and the assignment of the cargoes to the vessels, while accommodating several technical constraints. The issue of constructing a cost-effective ADP was addressed by Rakke et al. (2011) who presented a compact mixed-integer programming model while considering the opportunity of selling the LNG in the spot market. For large scale problems, the authors proposed a rolling horizon heuristic that breaks down the original problem into sub-problems with a restricted time horizon. The same problem was also studied by Stålhane et al. (2012). They proposed a heuristic approach that starts by constructing a set of initial solutions that are subsequently improved by applying different neighborhood operators. A second approach was later proposed by Rakke et al. (2014) and is based on delivery patterns and a branch-price-and-cut algorithm. Halvorsen-Weare and Fagerholt (2013) proposed a decomposition-based heuristic method. The first step considers the original problem without the berth and inventory level constraints. The objective is to find the routing of each vessel in such a way that all cargoes are serviced and the costs are minimized. The second step, called feasibility scheduling problem, uses the solution of the first step to find the starting dates to service the cargoes while considering the berth capacity and inventory level constraints. Recently, Mutlu et al. (2016) proposed a mixed-integer programming model to design an ADP that considers the possibility of achieving split deliveries. A heuristic solution method was developed and shown to yield good solutions within a short CPU time.

Furthermore, we mention that, in contrast to previous studies, Ghiami et al. (2015) considered the *inland* distribution of LNG. They investigated a sophisticated routing model with deteriorating inventory, and proposed both arc- and path-flow formulations.

In this paper, we investigate a real LNG distribution problem that arises at the world's largest LNG producer and that requires designing an optimal Annual Delivery Plan (ADP). Our main contribution is the development of a novel mixed-integer programming formulation for this problem while accommodating several realistic constraints. The proposed formulation is compact and enables, in our experience, optimal solutions to large-scale realistic instances using a general-purpose solver without resorting to sophisticated branch-and-price or branch-and-cut algorithms. We provide evidence that this formulation can be used for solving large-scale real-world instances.

The remainder of this paper is organized as follows. Section 2 presents a description of the investigated problem together with an overview of the LNG supply chain. Section 3 describes the underlying graph as well as the proposed compact mixed-integer programming model for building an ADP for LNG. Section 4 includes the results of extensive numerical experiments that were carried out on a set of real data. Finally, Section 5 provides some concluding remarks and outlines future research directions.

2. Problem description

The efficient supply of LNG is achieved through a supply chain that includes the following stages. First, onshore (or offshore) facilities are used to extract natural gas from the well. Usually, the extracted gas includes mostly methane,