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Short-term planning of liquefied natural gas deliveries

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ABSTRACT

The ability of a supplier of liquefied natural gas (LNG) to deliver cargoes at desired times, while effectively managing a fleet of cryogenic vessels can significantly impact its profits. We investigate in this paper an LNG short-term delivery planning problem by considering mandatory cargoes as well as optional cargoes to select, along with the scheduling of a heterogeneous vessel fleet with controllable cruising speeds. Several technical constraints are accommodated including time windows, berth availability, bunkering restrictions, inventory, liquefaction terminal storage capacity, maximum waiting time, and planned maintenance restrictions. The objective is to maximize the net profit.

We propose a mixed-integer programming formulation that includes a polynomial number of variables and constraints and accommodates all of the problem features. Also, we describe an optimization-based variable neighborhood search procedure that embeds the proposed compact formulation. To assess the quality of the generated solutions, we propose a second valid formulation with an exponential number of decision variables and we solve its linear programming relaxation using column generation. We provide the results of extensive computational results that were carried out on a set of large-scale set of realistic instances, with up to 62 vessels and 160 cargoes, provided by a major LNG producer. These results provide evidence that the proposed improvement procedure yields high-quality solutions.

1. Introduction

The last few years have witnessed remarkable advances in liquefied natural gas (LNG) processing and distribution technologies that have tremendously stimulated new prospects for reliable energy supplies at affordable prices. As a consequence, the number of LNG consuming countries has increased from 15 in 2005 to 39 in 2017 (IEA, 2017). Interestingly, natural gas is the only fossil fuel whose share of primary energy consumption is projected to grow. Indeed, the International Energy Agency has recently estimated that natural gas demand is expected to grow worldwide from 3630 billion cubic meters (bcm) in 2016 to 4000 bcm by 2022. For some emerging economies, the growth is even more impressive. For instance, China will account for 40% of the global growth, as its consumption of natural gas is forecast to grow at an annual rate of 8.1% from 2015 to 2030 (Asia Times, 2017). One reason of this ever-growing interest for natural gas stems from the fact that this latter is considered as the cleanest fossil fuel. This environmental advantage is illustrated by Table 1 where the emission levels of natural gas, oil, and coal are displayed.

We see from this table, that natural gas emissions of nitrogen oxides, sulfur dioxides, and particulates are incomparably smaller than those caused by oil and coal, respectively. These noxious air pollutants cause numerous cardiovascular and pulmonary diseases that are responsible for millions of premature deaths worldwide. In this regard, Health Effects Institute (2017) states that extensive, long-term exposure to fine particulate matter was the fifth most important risk factor for death and contributed to more than four

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Table 1
Fossil fuel emission levels (pounds per billion Btu of energy input).
Source: NaturalGas.org (2013).

Pollutant	Natural Gas	Oil	Coal
Nitrogen oxides	92	448	457
Sulfur dioxide	1	1122	2591
Particulates	7	84	2744

million premature deaths in 2015 (about half out these deaths occurred in India and China). In this regard, fine particles are considered as one of the great killers of our modern age. Indeed, in the same year, AIDS, tuberculosis, and malaria jointly caused three million deaths (Landrigan, 2017).

This evolution of the role of natural gas (NG) in the global energy market has prompted the energy industry to set-up complex multi-billion supply chains that aim at ensuring timely worldwide LNG deliveries at the required amount and at the cheapest cost. Typically, an LNG supply chain includes the following four main stages: (i) Exploration and extraction; (ii) Processing and liquefaction, where natural gas is cooled to $-162\,^{\circ}\mathrm{C}$ and thereby its volume reduced by a factor of approximately 600; (iii) Shipping, where LNG is transported in liquid state using cryogenic vessels, and (iv) Regasification and distribution, where LNG is converted back to its gaseous state and distributed to end-users.

The design, operation, and control of these stages pose serious challenges to the operations research community. Papers in this area cover the three standard decision levels: strategic, tactical, and operational. The strategic level focuses on the long-term planning of facilities, vessel fleet, and infrastructure, and also on setting-up long-term agreements that involve the periodic delivery of LNG over long periods of time (typically, 20–25 years). The tactical (mid-term) level focus on designing an Annual Delivery Plan (ADP) that specifies the amounts to be delivered along with a feasible delivery schedule with the aim of fulfilling the long-term (mandatory) contracts at minimum operational costs. The operational (short-term) planning stage aims at building a detailed delivery plan that takes into account the ADP while integrating opportunities of selling additional amounts of LNG in the spot market. Typically, the time horizon of an operational plan is three months.

In this regard, Koza et al. (2017) investigated a strategic problem arising in the LNG supply chain. The authors studied an infrastructure expansion problem for a liner shipping company that contemplates using LNG as a fuel for its fleet of vessels. Different components have to be determined: the cost of building LNG storage ports in different locations in Asia and Europe, the capacity of storage ports, and the fleet of LNG vessels (owned or chartered) to transport the LNG from the producer to the storage ports. The feasibility of an infrastructure alternative is studied by solving a tactical problem of inventory management and vessel routing, where the objective is to minimize the annual investment and operational costs.

However, it is noteworthy that a predominant fraction of the literature dealing with the optimization of the LNG supply chain is focused on tactical problems that require building an Annual Delivery Plan (ADP), where the horizon typically spans 12 months. The pioneering work of Grønhaug and Christiansen (2009) describes the LNG supply chain from the extraction of NG to the regasification and storage at the customer side. The paper mainly focused on the vessel routing and inventory control aspects of the problem. In this study, the company controls a fleet of vessels that can be supplied at multiple liquefaction ports. In Goel et al. (2012), similar assumptions were considered in addition to the berth capacity at the liquefaction port. However, partial unloading was not allowed and therefore the vessels were restricted to visit only one regasification terminal when delivering the LNG. Halvorsen-Weare and Fagerholt (2013) included the compatibility between vessels and ports, and the possibility to deliver a customer earlier or later than the agreed time window but at the cost of paying an additional penalty. Furthermore, Rakke et al. (2011) considered the vessel unavailability that may occur when vessels are either on their way to the loading port at the start of the planning horizon, or for the purpose of preventive maintenance. Mutlu et al. (2016) studied a similar problem variant with the additional possibility of making split deliveries. Al-Haidous et al. (2016) addressed the particular case of delivering LNG by a homogeneous fleet of vessels and where the objective is to minimize the number of vessels. The paper made the same problem assumptions as in Rakke et al. (2011), and included bunkering restrictions. It is noteworthy, that all the aforementioned papers proposed mixed-integer programming formulations to model the different variants. However, all these models, but one, fail to solve large and practical problem sizes. Indeed, Al-Haidous et al. (2016) developed a compact formulation that can solve real problem sizes with a general purpose solver. On the other hand, many heuristic algorithms and sophisticated optimization techniques have been proposed to build effective annual delivery plans. In this context, Grønhaug et al. (2010) developed a branch-and-price algorithm. Andersson et al. (2015) and Andersson et al. (2015) presented branch-and-cut algorithms. Rakke et al. (2015) proposed a combination of these two techniques to derive a branch-price-and-cut framework. Goel et al. (2015) developed a constraint programming model. Furthermore, Andersson et al. (2010), Stålhane et al. (2012), Goel et al. (2012), Mutlu et al. (2016) implemented different heuristic method strategies. Rakke et al. (2011) suggested a rolling horizon algorithm and Halvorsen-Weare and Fagerholt (2013) proposed a decomposition technique.

Despite its relevance to LNG producers, short-term planning has not received as much importance as the long-term planning. In this regard, the only paper that we are aware of and that addresses the operational level of the LNG supply chain is the one of Nikhalat-Jahromi et al. (2016). In this paper, the problem is to supply long-term contracted customers with the possibility of considering different cargo delivery arrangements, and taking advantage of selling the extra LNG production in the spot market for a planning time horizon of three months. The objective is to maximize the profit for the LNG producer by considering the price variations between the different markets. The problem is formulated using a mixed-integer programming model that accommodates