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A hybrid heuristic strategy for liquefied natural gas inventory routing

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ABSTRACT

As liquefied natural gas (LNG) steadily grows to be a common mode for commercializing natural gas, LNG supply chain optimization is becoming a key technology for gas companies to maintain competitiveness. This paper develops methods for improving the solutions for a previously stated form of an LNG inventory routing problem (LNG-IRP). Motivated by the poor performance of a Dantzig-Wolfe-based decomposition approach for exact solutions, we develop a suite of advanced heuristic techniques and propose a hybrid heuristic strategy aiming to achieve improved solutions in shorter computational time. The heuristics include two phases: the advanced construction phase is based on a rolling time algorithm and a greedy randomized adaptive search procedure (GRASP); and the solution improvement phase is a series of novel MIP-based neighborhood search techniques. The proposed algorithms are evaluated based on a set of realistic large-scale instances seen in recent literature. Extensive computational results indicate that the hybrid heuristic strategy is able to obtain optimal or near optimal feasible solutions substantially faster than commercial optimization software and also the previously proposed heuristic methods.

1. Introduction

As liquefied natural gas (LNG) steadily grows to be a common mode for commercializing natural gas, LNG supply chain optimization is becoming key for gas companies to maintain competitiveness in the market. The LNG supply chain includes one or multiple production terminals where natural gas is produced, liquefied into LNG, and stored temporarily; a specialized ship fleet that loads and delivers LNG; and a set of regasification terminals where LNG is unloaded, stored temporarily, regasified and shipped to customers through pipelines.

In the LNG business, an annual delivery schedule is agreed upon in advance by the LNG buyer and LNG producer every year. This annual delivery schedule is negotiated to best accommodate the expected requirements of each party for the planned year. The finalized schedule dictates when each cargo is to be delivered and by what ship. Developing an optimized annual delivery schedule can be highly impactful in optimizing the economics of an LNG project; moreover, it can also serve a key purpose from a supply chain design standpoint. Specifically, an optimized schedule for a given supply chain design can

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be used to evaluate the throughput and efficacy of that design. Because of the capital intensive nature of LNG projects, the optimal design of LNG supply chain is extremely important from a profitability perspective. In this paper, we address an LNG inventory routing problem where optimized ship schedules are developed for analyzing LNG supply chain design decisions.

In the research field of maritime transportation, most of the literature focuses on ship routing and scheduling problems (see Ronen, 1983, 1993; Christiansen et al., 2004, 2007). The problem being considered here is similar to the more complex class of problems known as maritime inventory routing problems (MIRP). MIRP combines inventory management and ship routing, which are typically treated separately in industrial practice. A basic maritime inventory routing problem (see Christiansen and Fagerholt, 2009) involves the transportation of a single product from loading ports to unloading ports, with each port having a given inventory storage capacity, a pre-specified production or consumption rate, a restriction on the number of visits to the port, and a limitation on the quantity of product to be loaded or unloaded. A recent survey of the state-of-the-art in ship routing and scheduling research over the last decade is given by Christiansen et al. (2013).

LNG inventory routing can be considered as a special case of the MIRP. An excellent overview of the business cases and common characteristics for LNG inventory routing can be seen in Andersson et al. (2010). The LNG inventory routing problem shares the fundamental properties of a single product MIRP with special features such as variable production and consumption rates, LNG specific contractual obligations, and berth constraints. The LNG-IRP seeks to generate schedules where each ship may make several voyages over a much longer time horizon than typically seen in the literature. While a rich model was proposed by Fodstad et al. (2011) for coordinating vessel routing, inventories and trade in LNG supply chain, Rakke et al. (2011) appears to be the first MIRP to address problems of developing annual delivery schedules for large LNG projects. Stalhane et al. (2012a) developed a construction and improvement heuristic combining greedy insertions, neighborhood searches and branch and bound scheme for large-scale LNG-IRP. Halvorsen-Weare and Fagerholt (2013) created a heuristic scheme in which LNG-IRP was decomposed by routing problems of individual ships. Halvorsen-Weare et al. (2013) have recently studied the introduction of robustness strategies in routing and scheduling methods for LNG-IRP.

In this paper, we develop a suite of heuristic methods and propose a hybrid heuristic strategy to improve solutions for the LNG-IRP model proposed by Goel et al. (2012), which is based on the arc-flow formulation for maritime inventory routing model introduced by Song and Furman (2013). The heuristic methods for LNG-IRP presented by Goel et al. (2012) were primarily based on large neighborhood search heuristics (see Ahuja et al., 2002 for a general review). In this paper, several new heuristics for both constructing initial solutions and improving incumbent solutions are developed to solve this model more efficiently. These new construction heuristics are based on a rolling time method with a commercial MIP solver as the black-box tool and a greedy randomized adaptive search procedure (GRASP) with a specifically designed candidate list structure for LNG-IRP.

The rolling time method is designed to solve problems with a long time horizon via a sequence of subproblems, each of which is simplified to only consider a smaller time block with limited information of future time periods. It was first proposed by Baker (1977) for manufacturing scheduling problems, and it has shown success when applied to MIRP by Sherali et al. (1999), Bredström and Rönnqvist (2006), Al-Khayyal and Hwang (2007), Rakke et al. (2011), Siswanto et al. (2011) and Agra et al. (2014).

GRASP was first introduced to solve combinatorial problems by Feo and Resende (1989). It typically consists of iterations that include a construction of a greedy randomized solution and a local search to further improve the initial solution. This algorithm has been applied successfully to many fields including routing (Kontoravdis and Bard, 1995). Unlike typical GRASP methods, our approach does not employ adaptive rules because our current algorithm setting is good enough for the instances that we tested.

Rolling time and greedy randomized solution methods might outperform each other in different instances given the diversity in their mechanisms for finding solutions. In our heuristic strategy, both methods are developed to construct a pool of feasible solutions. Among the solutions generated, the best one is further improved by applying a combination of local search methods which, when compared to complicated neighborhood structures, are simple yet effective and efficient. Agra et al. (2014) also proposed hybrid heuristics for a short sea IRP that has different properties than the LNG-IRP that we consider here. In their methods, the rolling horizon, local branching and feasibility pump are combined together to get a feasible solution, which is reported as the final solution without further improvements.

We also developed a Dantzig-Wolfe decomposition approach with the hope that it would tighten the lower bound or improve the upper bound. However, it fails to discover any integer solutions, and the improvement on the lower bound is also marginal. The failure of this exact method will be briefly presented in this paper to illustrate the complexity of LNG-IRP and to demonstrate the necessity and value of our hybrid heuristic system.

The main contribution of this paper is the novel hybrid heuristic strategy, which can be easily adapted for MIRP in general, and the demonstration that a proper combination of simple neighborhood search structures can outperform sophisticated neighborhood search structures.

The remainder of the paper is organized as follows: Section 2 gives a brief problem description; Section 3 addresses the model and formulation which are identical to those present in Goel et al. (2012); Section 4 briefly describes the motivating decomposition procedure aiming to obtain good lower bounds; Section 5 presents the hybrid heuristic strategy for getting near-optimal solutions; Section 6 analyzes computational results; and Section 7 summarizes the accomplished work.