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Optimization of a small-scale LNG supply chain

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ABSTRACT

Due to an increased interest in small to medium scale liquefied natural gas (LNG) use, a mathematical model has been developed to aid the decision making on tactical aspects in the design of such LNG logistic chains. The focus of the work is on inter-terminal maritime transportation between a set of supply ports and a set of sparsely distributed receiving ports with given demands. Similar problems have been largely studied in literature, but our approach differs in including simultaneously load splitting features, multi depots and a multiple journeys between ports on the same route. The model, which considers the LNG distribution by a heterogeneous fleet of ships, applies mixed integer linear programming to find the supply chain structure that minimizes costs associated with fuel procurement. A case study illustrating the features of the model is presented, where a base case is initially solved. An extensive sensitivity analysis is presented which demonstrates how the optimal solution evolves under different conditions (i.e. LNG price in the supply ports, time horizon and berthing time). A preliminary attempt to tackle uncertainty in the demand is also made. Finally, the performance of the model on a set of larger problems is reported, demonstrating its efficiency.

1. Introduction

According to the future scenarios presented by IEA, the demand of natural gas will witness the fastest growth rate among the fossil fuels. The global energy demand is expected to grow by 37% to 2040, at an average rate of 1.1% [1]. In this future scenario, fossil fuels will account for 55% of power generation with gas-firing taking over the dominant position from coal- and oil-firing [2]. The natural gas demand is expected to reach 5.4 trillion cubic meter in 2040, accounting for almost one fourth in the energy mix supply, and becoming the second largest energy source after oil [3].

The growing natural gas market requires huge investments in the gas supply chain. Investments in this field are particular capital-intensive due to the gaseous nature of the fuel, which makes its handling, transportation and storage much more expensive. Traditionally, natural gas has been transported from gas fields to consumers through pipelines in gaseous form. Pipeline transportation is a well-established technology and a relatively economical solution for short land distances, but when distances between supply and consumers are large or overseas, a more economical solution is to transport it as liquefied natural gas (LNG). In liquid form, the volume of natural gas is reduced 600 times making transportation and storage of large quantities easier. LNG, which is produced by cooling natural gas below −162 °C (at atmospheric pressure), can be transported by truck or by ship, with the second being preferable for longer distances and larger amounts. In the maritime transportation, LNG is shipped by specially designed insulated vessels capable of maintaining the fuel at the liquid state while travelling from liquefaction plants to consumers. Considering the high investment costs of infrastructure and operation, the LNG supply chain is often a large-scale one with vessels and storages at the receiving terminals of average capacity of 150,000 m^3. In recent years, as the use of natural gas has grown in popularity, LNG has become an interesting option also for small- to medium-scale supply chains [4,5]. Some examples can be found in Norway and in Japan, where small-scale supply chains satisfy the need of local consumers, such as power companies and chemical industry. Furthermore, the emission restrictions on maritime transportation imposed by the International Maritime Organization (IMO) in various areas of the world favor the use of LNG also as a cleaner propulsion fuel for vessels [6]. In a small-scale supply chain natural gas can be shipped from a large import terminal to consumers through a network of smaller satellite terminals with a combination of sea- and land-based transports. LNG carriers used in this type of systems have smaller capacities and can perform multistep voyages. The design of the optimum fleet composition

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(size and number of ships) and associated routing is a challenging strategic decision in the supply chain optimization. The large capital investments related to the fleet acquisition and operation make this a relevant problem for the operators involved in the LNG transportation, such as shipping companies and goods owners.

Mathematically, this type of problem can be classified as Vehicle routing problem (VRP). VRP has a long history, with the first papers published in the seventies [7], and therefore the literature on the topic is very rich. Several review papers on vehicle and maritime routing have also been published over the years. Christiansen et al. [8] presented an ample overview on maritime transportation with a comprehensive survey on mathematical models for ship routing and scheduling. In a more recent review [9], focused only on works presented in journals and edited volumes between 2002 and 2011, the same authors presented a broad coverage on different types of shipping and aspects related to the shipping business, including an extensive section on LNG transportation. Halvorsen-Weare and Fagerholt [10] studied large-scale LNG ship routing and scheduling, proposing a solution method by decomposition in sub-problems, where routing and scheduling were treated separately. A study of the short sea inventory routing problem for distribution of different oil products in the archipelago of Cape Verde was presented by Agra et al. [11], who proposed both a discrete time and a continuous time arc-load-flow formulation. In a later paper [12] the authors presented also a heuristic-based method to treat realistic routing problems.

A sub-problem of the general VRP is the so-called fleet size and mix vehicle routing problem (FSMVRP), on which Hoff et al. [13] presented a review paper focusing on contributions in FSMVRP for both maritime and land based transportation. Later, a survey on only maritime FSMVRP was published by Pantuso et al. [14]. Here, literature was analyzed for specific characteristics of the problem (i.e. heterogeneous/homogeneous fleet, single/multi period, etc.) pointing out weak aspects of the available methodologies and suggesting possible future improvement strategies. Many of the solution approaches for FSMVRP are based on heuristic methods [15,16], but some exact formulations have also been presented. Jokinen et al. [17] presented an MILP model for optimization of LNG transportation along the Finnish coastline. The authors combined a one-dimensional maritime transportation problem with a land transportation task. Baldacci et al. [18] proposed an MILP formulation with a heterogeneous fleet of vehicles in a problem generally similar to the one we study in this paper. However, our approach differs with respect to the concept of "feasible route", which Baldacci et al. [18] designed based on a generalization of the traveling salesman problem, with each consumer being associated with exactly one route. Furthermore, we consider multiple depots (supply ports) and we allow for load splitting to be performed by the vehicles (ships). To the best knowledge of the authors, a FSMVRP presenting all these variants has not been studied in literature.

In the paper, we present a model as a general framework for fleet composition and ship routing within a given time horizon. The purpose of the model is to identify optimal routes, supply-receiving port connections, and ship sizes to solve the FSMVRP in a small-scale LNG supply chain. In its present form the model is suited for scenario analysis and initial planning, where the feasibility of a small-scale LNG distribution network is studied. Since the model is fast for small- or medium-sized problems, it is also well suited for sensitivity analysis, where the system is repetitively optimized under different external conditions or constraints to gain an understanding of the general feasibility of the point-optimal solutions. It should be stressed that the model is not designed to tackle real-time planning or scheduling problems.

The article is organized as follows. In the next section a description of the LNG maritime transportation problem addressed is provided and the assumptions made in the modeling are listed. Section 3 presents the formulation of the mathematical model. In Section 4 computation results of a case study are illustrated, where an optimal supply chain of LNG distribution is designed for the Caribbean Islands. The sensitivity of the optimal results to changes in the conditions, e.g., in the LNG price in the supply ports, is presented, where the robustness of the optimal solutions can be evaluated. A brief study on the effect of uncertainty in the demands is also presented. Section 5 presents the performance of the method on a set of larger test problems. Finally, in Section 6 some conclusions are drawn and lines of future work are suggested.

2. Problem description

The problem studied in this paper can be classified as a strategic maritime transportation problem, and specifically as an FSMVRP. We consider the regional supply of LNG from a set of potential supply ports to a set of receiving terminals. The aim of the model is to select the optimal fleet and routing scheme to fulfil the demand during the planned time horizon at minimum cost. The model is mainly designed for initial planning or feasibility studies of introducing LNG in new market areas, such as Caribbean Islands, Southeast Asia, etc. where for geographical scattered regions a small LNG supply chain is the only option. In this context, it is crucial to make a good choice of ships and routing paths in order to guarantee a cost-efficient supply of LNG. The problem is formulated from the point of view of shipping companies interested in analyzing potential new customers, supply ports delivering LNG to consumers on demand ex-ship (DES) contracts, companies delivering full supply chain solutions (including terminal infrastructure vessels, logistics, power plants, etc.), or simply from governmental agencies interested in studying the feasibility of LNG-related projects.

The model is based on the following assumptions: the distances between all the ports are given; demands at the receiving terminals are given and must be fulfilled within a given time horizon. We assume the existence of a baseload consumer in the vicinity of the receiving port (e.g. power plant), so LNG storages exist at the site and further transportation of the LNG to distributed consumers is neglected. Demands for the time horizon are assumed to be smaller than the storage capacity. This is a reasonable assumption considering the comparatively small demands in the type of supply chain in question. Under these conditions, it is not necessary to consider inventory levels at the receiving terminals. The ships delivering the fuel to the receiving ports are selected from a heterogeneous fleet of vessels, where each type of ship has a given capacity, cruising speed, and fuel consumption. Different supply ports may have different price of the LNG. Every port can be visited more than once and some types of ships can visit several receiving ports on the same voyage, i.e., allow for load splitting, but LNG is not bunkered at other supply ports during the voyage. Some vessels can be restricted from visiting certain receiving ports due to their incompatibility with the port specifications (i.e., port depth). Constraints on the maximum amount of LNG available at the supply ports are included in the model formulation and can be parametrically set as limiting factors. Sailing time and fuel consumptions are calculated from the given distances between ports and the average speed of the ship type. For the case of simplicity, the speed is not dependent on the ship load (i.e., displacement).

3. Mathematical model

The problem formulation considers a set of port locations P, separated into two disjoint subsets S and J, where the former represents the supply ports and the latter the receiving ports. A set of