Supply chain design and planning for LNG as a transportation fuel

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Summary

Increasing environmental and social concerns regarding the use of heavily polluting transportation fuels have led to a growing interest in alternative fuels, such as liquefied natural gas (LNG). Supply chain management decisions (e.g. network design, transportation planning, and inventory management) play a critical role in realizing the potential environmental and economic advantages of LNG as a fuel. However, these decisions are complicated by two important challenges. First, both the distribution network and demand for LNG as a fuel are noticeably underdeveloped. Demand is expected to grow if the distribution network matures, yet such network investments require increased demand—resulting in a chicken-and-egg problem. Second, LNG is a cryogenic liquid that constantly boils off. This boil-off not only reduces the quantity of the fuel, but also affects its quality. Low-quality LNG cannot be sold as fuel below the market quality standards. Consideration of these challenges requires the development of new logistics/supply chain management decision models that take these aspects into account and consequently differ from those existing in the literature.

This PhD thesis presents four projects in which we study location-routing, inventory control and lot-sizing decision problems in the domain of LNG distribution networks. In Chapter 2, we address the challenge of the currently underdeveloped distribution network for LNG as a fuel. Specifically, we introduce a location-routing problem related to finding the locations for establishing small-scale LNG storage facilities while considering the planning of the vehicle routes required to transport the fuel from the facility to its customers. One particular characteristic of this problem is that it allows for direct shipments from terminals at different levels of the LNG supply chain to the end-users. To tackle this problem, we formulate the problem as a

mixed-integer program and we propose a hybrid exact algorithm to solve it. This algorithm is an extension of variable MIP neighborhood descent, which is an approach proposed in the literature to solve location-routing problems arising in the cash industry. A numerical study shows that the proposed solution approach outperforms both the original algorithm and a commercial solver. Furthermore, we make use of our model to develop a case study considering the LNG supply chain along the European TEN-T network corridors, where we provide insights into the opening of satellite facilities and investing in bunker barges when expanding the supply chain for LNG as a fuel into Europe.

In Chapters 3–5, we study new inventory management problems arising in the LNG supply chain. Specifically, these problems take into consideration—and propose solutions that mitigate the negative effects of—the quality deterioration of LNG due to boil-off. In Chapter 3, we address a novel inventory control problem for liquids that suffer from quality deterioration, whose quality can be influenced via mixing. In this project, the main goal is to gain insights into the effect that the properties of LNG have on inventory control decisions by means of an analytical study. With that aim, we consider a setting where demand is deterministic. Furthermore, we assume that two suppliers are available, one offering the liquid with low quality at a low price, and the other offering it with better quality at a high price. A thorough analysis of the problem leads us to identify some of the structural characteristics of an optimal policy for the problem at hand. This characterization shows that, for example, attempting to increase the quality of inventories via mixing should be avoided unless the quality of the inventories reaches the minimum requirement. This characterization not only provides an intuitive view of the effect of the quality deterioration of LNG on inventory control, but can also be useful in the design of heuristic and exact approaches to find optimal policies for inventory problems with liquid substances whose quality can be upgraded via mixing.

In Chapter 4, we formulate a lot-sizing problem where multiple LNG suppliers are available, each offering LNG with a different price and quality. Initially, we formulate the problem as a mixed-integer non-linear program, which we approximately reformulate using a linearization technique where some of the variables are discretized. In addition to this formulation, we design two heuristics, which are inspired by the Wagner and Within algorithm. The first heuristic is an approach where replenishment orders are exclusively placed in periods where the inventory level is zero, while the second approach is a decomposition heuristic where we exclusively consider policies in which the number of times where the LNG is mixed between zero-inventory periods is limited. By means of a numerical analysis, we show that the second approach outperforms the other approaches in terms of solution quality and computation times.

In Chapter 5, we consider a single-supplier inventory control problem for LNG storage facilities that face stochastic demand. Owing to the stochastic nature of the problem, we include the removal of LNG from the inventory system as a decision variable. The problem is modeled as a Markov decision process. Our analysis of the optimal policies for the problem leads us to propose the (S, s, v, k) inventory control policy, which dictates when and how much LNG should be replenished and/or removed from the inventory system. In a numerical study, we show that the difference in performance of our policy with respect to the optimal is 1.65$\%$ on average. One of the main conclusions of our study is that the removal of LNG is an essential element for inventory control policies for LNG systems because otherwise the system might reach a temporal deadlock situation where the on-hand LNG can neither be used to serve demand nor upgraded to meet the minimum quality requirement.

Together, these four projects provide both methodological contributions and managerial insights. The methodological contributions stem from the presentation of new decision problems and model formulations as well as from developing exact and heuristic approaches that are able to find high-quality solutions. Additionally, they provide insights for the design and planning of LNG distribution networks in practice, as well as a number of interesting open questions for future research.