Liquefied Natural Gas (LNG) inventory routing problem under weather disruptions: a case study of dust storm in Persian Gulf

Jaeyoung Cho, Gino J. Lim, Taofeek Biobaku.
Department of Industrial Engineering
University of Houston, Houston, TX, 77204-4003
Tel: (713)743-7010 Email Address: jcho12@uh.edu

Selim Bora, Hamid Parsaei.
Texas A&M University at Qatar, Doha, Qatar
Tel: +974-4423-0014 Email Address: hamid.parsaei@qatar.tamu.edu

Abstract
The purpose of this study is to propose a stochastic LNG transportation model under weather disruptions. The goal is to use information to find a stable solution that withstands disruptions in a better way. The model is formulated in two-stage stochastic integer programming model to decide optimal routes and sailing schedules satisfying each customer's demand maximizing revenue and minimizing production and inventory level avoiding dust storm days. We present computational results demonstrating the effectiveness of our proposed stochastic model comparing the solution with deterministic counterparts.

1. Introduction
Natural gas is a vital component of the world's supply of energy. It is one of the cleanest, safest, and most useful of all energy sources. World demand for natural gas is projected to increase by 70% between 2002 and 2025. Natural gas can be supplied to customers by pipelines or vessels. Pipeline transportation is economically attractive and convenient onshore, some of which can extend over distances of up to 2,500km. As the transportation distance increases, however, maritime transportation becomes more reasonable option. For sea transportation purpose, natural gas has to be converted to liquid form because it takes up about 1/600th the volume of natural gas in the gaseous state at a temperature of approximately -160°C. When a LNG vessel arrives at a discharge port, LNG is delivered to end-users in gaseous form through regasification process.
One of the most critical weather conditions that Qatar, the world's largest LNG supplier must take into account for the maritime transportation of LNG is dust storm which is called 'Shamal (شمال)' in Persian Gulf. Shamal normally last three to five days, and its' hourly mean speed is 17 knot or above. It severely disrupts LNG loading operations because strong dust wind shakes the LNG loading facilities which could cause gas leaks and can quickly reduce visibility to ¼ mile or less. In worst case, leaked gas causes 'rapid phase transition' fire and explosion, or it injures people through direct contact due to its extremely low temperature. Therefore, from a safe LNG supply viewpoint, LNG cargo loading must be strictly prohibited with Shamal periods.

2. Objective
The objective of this study is to present a stochastically stable LNG inventory routing model minimizing the impact of potential delays caused by Shamal satisfying multiple customers.

3. Analyses
We assumed the following conditions for the analyses. Qatar serves five customers in three time periods with multiple LNG cargo vessels. There are two categories of vessels in the model. One is a membrane type which has strict limit on partial loading or unloading of LNG cargo. Another is

the moss spherical LNG carriers and the latest LNG carriers without partial filling limit. Exact demands and sailing distances between Qatar and six regasification terminals at customers are known as constants. As an uncertain factor, ten years of historical Shamal data from 1990 to 1999 are given as shown in Fig 1. We also consider 0.01% of boil off gas per day during voyage which is calculated as a part of daily sailing costs.

4. Discussions

We modeled two-stage stochastic LNG inventory routing problem and compare the computational result with deterministic counterparts. An illustrative example of three time period solutions is presented in Fig 2. including optimal routes serving multiple customers with the amount of LNG cargo and boil off loss from departing terminal to each destination. Intuitively, if we have perfect information about Shamal, then it can simply be solved by deterministic model avoiding or minimizing Shamal delays. However, as we only know assumed probability distribution of Shamal days, we can design a two-stage stochastic model to get stochastic optimal solution. Especially in this experiment, we consider three Shamal scenarios per time period. After running deterministic models with single scenarios and stochastic model with all scenarios, we verified that stochastic model always guarantees stable solution (*RP*) than Expected Value of Expected Solution (*EEV*) from deterministic models as it satisfies the non-negative condition of Value of Stochastic Solution (*VSS;* $VSS = RP - EEV$) for this maximization problem.

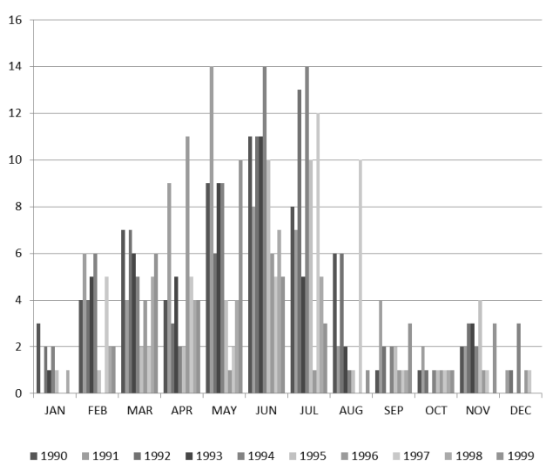

Fig. 1 Shmal days in Qatar (1990-1999)

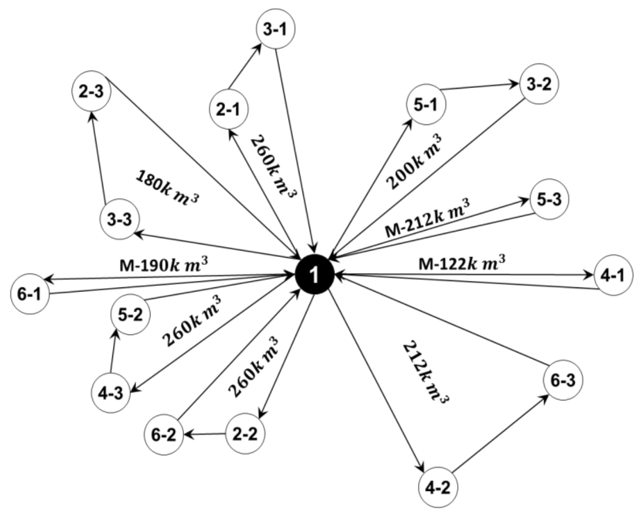

Fig. 2 Optimal sailing routes and vessels assignment

5. Conclusions

The major finding in this study is that the stochastic LNG inventory routing model minimizes cascading delay effects of Shamal by identifying robust schedules under uncertainty. The result obtained from numerical examples was compared with deterministic solutions and it illustrates the importance of utilizing available weather information.

6. Acknowledgement

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7. References

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