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A mixed-integer programming strategy for liquid helium global supply chain planning

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ABSTRACT

The global supply chain for liquid helium presents a complex structure due to increasing foreign demand, elaborate recovery techniques, and costly forms of distribution. Although the problem contains parallels to the liquid natural gas supply chain, supply requirements and problem-specific network constraints require a unique optimization model. We develop a large-scale, discrete time, path-based integer-programming model which solves optimally with CPLEX. Computational results implementing a rolling horizon structure and testing based on historical data are presented. A detailed sensitivity analysis demonstrates the effective use of our model, testing a variety of realistic parameter settings for the liquid helium supply chain.

1. Introduction

The global supply chain for liquid helium presents a unique and complex structure driven by characteristics of the product. The scarcity of helium promotes a global supply chain while also leading to high costs and sensitivity throughout components of this supply chain. The unique physical characteristics of helium, while particularly desirable for several applications, require specialized shipment methods and containers in order to preserve the product while in transit (Council, 2010).

1.1. Helium supply system

Helium has many unique properties which lend the element to a wide range of applications. A stable configuration and low atomic mass result in helium having the lowest melting and boiling points of any element. Other useful properties include helium's low density, low solubility, high thermal conductivity, and high speed of sound. The largest use of helium is related to the cooling of certain components in MRI machines, which falls into the cryogenics (study of materials at extremely low temperatures) application. Other applications of the element are summarized in Table 1 (Van Oss, 2013).

Prior to the mid-1990s nearly all helium production occurred in the United States, with limited availability, leading to minimal foreign consumption. Since then however, the foreign demand for helium has increased dramatically and production facilities have arisen overseas, causing U.S. consumption to drop as low as 50% of worldwide demand (Council, 2010). In addition, although helium is the second most abundant element in the universe, its rare properties cause it to diffuse into space resulting in scarce supply, thus necessitating elaborate recovery techniques. These reasons contribute to the complex, world-wide structure of the helium supply chain.

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Table 1
Applications and percent usage of helium.

Application	U.S. Usage (%)
Cryogenics (MRI/NMR)	~28–32
Pressurizing/purging systems	~18–26
Welding	~13–20
Controlled Atmospheres (semiconductors/fiber optics)	~13–18
Chromatography/lifting gas	~7
Leak detection	~4
Diving/medical breathing mixtures	~2–3
Other	~5–10

The supply chain begins with raw helium extraction from natural gas in particular locations. These locations depend on economic feasibility, namely where there are sufficient concentrations of helium (between 0.3 and 0.65 percent). The standard helium content in natural gas is only 0.1 to 0.5 percent, and 5.2 ppm in the air. Impurities such as water and CO_2 are removed from the natural gas which results in crude helium. This gas mixture is roughly 50–70% helium; United States specifications require at least 50% helium in a mixture to be considered crude. This crude mixture is then transferred to a refining location. There, it is liquefied to a point where most other gases in the mixture condense and are removed due to helium's low boiling point, leaving approximately 90% helium gas. This gas is then further refined depending on the desired usage, to helium purities ranging from 99.9% to 99.9999%, and finally liquefied.

Post-production distribution of helium can be divided into two categories: small scale gas and liquid customers, and large liquid helium customers, with our work focusing on the latter. These shipments are performed by specially designed intermodal or ISO containers. Helium ISO containers are approximately 1 million cubic feet, triple-walled, high-vacuum, and super-insulated, making them very costly. They are delivered to either customers or ports for shipment worldwide. Sample ISO container routes are shown in Fig. 1.

1.2. Problem and supply contract overview

We can represent the large liquid helium supply chain problem over a network with a discrete time, integer-programming model. Objectives include minimizing travel costs and times, following various supply contract parameters, and minimizing the number of ISO containers needed in the network to improve container utilization. These objectives aim towards reducing overall costs in the system. Location types throughout the network include fill plants, ports, maintenance facilities, and customers (see Fig. 1). Demand requests for customers range from a single container, to upwards of 50 full container requests per year, while the historical average is roughly 20 container requests.

Each location has an associated holding time for containers to incur after arrival and prior to departure. The network is unique in

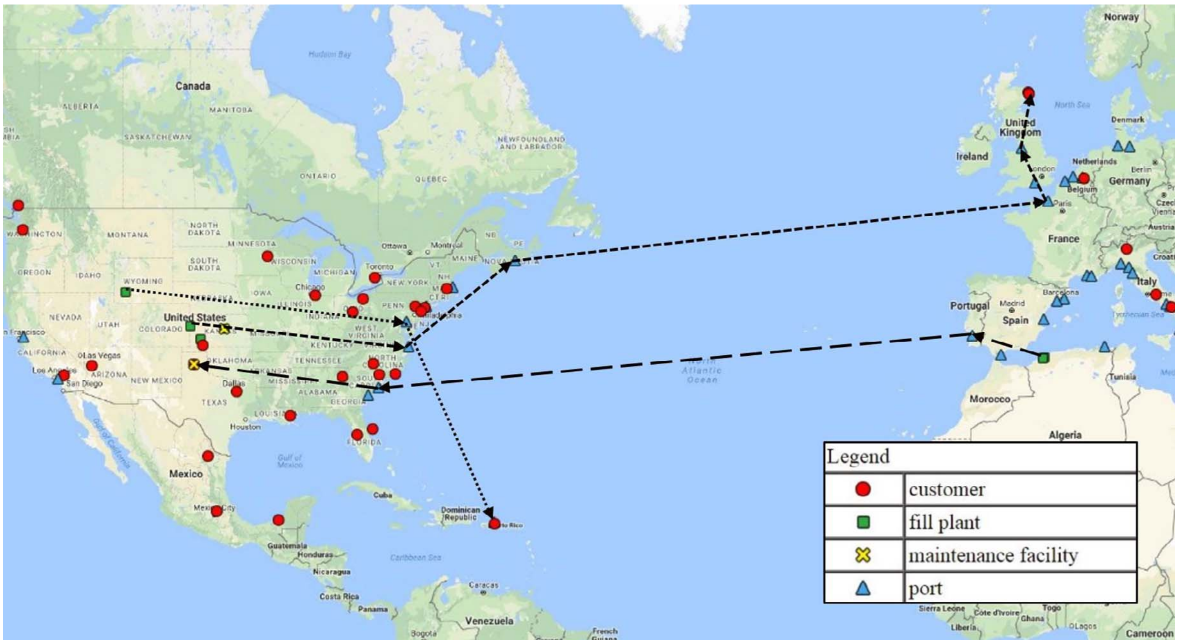

Fig. 1. Sample ISO container routes in supply chain network.