Underground Freight Pipeline System Logistic Network Design

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Many large metro areas in the world such as New York, Tokyo, Sydney, Beijing, Shanghai, and Seoul are becoming increasingly congested due to the amount of freight that flows in and out each day. One means of transportation that has not yet been exploited for freight transportation is the use of underground pipelines. Use of underground capsule pipelines for freight transport has a number of advantages: use unutilized space, reduce overcrowding above ground, not affected by weather, and less susceptible to disruption.

Building an underground freight pipeline system in a metropolitan area is a major endeavor that requires long-term planning. These types of projects are very costly without mentioning the uncertainties, schedule and budget constraints. The decision-making process always involves different stakeholders such as politicians, urban planners, engineers, management consultants and citizen groups. These stakeholders often have different or even conflicting objectives and constraints, which make it hard to solve the problem by a direct application of mathematical models and optimization algorithms. However, given the multi-stakeholder and multi-objective nature of the problem, we see a clear potential for the use of operations research methods and systems optimization techniques to construct and assess solutions that are submitted to decision makers.

The research into the development of underground freight pipeline systems since the 1960s has been focused mainly on technology issues. Liu (2009) proposed the preliminary design of several major components of an LIM-PCP based underground freight transportation including capsule and guide rails, station layout, tunnel structure, and basic operations. However, beyond all the effort put into the technological development throughout the years, little work had been done on the design of larger and more complex freight pipeline systems and the related logistic issues when operating such a system. This is primarily because most demonstration or pre-commercialization freight pipeline systems have been based on simple network configurations with a limited number of capsules as well as loading/unloading stations.

In order to satisfy the freight transportation needs between the sources and customer destinations, an underground freight pipeline system needs to be built to connect these locations. This then highlights the question of how to design such a network. In this paper, we present the network design problem and the associated mathematical model for the underground freight pipeline system. The mathematical model considers a network with a set of predefined station nodes and all possible edges connecting each pair of nodes. With knowledge of the amount of cargo needed to be transported, the objective of the model is to minimize the construction cost and the operational cost. Overall the model can answer the following questions: 1) Which edges/tunnels need to be constructed?, 2) Which line does each edge/tunnel belong to?, 3) Which edges and lines does each cargo use that form the shortest path from the origin station to the destination station?

In this paper, the Underground Freight Pipeline Network Design (UFP) problem is formulated to take into account the minimization of four cost components: tunnel construction cost, station construction cost, transportation cost and the operational cost in transfer stations. Three versions of the UFP network design model are explored. First, the UFP network design *comprehensive model* is introduced. This model is only able to handle a small size problem due to its computational complexity. Second, the idea of the *Intuitive two-step model* is discussed. This way of modeling requires far less computational effort. However, it lacks the ability to optimize the network comprehensively as there is a missing link between the two modeling steps: the transfer station construction cost. An example is given to show that the transfer station construction cost does affect overall network configuration. Then, based on the *Intuitive two-step model*, we present the *Enhanced Two Step Model.* The added enhancement estimates the approximate number of lines intersected at the same station node based on the degrees of each station node. The *Enhanced Two Step Model* is not only able to solve the UFP network design problem with much less computational time, but also maintains the ability to generate high-quality network design solutions.

Finally, we present a case study for the design of a New York UFP network. This UFP network is designed to transport ocean containers between customer stations within the Greater New York region and the major ocean ports in New York and New Jersey. In this case study, a series of experiments and analysis are conducted to provide more insights into how different parameters and variables affect the strategic planning of the UFP system for dispatching ocean containers in New York area. It includes analysis of container flow pattern, analysis of varied station construction cost and analysis of central inspection stations.

There is a wide range of potential applications for an underground freight pipeline system; such as a pallet-tube system for transporting pallets and other goods, dispatching containers, truck-ferry system, solid waste transportation, and mail and parcel transportation, in this paper we lay the logistics network foundation which supports further development in this research area.