



Hub-and-spoke network design under operational and disruption risks



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ABSTRACT

This paper proposes a novel decision-making framework to design a resilient hub network under operational and disruption risks. The proposed framework accounts for disruption risks via considering three primary resilience dimensions involving proactive capability, reactive capability, and design quality. Also, a new objective function is introduced to assess the resilience level of the designed hub network. A hybrid solution approach is proposed to solve such a multi-facet complex problem efficiently. Finally, several in-depth analyses are conducted to validate the proposed solution approach by which some managerial insights are also provided.

1. Introduction

Hub-and-spoke (simply hub) networks play a critical role in today's logistics systems. These networks have received increasing attention in a wide range of application areas such as transportation, telecommunication and computer networks. In today's global marketplace, freight transportation is known as one of the most critical parts of the global economy, given the increased rate of trade across the globe. For instance, companies such as UPS, DHL, FedEx and the United States Postal Service (USPS) receive and deliver millions of shipments every day (Vidyarathi et al., 2013). The hub location problem (HLP) is concerned with satisfying the demands of a number of origin-destination (O-D) nodes through several hub nodes. Hubs are sorting, transshipment and consolidation points in many-to-many transportation/distribution networks. In a hub network, incoming flows into the hub facilities are consolidated and re-routed to their destinations to take advantage of economies of scale. The classical HLP aims to find the location of hub nodes and the allocation of non-hub (i.e., spoke) nodes to the located hub nodes.

The concept of resilience has gained significant attention in recent years as the logistics networks are prone to various risks continuously. There are numerous definitions of resilience in the literature. According to Falasca et al. (2008), resilience is the ability of a network to reduce likelihood of disruptions, their consequences, as well as the time needed to recover disrupted operations. Generally, there are two major types of risk, including operational and disruption risks (Tang, 2006). Although accounting for both disruption and operational risks can significantly improve the so-called *resilience level* of a network, there is scant research in the literature of hub networks.

Disruption risks refer to the large disruptions caused by natural and man-made disasters such as hurricanes, floods, earthquakes and terrorist attacks. Several resilience strategies of different categories (e.g., proactive and reactive ones) can be implemented to protect the designed network against various disruption risks and enhance its resilience level. To this end, in this paper, improving network design characteristics (i.e., network density, network complexity and node criticality), fortifying hub nodes against

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disruptions, and allowing multiple allocation are considered in the design phase of the resilient hub network. Furthermore, business continuity plans (BCPs) can be used to resume the disrupted hub network to some extent immediately after the occurrence of disruptive events.

Recently, business continuity management (BCM) has been recognized as an effective tool to resume critical functions of an organization after the occurrence of any disruptive event. BCM is a management process by which the possible internal and external threats/risks and their relative impacts on business processes can be identified to provide a framework for organizational resilience (ISO 22301, 2012). According to Bhamra et al. (2011), there is a direct relation between the level of business continuity in an organization and its resilience level. Hence, an organization can enhance its resilience level and protect itself against various disruptive events by implementing a business continuity management system (BCMS) and providing appropriate BCPs.

Furthermore, operational risks refer to inherent uncertainties in input data that inevitably exist in logistics/supply chain networks (e.g., fluctuations in the estimated demands, cost rates and times). This type of risk is usually captured by incorporating inherent uncertainties in the input data. In other words, operational risks correspond to possible deviations from the expected values of input data in the future. Usually, a hub network design problem is solved as part of a strategic decision-making process where the obtained solution may have a long-lasting effect, and its implementation is usually time-consuming and capital-intensive. In this regard, several parameters in the HLPs may not be known precisely when decisions are made (Alumur et al., 2012). For example, establishment and transportation costs are usually estimated before decisions are made. However, in practice, there might be an unanticipated fluctuation in costs due to many factors such as price of the property, price of the raw-materials and gas price. Therefore, lack of knowledge to estimate the exact values of some parameters (often called epistemic uncertainty) can cause operational risks. Three types of modeling techniques are frequently used in the literature to incorporate inherent uncertainties in input data, including stochastic programming, fuzzy/possibilistic programming and robust optimization approaches (Sadghiani et al., 2015; Torabi et al., 2015; Rabbani et al., 2018). In this paper, an efficient possibilistic programming method (i.e., *Me*-based possibilistic programming) is implemented to deal with inherent epistemic uncertainty in input data.

Many aspects of disruption risks in hub networks have remained unexplored in the existing literature. Furthermore, there is a significant gap in accounting for both operational and disruption risks. Accounting for these risks would improve the resilience level of a hub network through protecting it against various risks and keeping its operability (i.e., business continuity) (Sadghiani et al., 2015; Torabi et al., 2015). In this regard, this paper develops a novel decision-making framework to design a resilient hub network under operational and disruption risks. Three primary dimensions of resilience are considered to enhance resilience level of the designed hub network, including proactive capability, reactive capability and design quality. Furthermore, the presented model can capture mixed uncertainties in input data (i.e., operational risks) by accounting for both epistemic uncertainty in critical parameters as well as random disruption scenarios in the hub network.

The remainder of this paper is organized as follows. Section 2 provides an overview of the related literature. Problem description and mathematical formulation are presented in Section 3. In Section 4, the solution method is elaborated. Numerical example and some computational results are provided in Section 5. Finally, Section 6 presents the conclusion and some new avenues for future research.

2. Literature review

There is a wide literature on traditional hub networks due to the critical role of hub networks in today's logistics systems. The interested readers are referred to two comprehensive review papers to see more details about classical HLPs (Alumur and Kara, 2008; Campbell and O'Kelly, 2012).

In this paper, the literature review is focused on two main categories which address disruption risks and operational risks.

2.1. Disruption risks

Risk management (RM) and the concept of resilience have received significant attention over the past decade. We believe that some of the resilience strategies, which are mostly used in designing resilient supply chain networks, can be modified and used to mitigate disruption risks in the hub networks.

In the literature, the most commonly used approach to decrease the impact of disruption risks is multiple sourcing (i.e., multiple allocation). Generally, there are two types of allocation strategies for HLPs, namely single allocation and multiple allocation. In the single allocation strategy, each spoke node should be allocated to just one hub node, but in the multiple allocation strategy, each spoke node can be allocated to more than one hub node. Single allocation strategy is usually less expensive than multiple strategy, but it can lead to a greater loss when a disruption occurs. Campbell (1992) formulated a multiple allocation HLP for the first time. After that, several scholars used the multiple allocation strategy in their studies (e.g., Cardoso et al., 2015; Ernst et al., 2009).

The importance of network design quality and its impact on network resilience are highlighted in several papers. Craighead et al. (2007) argued that there is a relation between the severity of a network disruption and its density, complexity and node criticality. Falasca et al. (2008) explained that network design quality can affect the network resilience level. Recently, Cardoso et al. (2015) considered five SCNs and used a number of network design indicators alongside the other indicators to assess the resilience level of the considered SCNs.

Fortification is another mitigation strategy, which can be implemented in the design/redesign phase of supply chains. In this respect, each facility according to its importance and functionality can be established at a specific fortification level to mitigate the impact of disruption risks at post-disruption. Recently, managers have tended to fortify vital facilities against major disruptions to

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