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Evaluating the reliability of a stochastic distribution network in terms of minimal cuts

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ABSTRACT

This paper presents a *d*-minimal cut based algorithm to evaluate the performance index R_{d+1} of a distribution network, defined as the probability that a specified demand $d+1$ can be successfully distributed through stochastic arc capacities from the source to the destination. To improve the efficiency of solving *d*-minimal cuts, a novel technique is developed to determine the minimal capacities of arcs. Also, two new judging criteria are proposed to detect duplicate *d*-minimal cuts. Both theoretical and computational results indicate that our algorithm outperforms the existing methods. Furthermore, a real case study is provided to illustrate the application of the algorithm.

1. Introduction

1.1. Background

Logistics distribution networks provide the infrastructure for the storage and distribution of products. In the context of either general business logistics (Chopra, 2003; Sheu, 2006) or emergency logistics (Edrissi et al., 2015; Sheu, 2007, 2010), distribution activity is considered as the process of the transfer of products from supply points to demand points. Relative to other logistics functions, such as procurement, manufacturing, warehousing, inventory and information systems, distribution is a key function in the entire logistics system and the key link between manufacturers and customers in a supply chain (Yang, 2013). Furthermore, distribution is a major driver of profitability in a company due to its direct impact on both the logistics cost and the customer experience (Chopra, 2003). Therefore, a distribution network with better performance plays a significant role in achieving a number of logistics and supply chain goals, ranging from low operational cost to high customer service level (Chopra, 2003; Ho and Emrouznejad, 2009; Peng et al., 2011; Tsao and Lu, 2012; Whicker et al., 2009; Yang, 2013).

The performance evaluation of distribution networks is a popular issue in the field of logistics and supply chain management. Chopra (2003) pointed out that at the highest level, the performance of a distribution network can be evaluated along two dimensions: meeting customer needs, and cost of meeting customer needs. Also, many researchers have studied the performance evaluation of distribution networks according to the following questions: "Have customer demands been fulfilled?" "Is the total cost minimized?" and "Have products been timely delivered?" in which several important factors

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affecting the performance are considered, such as cost, service level, lead time, product availability, transportation capacity, or market demand (Ho and Emrouznejad, 2009; Nagurney et al., 2014, 2015; Tsao and Lu, 2012; Whicker et al., 2009; Yu and Nagurney, 2013). Of note is that the distribution networks addressed in the aforementioned studies are deterministic. In practical applications, deterministic models fail to fully characterize the actual performance of a distribution network that is always subject to many types of uncertainty (Soltani-Sobh et al., 2015, 2016a). Lin et al. (2013) and Yeh et al. (2014) argued that any distribution network can be regarded as a typical stochastic-flow network (also called multi-state network), and assessing the performance of distribution networks in uncertain states is of crucial importance to maintain a high level of operation in the whole logistics system (Lin, 2007, 2009; Niu et al., 2014; Jane, 2011).

A distribution network can be represented as both sets of nodes and arcs, where each node stands for a supplier, a transfer center, or a market (e.g., a wholesaler, a retailer, or a customer), and each arc (or called route, link) connecting a pair of nodes stands for an air route, a land route, or an ocean route. Along each arc, there is a carrier to provide the transportation service. Owing to the effect of unexpected situation in reality, the available capacity of each carrier is stochastic (Lin et al., 2013; Yeh et al., 2014). For example, the vehicles owned by one carrier may be in a failure state, partial failure state, or maintenance state, such that the number of vehicles available is stochastic. In that sense, each arc has several random capacities that can be described with a probability distribution. And, the goods transported through such a distribution network are reckoned as a flow. For a distribution network with random arc capacities, the network capacity (the maximum flow from the source to the destination) is not a fixed value, so whether the network can successfully deliver sufficient amount of commodity to meet market demand is not a simple yes or no question. In such a case, reliability analysis can serve as a useful tool to measure the network performance.

1.2. Network reliability

Reliability is a fundamental attribute for the safe operation of any modern technological system, and is generally defined as the probability that a system performs its intended function within a given time horizon and environment (Zio, 2009; Peng et al., 2011). This definition is particularly focused on the situation in which components of the system may fail or partially fail due to a variety of uncertainties during operation. Traditionally, network reliability study has been centered mainly on three aspects (Soltani-Sobh et al., 2016a, 2016b; Chen et al., 2002, 2013; Cedillo-Campos et al., 2014): (i) connectivity reliability—the probability that the nodes of the network remain connected; (ii) travel time reliability—the probability that a successful travel from the source to the destination can be made within a specified interval of time; and (iii) capacity reliability—probability that a specified flow demand can be successfully transported from the source to the destination. In addition to the above-mentioned three types, research has also been dedicated to other reliability measures. For instance, the study by Soltani-Sobh et al. (2016a) is focused on behavioral reliability by considering the uncertainty in people's travel making decision, where behavioral reliability is concerned with the effect of the modified mean behavior of travelers on the mean network performance. Soltani-Sobh et al. (2016b) utilized performance reliability, defined as the probability that the performance measure as a function of random variables are in the safe region and acceptable level, to analyze a transportation network subject to unexpected events with multiple uncertainties. Among these reliability measures, capacity reliability which combines the source–destination connection, arc capacity constraint and flow demand is the most commonly employed indicator to assess the performance of many real-world systems, and is the focus of this paper.

1.3. Capacity reliability evaluation

Reliability evaluation has been shown to be an NP-hard problem (Ball, 1993; Colbourn, 1987), although it has been extensively studied. Common in the literature is the two-terminal capacity reliability (2TCR), a classical reliability index with a broad range of practical applications (Ramirez-Marquez and Coit, 2005b). Given a stochastic-flow network whose components take discrete, non-negative integer values following a certain probability distribution, two-terminal capacity reliability at demand level $d+1$ ($2TCR_{d+1}$) is defined as the probability that $d+1$ units of flow demand can be successfully distributed from the source to the destination. Virtually, $2TCR_{d+1}$ can be looked upon as a combination of the source–destination delivery, arc capacity, and flow demand (Jane, 2011).

From the perspective of reliability evaluation, a great deal of research (Alexopoulos, 1995; Doulliez and Jamoulle, 1972; Jane and Laih, 2008, 2010; Jane et al., 1993; Lin, 2002; Yeh, 2002, 2004; Yan and Qian, 2007; Yeh, 2008; Forghani-elahabad and Mahdavi-Amiri, 2014; Yeh et al., 2015) has been devoted to calculating $2TCR_{d+1}$. The algorithms in these studies can be broadly categorized as direct and indirect methods (Jane and Laih, 2008). The complete enumeration method solves $2TCR_{d+1}$ in a simple, and straightforward manner. It enumerates all possible combinations of arc states, so it is computationally expensive. The popular decomposition method for $2TCR_{d+1}$ is proposed by Doulliez and Jamoulle (1972). However, Alexopoulos (1995) pointed out that this direct decomposition method may yield incorrect results. Recently, Jane and Laih (2008, 2010) proposed two decomposition algorithms for the straightforward computation of $2TCR_{d+1}$. Based on a special capacity vector, Jane and Laih's algorithms repeatedly apply a novel decomposition technique to divide the set of capacity vectors, such that all acceptable (unacceptable) capacity vectors which are capable (incapable) of transmitting the required flow demand from the source to the destination can be attained. As a result, $2TCR_{d+1}$ can be easily obtained by computing the probabilities of all acceptable (unacceptable) capacity vectors.