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An efficient algorithm for evaluating logistics network reliability subject to distribution cost

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ABSTRACT

This paper presents a (d, c)-minimal paths based algorithm to evaluate the reliability index $R_{(d,c)}$, defined as the probability that the source distributes a demand d successfully to the destination with the total distribution cost not exceeding budget constraint c. The proposed algorithm employs two schemes to reduce the search space of (d, c)-minimal paths: (1) by proposing some conditions, an improved method for solving (d, c)-minimal paths is developed; (2) an existing decomposition technique is applied to limit the search space. Computational results show a clear advantage of the proposed algorithm in seeking (d, c)-minimal paths.

1. Introduction

It is well known that logistics has been an integral part of our daily lives by means of promoting the efficient and safe movement of goods over time and space. Due to the fact that logistics has a major impact on economic activities, improving logistics performance has become an important development policy objective in recent years (World Bank, 2010). In a fully competitive market, an efficient, reliable, and cost-effective logistics network substantially affects a firm's benefits, and potentially influence a firm's long-term development. In its presence, a firm is to stay ahead of its competitors; conversely, in its absence, a firm may lose out to its competitors in spite of having a better product. Thus, a competitive logistics network is regarded as the backbone of a robust supply chain connecting various functions together.

In the second report of *The Logistics Performance Index and Its Indicators* (World Bank, 2010) which was designed and implemented by the World Bank International Trade and Transport Departments, it is particularly emphasized that "Even more than time and cost, logistics performance depends on the reliability and predictability of the supply chain." and "The reliability of the supply chain is the most important aspect of logistics performance." More recently, the third report of *The Logistics Performance Index and Its Indicators* (World Bank, 2012) has been issued by the World Bank. It is highlighted once again in this report that "Logistics performance is strongly associated with the reliability of supply chains," and "The lack of reliability and unpredictable delays, which do more damage than the average costs and time that can be factored into the supply chains, create high induced-logistics costs in low logistics-performance environments and add dramatically to the challenge of economic diversification in low-income and many middle-income economies."

For a logistics network, reliability is the probability that a specified demand d can be successfully distributed from the source to the destination, while distribution cost is concerned with the problem that the total distribution cost should

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not exceed a given budget constraint c (Jane, 2011). Network reliability without budget constraint has always been used as an index to analyze the service level of a supply chain network. For example, Lin and Yeh (2010) recently discussed the optimal carrier selection problem based on network reliability criterion. Practically, in addition to capacity and operational reliability, each edge is often associated with a cost that must be paid for every unit of flow that passes through it (Jane, 2011). As a combination of reliability and distribution cost, the performance index $R_{(d,c)}$ is defined as the probability that a specified demand d can be distributed from the source to the destination with the total distribution cost less than or equal to budget constraint c (Jane, 2011; Lin, 1998; Lin, 2004; Niu and Xu, 2012; Yeh, 2005a, 2011). For a logistics network which attaches importance to both reliability as well as distribution cost, $R_{(d,c)}$ can serve as a desirable index to assess its operational performance, and to indicate possible improvement. For instance, Hong et al. (2013) considered an emergency logistics network design problem by taking the logistics reliability, cost, and robustness as major performance measures.

A variety of algorithms (Jane, 2011; Lin, 1998; Lin, 2004; Niu and Xu, 2012; Yeh, 2005a, 2011) have been proposed to evaluate $R_{(d,c)}$ in recent years. Jane (2011) proposed a hybrid algorithm for the straightforward computation of $R_{(d,c)}$. This hybrid algorithm is intermediate between the decomposition algorithm of Jane and Laih (2004) for solving two-terminal capacity reliability and the capacity-scaling algorithm of Edmonds and Karp (1972) for solving the minimum cost maximum flow problem. The logistics network discussed by Jane's article (2011) is assumed to be a binary-state network model. That is, the capacity of each edge is a binary-state variable: perfectly good or completely failed. When the state of one edge is perfectly good, the total amount of flow through it is not greater than the capacity; when the state of one edge is completely failed, no flow can be transmitted through it. The binary-state model fails to represent the true behavior of real-life networks (Lisnianski and Levitin, 2003), since the edges of many real-life networks, such as logistics network, may be operating in any of several intermediate states ranging from the smallest state to the largest state, such that the networks are able to provide different acceptable levels of service (Ramirez-Marquez et al., 2006). Considering a multi-state network model, a number of algorithms which solve $R_{(d,c)}$ by way of (d, c)-minimal paths ((d, c)-MPs) (Lin, 1998, 2004; Niu and Xu, 2012; Yeh, 2005a, 2011) have also been developed. A (d, c)-MP is a minimal state vector meeting the demand d and the budget constraint c (Lin, 2004). If a state vector x is a minimal state vector meeting the demand d and the budget constraint c, it means that for any component-wise smaller state vector y, y does not meet the demand d or the budget constraint c. When all (d, c)-MPs are found, $R_{(d,c)}$ can be calculated by using the inclusion–exclusion principle (Lin, 1998, 2004; Niu and Xu, 2012; Yeh, 2005a, 2011). Therefore, solving the (d, c)-MP problem is the first important step.

Based on minimal paths (MPs), Lin (1998) proposed a simple algorithm to search for all (d, c)-MPs. A minimal path (MP) is a subset of edges, such that if any edge is removed from this set, the remaining set is no longer a path (Yeh, 2005a). Lin's algorithm (1998) first uses the enumeration algorithm to search for (d, c)-MP candidates by solving a mathematical model which is built on the basis of max-capacity, flow-conservation law and distribution cost. Then, all (d, c)-MP candidates are checked by a comparison process to determine whether they are (d, c)-MPs. In other words, each (d, c)-MP candidate must be verified by comparing it with all of the other (d, c)-MP candidates. It is a time-consuming task to check (d, c)-MP candidates by a comparison method due to the exponentially growing number of (d, c)-MP candidates (Yeh, 2005a). Lin (2004) extended the work to the case with unreliable nodes. That is, Lin (2004) considered not only unreliable edges but also unreliable nodes. The method of Lin (2004) uses MPs to assign the flow to each component (edge or node). All (d, c)-MPs can be obtained by using the enumeration method. It is noted that Lin's algorithm (2004) also involves the comparison process in checking (d, c)-MP candidates. With improvement on checking (d, c)-MPs candidates, Yeh (2005a) proposed an approach to seek all (d, c)-MPs based on MPs. To search for (d, c)-MP candidates, Yeh's algorithm (2005a) first solves the same mathematical model as Lin's algorithm (1998). Then, a cycle-checking method is employed to verify whether a (d, c)-MP candidate is a (d, c)-MP. Since Yeh's algorithm (2005a) does not involve a comparison process, it is more efficient in searching for (d, c)-MPs. However, Yeh's algorithm (2005a) also requires all MPs information.

Without requiring all MPs information, Yeh (2011) proposed an enumeration method to search for all (d, c)-MPs by solving a simple mathematical model which is built on the flow-conservation law. Instead of involving a comparison process, Yeh's algorithm (2011) employs a cycle-checking method to check each (d, c)-MP candidate. Compared with the MPs-based algorithms (Lin, 1998; Lin, 2004; Yeh, 2005a), Yeh's algorithm (2011) is more efficient in solving the (d, c)-MP problem. But, one marked defect is that a huge number of state vectors need to be enumerated. Recently, Niu and Xu (2012) proposed a method to solve the (d, c)-MP problem. Niu and Xu's method (2012) does not require any MPs information. Besides, lower capacity constraints of edges are introduced to cut down the total amount of enumerated state vectors. The algorithm of Niu and Xu (2012) is more efficient than Yeh's (2011) algorithm under certain conditions (Niu, 2012). It is noteworthy, however, that when the demand d is low, the amount of state vectors enumerated by the two algorithms is identical. In such case, since the algorithm of Niu and Xu (2012) needs to find lower capacity constraints of edges, it becomes less efficient than Yeh's algorithm (2011).

There is no doubt that the existing algorithms (Lin, 1998; Lin, 2004; Niu and Xu, 2012; Yeh, 2005a, 2011) have been devoted to solving the (d, c)-MP problem. But, as an NP-hard problem, searching for all (d, c)-MPs is a challenging task. Thus, there is a growing demand for developing more efficient algorithms for solving the (d, c)-MP problem.

The main purpose of this paper is to present an efficient algorithm to search for all (d, c)-MPs. In particular, the proposed algorithm employ two schemes to reduce the search space of (d, c)-MPs: (1) by proposing some conditions, an improved method is developed to search for (d, c)-MPs without requiring any MPs information; (2) an existing decomposition technique is applied to further limit the search space of (d, c)-MPs. Compared with algorithms of Yeh (2011) and Niu and Xu (2012), a major advantage of the proposed algorithm is that it requires a smaller number of state vectors to be enumerated,