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System reliability for a multistate intermodal logistics network with time windows

Yi-Kuei Lin[a]*, Cheng-Fu Huang[b], Yi-Chieh Liao[a] and Chih-Ching Yeh[c,d]

[a]*Department of Industrial Management, National Taiwan University of Science and Technology, Taipei, Taiwan, ROC;* [b]*Department of Business Administration, Feng Chia University, Taichung, Taiwan, ROC;* [c]*School of Public Health, College of Public Health and Nutrition, Taipei Medical University, Taipei, Taiwan, ROC;* [d]*Department of Public Health, College of Public Health, China Medical University, Taichung, Taiwan, ROC*

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Network structures have been diffusely adopted in logistics systems, where the most critical target is completing the delivery within the promised timeframe. This paper focuses on a single commodity in a multistate intermodal logistics network (MILN) with transit stations and routes to involve three parameters: a route's capacity, delivery time and time window. There is a carrier along each route whose number of available containers is multistate because the containers can be occupied by other customers. The delivery time consisting of the service time, travel time and waiting time varies with the number of containers and vehicle type. The arrival time at the transit station should be within the time window, the interval between the earliest and latest acceptable arrival times. This paper evaluates the system reliability, the probability that the MILN can successfully deliver sufficient amount of the commodity to meet market demand via several transit stations under the delivery time threshold and time windows. The system reliability can be treated as a delivery performance index and is evaluated with a proposed algorithm in terms of minimal paths. A practical case of scooter parts distribution between Taiwan and China is presented to emphasise the management implications of system reliability.

Keywords: multistate intermodal logistics network (MILN); time window; system reliability; transit station; time threshold; delivery performance

1. Introduction

Owing to global economic development, the logistics to meet requirements from worldwide customers is playing a more critical role in supply chain management. A growing trend is to develop intermodal logistics (Macharis and Bontekoning 2004; Crainic et al. 2007; Tsamboulas 2008; Ruan et al. 2016) to achieve worldwide requirements. Intermodal logistics is defined as combining of at least two types of vehicles from the origin to the destination through several regions, and the transfer from one type of vehicle to the next is performed at an intermodal terminal. Arnold, Peeters, and Thomas (2004) and Limbourg and Jourquin (2009) dealt with the problem of optimally locating rail/road terminals for freight transport. Bookbinder and Fox (1998) solved the optimal routings problem with minimum total cost and time for container transport from Canada to Mexico by rail and water. Givoni and Banister (2006) found that delivery by intermodal logistics with airway and railway has better benefits than that by a single type of vehicle. These studies integrated at least two types of vehicles and highlighted the importance of intermodal logistics.

In logistics systems, on-time delivery (OTD) (Grout 1998; Tu, Huang, and Zhao 2015; Zhang, Lam, and Chen 2016) is a critical criterion that measures the efficiency of a process and supply chain by calculating the amount of a commodity (or services) that are delivered to customers on time. Wang (2010) proposed a logistics delivery model based on time and found the optimal distribution with minimum total cost to the customers depending on time factors. However, in actual situations, when a vehicle arrives at the transit station, the workers can process the containers immediately or wait until an acceptable time. The time window (Chen and Yang 2004; Low et al. 2012) is defined as the interval between the earliest and latest acceptable arrival times at a transit station. If the arrival time is within the time window, the transit station permits service to start. However, if the vehicle arrives at the transit station too early, workers have to wait until the earliest acceptable time. The time window is widely used to deal with the vehicle routing problem (Kolen et al. 1987; Solomon 1987; Ritzinger et al. 2016) of finding the optimal set of routes with the minimum total length for a fleet of vehicles in order to serve a given set of customers. Therefore, a time threshold with time windows should be considered in logistics systems to meet practical needs.

*Corresponding author. Email: yklin@mail.ntust.edu.tw

Network modelling is a useful methodology for representing an intermodal logistics system (Southworth and Peterson 2000; Chang 2008; Ghane-Ezabadi and Vergara 2016) in which each node denotes a transit station (e.g. a freight station, port or airport) and each route connects a pair of nodes. Each route has a carrier to provide the logistics containers. The carrier's available capacity is multistate (Warren and Huseyin 2002; Yu and Li 2005; Lin and Yeh 2010a; Chen 2012) because the containers can be occupied by other customers. Thus, the logistics network can be regarded as a multistate network with multistate routes, namely a multistate intermodal logistics network (MILN) herein. In the past decades, multistate networks have been widely used in many real systems, such as for manufacturing (Lin and Yeh 2010b; Chang and Lin 2015; Lin and Chang 2015), electric power (Hsieh and Lin 2006) and computers (Hassan 2012; Lin et al. 2013). To evaluate the performance of a multistate network, researchers (Hsieh and Lin 2006; Lin and Yeh 2010a; Hassan 2012; Lin et al. 2013, 2014; Chang and Lin 2015; Lin and Chang 2015) have concentrated on calculating the probability that the multistate network can send a requested flow from the source to the sink based on the concept of minimal paths (MPs). An MP is a path whose proper subsets cannot be paths. The MP concept can be used to derive the minimal capacity vectors for the requested flow, and the probability that the flow is satisfied can be calculated in terms of those vectors. Such a probability is defined as the system reliability and can be regarded as a performance index from the perspective of quality management. Several methods can be applied to calculating the system reliability in terms of minimal capacity vectors, such as state-space decomposition (Aven 1995; Lin et al. 1995; Hsieh and Lin 2006), inclusion-exclusion (Hudson and Kapur 1985; Xue 1985; Lin 2003), disjoint-event method (Hudson and Kapur 1985; Yarlagadda and Hershey 1991) and recursive sum of disjoint products (RSDP; Zuo, Tian, and Huang 2007; Bai, Zuo, and Tian 2015).

This paper focuses on an MILN with a time threshold by considering multistate capacity for each carrier and time window at each transit station. In order to develop a delivery performance index, we evaluate the system reliability, which is the probability that the MILN can successfully deliver sufficient amount of the commodity to meet the market demand via several transit stations within the time threshold and time windows. The MILN is first decomposed into subnetworks. Subsequently, an algorithm in terms of MPs is proposed to evaluate the system reliability. The remainder of this paper is organised as follows. The MILN model is constructed in Section 2 and an algorithm to evaluate the system reliability is proposed in Section 3. Then an illustrative example is utilised to present the proposed algorithm in Section 4. A practical case of scooter parts distribution between Taiwan and China is described in Section 5. Finally, numerical experiments and conclusions are presented in Sections 5 and 6, respectively.

2. MILN model and system reliability evaluation

In this section, the notations and assumptions are introduced first. The MILN is composed of nodes, routes and travel time, where each node denotes a transit station and each route connects a pair of nodes. On each route, a carrier provides containers and vehicles for delivery. The commodities are delivered from a single supplier to a single market. The travel time depends on the loading of the containers with the commodities. The MILN involves several parameters: the route's capacity, the delivery time and the time window. The MILN is decomposed into two or more subnetworks based on transit stations. Each subnetwork is denoted by U^α, $\alpha = 1, 2, \ldots, o$. Let $G \equiv (\mathbf{N}, \mathbf{A}, \mathbf{L})$ represent an MILN with a source node and sink node, where $\mathbf{N}$ denotes the set of nodes, $\mathbf{A} = \{a_i^\alpha | \alpha = 1, 2, \ldots, o, i = 1, 2, \ldots, n^\alpha\}$ denotes the set of routes with n^α being the number of routes in U^α, and $\mathbf{L} = \{\lambda_i^\alpha | i = 1, 2, \ldots, n^\alpha, \alpha = 1, 2, \ldots, o\}$ denotes the set of travel times. Each node represents a transit station (e.g. a freight station, port or airport), and each route connects a pair of nodes. Each route has a carrier to provide the logistics containers. The current capacity of route a_i^α, which is denoted by x_i^α, is an integer random variable with a maximum value of M_i^α. The capacity vector is $\theta = (x_1^1, x_2^1, \ldots, x_{n^1}^1, x_1^2, x_2^2, \ldots, x_{n^2}^2, \ldots, x_1^o, x_2^o, \ldots, x_{n^o}^o)$. Because the containers can be occupied by other customers, the carrier's available capacity is multistate on each route. The number λ_i^α is the travel time on route a_i^α, $i = 1, 2, \ldots, n^\alpha$, $\alpha = 1, 2, \ldots, o$. The following assumptions are made:

(I) The flow in G must satisfy the flow-conservation principle (Ford and Fulkerson 1962). That is, no commodity is reduced or increased during delivery.
(II) The flow in G and time units are integer values.
(III) The capacities of different carriers are statistically independent.
(IV) The transit stations do not provide inventory service. That is the transit stations have no capacity.

Vector operations are depicted as following rules:

(1) $X \le Y$ $(x_1, x_2, \ldots, x_n) \le (y_1, y_2, \ldots, y_n)$: $x_i \le y_i$ for each $i = 1, 2, \ldots, n$.

(2) $X < Y$ $(x_1, x_2, \ldots, x_n) < (y_1, y_2, \ldots, y_n)$: $X \le Y$ and $x_i < y_i$ for at least one i.
(3) $X \not\gtrless Y$ $(x_1, x_2, \ldots, x_n) \not\gtrless (y_1, y_2, \ldots, y_n)$: neither $X \ge Y$ nor $X < Y$.

2.1 d^α-*LB for a subnetwork*

The MILN can be decomposed into two or more areas by region. Each subnetwork U^α is part of G, $\alpha = 1, 2, \cdots, o$. According to Assumption I, no flow is lost during delivery. That is, the demand of each subnetwork is the same: $d^1 = d^2 = \cdots = d^\alpha = d$. Let $F^\alpha = (f_1^\alpha, f_2^\alpha, \ldots, f_{m^\alpha}^\alpha)$ be a flow vector in U^α where f_j^α is the flow through the MP E_j^α and s^α and t^α are the source and sink nodes, respectively. In particular, $t^{\alpha-1} = s^\alpha$ for $\alpha > 1$; this means that the sink node in $U^{\alpha-1}$ is the source node in U^α. Under the flow-conservation principle, the total flow-in should be equal to the total flow-out for any node except for the sink and source nodes (Lin et al. 1995, 2014). Hence, any flow vector F^α in U^α that satisfies the following constraint is said to meet the demand d^α:

$$\sum_{E_j^\alpha} f_j^\alpha = d^a, \qquad \text{for } i = 1, 2, \ldots, m^a, \tag{1}$$

where $\sum_{E_j^\alpha} f_j^\alpha$ represents the total flow travelling into t^α. Any F^α that satisfies the following constraint is said to be feasible:

$$\left\lceil \sum_{j:a_i^\alpha \in E_j^\alpha} \left\{ w_i^\alpha f_j^\alpha \right\} \right\rceil \le M_i^\alpha \quad \text{for } i = 1, 2, \ldots, n^a, \tag{2}$$

where w_i^α is the consumed capacity on route a_i^α by each flow, $w_i^\alpha f_j^\alpha$ is the consumed capacity by flow f_j^α on route a_i^α and $\sum_{j:a_i^\alpha \in E_j^\alpha} \left\{ w_i^\alpha f_j^\alpha \right\}$ is the total consumed capacity on route a_i^α under F^α. Constraint (2) represents the consumed capacity on route a_i^α cannot exceed its maximal capacity M_i^α (Lin et al. 1995, 2014). Because the flow must be an integer value according to Assumption II, we consider the smallest integer value $\left\lceil \sum_{j:a_i^\alpha \in E_j^\alpha} \left\{ w_i^\alpha f_j^\alpha \right\} \right\rceil$, which is greater than or equal to $\sum_{j:a_i^\alpha \in E_j^\alpha} \left\{ w_i^\alpha f_j^\alpha \right\}$.

For convenience, let $\mathbf{F}^\alpha = \{F^\alpha | F^\alpha$ satisfies constraints (1) and (2)$\}$. Similarly, any F^α that satisfies the following constraint is said to be feasible under the capacity vector $X^\alpha = (x_1^\alpha, x_2^\alpha, \ldots, x_{n^\alpha}^\alpha)$ if and only if

$$\left\lceil \sum_{j:a_i^\alpha \in E_j^\alpha} \left\{ w_i^\alpha f_j^\alpha \right\} \right\rceil \le x_i^\alpha \quad \text{for } i = 1, 2, \ldots, n^a. \tag{3}$$

The capacity vector X^α satisfies the demand d^α if there exists at least one $F^\alpha \in \mathbf{F}^\alpha$ that meets constraint (3) (Lin et al. 1995, 2014). The minimal capacity vector that satisfies d^α is denoted as d^α-LB. A critical property of d^α-LB is that there exists an $F \in \mathbf{F}^\alpha$ such that

$$x_i^\alpha = \left\lceil \sum_{j:a_i^\alpha \in E_j^\alpha} \left\{ w_i^\alpha f_j^\alpha \right\} \right\rceil \quad \text{for } i = 1, 2, \ldots, n^a. \tag{4}$$

Lemma: *Any vector* $X^\alpha = (x_1^\alpha, x_2^\alpha, \ldots, x_{n^\alpha}^\alpha)$ *that is obtained by solving constraints* (1) *and* (2)*, and is then transformed according to Equation* (4) *is taken as a* d^α*-LB candidate.*

In order to generate all d^α-LBs, let Ω^α be the set of such candidates and $\Omega_{\min}^\alpha$ be the set of the minimal elements in Ω^α. The following theorem shows that $\Omega^\alpha{}_{\min}$ is the set of d^α-LBs.

Theorem 1: $\Omega_{\min}^\alpha$ *is the set of* d^α*-LBs.*

Proof: Suppose X^α is a d^α-LB but $X^\alpha \notin \Omega_{\min}^\alpha$. It is known that $X^\alpha \in \Omega^\alpha$ according to the definition of d^α-LB. There exists a $Y^\alpha \in \Omega_{\min}^\alpha$ such that $Y^\alpha < X^\alpha$. Then, the fact that Y^α satisfies d^α contradicts the supposition that X^α is a d^α-LB. Thus, we obtain that $X^\alpha \in \Omega_{\min}^\alpha$ if X^α is a d^α-LB. Conversely, suppose that $X^\alpha \in \Omega_{\min}^\alpha$ but X^α is not a d^α-LB, which means X^α is a minimal capacity vector in Ω^α. That is, there exists a d^α-LB Y^α such that $Y^\alpha < X^\alpha$. Then, $Y^\alpha \in \Omega^\alpha$, which contradicts $X^\alpha \in \Omega_{\min}^\alpha$. Hence, $\Omega_{\min}^\alpha$ is the set of d^α-LBs. □

2.2 *(d, T)-LBs with Delivery time*

The total delivery time consists of the service time, travel time and waiting time. Both different loading containers with commodities and different vehicles (e.g. truck or freighter) lead to different service times. This means that more containers require more time spent by workers. Moreover, the service time includes the time to load the containers to the vehicle. If the containers arrive at the transit station earlier, workers should wait until the earliest acceptable time at the transit station. This period of time is defined as the waiting time. The arrival time should be within the time window, which is the interval between the earliest and latest acceptable arrival times at the transit station.

The start processing time of containers at the source node s^α in U^α is denoted as Z^α, and the arrival time at the sink node t^α in U^α is C^α, $\alpha = 1, 2, \ldots, o$. In the first subnetwork U^1, the start processing time at the source node s^1 is

$$Z^1 = 0, \tag{5}$$

and the arrival time at the sink node t^1 is

$$C^1 = \max_{1 \le j \le m^1} \left(S\left(\left\lceil w_i^1 f_j^1 \right\rceil \right) + \sum_{a_i^1 \in E_j^1} \lambda_i^1 \right), \tag{6}$$

where $S(\lceil w_i^1 f_j^1 \rceil)$ is the expect service time for the flow f_j^1 with $\lceil w_i^1 f_j^1 \rceil$ being the corresponding number of containers. The service time may be changed due to the amount of containers. Thus, the service time is an expected (average) value for a specified transit station obtained by a long-term observation. The travel time at a_i^1 is denoted by λ_i^1, and $\sum_{a_i^1 \in E_j^1} \lambda_i^1$ is the total travel time through E_j^1 for $j = 1, 2, \ldots, m^1$. The commodities through E_j^1 reaches the sink node t^1 after ($S(\lceil w_i^1 f_j^1 \rceil) + \sum_{a_i^1 \in E_j^1} \lambda_i^1$). Maximising these times guarantees that all flows arrive at t^1.

For the other subnetwork U^α, the start processing time Z^α at the source node s^α can be presented as follows:

$$Z^a = \begin{cases} C^{\alpha-1} & \text{if}\, e_{t^{\alpha-1}} \le C^{\alpha-1} \le l_{t^{\alpha-1}} \\ e_{t^{\alpha-1}} & \text{if}\, C^{\alpha-1} \le e_{t^{\alpha-1}} \\ \text{not exist} & ;o.w. \end{cases}, \quad \text{for } a = 1, 2, \ldots, o, \tag{7}$$

The time window is defined by the earliest acceptable time $e_{t^{\alpha-1}}$ and latest acceptable time $l_{t^{\alpha-1}}$. According to the inventory cost and availability of space considerations, the times $e_{t^{\alpha-1}}$ and $l_{t^{\alpha-1}}$ are given up previously by the supervisor. When the vehicle arrives at the transit station t^α, the workers can process the containers between $e_{t^{\alpha-1}}$ and $l_{t^{\alpha-1}}$, i.e. $e_{t^{\alpha-1}} \le C^{\alpha-1} \le l_{t^{\alpha-1}}$. If the arrival time is less than $e_{t^{\alpha-1}}$, the workers should wait until $e_{t^{\alpha-1}}$. If the arrival time exceeds $l_{t^{\alpha-1}}$, the workers cannot process the containers. The arrival time at the sink node t^α can be represented as

$$C^a = Z^a + \max_{1 \le j \le m^\alpha} \left(S\left(\left\lceil w_i^\alpha f_j^\alpha \right\rceil \right) + \sum_{a_i^\alpha \in E_j^\alpha} \lambda_i^\alpha \right), \quad \text{for } a = 2, 3, \ldots, o-1. \tag{8}$$

In U^α, the commodities through E_j^α reaches the transit station t^α after ($S(\lceil w_i^\alpha f_j^\alpha \rceil) + \sum_{a_i^\alpha \in E_j^\alpha} \lambda_i^\alpha$). Maximising these times guarantees that all flows arrive at t^α. When the containers are transferred to the sink node of G, the arrival time at the sink node t^o must satisfy the time threshold T:

$$C^o \le T. \tag{9}$$

2.3 *(d, T)-LB and reliability evaluation*

According to the delivery time threshold, any capacity vector $\theta = (x_1^1, x_2^1, \ldots, x_{n^1}^1, x_1^2, x_2^2, \ldots, x_{n^2}^2, \ldots, x_1^o, x_2^o, \ldots, x_{n^o}^o)$ with $C^o \le T$ means that θ can allow d units of the commodity to be transmitted through the MILN within T. Let Γ be the set of θ with $C^o \le T$. However, enumerating all $\theta \in \Gamma$ is inefficient. In this situation, let $\Gamma_{\min}$ be the set of minimal capacity vectors that fulfil d and T. Such vectors are called (d, T)-LBs. The (d, T)-LBs can be obtained from d^α-LBs because there are no overlapping routes among subnetworks. Let $\theta = (x_1^1, x_2^1, \ldots, x_{n^1}^1, x_1^2, x_2^2, \ldots, x_{n^2}^2, \ldots, x_1^o, x_2^o, \ldots, x_{n^o}^o)$ be a (d, T)-LB, where the values of $(x_1^\alpha, x_2^\alpha, \ldots, x_{n^\alpha}^\alpha)$ are from d^α-LBs.

For example, suppose $d = 5$, $o = 2$, d^1-LB = $(x_1^1, x_2^1, x_3^1) = (1, 2, 3)$ and d^2-LB = $(x_1^2, x_2^2) = (4, 5)$. Then, $\theta = (x_1^1, x_2^1, x_3^1, x_1^2, x_2^2) = (\underline{1, 2, 3}, \underline{4, 5})$ is the minimal capacity vector ((d, T)-LB) to transmit $d = 5$ from the source s^1 to the sink t^2 through the entire network G.

The system reliability $R_{d,T}$ is defined as the probability that the MILN can successfully deliver d units of the commodity from the supplier s^1 to the market t^o within the time threshold T. That is, $R_{d,T} = \sum \Pr(\theta|\theta \in \Gamma)$. However, enumerating all $\theta \in \Gamma$ and then summing up their probabilities is not an efficient way to obtain the system reliability. Instead, this paper proposes the concept of minimal capacity vectors, i.e. (d, T)-LB, to improve the computational efficiency for system reliability evaluation. Suppose there are w (d, T)-LBs: $\theta_1, \theta_2, \ldots, \theta_w$ in total; then, $\Gamma = \{\cup_{i=1}^{w} \{\theta|\theta \geq \theta_i\}$ for $\theta_i \in \Gamma_{\min}\}$. Thus, the system reliability $R_{d,T}$ is represented as follows:

$$R_{d,T} = \Sigma \Pr\{\theta|\theta \in \Gamma\} = \Pr\left\{\bigcup_{i=1}^{w} \{\theta|\theta \geq \theta_i\} \text{ for } \theta_i \in \Gamma_{\min}\right\}. \tag{10}$$

There are several methods that can be applied to calculate $\Pr\{\cup_{i=1}^{w}\{\theta|\theta \geq \theta_i\}\}$, such as state-space decomposition, inclusion-exclusion, disjoint-event method and recursive sum of disjoint products (RSDP). The RSDP algorithm, which is based on the sum of disjoint products principle, is more efficient than the others when computing for large network. Hence, the RSDP algorithm is applied to derive the system reliability herein.

3. The algorithm to evaluate system reliability

According to the above MILN model within the delivery time threshold, an algorithm is developed to evaluate the system reliability as follows.

Input: Subnetwork U^α, demand d, MPs E_j^α, time windows $(e_{t^\alpha}, l_{t^\alpha})$, time threshold T

Step 1. For each U^α, generate d^α-LBs by the following steps:

(1.1) For $\alpha = 1$ to o, find all F^α satisfying the following demand constraint:

$$\sum_{E_j^\alpha} f_j^\alpha = d^a. \tag{11}$$

(1.2) Check each F^α whether it is a feasible flow vector or not,

$$\left\lceil \sum_{j: a_i^\alpha \in E_j^\alpha} \left\{ w_i^\alpha f_j^\alpha \right\} \right\rceil \leq M_i^\alpha \quad \text{for } i = 1, 2, \ldots, n^a. \tag{12}$$

(1.3) Transform each F^α into X^α via the following equation,

$$x_i^\alpha = \left\lceil \sum_{j: a_i^\alpha \in E_j^\alpha} \left\{ w_i^\alpha f_j^\alpha \right\} \right\rceil \quad \text{for } i = 1, 2, \ldots, n^a. \tag{13}$$

(1.4) Suppose $X_1^\alpha, X_2^\alpha, \ldots, X_{g^\alpha}^\alpha$ are d^α-LB candidates, $\Xi = \varnothing$ (Ξ is the stack which stores the indexes of d^α-LBs. Initially, Ξ is empty.)

(1.4.1) For $i = 1$ to k and $i \notin \Xi$.

(1.4.2) For $j = i + 1$ to k and $j \notin \Xi$.

(1.4.3) If $X_i^\alpha \leq X_j^\alpha$, $\Xi = \Xi \cup \{j\}$. Else $X_i^\alpha > X_j^\alpha$ $\Xi = \Xi \cup \{i\}$ and go to **Step 1.4.6**).

(1.4.4) $j \leftarrow j + 1$.

(1.4.5) X_i^α is a d^α-LB.

(1.4.6) $i \leftarrow i + 1$.

(1.5) $\alpha = \alpha + 1$ and go to Step 1.1.

Step 2. Generate (d, T)-LBs by the following steps:

(2.1) For $\alpha = 1$ to o.

(2.2) Select one d^α-LB for each subnetwork U^α.

If $\alpha = 1$, the start processing time at node s^1 is

$$Z^1 = 0, \tag{14}$$

and arrival time at node t^1 is

$$C^1 = \max_{1 \le j \le m^1} \left(S\left(\left\lceil w_i^1 f_j^1 \right\rceil \right) + \sum_{a_i^1 \in E_j^1} \lambda_i^1 \right). \tag{15}$$

Else,

the start processing time at node s^α is

$$Z^a = \begin{cases} C^{\alpha-1} & \text{if } e_{t_{\alpha-1}} \le C^{\alpha-1} \le l_{t_{\alpha-1}} \\ e_{t_{\alpha-1}} & \text{if } C^{\alpha-1} \le e_{t_{\alpha-1}} \\ \text{not exist} & ; o.w. \end{cases}, \tag{16}$$

and the arrival time at node t^α is

$$C^a = Z^a + \max_{1 \le j \le m^\alpha} \left(S\left(\left\lceil w_i^\alpha f_j^\alpha \right\rceil \right) + \sum_{a_i^\alpha \in E_j^\alpha} \lambda_i^\alpha \right). \tag{17}$$

(2.3) If the arrival time at node t^o is within the time threshold T,

$$C^o < T, \tag{18}$$

then $\theta = (x_1^1, x_2^1, \ldots, x_{n^1}^1, x_1^2, x_2^2, \ldots, x_{n^2}^2, \ldots, x_1^o, x_2^o, \ldots, x_{n^o}^o)$ is a (d, T)-LB where the values of $(x_1^\alpha, x_2^\alpha, \ldots, x_{n^\alpha}^\alpha)$ are from d^α-LBs.

(2.4) Back to Step 2.2 for next selection.

Step 3. Suppose $\theta_1, \theta_2, \ldots, \theta_w$ are all (d, T)-LBs. Use the RSDP to calculate

$$R_{d,T} = \Pr\left\{ \bigcup_{i=1}^{w} \{\theta | \theta \ge \theta_i\} \right\}. \tag{19}$$

Output: System reliability $R_{d,\ T}$.

In Step 1, we generate a total of g^α d^α-LBs for each U^α. In order to generate (d, T)-LBs in Step 2, there are at most $\prod_{\alpha=1}^{o} g^\alpha$ capacity vectors in the MILN and delete those capacity vectors whose arrival time at node t^o violates the time threshold T. Then the remainders are all (d, T)-LBs. Step 3 calculates $R_{d,\ T}$ by the RSDP.

4. An illustrative example

A simple logistics system shown in Figure 1 is adopted to illustrate the proposed algorithm; there are one supplier, two transit stations, two main stations, one market, six routes and the corresponding travel times (unit: hour). Table 1 lists the probability of each route's capacity, which is measured in twenty-foot equivalent unit (TEU). Table 2 lists the

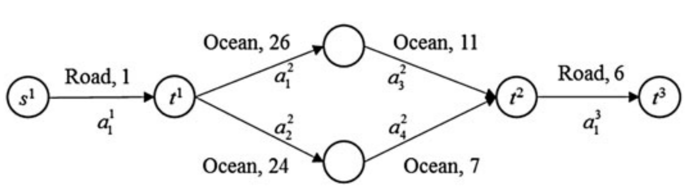

Figure 1. A simple intermodal logistics network.

Table 1. The probability of route's capacity in Figure 1.

Route	Capacity (unit: TEU) 0	1	2	3	4
a_1^1	0.01	0.01	0.04	0.07	0.87
a_1^2	0.01	0.05	0.05	0.08	0.81
a_2^2	0.01	0.02	0.05	0.1	0.82
a_3^2	0.01	0.01	0.05	0.93	0
a_4^2	0.005	0.005	0.02	0.97	0
a_1^3	0.01	0.02	0.06	0.91	0

Table 2. The data of service time.

Type	Service time (unit: h) $S(0)$	$S(1)$	$S(2)$	$S(3)$	$S(4)$
Truck	0	1	1	2	2
Freighter	0	2	3	4	5

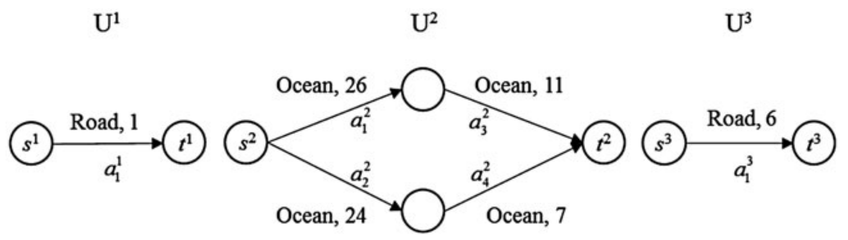

Figure 2. Three subnetworks U^1, U^2 and U^3.

service time data depending on the number of TEUs and type of vehicle (truck or freighter). Figure 2 shows three subnetworks decomposed from Figure 1. Note that $s^2 = t^1$ and $s^3 = t^2$. The time window at node t^1 is set to $\{e_{t^1}, l_{t^1}\} = \{2, 5\}$ and that at node t^2 is set to $\{e_{t^2}, l_{t^2}\} = \{36, 43\}$, $w_i^1 = w_i^2 = w_i^3 = 0.6$, $d = 3$ and $T = 51$ h. The following steps describe how to evaluate the system reliability.

Step 1. For each U^α ($\alpha = 1, 2, 3$), generate d^α-LBs by the following steps:

(1.1a) $\alpha = 1$. For U^1, find all $F^1 = (f_1^1)$ satisfying the following demand constraint:

$f_1^1 = 3$. Then $F^1 = (3)$.

(1.2a) Utilise the following constraints to check whether F^1 is a feasible flow vector or not.

$\lceil 0.6 \times f_1^1 \rceil \leq 4$,

and this flow vector $F^1 = (3)$ passes this constraint.

(1.3a) Transform each F^1 into X^1 via the following equation,

$x_1^1 = 2$. We obtain $X_1^1 = (2)$.

(1.4a) After comparison, d^1-LB = (2).

(1.1b) $\alpha = 2$. For U^2, find all $F^2 = (f_1^2, f_2^2)$ satisfying the following demand constraint:

$f_1^2 + f_2^2 = 3$.

This step generates 4 flow vectors: (0, 3), (1, 2), (2, 1), (3, 0). The results are also listed in the second column of Table 3.

(1.2b) Utilise the following constraints to check whether each F^2 is a feasible flow vector or not

$\lceil 0.6 \times f_1^2 \rceil \leq 4$,

$\lceil 0.6 \times f_2^2 \rceil \leq 4$,

Table 3. The results of d^{α}-LBs.

α	Step 1.1 F^{α}	Step 1.2 Is F^{α} feasible?	Step 1.3 d^{α}-LB candidates	Step 1.4 d^{α}-LBs
1	$F_1^1 = (3)$	Yes	$X_1^1 = (2)$	X_1^1 is d^1-LB
2	$F_1^2 = (0, 3)$	Yes	$X_1^2 = (0, 2, 0, 2)$	X_1^2 is d^2-LB
	$F_2^2 = (1, 2)$	Yes	$X_2^2 = (1, 2, 1, 2)$	No, $X_2^2 > X_1^2$
	$F_3^2 = (2, 1)$	Yes	$X_3^2 = (2, 1, 2, 1)$	No, $X_3^2 > X_4^2$
	$F_4^2 = (3, 0)$	Yes	$X_4^2 = (2, 0, 2, 0)$	X_4^2 is d^2-LB
3	$F_1^3 = (3)$	Yes	$X_1^3 = (2)$	X_1^3 is d^3-LB

$\lceil 0.6 \times f_1^2 \rceil \leq 3$,
$\lceil 0.6 \times f_2^2 \rceil \leq 3$.
All of four flow vectors pass these constraints.
(1.3b) Transform each F^2 into X^2 via the following equations,
$x_1^2 = 0$,
$x_2^2 = 2$,
$x_3^2 = 0$,
$x_4^2 = 2$.
There are four capacity vectors: (0, 2, 0, 2), (1, 2, 1, 2), (2, 1, 2, 1) and (2, 0, 2, 0) (listed in the fourth column of Table 3).

(1.4b) After comparison, two out of four capacity vectors are d^2-LBs: (0, 2, 0, 2), and (2, 0, 2, 0). In total, all d^2-LBs are listed in the fifth column of Table 3.

(1.1c) $\alpha = 3$. For U^3, find all $F^3 = (f_1^3)$ satisfying the following demand constraint:
$f_1^3 = 3$. Then $F^3 = (3)$.
(1.2c) Utilise the following constraints to check whether F^3 is a feasible flow vector or not.
$\lceil 0.6 \times f_1^3 \rceil \leq 3$,
and this flow vector passes this constraint.
(1.3c) Transform each F^3 into X^3 via the following equation,
$x_1^2 = 0$, we obtain $X_1^3 = (2)$.
(1.4c) After comparison, d^3-LB = (2).
Step 2.Generate all (3, 51)-LBs by the following steps:
(2.1a) $\alpha = 1$. Choose $X^1 = (3)$.
(2.2a) The start processing time at source node s^1 is $Z^1 = 0$ and arrival time at sink node t^1 is
$C^1 = S(\lceil w_1^1 f_1^1 \rceil) + \sum_{a_i^1 \in E_j^1} \lambda_i^1 = 1 + 1 = 2$.
(2.1b) $\alpha = 2$. Choose $X^2 = (0, 2, 0, 2)$.
(2.2b) The start processing time at node s^2 is
$Z^2 = 2$ since $e_{t^1} \leq C^1 \leq l_{t^1}$,
and the arrival time at node t^2 is
$C^2 = Z^1 + \max_{1 \leq j \leq 2}(S(\lceil w_i^2 f_j^2 \rceil) + \sum_{a_i^2 \in E_j^2} \lambda_i^2) = 2 + \max(0, 3 + 24 + 7) = 36$.
(2.1c) $\alpha = 3$. Choose $X^3 = (2)$.
(2.2c) $Z^3 = 36$ since $e_{t^2} \leq C^2 \leq l_{t^2}$,
and the arrival time at node t^2 is
$C^3 = Z^2 + S(\lceil w_1^3 f_1^3 \rceil) + \sum_{a_i^3 \in E_j^3} \lambda_i^3 = 36 + 1 + 6 = 43$.
(2.3) C^3 follows the time threshold T. Then $\theta_1 = (\underline{2}, \underline{0, 2, 0, 2}, \underline{2})$ is a (3, 51)-LB.
⋮
$\theta_2 = (\underline{2}, \underline{2, 0, 2, 0}, \underline{2})$ is a (3, 51)-LB.
Step 3. θ_1 and θ_2 are (3, 51)-LBs from Step 2. The system reliability $R_{3,\ 51} = 0.9476$ by executing the RSDP.

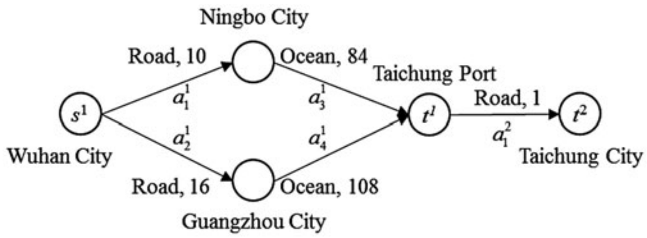

Figure 3. Intermodal logistics network of scooter parts.

5. A case study of scooter parts distribution between Taiwan and China

Ever since Taiwan and China signed the Economic Cooperation Framework Agreement, many scooter parts distributors in Taiwan have expanded their supply system to China because China is the second biggest importer of scooter parts from Taiwan. The proposed algorithm is applied to the retail sale of scooter parts in Taichung City, Taiwan. The main manufacturer is located in Wuhan City, China, and the scooter parts are delivered to Taichung Port via Ningbo City or Guangzhou City before finally reaching Taichung City. Figure 3 illustrates the intermodal logistics network that can be decomposed into two subnetworks: the first is from Wuhan City s^1 to Taichung Port t^1 and the second is from Taichung Port s^2 (notably, $s^2 = t^1$) to Taichung City t^2.

This case focused on the starter, which is a scooter part. Scooter parts such as the starter, gear, brake shoes are packed into several boxes shipped together in a certain combination because of the tariff (details are presented in Table 4). When these scooter parts are delivered by sea with a freighter or by road with a truck, they are loaded into one or more refrigerated TEU which can load a maximum of 19,832 kg. One unit of demand for starter is counted in terms of 3810 kg. That is, one unit of demand for a starter consumes approximately 0.192 refrigerated TEU. Because the containers can be shipped via truck or freight, the consumed capacity of each subnetwork is the same: $w_i^1 = w_i^2 = \cdots = w_i^o = 0.192$. The capacity data of carriers on routes are presented in Table 5. Each carrier on the route owns multiple capacities of 0, 1 TEU, …, 8 TEU with a probability distribution from the carriers' database. Table 6 lists the service time data depending on the number of TEUs and type of vehicle. In the intermodal logistics network of scooter parts (refer to Figure 3), the time window of Taichung Port is {108, 130}, and the travel times (unit: hour) for each route are $\lambda_1^1 = 10$, $\lambda_2^1 = 16$, $\lambda_3^1 = 84$, $\lambda_4^1 = 108$ and $\lambda_1^2 = 1$. The data are taken from the agency's database.

The following case is considered: $d = 15$ starters and $T = 133$ h. When the proposed algorithm is executed, four d^1-LBs for U^1 and one d^2-LB for U^2 are generated, as presented in Table 7. In order to find all (15, 133)-LBs, we generate Z^α and C^α and check whether the arrival time at Taichung City for each capacity vector in the MILN meets the time threshold or not. In total, three (15, 133)-LBs are obtained: (1, 2, 1, 2, 3), (2, 1, 2, 1, 3) and (3, 0, 3, 0, 3). The system reliability is 0.9114.

Table 4. The scooter parts of 1 TEU.

Part No.	Boxes	Description	Number	kg
1–206	206	DISC BRAKE	4120	2898
207–317	111	STARTER CUTCH	4813	2388
318–328	11	AIR CLEANER ASSY	144	121
329–367	39	HORN	3540	507
368–470	103	FR FORK COMP	515	1751
471–733	263	FORK SET	1284	4482
734–800	67	CHSHION, REAR	955	1171
801–874	74	MASTER CYLINDER	3587	2269
875–938	64	DRIVE AXLE ASSY	300	435
939–1130	192	STARTING MOTOR	3920	3810
Total	1130 boxes			19,832 kg

Table 5. The probability of route's capacity in Figure 3.

Route	Capacity (unit: TEU)								
	0	1	2	3	4	5	6	7	8
a_1^1	0.002	0.008	0.05	0.05	0.89	0	0	0	0
a_2^1	0.01	0.03	0.04	0.04	0.06	0.82	0	0	0
a_3^1	0.006	0.007	0.007	0.011	0.013	0.016	0.016	0.024	0.9
a_4^1	0.003	0.003	0.004	0.007	0.012	0.013	0.013	0.02	0.925
a_1^2	0.01	0.03	0.04	0.05	0.87	0	0	0	0

Table 6. The data of service time.

Type	Service time (unit: h)								
	$S(0)$	$S(1)$	$S(2)$	$S(3)$	$S(4)$	$S(5)$	$S(6)$	$S(7)$	$S(8)$
Truck	0	1	2	3	4	5	6	7	8
Freighter	0	2	3	4	5	6	7	8	9

Table 7. The results of d^α-LBs.

α	Step 1.1 F^α	Step 1.2 Is F^α feasible?	Step 1.3 d^α-LB candidates	Step 1.4 d^α-LBs
1	$F_1^1 = (0, 15)$	Yes	$X_1^1 = (0, 3, 0, 3)$	(0, 3, 0, 3)
	$F_2^1 = (1, 14)$	Yes	$X_2^1 = (1, 3, 1, 3)$	No, $X_2^1 > X_1^1$
	$F_3^1 = (2, 13)$	Yes	$X_3^1 = (1, 3, 1, 3)$	No, $X_3^1 > X_1^1$
	$F_4^1 = (3, 12)$	Yes	$X_4^1 = (1, 3, 1, 3)$	No, $X_4^1 > X_1^1$
	$F_5^1 = (4, 11)$	Yes	$X_5^1 = (1, 3, 1, 3)$	No, $X_5^1 > X_1^1$
	$F_6^1 = (5, 10)$	Yes	$X_6^1 = (1, 2, 1, 2)$	(1, 2, 1, 2)
	$F_7^1 = (6, 9)$	Yes	$X_7^1 = (2, 2, 2, 2)$	No, $X_7^1 > X_6^1$
	$F_8^1 = (7, 8)$	Yes	$X_8^1 = (2, 2, 2, 2)$	No, $X_8^1 > X_6^1$
	$F_9^1 = (8, 7)$	Yes	$X_9^1 = (2, 2, 2, 2)$	No, $X_9^1 > X_6^1$
	$F_{10}^1 = (9, 6)$	Yes	$X_{10}^1 = (2, 2, 2, 2)$	No, $X_{10}^1 > X_6^1$
	$F_{11}^1 = (10, 5)$	Yes	$X_{11}^1 = (2, 1, 2, 1)$	(2, 1, 2, 1)
	$F_{12}^1 = (11, 4)$	Yes	$X_{12}^1 = (3, 1, 3, 1)$	No, $X_{12}^1 > X_{11}^1$
	$F_{13}^1 = (12, 3)$	Yes	$X_{13}^1 = (3, 1, 3, 1)$	No, $X_{13}^1 > X_{11}^1$
	$F_{14}^1 = (13, 2)$	Yes	$X_{14}^1 = (3, 1, 3, 1)$	No, $X_{14}^1 > X_{11}^1$
	$F_{15}^1 = (14, 1)$	Yes	$X_{15}^1 = (3, 1, 3, 1)$	No, $X_{15}^1 > X_{11}^1$
	$F_{16}^1 = (15, 0)$	Yes	$X_{16}^1 = (3, 0, 3, 0)$	(3, 0, 3, 0)
2	$F_1^2 = (15)$	Yes	$X_1^2 = (3)$	$X_1^2 = (3)$

6. Numerical experiments

A manager would worry about the lower system reliability and would like to improve it. Utilising the scooter parts case, the sensitivity analysis on the system reliability is conducted by changing the time threshold and demand. The time threshold T from 116 to 136 in increments of 4, and the demand constraint d from 5 to 20 in increments of 5 are tested. The experimental results are summarised in Table 8. The proposed algorithm is programmed with MATLAB and executed on a personal computer with Core™ i7-6700 CPU 3.4 and 4G RAM. The average CPU time to execute the proposed algorithm is less than 5×10^{-4} s. For the same demand constraint d of 15, the system reliability increases from

Table 8. The system reliability of various demand and time threshold.

	Demand (unit: starter)			
Time (unit: h)	5	10	15	20
116	0.9821	0.938	0.8475	0.7503
120	0.9821	0.938	0.8475	0.7503
124	0.9821	0.938	0.8475	0.7503
128	0.9821	0.938	0.8475	0.7503
132	0.9899	0.9595	0.8983	0.8008
136	0.9899	0.9595	0.9114	0.8472

0.8475 ($T = 128$) to 0.8983 ($T = 132$) because the commodities could only be transported via Ningbo City when $T = 128$ while the commodities could be transported via Guangzhou City or Ningbo City when $T = 132$. Hence, the time threshold is suggested to be above 132 h and an alternative appropriate time threshold is 136 h because the system reliability does not increase significantly when $T > 136$. Figure 4 shows the trend of the time (116 - 136 h) versus system reliability.

We also observe the influence of the demand on the system reliability. When the demand increases, the consumed capacity on the route may exceed the maximal capacity, or more containers may mean that the workers need to spend more time. Figure 5 shows the trend of demand (5–20 units of starters) versus the system reliability. When $T = 136$, the system reliability decreases significantly from 0.9899 ($d = 5$) to 0.8472 ($d = 20$). When the system reliability is set to be more than 0.9, the combination of the demand and time threshold should be ($d \le 15$, $T \ge 136$) or ($d \le 10$, $T \ge 116$). Both settings are good choices if the manager merely requires the system reliability to exceed 0.9.

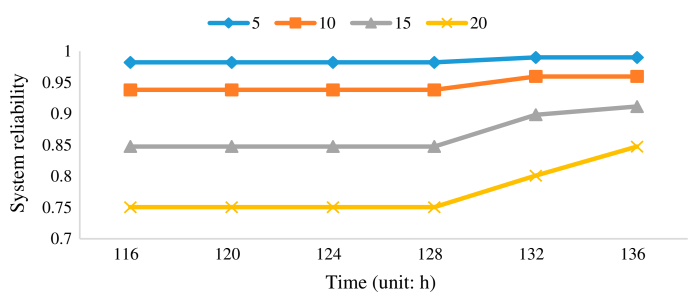

Figure 4. The system reliability for different times.

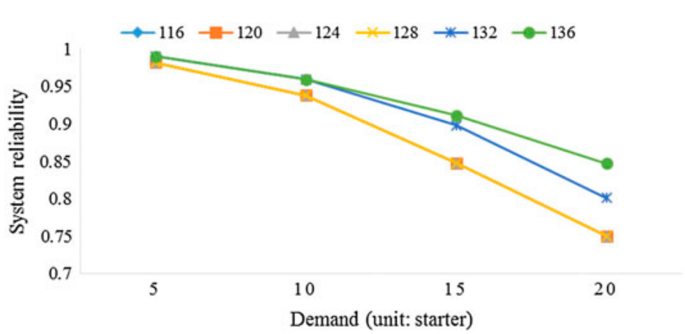

Figure 5. The system reliability for various demands.

7. Conclusions

This paper considers the route's capacity, delivery time and time window of a multistate intermodal logistics network (MILN). The MILN is decomposed into two or more subnetworks based on the transit stations. When the containers arrive at a transit station early, the workers should wait until the earliest acceptable time to process the containers. If the arrival time is within the time window, the workers can process the containers immediately. In the past, no studies developed an algorithm that considers the time windows and demand for an MILN together to evaluate the system reliability, which is the probability that MILN can successfully deliver sufficient amount of the commodity to meet the market demand via several transit stations within the delivery time threshold and time windows. We develop an algorithm to find all d^{α}-LBs for each subnetwork first and then delete those capacity vectors whose arrival time at sink node t^{o} violates the time threshold T. The remainder can generate all (d, T)-LBs. The RSDP is adopted to compute the system reliability in terms of all (d, T)-LBs. A practical case of scooter parts distribution between Taiwan and China is used to demonstrate the proposed algorithm. From a decision-making viewpoint, the system reliability can be regarded as a delivery performance index for logistics activity in supply chain management. Furthermore, a manager can conduct a sensitivity analysis on the system reliability to find the appropriate threshold and make better choices.

Although we have addressed an MILN to evaluate the system reliability, there are still several issues that should be addressed with regard to the current study. For example, commodities may be spoiled or rot during delivery due to traffic accidents, collisions, natural disasters, weather, time, etc. Thus, the intact commodities may not satisfy the market demand. Budget issues, such as how much money should the carrier spend during delivery, also need to be considered. Besides, the delivery time in this paper focus on formulating the delivery time model for the MILN. How to evaluate the service, waiting and delivery times on routes and nodes in detail with practical situation is also worth studying in the future. These issues can be discussed in the future.

Disclosure statement

No potential conflict of interest was reported by the authors.

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