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## Investigation of the influence of transit time on a multistate transportation network in tourism

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### Highlights

- Propose an algorithm to investigate how transit times affect the performance of an MTN.
- A performance indicator termed “reliability” is used as a basis for the investigation.
- The sufficient levels of transit time are determined to examine.
- Provide management suggestions about appropriate transit times to maintain reliability.


### Abstract

Abstract

Reliability has been widely used as a potential indicator of the performance assessment for several real-life networks. Focus on a multistate transportation network in tourism (MTN), this study evaluates the reliability of the MTN as a basis for investigating the influence of transit time. Reliability is the probability to fulfill transportation demand under the given time threshold and budget limitation and evaluated at various levels of transit times. An algorithm, which employs the boundary points and recursive sum of disjoint products technique, is proposed to evaluate the MTN reliability. According to the obtained results, this paper analyzes the influence of transit times on MTN reliability. Particularly, this paper discusses and provides some suggestions about the appropriate transit time to maintain reliability. Decision-makers in the tourism industry also can predetermine the significant drops of reliability to improve the relevant transit times. Besides, the proposed investigation is indicated and proved through an illustrative example and a practical case.

### Keywords

multistate transportation network, reliability, transit times, budget limitation, time threshold.

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## 1. Introduction

A transportation network, which combines various modes of transport such as sea, air, road, and rail, becomes more popular and is applied in many systems [1, 8, 11, 14, 20, 23, 28, 34]. Toward environmental and economic sustainability, decision-makers in logistics management often consider trains, trucks, and barges to design their multimodal transportation networks [14, 34]. As a crucial part, a transportation network contributes to thriving travel agents who business the tourism industry [2, 3, 30]. Besides, maintaining service quality stable and reliable is vital from the management perspective in most service industries. Thus, a reliable transportation network can efficiently complete operational functions and smoothly provide customers high-quality tourism services. It raises a need to evaluate the performance of transportation networks in tourism. In recent decades, reliability, which is the ability to complete requested functions/ tasks under given constraints in a predetermined period, is an appropriate and widely used performance indicator [7]. In terms of connectivity

performance, reliability has been defined as the probability that the source can link with the sink [10, 31]. Concerning the terms “flow” and “capacity”, the ability to fulfill a required demand is considered as reliability [6, 9, 11, 25]. For instance, reliability has been studied as the probability that a logistic network can deliver a given volume of goods to a specific destination [11]. Considering on-time performance, Nguyen and Lin [25] measured reliability as the ability of an air transport network to successfully carry a given number of passengers to the final destinations within a specific time threshold. To address the reliability evaluation, various methods including cross-entropy [24], state enumeration [21], percolation theory [16, 19], and minimal cut-sets and path-sets [25, 26, 31, 32] have been proposed.

Furthermore, many studies consider time and budget, which are two of the key influencing factors in customer satisfaction and transportation choices [8, 15, 17, 18, 22, 27], when investigating the reliability of transportation networks. Survey the transport behavior during the COVID-19 pandemic, Das et al., indicated a significant

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impact of some factors including monthly income and travel time on the transport switch of the participants [8]. Besides, the flights operated by low-cost carriers at Incheon international airport (Korea) reported a double increase during the year 2012 to 2015, which differs from a 10% growth of full-service carriers [12]. In the same report, the passenger market share of low-cost carriers increased from 5.7% in 2012 to 15.9% in 2015. This boom of low-cost carriers infers an attractiveness of price to customers [5, 13]. In developing countries, people with low income tend to have a higher frequency of using public transports [1]. This issue may be explained by the budget gap between the two groups. Regarding transportation time, the choice of customers may be affected by both the time to change routes if necessary and the total transportation time. For example, if the first choice for customers to arrive at the destination is taking a bus in one and a quarter-hour to the nearest airport thirty minutes before their one-hour flight. Another choice is riding a public bike in forty to the metro station in their area, walking around fifteen minutes to enter the metro line, then taking the two-hour metro to the destination. Clearly, the first choice takes ten minutes less time than the second one, but its transit time from bus to flight is a half-hour while that of the second choice is only fifteen minutes. Thus, customers may choose the second choice if they have enough time and do not want to check-in at the airport; otherwise, the first choice is a priority. Simply speaking, not only the total transportation time but also transit times (i.e., the required time to transfer between two routes in the tourism trip) are considered by customers. Since the transit time is the necessary time to take the next route, the transit time in the first choice is thirty minutes to walk from the bus station to the boarding gate of the flight, check-in, and customs check. In the second choice, the transit time infers the time that is around fifteen minutes for entering the metro line from the bicycle parking. Obviously, shortening the transit time can reduce the total transportation time and let customers enjoy journeys with multiple transport modes. However, not many studies appraise the effect on the transportation networks' reliability of the transit time. Therefore, this study targets to fill this academic gap.

The purpose of this study is to provide a new reliability-based approach to investigate the influence of transit time. Normally, a transportation network in tourism is a combination of air, sea, and road networks [23]. Like the studies in the literature [11, 20, 28], the transportation network in tourism is a typical flow-network that contains vertices (i.e., stations, airports, seaports) and directed edges (routes). Each route connecting a pair of stations is served by a particular vehicle and its capacity is the number of available seats. In general, the capacity is given and depends on the vehicle's size and design. However, some seats may be booked or reserved by others such as individual tourists and travel agents/ tours operators. That is, the capacity (available seats) of edges is multistate. Regarded as multistate capacity, a transportation network in tourism can be formulated as a multistate flow-network [32, 33, 35]. "A multistate transportation network (MTN)" is referred to as a transportation network in tourism herein. The MTN's reliability is calculated as the probability to meet transportation demand within a specific time threshold and budget limitation under different required transit times. To address the research problem, an algorithm, which employs the concept of boundary points, is proposed for evaluating reliability and analyzing the influence of transit times accordingly. Simultaneously, this study applies the recursive sum of disjoint product (RSDP) technique [4, 33] to compute reliability as the probability of the MTN's states demarcated by the boundary points. As a basis, the obtained reliability contributes to indicating the performance of the MTN and investigating the effect of transit time. In addition, appropriate transit times are provided towards a more reliable performance of the MTN.

## 2. MTN model

In this section, the constructed model of a multistate transportation network (MTN) is introduced first. An MTN is characterized by  $V$  – set of vertices (stations),  $E$  – set of directed edges (routes)  $e_j$  for  $j = 1, 2, \dots, m$ ,  $G$  – set of transport costs  $g_j$ , and  $M$  – set of transport modes. Besides, the maximal capacity vector  $C = (c_1, c_2, \dots, c_m)$  bounds all states (capacity vectors,  $Y$ ) of the MTN. Thus, the maximal capacity  $c_j$  of each edge limits its current capacity  $y_j$  and flow  $f(e_j)$ . In short, the MTN is denoted as  $N = (V, E, G, M, C)$ . Each directed edge  $e_j$  in  $E$  is scheduled to move from its departure station  $d_j$  at  $td_j$  (departure time) to its arrival station  $a_j$  at  $ta_j$  (arrival time). Note that  $d_j$  and  $a_j$  belong to  $V$ . Besides, each edge uses a particular transport mode ( $m_j \in M$ ) with a specific transport cost ( $g_j \in G$ ). The remaining notations are listed below.

$s, t$	source and sink, $\in V$
$f(s, t)$	flow from $s$ to $t$
$T$	time threshold
$B$	budget limitation
$A$	transportation demand
$w$	transit time between the same modes
$w^*$	transit time between different modes
$W$	$(w, w^*)$ : transit time vector
$W \leq W^i$	$i^{\text{th}}$ level of transit times
$P_k$	minimal path feasible under $T$ and $B$ (MTBP)
$\mathbf{P}$	set of all MTBPs
$U_k$	$(u, u^*)$ : maximal transit time vector that guarantees the validity of $P_k$
$\mathbf{P}^i$	set of all feasible $P_k$ if $W \leq W^i$
$f(P_k)$	flow through the minimal path $P_k \in \mathbf{P}^i$
$F$	$(f(P_k)   P_k \in \mathbf{P}^i)$ : flow vector feasible under $T$ and $B$ with $W \leq W^i$
$\mathbf{F}^i$	set of all flow vectors meeting $A$ under $T$ and $B$ with $W \leq W^i$
$Y$	$(y_1, y_2, \dots, y_m)$ : capacity vector
$X^i$	set of lower boundary point (LBP) candidates
$L^i$	set of lower boundary points of $X^i$
$R_{B,A,T}^i$	reliability that $N$ can meet transportation demand $A$ under time threshold $T$ and budget limitation $B$ transit times $W \leq W^i$

Furthermore, the following are all assumptions made in this study.

- (i) The conservation law of flows is followed.
- (ii) The capacity of all routes is independent statistically.
- (iii) Transit times between the same and different transport modes are considered.
- (iv) All routes are on time.

## 3. Assess the MTN reliability

According to the research problem, it is not efficient to calculate the reliability of all transit times  $W = (w, w^*)$ , where  $w$  and  $w^*$  are the required time for transferring to the next route with the same transport mode and different transport mode, respectively. In this study, we consider different levels of transit times,  $W \leq W^i$ , and accordingly assess the MTN's reliability ( $R_{B,A,T}^i$ ). Note that all transit times ( $W \leq W^i$ ) have the same influence on reliability, and reliability is the probability to satisfy transportation demand  $A$  under the time threshold  $T$  and budget limitation  $B$ . In other words,  $R_{B,A,T}^i$  is the probability that

the MTN can transport at least  $A$  passengers within  $T$  hours and the total transport cost does not exceed  $B$  with the required transit time  $W \leq W^t$ . Let  $Y$  be a capacity vector meeting  $A$  under  $T$  and  $B$  with  $W \leq W^t$  and store it in  $\Delta$ . Any capacity vectors satisfying the following condition belong to  $\Delta$ .

**Condition 1.** Under time threshold  $T$  and budget limitation  $B$  with the required transit time  $W \leq W^t$ , there are at least  $A$  passengers transported. The MTN's reliability is the probability of all  $Y$ s in  $\Delta$ ,  $R_{B,A,T}^i = \Pr\{\bigcup_{Y \in \Delta} \{Y | Y \leq C\}\}$ . However, employing the concept of all upper and lower boundary points to calculate is more efficient than enumerating to determine the set  $\Delta$ . In fact, both lower and upper boundary points are in  $\Delta$  such that none in  $\Delta$  is less than lower boundary points (LBP) and greater than upper boundary points (UBP). That means any  $Y$  in  $\Delta$  is between at least one LBP and one UB. Note that the maximal capacity vector  $C$  is the only UB of the MTN and the LBPs ( $X$ ) must meet not only Condition 1 but also Condition 2.

**Condition 2.** There exists no  $Y \in \Delta$  that  $Y \leq X$ .

After determining all LBPs and storing them in a set  $L^i$ , the following formula is used to compute the reliability:

$$R_{B,A,T}^i = \Pr\{\bigcup_{X \in L^i} \{Y | X \leq Y \leq C\}\} \quad (1)$$

### 3.1. Minimal paths feasible under time threshold and transit times

To partly fulfill Condition 1, we first determine all minimal paths feasible under  $T$  and  $B$  (MTBPs). Namely, a MTBP is a sequence of edges that can link  $s$  to  $t$  within  $T$  hours and  $B$  with  $W \leq W^t$  and do not visit any vertex twice. Assume that all MTBPs are stored in  $\mathbf{P}^i$ . Each  $P_k$  in  $\mathbf{P}^i$  must satisfy that:

- If  $e_j$  is the first edge and  $e_h$  is the last edge of  $P_k$  then
  - The edge  $e_j$  departs from the source ( $d_j = s$ ).
  - The edge  $e_h$  arrives at the sink ( $a_h = t$ ).
  - The transportation time on  $P_k$  does not exceed the time threshold ( $ta_h - td_j \leq T$ ).
- Only edge  $e_j$  arrives at the departure station of  $e_h$  ( $a_j = d_h$ ) with  $W = (w, w^*)$  satisfying the following can connect to  $e_h$ .
  - If the transport mode of two edges is the same ( $m_j = m_h$ ) then  $td_h \geq ta_j + w$ .
  - Otherwise,  $td_h \geq ta_j + w^*$ .
- The total transport cost on  $P_k$  does not exceed the limitation budget ( $\sum_{e_j \in P_k} g_j \leq B$ ).

Let  $f(P_k)$  be a flow through the minimal path  $P_k$ . Based on the conservation law and the MTN's capacity, the following constraints must be satisfied:

$$\begin{cases} f(e_j) = \sum_{e_j \in P_k} f(P_k) \\ f(e_j) \leq c_j \end{cases}, \text{ for } j = 1, 2, \dots, m. \quad (2)$$

Consequently, a flow vector  $F = (f(P_k) | P_k \in \mathbf{P}^i)$  meeting the time threshold  $T$  and budget limitation  $B$  with transit times  $W \leq W^t$  is feasible under capacity  $Y$  if:

$$\sum_{e_j \in P_k} f(P_k) \leq y_j \leq c_j, \text{ for } j = 1, 2, \dots, m. \quad (3)$$

Like constraint (2),  $f(s, t) = \sum_{P_k \in \mathbf{P}^i} f(P_k)$ . The remaining of Condition 1 becomes:

$$f(s, t) \geq A \text{ where } f(s, t) = \sum_{P_k \in \mathbf{P}^i} f(P_k). \quad (4)$$

Hence, any capacity vector ( $X$ ) is said to belong to  $\Delta$  if its feasible flows ( $F$ ) meet constraint (5).

$$\sum_{P_k \in \mathbf{P}^i} f(P_k) \geq A, \text{ for } j = 1, 2, \dots, m. \quad (5)$$

### 3.2. Lower boundary points and reliability evaluation

From all capacity vectors ( $Y$ ) above, Condition 2 is tested to obtain lower boundary points ( $X$ ). Let  $\mathbf{F}^i$  be a set of all flow vectors fulfilling the following constraint:

$$\sum_{P_k \in \mathbf{P}^i} f(P_k) = A \quad (6)$$

Any capacity vector  $X = (x_1, x_2, \dots, x_m)$  satisfying constraint (6) and the following constraint belongs to  $\Delta$ . They are less than or equal to other capacity vectors  $Y \in \Delta$  that  $\sum_{e_j \in P_k} f(P_k) \leq y_j \leq c_j$  for at least one  $j$  or  $\sum_{P_k \in \mathbf{P}^i} f(P_k) > A$ :

$$\sum_{e_j \in P_k} f(P_k) = x_j, \text{ for } j = 1, 2, \dots, \quad (7)$$

However, it is not sufficient for them to meet condition 2 because they may less than or equal to others. Hence, they are called lower boundary point candidates herein. Remark 1 indicates the features of an LBP candidate.

**Remark 1.**  $X$  is an LBP candidate if at least one  $F$  that satisfies constraints (6) and (7).

Let  $\mathbf{X}^i$  store all LBP candidates. To gain exact LBPs in  $L^i$ , compare and remove the duplicates and the components that are greater than others from  $\mathbf{X}^i$ . By applying the RSDP method [4, 35], the MTN's reliability can be easily derived through the formula (8):

$$R_{B,A,T}^i = \Pr\{\bigcup_{X \in L^i} \{Y | X \leq Y \leq C\}\} \quad (8)$$

### 3.3. Main algorithm to investigate the influence of transit time on the MTN reliability

The provided process describes how to evaluate the MTN reliability. However, to examine the effect of different transit times on reliability, evaluating reliabilities under all possible transit times is not efficient enough. This study employs the reliability evaluation and proposes an assessment algorithm under the budget limitation and time threshold. Firstly, suppose that the transit times are not required,  $W = (0, 0)$ , we determine all minimal paths ( $P_k$ ) feasible under  $B$  and  $T$  then record them in a set  $\mathbf{P}^0$ . Simultaneously, obtain the maximal transit time  $U_k = (u, u^*)$  – the validity condition of each  $P_k$ . Namely, each MTBP ( $P_k$ ) is valid if  $W \leq U_k$ ; otherwise, it is broken. A search procedure shown in Fig. 1 is developed to determine all MTBPs in  $\mathbf{P}^i$  and their corresponding maximal transit time vectors.

Without considering the impact of transit times, the set  $\mathbf{P}^0$  contains all possible minimal paths of the MTN. And some of MTBPs in  $\mathbf{P}^0$  may be broken at a specific  $W = (w, w^*)$  that  $w > u$  and/ or  $w^* > u^*$ .

$$\sum_{P_k \in \mathbf{P}^i} f(P_k) = A, \text{ for } j = 1, 2, \dots, m. \quad (9)$$

Step 3.3: Through the following equation, convert from each  $F$  in  $\mathbf{F}^i$  to gain LBP candidates  $X$  and store in  $\mathbf{X}^i$ :

$$x_j = \sum_{e_j \in P_k} f(P_k), \text{ for } j = 1, 2, \dots, m. \quad (11)$$

Step 3.4: Compare all candidates in  $\mathbf{X}^i$  to remove the duplicates and the components that are greater than others. Exact LBPs are obtained as a set  $\mathbf{L}^i$ .

Step 3.5: By utilizing the RSDP method, compute the MTN's reliability as equations (12):

$$R_{B,A,T}^i = \Pr\left\{ \bigcup_{X \in \mathbf{L}^i} \{Y | X \leq Y \leq C\} \right\}. \quad (12)$$

Step 4: List all reliabilities under different levels of transit time in order of  $W^i$ .

#### 4. Numerical example

This section introduces an MTN example that consists of four stations, eight routes, and three transport modes, shown in Fig. 2. Then, we demonstrate how to analyze the impacts of transit times on the MTN's reliability. The source is the first station, and the sink is the last station. The relevant data of eight routes in the MTN is shown in Table 1. After applying the main algorithm, the MTN's reliabilities to meet transportation demand  $A = 80$  passengers under budget limitation  $B = 200$  USD and time threshold  $T = 8$  hours with different transit times are evaluated as follows:

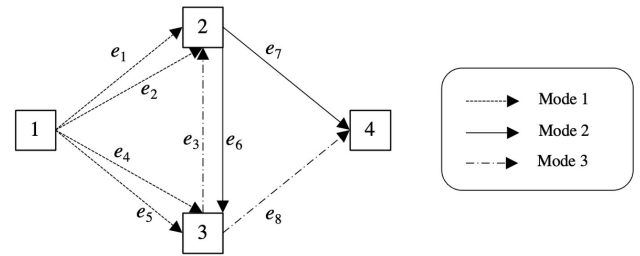


Fig. 2. An MTN example

Table 1. The relevant data about all routes in the MTN

Route	Departure - Arrival time	Departure - Arrival station	Transport mode	Transport Cost (USD)
$(e_i)$	$(d_j - a_i)$	$(td_j - ta_i)$	$(g_i)$	$(g_i)$
1	8:00 - 9:00	1 - 2	1	45
2	7:45 - 11:40	1 - 2	1	25
3	10:00 - 11:30	3 - 2	3	50
4	8:15 - 9:30	1 - 3	1	50
5	8:15 - 12:05	1 - 3	1	25
6	9:45 - 11:15	2 - 3	2	45
7	12:00 - 15:30	2 - 4	2	100
8	12:30 - 16:00	3 - 4	3	110

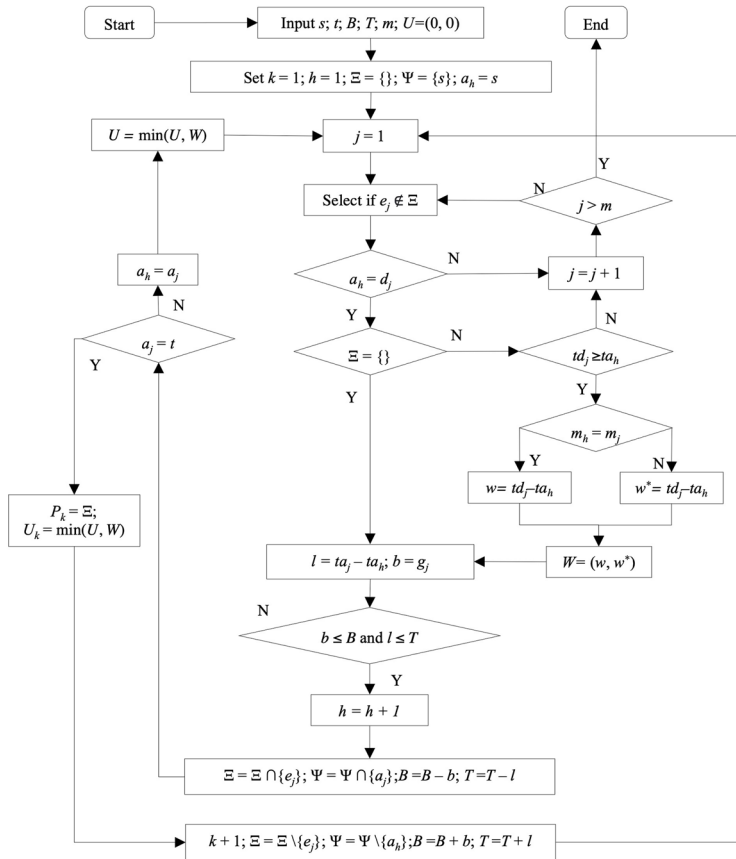


Fig. 1. Procedure to determine all MTBPs ( $P_k$ ) and their maximal transit time vectors ( $U_k$ )

Thus, the set  $\mathbf{P}^i$  of all MTBPs in the case of existing transits times,  $W \leq W^i$ , is the sub-union of  $\mathbf{P}^0$ . The MTN's reliability is impacted if and only if the  $W \leq W^i$  can make at least one MTBP in  $\mathbf{P}^0$  invalid (i.e.,  $\mathbf{P}^i \subset \mathbf{P}^0$ ). This research combines the values  $u$  and  $u^*$  of the same or different maximal transit times  $U_k$  to create  $W^i$ . Considering levels of transit time  $W \leq W^i$  is sufficient for the study's analysis. The following algorithm is used to access the effect of transit time on reliability under the time threshold and budget limitation.

**Main algorithm** – Reliability assessment subject to the impact of transit times

**Input:**  $N = (\mathbf{V}, \mathbf{E}, \mathbf{G}, \mathbf{M}, \mathbf{C}), T, B$ , and  $A$

**Step 1:** Apply the search procedure shown in Fig. 1 to generate  $\mathbf{P}^0$  – set of all feasible minimal paths  $P_k$  under time threshold  $T$  and budget limitation  $B$  without required transit times. At the same time, obtain the corresponding maximal transit times  $U_k$ .

**Step 2:** From all maximal transit times  $U_k$ , create all possible  $W^i$ . Some  $W^i = U_k$  and other  $W^i = (w, w^*)$  where  $w = u$  and  $w^* = u^*$  of two different  $U_k$ .

**Step 3:** Conduct the following steps for each level of transit times  $W \leq W^i$ :

Step 3.1: Accept from  $\mathbf{P}^0$  all minimal paths  $P_k$  such that  $W^i \leq U_k$  and store them as  $\mathbf{P}^i$ .

Step 3.2: Determine all flow vectors  $F = (f(P_k) | P_k \in \mathbf{P}^i)$  that satisfy the following constraints to store as  $\mathbf{F}^i$ :

Table 2. The capacity probability of all routes in the MTN

Route ( $e_i$ )	Probability Pr ( $y_j$ passengers)					
	41 – 50	31 – 40	21 – 30	11 – 20	1 – 10	0
1	0.81	0.05	0.1	0.02	0.01	0.01
2	0.80	0.1	0.05	0.02	0.01	0.02
3		0.93	0.05	0.01	0.005	0.005
4	0.81	0.05	0.06	0.05	0.02	0.01
5	0.80	0.08	0.05	0.05	0.01	0.01
6		0.93	0.04	0.005	0.015	0.01
7	0.86	0.01	0.1	0.01	0.01	0.01
8	0.90	0.05	0.02	0.01	0.01	0.01

**Input:**  $N = (V, E, G, M, C)$ ,  $T = 8$  hours,  $B = 200$  USD, and  $A = 80$  passengers.

**Step 1:** Apply the search procedure shown in Fig. 1 to generate  $P^0$ . In total, it contains six MTBPs in and the corresponding maximal transit times  $U_v$  are presented as below. Note that the unit of  $U_k$  is minute and the symbol “\_” means that all transit times are accepted.

$P_1 = \{e_1, e_6, e_8\}$	$U_1 = (45, \_)$
$P_2 = \{e_1, e_7\}$	$U_2 = (180, \_)$
$P_3 = \{e_2, e_7\}$	$U_3 = (\_, 20)$
$P_4 = \{e_4, e_3, e_7\}$	$U_4 = (30, \_)$
$P_5 = \{e_4, e_8\}$	$U_5 = (180, \_)$
$P_6 = \{e_5, e_8\}$	$U_6 = (\_, 25)$

**Step 2:** From all minimal transit times  $U_v$ , create and gain eight possibilities of  $W$  that are  $W^1 = (30, 20)$ ,  $W^2 = (30, 25)$ ,  $W^3 = (45, 20)$ ,  $W^4 = (45, 25)$ ,  $W^5 = (180, 20)$ , and  $W^6 = (180, 25)$ .

**Step 3:** Conduct the following steps for all levels of transit times from  $W \leq W^1$  to  $W \leq W^6$ . For example, with the required transit time  $W \leq (30, 25)$ , the reliability is computed as follows.

Step 3.1: From  $P^0$ , five minimal paths are accepted to get  $P^2 = \{P_1, P_2, P_4, P_5, P_6\}$  because their  $U_k \geq W^2$ .

Step 3.2: Obtain 154 flow vectors  $F = (f(P_1), f(P_2), f(P_4), f(P_5), f(P_6))$  that satisfy the following constraints and store them as  $F^2$ :

$$\sum_{P_k \in P^2} f(P_k) = 80 \quad (13)$$

$$\begin{aligned} f(P_1) + f(P_2) &\leq c_1; \\ f(P_4) &\leq c_3; \\ f(P_4) + f(P_5) &\leq c_4; \\ f(P_6) &\leq c_5; \\ f(P_1) &\leq c_6; \\ f(P_2) + f(P_4) &\leq c_7; \\ f(P_1) + f(P_5) + f(P_6) &\leq c_8. \end{aligned} \quad (14)$$

Since  $c_1 = c_4 = c_5 = c_7 = c_8 = 50$  and  $c_3 = c_6 = 40$ , constraint (14) can be shortened as follows:

$$\begin{aligned} f(P_1) + f(P_2) &\leq 50; \\ f(P_4) + f(P_5) &\leq 50; \\ f(P_1) &\leq 40; \\ f(P_2) + f(P_4) &\leq 50; \\ f(P_1) + f(P_5) + f(P_6) &\leq 50. \end{aligned} \quad (15)$$

Step 3.3: Convert from each  $F$  in  $F^2$  through the following equation to gain candidates  $X$  and store in  $X^2$ :

$$\begin{aligned} x_1 &= f(P_1) + f(P_2); \\ x_3 &= f(P_4); \\ x_4 &= f(P_4) + f(P_5); \\ x_5 &= f(P_6); \\ x_6 &= f(P_1); \\ x_7 &= f(P_2) + f(P_4); \\ x_8 &= f(P_1) + f(P_5) + f(P_6). \end{aligned} \quad (16)$$

Step 3.4: Compare 154 candidates stored in  $X^2$  and remove the duplicates and the components that are greater than others. There are 67 exact LBPs obtained and recorded in a set  $L^2$ .

Step 3.5: Through the RSDP method, compute the MTN's reliability as equations (17):

$$R_{200,80,8}^2 = \Pr\left\{ \bigcup_{X \in L^2} \{Y \mid X \leq Y \leq C\} \right\} = 0.927964. \quad (17)$$

**Step 4:** All reliabilities under different levels of transit time from  $W \leq W^1$  to  $W \leq W^6$  are listed in the following figure.

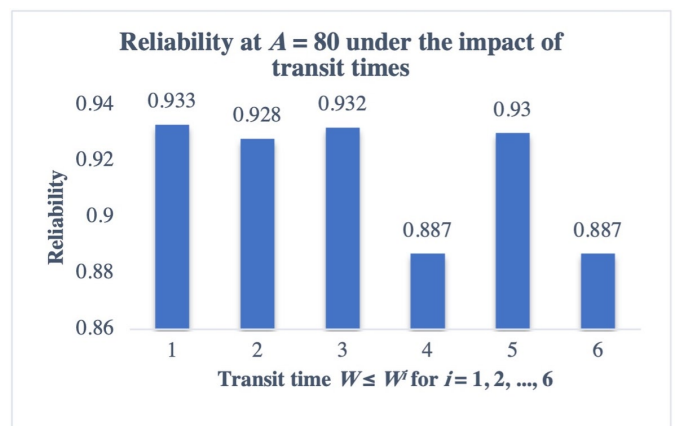


Fig. 3. The MTN's reliabilities at  $A = 80$  passengers under the impact of transit times

As the results shown in Fig. 3, the MTN's reliability varies from 0.886554 to 0.933458. In which, it reaches a peak with transit times  $W \leq \{W^1 \mid W^1 = (30, 20)\}$  and drops a bottom with  $W \leq \{W^6 \mid W^6 = (180, 25)\}$ . The reliability is higher than 0.8 at all cases of transit times and higher than 0.9 with four of six levels of transit times, which means that the ability to transport 80 passengers within 8 hours and 200 USD of the MTN is quite high. That means this MTN is quite reliable under the given time and budget limitations. When increasing the required transit time between the same modes, the reliability changes slightly with the required transit time between different transport modes  $w^* \leq 20$ ; but it changes significantly with  $w^* \leq 25$ . At the same time, the

Table 3. The relevant data of the practical MTN

Route	Dep.	Arr.	Dep.	Arr.	Mode	Cost
	time	time	station	station		
$(e_i)$	$(td_i)$	$(ta_i)$	$(d_i)$	$(a_i)$	$(m_i)$	$(g_i)$
1	10:00	11:15	CHU	TPE	HSR	10
2	7:15	12:00	CHU	TPE	Rail	5
3	11:55	14:15	TPE	HAN	Air	95
4	19:45	22:00	TPE	HAN	Air	100
5	16:00	18:05	HAN	HPH	Bus	10
6	17:30	19:35	HAN	HPH	Bus	10
7	19:00	21:05	HAN	HPH	Bus	10
8	20:30	22:35	HAN	HPH	Bus	10
9	22:00	0:05	HAN	HPH	Bus	10
10	23:30	1:35	HAN	HPH	Bus	10
11	14:30	17:15	TPE	DAD	Air	115
12	17:45	18:40	DAD	HPH	Air	45
13	11:45	12:40	DAD	HPH	Air	45
14	9:10	12:00	TPE	SGN	Air	110
15	12:10	15:00	TPE	SGN	Air	110
16	15:10	18:00	TPE	SGN	Air	110
17	13:20	14:25	SGN	HPH	Air	55
18	15:20	15:30	SGN	HPH	Air	55
19	18:20	19:25	SGN	HPH	Air	55
20	9:05	9:20	CHU	RMQ	Rail	2
21	11:05	10:20	CHU	RMQ	Rail	2
22	12:05	11:20	CHU	RMQ	Rail	2
23	13:05	12:20	CHU	RMQ	Rail	2
24	14:05	13:20	CHU	RMQ	Rail	2
25	15:05	14:20	CHU	RMQ	Rail	2
26	16:05	15:20	CHU	RMQ	Rail	2
27	17:05	16:20	CHU	RMQ	Rail	2
28	15:00	18:15	RMQ	HAN	Air	115
29	13:15	16:45	RMQ	DAD	Air	120
30	10:00	11:15	CHU	KHH	HSR	10
31	7:15	12:00	CHU	KHH	Rail	5
32	9:10	12:00	KHH	SGN	Air	110
33	12:10	15:00	KHH	SGN	Air	110
34	15:10	18:00	KHH	SGN	Air	110
35	18:10	21:00	KHH	SGN	Air	110

reliability also drops much when increasing the required transit time between different transport modes from  $w^* \leq 20$  to  $w^* \leq 25$ , except from the case  $w \leq 30$ . Namely, the reliability decreases only 0.5% from 0.933458. In short, it is recommended to put much effort into shortening transit time between the different transport modes. However, if the acceptable reliability is no lower than 0.9, the MTN will not qualify only at two levels of transit times:  $W \leq (45, 25)$  and  $W \leq (180, 25)$ . A suggestion in this situation for the travel agent is controlling the transit time between the different transport modes at  $w \leq 20$  (ie. up to 5% of the time threshold).

### 5. Practical case

This sub-section introduces a practical MTN in Fig. 4, constructed by 35 routes and 8 stations. The reliability to transport from the source – Changhua (CHU) in Taiwan to the sink – Haiphong (HPH) in Vietnam within 200 USD and 8 hours will be analyzed with various transit

times at a range of demands. The relevant information and results are shown in Tables 3, 4, and 5.

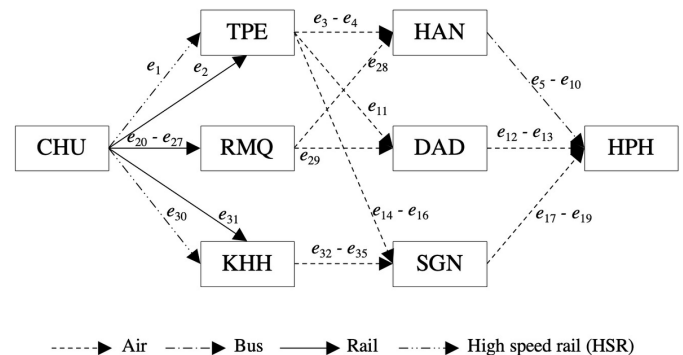


Fig. 4. A practical MTN

Table 4. The capacity probability

Route ( $e_i$ )	Probability Pr ( $y_j$ passengers)					
	0	1 – 10	11 – 20	21 – 30	31 – 40	41 – 50
1, 8, 15, 22, 29	0.015	0.025	0.01	0.05	0.1	0.8
2, 9, 16, 23, 30	0.005	0.005	0.005	0.05	0.935	
3, 10, 17, 24, 31	0.01	0.05	0.02	0.06	0.05	0.81
4, 11, 18, 25, 32	0.015	0.05	0.055	0.88		
5, 12, 19, 26, 33	0.02	0.005	0.015	0.03	0.93	
6, 13, 20, 27, 34	0.01	0.01	0.01	0.1	0.01	0.86
7, 14, 21, 28, 35	0.01	0.02	0.01	0.01	0.95	

Table 5. The reliability under time impacts of transit times and CPU time

Demand (A) unit: passengers	10	30	50	70	90	110
$W \leq (20, 40)$	0.9999	0.9997	0.996	0.98	0.8548	0.6593
$W \leq (20, 45)$	0.9999	0.9997	0.9953	0.9763	0.8427	0.6176
$W \leq (20, 55)$	0.9995	0.9933	0.9141	0.7319	0	0
$W \leq (20, 115)$	0.9556	0.8755	0	0	0	0
$W \leq (60, 40)$	0.9993	0.995	0.9391	0.8371	0	0
$W \leq (60, 45)$	0.9991	0.9941	0.9323	0.8218	0	0
$W \leq (60, 55)$	0.9652	0.9107	0	0	0	0
$W \leq (60, 115)$	0.9556	0.8755	0	0	0	0
CPU time (second)	0.179	0.3013	0.7333	0.6634	0.3663	0.0967

According to Table 5, the impact of transit times is not significant at the demands  $A = 10$  and  $A = 30$  passengers, but that becomes more remarkable when the demand increases. In particular, the reliability is higher than 0.8 at the demand of 10 and 30 passengers, but it is zero at the higher demands with  $W \leq (20, 115)$ ,  $W \leq (60, 55)$ , and  $W \leq (60, 115)$ . Besides, the reliability drops to zero at the demand from 90 passengers or more, except the transit times  $W \leq (20, 40)$  and  $W \leq (20, 45)$ . From these results, we can conclude that the travel agent should keep the transit time no longer than 45 minutes between different modes to maintain the high reliability of transporting more than 30 passengers. To satisfy this requirement, the travel agent can arrange a private car or shuttle bus to carry passengers from the arrival gate of the previous route to the departure gate of the next route. To reliably transport up to 110 passengers, the required transit time should be lower than (20, 45). To keep the transit time between the same modes around twenty minutes, the travel agent should provide passengers the

stations' map with clear directions. Furthermore, the CPU time for the investigation is lower than one second for all experiments, which proves the efficiency of the proposed algorithm.

## 6. Conclusions

This study focuses on investigating the influence of transit time on the performance of a multistate transportation network reliability (MTN). The reliability, which is the probability to transport the given demand from the source to the sink within the time threshold and budget limitation, is the basis

of the investigation. This research proposes an algorithm that evaluates the MTN reliability under several levels of transit times. Instead of enumerating all possibilities, this study only takes significant levels of transit times under consideration. Namely, all examined transit time levels are generated through the maximal transit time vector of MTBPs. This paper also contributes a procedure determining all MTBPs and their maximal transit time vectors. The results of this study are used to provide some management suggestions such as the appropriate transit times to sustain reliability and transit time that exceeds the allowable reliability under certain circumstances. The proposed investigation is presented through a numerical example and a real case to demonstrate its application. In the future, estimating the impacts of other factors like economic or society [29] on reliability is a potential topic. Also, conducting the same analysis with a lack of probability information can earn more realistic findings.

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