Small-world network theory in the study of network connectivity and efficiency of complementary international airline alliances

Chaug-Ing Hsu *, Hsien-Hung Shih

Department of Transportation Technology and Management, National Chiao Tung University, Hsinchu 30010, Taiwan, ROC

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ABSTRACT

This paper investigates the network connectivity and efficiency of international airline alliances, and conceptually applies the shortcuts of small-world networks to analyze alliance routes. Based on travel time, mobility and accessibility models are formulated to evaluate the effects of alliance on network connectivity. The results show that the connectivity of the alliance network is better than before, and the alliance effectively improves accessibility from high–medium traffic airports to low traffic airports. After the alliance, the shortest paths between origin–destination pairs will involve more transfers but less travel time.

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1. Introduction

International aviation markets have been globalized and have become increasingly competitive in recent years. More and more carriers are using international airline alliances to strengthen their competitive advantage, extend their networks, and access new markets under air traffic rights and resource limitations. The number of new alliance agreements has increased every year since 2001 (Kemp et al., 2005). The top three alliance groups, Star Alliance, oneWorld, and SkyTeam collectively account for over half of the world's passenger traffic (Field, 2005), showing that international airline alliances have become mainstream in today's international industry. An international airline alliance is an agreement between two or more air-carriers cooperating in a commercial relationship or jointly operating activities in various fields. Alliances provide opportunities for the allied airlines to extend their networks, increase passenger traffic, and consequently improve profitability. The literature on airline alliances can be classified into theoretical, empirical and comprehensive studies (Park, 1997; Gudmundsson and Rhoades, 2001; Park et al., 2001; Iatrou and Alamdari, 2005). The majority of this work focused on the economic outcomes of alliances. Little research, however, has been carried out on the effects these alliances have on the connectivity of airline networks.

A series of recent studies have explored the issue of connectivity of a variety of networks. These studies mainly followed the work of Watts and Strogatz (1998) who developed a small-world theory to analyze distinctive characteristics in some

real networks, such as social, technological and biological networks. However, Latora and Marchiori (2001, 2002) found that the model of Watts and Strogatz (1998) has some problems regarding its application to transportation systems, and then proposed global and local efficiency models. In the literature of small-world networks, few studies have considered travel time between two nodes, which is one of the most significant measures of performance in an air transportation system. More important for transportation systems, mobility and accessibility may be more appropriate for measuring system performance and effectiveness than the efficiency models. Furthermore, travel time is the most common and significant measure in formulating mobility and accessibility models in transportation literature (Levine and Garb, 2002; Geurs and van Wee, 2004).

2. Network component definitions and shortcut application

International airlines provide air services with various routes, types of aircraft, and flight frequencies for passengers to accomplish their travel requirements. Routes served by a carrier forms its own network. In a given airline network, a node should not be defined as a city because several airports may be located in the same city, and therefore this definition may result in errors in the analyses. Consequently, this study defines a node as an airport, which may represent an airport of origin, destination, or transfer along a route served by a given carrier. In addition, this study defines a passenger-flight between two airports operated by a given airline as a link. In other words, when no link exists between two nodes in a given airline network, passengers must take a flight served by other carriers for accomplishing trips between the nodes. Consider a given airline (airline 'x') network before it enters

* Corresponding author.
   E-mail address: cihsu@mail.nctu.edu.tw (C.-I. Hsu).

an international alliance, $\mathbf{G}^x(\mathbf{N}^x, \mathbf{A}^x)$, where $\mathbf{N}^x$ and $\mathbf{A}^x$ represent, respectively, the set of nodes and the set of links in graph $\mathbf{G}^x$. Let $\|\mathbf{N}^x\|$ and $\|\mathbf{A}^x\|$ represent the number of nodes and the number of links, respectively. The set of all origin–destination (OD) pairs r–s served by carrier 'x' is denoted as $\mathbf{J}^x$ ($r, s \in \mathbf{N}^x$), and the number of OD pairs is denoted as $\|\mathbf{J}^x\|$.

There are two typical alliance types used in international airline alliances, i.e. parallel and complementary alliances. Following Park et al. (2001), a parallel alliance refers to the collaboration between two air-carriers who, prior to their alliance, are competitors on some routes of their networks. For example, United Airlines and Lufthansa formed a parallel alliance on the San Francisco–Frankfurt route on which they previously competed. A complementary alliance refers to a situation where two air-carriers link up their existing networks and build a new complementary network to feed traffic to each other. For example, China Airlines (CI) and Delta Airlines (DL) signed this type of alliance on the Taipei–Dallas route, where CI served the Taipei–Los Angeles route and DL served the Los Angeles-Dallas route. Before entering the alliance, CI served the Asia routes and the routes from Taipei to the West Coast of the US, but lacked the inland routes in the US. In contrast, DL possessed a dense network of routes in the US, but lacked US–Southeast Asia routes. Through their complementary alliance, the two air-carriers now complement networks with each other, and carry passengers to more airports.

This study focuses on the complementary alliances of carriers and investigates the effects due to these alliances. The reason for this is that complementary alliances not only can benefit airlines by reducing operating costs, improving load factor, and enhancing market share, but they can also extend their networks and provide them with access to new markets, something which parallel alliances cannot provide. This study supposes that complementary-alliance routes are similar to the shortcuts of a small-world network. The functions of shortcuts in a small-world network are shown in Fig. 1. In Fig. 1, all nodes are connected to four neighbor nodes, except for nodes A, B, C, D, E, and F, which are connected by dotted lines called shortcuts. Such shortcuts are long-range links and connect nodes that are distant from each other. Each shortcut can shorten the separation distance,[1] not only between the pair of nodes that it connects, but also between their immediate neighbor nodes, neighbor nodes of neighbor nodes, and so on. For example, as in Fig. 1, the shortcut between nodes A and C can shorten the separation distance from 4 to 1, and further shorten the distance between nodes G and C from 4 to 2. In other words, shortcuts provide opportunities to reduce the steps and the time required for transmitting any kind of communication among nodes, to enhance the connectivity of those nodes located at different regions, and to increase the overall interaction of the network. For a detailed description of shortcuts, see Watts and Strogatz (1998).

This study further analyzes the functions of complementary-alliance routes using the concepts of shortcuts of the small-world network. These functions can be described as

- *Increase connectivity efficiency*: Shortcuts can increase the connectivity efficiency among nodes in a small-world network. Complementary-alliance routes also provide this function through the collaboration among airlines, such as coordinating flight schedules. This collaboration allows passengers to fly from origins to destinations in a way that minimizes their transfer time between flights of alliance partners.
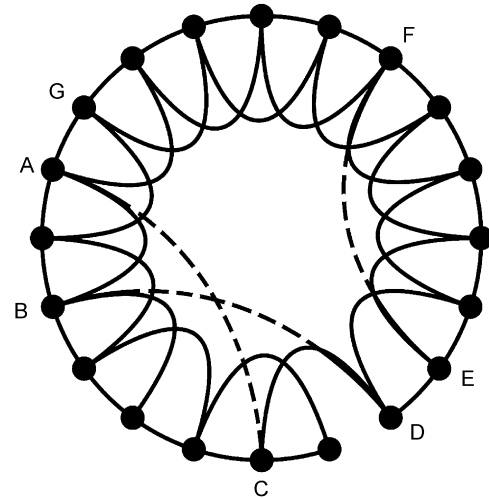

Fig. 1. Small-world network and shortcuts.

- *Shorten separation*: In addition to the separation distances between pairs of nodes connected by shortcuts, the distance between their neighbor nodes can be shortened as well through shortcuts, providing the connectivity is of benefit to the inter-regions. With an alliance, passengers can take partner carriers' flights to airports served by the alliance routes, and they can successively transfer to local flights to a neighbor region. As a result, alliance routes indirectly reduce the separation between neighbor regions at two ends, thereby increasing the flying convenience and the efficiency of the passengers to those neighbor regions.

- *Reduce steps and time*: In a small-world network, shortcuts can reduce the steps and the time required for any kind of communication between nodes. The complementary-alliance routes provide similar advantages because the alliances may allow the airlines involved to sell seats on each other's flights. As a result, passengers may acquire all boarding passes for their entire tours at the airport of origin and reduce their procedures and time normally necessary to check-in again at the connecting airports.

- *Enhance network interaction*: In a small-world network, the interaction of the whole network can be enhanced by the introduction of a few shortcuts. By analogy, airlines can access new regions more easily by introducing a few complementary-alliance routes in their networks, something which is difficult without an alliance. This enables passengers to fly to various regions and countries more efficiently, and enables the whole carrier network to enhance its interaction.

Airline 'x' can obtain the advantage of network extension by establishing a new complementary-alliance route with a foreign partner airline, where that route is served by the partner carrier. This study uses a new link added to the network of airline 'x' to represent the new route and the advantage of network extension. Further, it is assumed that airline 'x' may sign complementary alliances with several foreign carriers at the same time. A set of these allied airlines is denoted as $\mathbf{S}^c$. After airline 'x' signs the alliance agreement with one of $\mathbf{S}^c$, e.g. airline 'y' ($y \in \mathbf{S}^c$), they will build a new complementary network. Let $\mathbf{N}_c^{xy}$, $\mathbf{A}_c^{xy}$, and $\mathbf{J}_c^{xy}$ represent, respectively, the sets of additional nodes, links, and OD pairs for carrier 'x' after it has signed a complementary alliance agreement with airline 'y' ($y \in \mathbf{S}^c$). The sets of nodes, links, and OD pairs of the airline 'x' network in the post-alliance

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[1] The separation distance herein represents the number of links in the shortest path between any two nodes.

situation can then be represented as $\mathbf{N}_c^{xy} = \mathbf{N}^x + \mathbf{N}_c^{xy}, \mathbf{A}^{xyc} = \mathbf{A}^x + \mathbf{A}_c^{xy}$, and $\mathbf{J}^{xyc} = \mathbf{J}^x + \mathbf{J}_c^{xy}$, respectively. With the shortcut functions of the complementary-alliance routes as discussed above, carrier 'x' can expand its network through the complementary alliance, i.e. $\|\mathbf{J}^{xyc}\| > \|\mathbf{J}^x\|$, which may positively affect its amount of passengers and profit. Through complementary-alliance routes, i.e. shortcuts, passengers can also fly more efficiently to new destinations, i.e. $\mathbf{N}_c^{xy}$, and may subsequently transfer to other flights and fly to the neighbor regions of $\mathbf{N}_c^{xy}$. In other words, complementary-alliance routes not only reduce passengers' travel time between OD pairs, but also enable them to fly to more destinations to carry out their socioeconomic activities than prior to the alliance.

3. Model formulation

Travel time is considered as a determinant to formulate models for analyzing the mobility and accessibility of an alliance network. In particular, the mobility model is formulated in global and local scales based on the efficiency model proposed in the literature. The model is then used to analyze the difference of the mobility between pre- and post-alliance situations.

3.1. Mobility model

To simplify, this study defines a traveler's travel time between OD pair i–j as the sum of his/her flying time on the flights and transfer time incurred at intermediate airports, not including the access time from the traveler's origin to the origin airport i, and not including the travel time from the destination airport j to the final destination. Let $\mathbf{G}^{xy}(\mathbf{N}, \mathbf{A})$ be the alliance network of carriers 'x' and 'y' ($y \in \mathbf{S}^c$) after they have formed a complementary alliance, where $\mathbf{N}$ and $\mathbf{A}$ are the set of nodes and the set of links, respectively. Each link of $\mathbf{G}^{xy}(\mathbf{N}, \mathbf{A})$ is weighted by travel time so as to reflect its actual measure of performance in this study. Let t_{ij} represent the travel time between OD pair i–j ($i \neq j \in \mathbf{G}^{xy}$). If there are direct or connecting flights between OD pair i–j, then t_{ij} is the sum of the flying time on the flights and the transfer time incurred at intermediate airports, otherwise, t_{ij} is assumed as infinite. This study formulates the global mobility model based on travel time between OD pairs, which is shown as follows:

$$M_{\text{glob}}(\mathbf{G}^{xy}) = \frac{1}{\|\mathbf{N}\|(\|\mathbf{N}\| - 1)} \sum_{i \neq j \in \mathbf{G}^{xy}} \frac{1}{t_{ij}^m} \quad (1)$$

where $\|\mathbf{N}\|$ is the number of nodes in $\mathbf{G}^{xy}$; $\|\mathbf{N}\|(\|\mathbf{N}\|-1)$ is the number of all possible OD pairs; t_{ij}^m is the shortest travel time between OD pair i–j; and $1/t_{ij}^m$ is defined as the mobility between OD pair i–j. A greater t_{ij}^m and a consistently smaller $1/t_{ij}^m$ mean that the mobility between the OD pair is worse, i.e. passengers starting from node i are less likely to arrive at node j in a reasonable amount of time. When there is no path connecting OD pair i–j in $\mathbf{G}^{xy}$, then $t_{ij}^m = \infty$, and accordingly $1/t_{ij}^m = 0$, which yields the minimal mobility between OD pairs. In Eq. (1), the global mobility of $\mathbf{G}^{xy}$, $M_{\text{glob}}(\mathbf{G}^{xy})$, is the mean of the reciprocal of the shortest travel time between OD pairs.

Latora and Marchiori (2001) develop a general model to measure the performance of the Boston underground transportation system (MBTA) in terms of the shortest geographical distance. However, their model cannot be used to correctly describe the specific characteristics of the alliance network. The evidence that our proposed mobility model is more appropriate for the alliance network than the efficiency model is as follows. As shown in Fig. 2, there are five nodes and five links, and link BC is the alliance route expressed as a dotted line. It is assumed that the
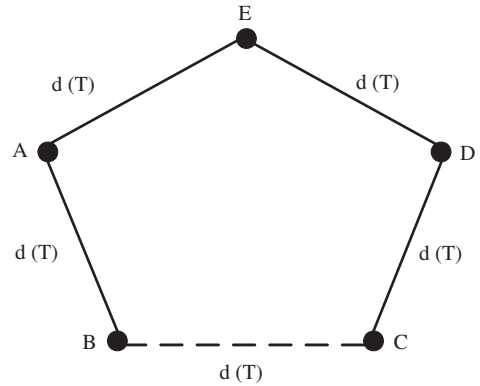

Fig. 2. The illustration of the difference between mobility and efficiency models.

geographical distance and the flying time of each link are d and T, respectively. The shortest path in terms of geographical distance between nodes A and D will be A–E–D, and implicitly, link BC cannot provide any function of shortcuts and does not affect the choice of the shortest path. In contrast, if we search the shortest path between nodes A and D in terms of travel time, then the shortest path may change because the alliance route can reduce the transfer times incurred at nodes B and C, and provide the functions of shortcuts. When the transfer time at node E (w_E) minus T is greater than the sum of the transfer times at node B (w_B) and node C (w_C), i.e. $w_E - T > w_B + w_C$, then the shortest path will shift to A–B–C–D, whose travel time is smaller than that of A–E–D. As a result, by taking travel time into account, the mobility model is more appropriate for measuring the performance and describing the distinctive characteristics of the alliance network than the efficiency model.

For consistency, $M_{\text{glob}}(\mathbf{G}^{xy})$ is normalized to the interval [0, 1] by factor $M_{\text{glob}}(\mathbf{G}_{\text{ideal}}^{xy})$, which is the global mobility of the ideal case. In the ideal case of $\mathbf{G}^{xy}$, $\mathbf{G}_{\text{ideal}}^{xy}$, each OD pair is connected by a link with the shortest travel time, i.e. individuals can move between nodes in the most efficient way.[2] Consequently, $M_{\text{glob}}(\mathbf{G}_{\text{ideal}}^{xy})$ is the maximum value of $M_{\text{glob}}(\mathbf{G}^{xy})$, and the normalized global mobility of $\mathbf{G}^{xy}$, $M_{\text{glob}}^N(\mathbf{G}^{xy})$, can be shown by

$$M_{\text{glob}}^N(\mathbf{G}^{xy}) = \frac{\frac{1}{\|\mathbf{N}\|(\|\mathbf{N}\|-1)} \sum_{i \neq j \in \mathbf{G}^{xy}} \frac{1}{t_{ij}^m}}{M_{\text{glob}}(\mathbf{G}_{\text{ideal}}^{xy})} \quad (2)$$

By normalizing, the value of $M_{\text{glob}}^N(\mathbf{G}^{xy})$ is a nonnegative real number with the maximum value 1. Eq. (2) can easily be used to compare global mobility under various conditions, and can provide information about the difference of network performance between real and ideal cases.

The global mobility in the post-alliance situation will be higher than that in the pre-alliance situation by introducing several alliance routes. This is shown as follows. In the pre-alliance network of carriers 'x' and 'y', denoted as graph $\mathbf{G}^{xy'}$, when a passenger taking a flight of airline 'x' wants to fly to destinations served by carrier 'y' instead of carrier 'x', he/she must transfer to the flight of airline 'y' at the connecting airport. However, such interline connection usually results in a less convenient experience and more transfer time, due to the lack of coordination between the airlines. In contrast, after two carriers form an alliance, OD pairs served by alliance routes will change their original shortest paths to the alliance routes based on the complementary alliance's available shortcuts. Besides, other OD

[2] The establishment of the ideal case is discussed later in the case study.

pairs may also change their original shortest paths. If the alliance routes provide a shorter travel time for them, they will shift their shortest paths to those paths involving alliance routes; otherwise, they hold their original shortest paths, and their shortest travel time do not change. Let those OD pairs with changed shortest paths be denoted as $\mathbf{R}$, then the difference of global mobility between post-alliance ($M_{glob}(\mathbf{G}^{xy})$) and pre-alliance ($M_{glob}(\mathbf{G}^{xy'})$) situations can be shown by

$$
\begin{aligned}
& M_{glob}(\mathbf{G}^{xy}) - M_{glob}(\mathbf{G}^{xy'}) \\
& = \frac{1}{\|\mathbf{N}\|(\|\mathbf{N}\|-1)} \sum_{i-j \in \mathbf{R}} \left(\frac{1}{t_{ij}^m} - \frac{1}{t_{ij}^{m'}} \right) \\
& = \frac{1}{\|\mathbf{N}\|(\|\mathbf{N}\|-1)} \sum_{i-j \in \mathbf{R}} \left(\frac{t_{ij}^{m'} - t_{ij}^m}{t_{ij}^m \cdot t_{ij}^{m'}} \right) > 0
\end{aligned}
\tag{3}
$$

In Eq. (3), the OD pairs whose shortest travel time in the pre-alliance situation is the same as in the post-alliance situation are eliminated, and only those OD pairs belonging to $\mathbf{R}$, which changed their shortest paths, are left. Furthermore, for each OD pair $i-j \in \mathbf{R}$, the shortest travel time in the post-alliance situation, t_{ij}^m, will be smaller than that in the pre-alliance situation, $t_{ij}^{m'}$, thereby increasing the global mobility in the post-alliance situation over that in the pre-alliance situation.

We then formulate the local mobility model so as to analyze local features, including the connectivity and interaction among neighbor nodes of destinations. We define nodes that connect to node i as neighbor-nodes of node i, and k_i denotes the number of neighbor nodes. The subgraph of node i, $\mathbf{G}_i$ ($i \notin \mathbf{G}_i$), is composed of its neighbor nodes, and the local property of $\mathbf{G}_i$ can be characterized by the local mobility model, which is formulated as follows:

$$
M_{loc}(\mathbf{G}_i) = \frac{1}{k_i(k_i - 1)} \sum_{p \neq q \in \mathbf{G}_i} \frac{1}{t_{pq}^m}
\tag{4a}
$$

$$
M_{loc}(\mathbf{G}^{xy}) = \frac{1}{\|\mathbf{N}\|} \sum_{i \in \mathbf{G}^{xy}} M_{loc}(\mathbf{G}_i)
\tag{4b}
$$

In Eq. (4a), t_{pq}^m is the shortest travel time between OD pair $p-q$, where both nodes p and q are neighbor nodes of node i; and there are at most $k_i(k_i-1)$ OD pairs in $\mathbf{G}_i$. $M_{loc}(\mathbf{G}_i)$ is affected by local structural properties, such as the shortest travel time and the connectivity between neighbor nodes of node i. By averaging $M_{loc}(\mathbf{G}_i)$ over all subgraphs, the local mobility of $\mathbf{G}^{xy}$, $M_{loc}(\mathbf{G}^{xy})$, can be yielded, as shown in Eq. (4b). The local mobility can be further normalized by the factor $M_{loc}(\mathbf{G}_i^{ideal})$, which is the maximum value of $M_{loc}(\mathbf{G}_i)$, and the normalized local mobility, $M_{loc}^N(\mathbf{G}^{xy})$, is formulated as

$$
M_{loc}^N(\mathbf{G}^{xy}) = \frac{1}{\|\mathbf{N}\|} \sum_{i \in \mathbf{G}^{xy}} \frac{M_{loc}(\mathbf{G}_i)}{M_{loc}(\mathbf{G}_i^{ideal})}
\tag{5}
$$

3.2. Accessibility model

In addition to mobility, a transportation system provides accessibility. In the literature, the potential model is a well-known model for measuring accessibility, and it is derived from the concept of the gravity model of spatial interaction. In this model, accessibility is assumed to be positively related to the scale of the attractiveness of the location and negatively related to the travel time or impedance (Geertman and Ritsema van Eck, 1995). The potential model is usually used to evaluate the intensity of the interaction between socioeconomic groups at different locations, and is also suitable as a social indicator for measuring the level of access to socioeconomic opportunities (Geurs and van Wee,

2004). To analyze how passengers can reach more destinations so as to accomplish socioeconomic activities by using the alliance network, this study applies the potential model, and modifies it to construct the accessibility model of the entire network, as shown in

$$
A_i = \sum_{j \neq i} \frac{P_j}{(t_{ij}^m)^\alpha}, \quad \forall i, j \in \mathbf{G}^{xy}
\tag{6a}
$$

$$
A(\mathbf{G}^{xy}) = \sum_{i \in \mathbf{G}^{xy}} A_i
\tag{6b}
$$

where A_i and $A(\mathbf{G}^{xy})$ are the accessibility of origin node i and $\mathbf{G}^{xy}$; P_j is the attraction of destination node j; and α is the decay parameter of the shortest travel time. In Eq. (6b), the accessibility of $\mathbf{G}^{xy}$ is defined as the sum of the accessibility of all nodes in the network. In general, airport traffic, such as the number of passengers and the number of aircraft movements at an airport, can reflect the level of economic prosperity of the region in which the airport is located. A high level of airport traffic implies that a lot of economic activities take place in the region where the airport is located, i.e. the region is prosperous, which will further attract more passengers to go there for either business or pleasure. So, this study assumes that the attraction of a given destination node, P_j is related to its airport traffic, and that this attraction increases as the airport traffic increases.

The shortcut functions of the complementary-alliance routes enable carriers to provide flights to more destinations and gain the advantage of inter-regional connectivity. Passengers can also take advantage of the shortcuts to get access to more cities, which may not only be located in different regions or be distant from their origins, but also may have various attractions. In other words, the complementary-alliance routes can improve the accessibility of the entire network, which can be shown as follows. After airline 'x' and carrier 'y' form alliance routes, some OD pairs, i.e. $\mathbf{R}$, will change their shortest paths to reduce travel time by taking advantage of the alliance routes. Therefore, the difference of accessibility between post-and pre-alliance situations can be shown as $\sum_{i-j \in \mathbf{R}} P_j[1/(t_{ij}^m)^\alpha - 1/(t_{ij}^{m'})^\alpha]$, where OD pairs holding their original shortest paths are eliminated. Since the shortest travel time in the pre-alliance situation ($t_{ij}^{m'}$) is larger than that in the post-alliance situation (t_{ij}^m), for each OD pair $i-j \in \mathbf{R}$, the accessibility is improved by the airline alliance.

3.3. Connection with economic benefits of airlines

The majority of carriers are interested in expanding their networks, increasing the amount of passenger traffic, and improving revenues. These are the important operational goals of airlines. Here, we have shown that airlines can expand their networks through alliances, which is consistent with the observations in the literature (e.g., Park, 1997). Furthermore, Bissessur and Alamdari (1998) confirmed that the travel time between OD pairs significantly affects the amount of passenger traffic of an airline alliance, and that a shorter transfer time can attract more passengers to take an alliance flight and increase the amount of passenger traffic. Consequently, the travel/transfer time is a key factor for the operation of airline alliance. Our study has shown that the mobility and accessibility can be improved by the alliance, i.e. decreasing the travel time between OD pairs and, by doing so, the amount of passenger traffic on the alliance routes will be increased, as said by Bissessur and Alamdari (1998).

Furthermore, the increase in the amount of passenger traffic also improves the airline's revenue, as the finding of Iatrou and Alamdari (2005) who carried out a comprehensive survey of
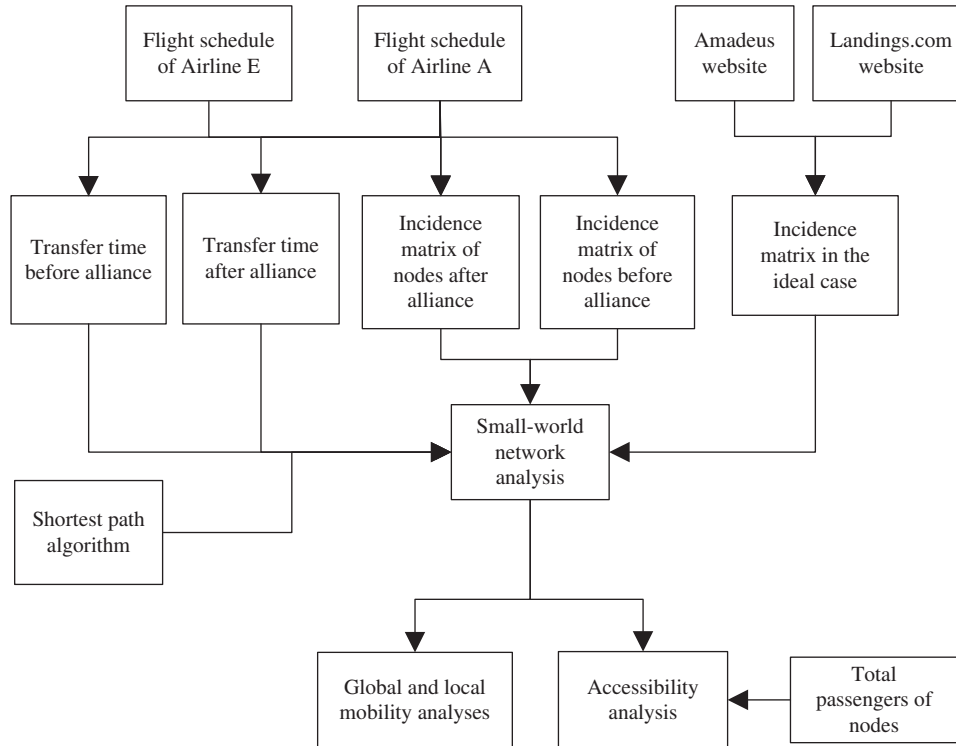
Fig. 3. Flow chart of the case study.

the impact of alliances on airlines' operation. Therefore, the efficiencies, such as mobility and accessibility, are connected with the economic benefits of airlines, and make airlines form the alliance network. Such connection between efficiencies and airlines' benefits may provide guidance for airlines to optimize their alliances, i.e. carriers can form alliances with optimal efficiency, and accordingly optimize their benefits.

4. Case study

The approach can be illustrated using an actual case study embracing airline E of Taiwan and A of the US. Airline E's operation is focused on the Asian area market, where it operates dense routes, while A is focused on the North American market where it cooperates with a local carrier to provide numerous routes for their passengers. The integrated network of carriers E and A has 265 nodes throughout America, Asia, Europe, and Oceania, and 11 of these 265 nodes are chosen to form the complementary alliances. The alliances can be grouped into two types: E carries passengers on the routes Taipei (TPE)–Seattle (SEA), –San Francisco (SFO), and –Los Angeles (LAX); and A carries passengers on the routes from/to the three nodes, SEA, SFO, and LAX, to/from seven nodes, Chicago (ORD), Dallas (DFW), Austin (AUS), Boston (BOS), New York (JFK), Washington (IAD), and Miami (MIA). Therefore, SEA, SFO, and LAX are the connecting airports between E and A.

The data required for the models are collected according to the flow chart shown in Fig. 3. First, the flight schedules and routes of airlines E and A are re-collected. Then, the incidence matrices of the nodes are set-up for the pre- and post-alliance situations. In the network of airlines E and A, since links are weighted by travel time, they are nonnegative and directed. The label-setting algorithm (Dijkstra, 1959) is used to calculate the shortest travel time between two nodes. Further, all nodes are divided into four

Table 1
Transfer time at transfer airport

Category	Annual passengers (thousand persons)	Amount of airports	Transfer time (h)	
			Mean	Standard deviation
High	40,000 above	10	1.67	0.93
High–medium	15,000–40,000	48	4.23	2.13
Medium	9000–15,000	19	7.2	5.17
Low	9000 below	188	9.93	6.85

categories based on airport traffic[3] and transfer time (Table 1), where the airports of category 'high' have the highest traffic level and take the shortest transfer time, and those of category 'low' have the lowest traffic level and have the longest transfer time. Moreover, the ideal case of the alliance network is established using the Amadeus website (www.amadeus.net) and the Landings.com website (www.landings.com/_landings/pages/search/search_dist_apt.html) is used to set travel time when there is no flight actually operated between two nodes. Finally, the mobility and accessibility of the networks before and after alliance are measured. When calculating accessibility, the attraction of a given node is represented as its number of passengers according to the ACI airport traffic statistics, and the decay parameter α is assumed to be 1 based on the work of Gutiérrez and Gómez (1999).

The results of the connectivity and efficiency analysis for the integrated network of airlines E and A (Table 2) show that the mobility and accessibility in the post-alliance situation are better

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[3] Source: 2004 Worldwide Airport Traffic Statistics, Airports Council International (ACI).

than those in the pre-alliance situation, thereby confirming the alliance advantages. The difference in the normalized local mobility is more significant than that in the normalized global mobility, and the reason is discussed as follows. The main purposes of airline alliances are to make airlines more connectable with other local markets served by partner airlines, and to increase the network's local performance. So, forming alliances will result in direct improvement in local mobility but in indirect improvement in global mobility. This indicates that the improvement in local mobility is more appropriate for measuring the effect of alliances. The pattern of the shortest travel time in the alliance network is also examined (Fig. 4). The mode of the shortest travel time is 5–6 h, and the pattern is a left-shifted distribution, indicating that the shortest travel time between most OD pairs is not long.

Table 2
Connectivity and efficiency of the integrated network

	Normalized global mobility	Normalized local mobility	Accessibility (person/h)
Post-alliance	0.71638	0.60614	7.65×10^{10}
Pre-alliance	0.71578	0.59924	7.64×10^{10}

Table 3
Accessibility[a]

| Origin airport	Destination airport				
	High	High–medium	Medium	Low	Total
High	8.91×10^8 0.02%	1.56×10^9 0.06%	3.26×10^8 0.03%	5.37×10^8 0.04%	3.31×10^9 0.05%
High–medium	3.52×10^9 0.15%	5.83×10^9 0.21%	1.06×10^9 0.22%	1.76×10^9 0.24%	1.22×10^{10} 0.20%
Medium	1.73×10^9 0.03%	2.52×10^9 0.11%	4.53×10^8 0.07%	8.23×10^8 0.06%	5.53×10^9 0.07%
Low	1.75×10^{10} 0.02%	2.48×10^{10} 0.10%	5.02×10^9 0.05%	8.14×10^9 0.04%	5.55×10^{10} 0.06%

[a] Unit: person/h.

In addition, the categories of airports in Table 1 are used to analyze the accessibility for each combination of airports, as shown in Table 3, where the first and second number of each element represents the accessibility and improvement rate of a particular combination after the alliance. First, of all categories, the improvement rate of accessibility after the alliance is the highest for the origin airports with high–medium traffic, which is better than the origin airports with high traffic. Although the origin airports with high–medium traffic have a lower flight frequency and longer travel times than those with high traffic prior to the alliance, they can efficiently reduce travel time to destinations by alliance routes and markedly improve their accessibility. Second, after the alliance, the improved level of accessibility for the combination of origin airports with high–medium traffic and destination airports with low traffic is superior. The shortest path of such combination involves those intermediate airports with high–medium and medium traffic, and travelers from the origin airports of this combination can get substantially improved accessibility to the intermediate airports, as shown in the table. These advantages cumulatively allow travelers to gain the highest level of improvement in accessibility to destination airports with low traffic. Thus, the alliance may indirectly induce economic activities at airports with limited traffic because it improves accessibility.

One can also look at the number of transfers involved in the shortest path connecting an OD pair (Table 4). The number of transfers is at most four in the alliance network, and the

Table 4
Number of transfers involved in the shortest paths

No. of transfers	No. of OD pairs		(A)–(B)
	Post-alliance (A)	Pre-alliance (B)	
0	1772	1756	16
1	40655	40348	307
2	22485	24967	−2482
3	4773	2625	2148
4	11	0	11
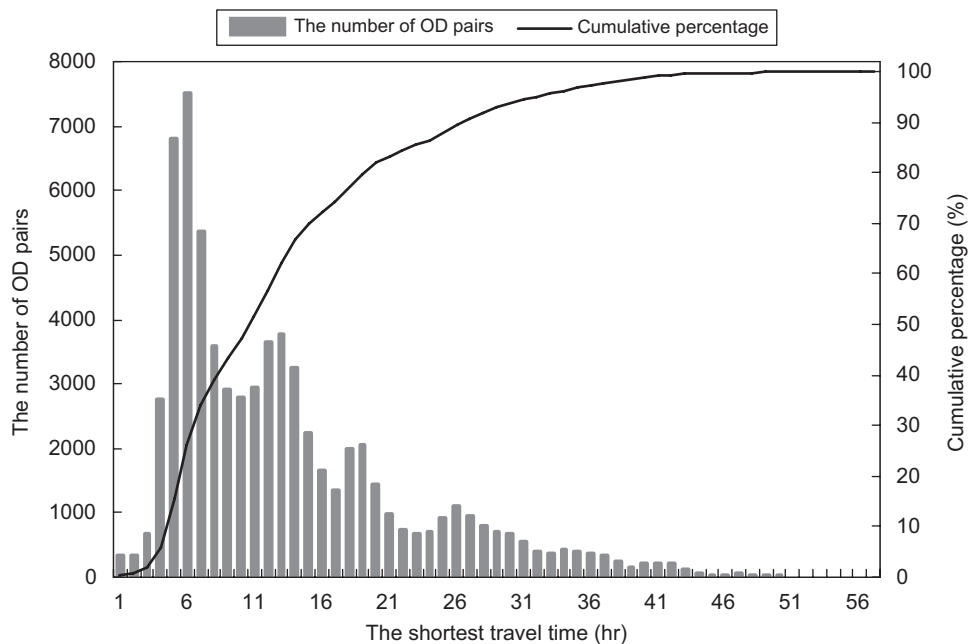
Fig. 4. Pattern of the shortest travel time.

Table 5

Mobility and accessibility for the three-airlines alliance

	Normalized global mobility	Normalized local mobility	Accessibility (person/h)
Post-alliance	0.719	0.616	7.70×10^{10}
Pre-alliance	0.718	0.603	7.69×10^{10}

proportion of OD pairs with the number of transfers less than three is about 93%. Besides, the last column of Table 4 shows the changes of the shortest paths after the alliance. It indicates that the number of transfers involved in the shortest paths mostly changes from two to three times after the alliance. This may be due to the shortcut functions of the complementary-alliance routes altering the shortest paths to take advantage of these routes in the post-alliance situation leading to an increase in the number of transfers. However, the additional transfers can shorten a passenger's transfer time as well as travel time. As a result, the shortest path may involve more transfers but result in less travel time in the post-alliance situation. The flight data of carrier Q of Australia can also be added into the alliance network. In this three-airlines alliance, Brisbane and Los Angeles are selected as the connecting airports between E and Q and between A and Q, respectively. As shown in Table 5, the mobility and accessibility are improved by the alliance—the normalized local mobility increases from 0.603 to 0.616—where the increment of the increase is nearly twice as big as that involving a two-airlines alliance. Analyses of the three-airlines alliance, such as the improvement rate of accessibility, show similar patterns to those for the two-airlines situation.

5. Conclusions

This study investigated the effects of alliances on airline networks, such as the improvement of network connectivity and accessibility of economic activities in regions. Models were formulated based on travel time to evaluate the connectivity, mobility and accessibility of the entire network before and after alliances. A case study of a complementary alliance between airlines E and A indicated that the alliance not only improved the mobility, but also effectively improved the accessibility from high–medium traffic airports to low traffic airports. After the alliance, the shortest paths involve more transfers but shorter travel time.

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