Physica A 413 (2014) 266–279

Contents lists available at ScienceDirect

Physica A

journal homepage: www.elsevier.com/locate/physa

An exploratory analysis on the evolution of the US airport network

Tao Jia [a,*], Kun Qin [a], Jie Shan [a,b]

[a] School of Remote Sensing and Information Engineering, Wuhan University, Wuhan, China

[b] School of Civil Engineering, Purdue University, West Lafayette, USA

HIGHLIGHTS

- We examine the evolution of the US airport network (USAN) from 1990 to 2010.
- The USAN has experienced drastic changes in both its structure and traffic in 2002.
- The USAN preserves the scale-free, small-world, and disassortative mixing properties over time.
- Stable cities in the USAN form the backbone and show structural regularity over time.
- New cities in the USAN indicate an evolution of continuous densification and intense exploration.

ARTICLE INFO

Article history:
Received 19 November 2013
Received in revised form 6 April 2014
Available online 8 July 2014

Keywords:
Complex network
US airport network (USAN)
Evolution
Exploration
Densification

ABSTRACT

Airport network has a nontrivial impact on shaping the development of a country or region, and decision makers or researchers can benefit from its evolution characteristics. This paper presents an exploratory analysis on the evolution of the US airport network from 1990 to 2010. Generally, we find that (1) the USAN has experienced a drastic change in both its structure and traffic amount in the year 2002. Particularly, regarding the entire USAN, we show that (2) it preserves the scale-free, small-world, and disassortative mixing properties over time which is consistent with the previous studies. Thereafter, the evolution of the USAN is examined from two perspectives: stable cities that never disappear in the time period and new cities that only appear in certain years. Findings from the first perspective imply that (3) stable cities form the backbone of the USAN over time and their structural similarity over time shows regularity. On the other hand, results from the second one indicate that (4) the USAN is undergoing a process of continuous densification intertwined with intense exploration in 1991 and 2002, which consequently leads to a stable USAN.

1. Introduction

The past few years have witnessed the availability of huge data [1], which allow researchers from many disciplines to analyze and model a diverse range of networked structures. Typical examples include the information network like the World Wide Web [2], technical network like power grid network [3], biological network like brain neural network [4], social network like scientific collaboration network [5], and even the transportation network e.g., railway network or airport network [6]. A network is composed of nodes and links and hides the principles or mechanisms of the underlying phenomena in a large extent. Due to the development of network theory, we can employ the tools or methods in complex network theory

* Corresponding author. Tel.: +86 02768770771; fax: +86 02768778086.
E-mail address: jiatao83@hotmail.com (T. Jia).

http://dx.doi.org/10.1016/j.physa.2014.06.067
0378-4371/

to understand its structure and function. Taking the transportation network as an example, it is composed of stations and routes, from which one may understand how the transportation organizes and the traffic flows.

Transportation network tends to act as a useful indicator to imply the socioeconomic development level of a country or region. Extensive attentions have been paid to investigate its structural and traffic properties as well as the evolution regularities with respect to different transportation modes. The global maritime transportation network was revealed to have the small-world property, hierarchical structure, and the rich-club phenomenon [7]. The evolution of urban road network in Italy has been recently examined in Ref. [8], and their findings suggest that urban road network evolves with a mutual process of exploration and densification. Moreover, the evolution of railway transportation network in China has been evaluated in terms of its spatial accessibility, relation to economic growth, and the formation of urban systems [9]. Similarly, the public transportation network in Singapore has been investigated in Ref. [10]. Their investigation of travel routes with both railways and buses endorses the importance of dynamical and temporal analysis, apart from the traditional topological analysis.

Compared with the aforementioned transportation modes, airport transportation network is expanding at a fast pace in recent years, and it occupies a large proportion of domestic and intercontinental traffic due to advantages of time-saving and economical cost. Although the flight prices are high in some regions, the short travel time may overwhelm this disadvantage and instead become the major motivation for traveling by air [11]. In the US, the deregulation of airline industry has resulted in a wide spread studies from both academic community and policy making agencies [12]. These studies show that the general public in the US have benefited a lot from this deregulation policy, and particularly it leads to the formation of hub-and-spoke structure [13], which in turn motivates more people to use air transportation as their travel mode. Moreover, airport network has nontrivial impact on the economy of a country or region such that understanding its evolution characteristics can benefit decision makers in different fields and researchers in network modeling and prediction.

Hence, research on airport network and its evolution has become a hot topic that attracts a wide range of attentions. The evolution of Chinese airport network has been investigated in Ref. [14] from the year 1950 to 2008, and they reported the stability of topological structure over years and the exponential growth of traffic with evident seasonal fluctuations. The evolution of Brazilian airport network has been examined in Ref. [11] for a period of 11 years from 1995 to 2006, and the findings indicate that the structure is dynamic with changes in relevance to airports and the traffic grows almost double times along with the shrinkage of network at route level. Ref. [15] studied the evolution of the US airport network in the period of 1990–2000 and found that most network metrics are stable with a small fluctuation and the dynamics of connections with appearing/disappearing between airports occur intensively at the local level. As for the evolution of European airport network from 1990 to 1998, Ref. [13] showed that intra-European traffic does not concentrate on a small number of hubs while inter-continental traffic does at the airport level and that hub-and-spoke structure is observed at the route level.

Inspired from the above findings, this paper explores the evolution of the US airport network (USAN) in the time period 1990–2010, and presents several findings that were not observed in the previous studies. In this paper, the USAN is modeled as a weighted network with cities as nodes and airlines between cities as links. Particularly, the evolution of the USAN is examined from three aspects: the entire USAN, stable cities and their traffic, new cities and their traffic. Stable cities refer to the ones occurring during the study period and new cities denote the ones being newly occurred in the current year not found in the previous year. The first view allows us to understand how traffic dynamics and topological structure as a whole change over time, while the second view sheds clear insight on the evolution of stable cities, which form the backbone of the entire USAN and helps on comprehending how individual stable cities evolve using similarity measurement. The last view gives us the opportunity to look at the evolution of new cities and their traffic, which opens a vista to depict the evolution mechanism of the USAN.

The remainder of this article is structured as follows. In Section 2, we describe the dataset adopted and the corresponding methodologies. The evolution of the entire USAN is investigated in Section 3. In Section 4, we report the findings on the evolution of the USAN from the perspective of stable cities. In Section 5, we elaborate the results on the evolution of the USAN from the perspective of new cities. In Section 6, issues regarding the evolving network or particularly the USAN are discussed. Finally, conclusions are drawn in Section 7.

2. Dataset and measurements

2.1. Dataset

This paper adopts the dataset provided by the Bureau of Transportation Statistics which can be downloaded via its official website (http://www.transtats.bts.gov/). The transportation data is organized into individual tables according to year, and hence we manually downloaded 21 tables from year 1990 to 2010. Each row in a table records the aggregated information of one airline operated from one original city to another destination city in one month, while the number of rows in each table gradually increases from around 150,000 in 1990 to 260,000 in 2010 (cf. Table 1). Each table includes 36 fields which cover much detailed information of the airline, such as passengers, freight, mail, distance, airline ID, original city, destination city, month, and so on. Besides, the total size of our dataset reaches about 750 MB.

The raw dataset is subsequently processed to build the US airport network for each year. Three steps are involved in this process, namely record validation, city geo-coding, and network construction. The first step aims to remove the invalid

Table 1
Number of records from 1990 to 2010.

Year	Records	Year	Records	Year	Records
1990	151 680	1997	132 018	2004	271 305
1991	144 565	1998	130 083	2005	268 435
1992	141 378	1999	136 138	2006	262 131
1993	144 781	2000	143 631	2007	274 786
1994	141 477	2001	153 288	2008	260 969
1995	133 525	2002	279 485	2009	246 264
1996	134 544	2003	261 106	2010	261 132

Table 2
Terms of the USAN for analysis.

Name	Description
Stable city	A node in the USAN, which never disappears during the study period.
New city	A node in the USAN, which appears in the network of current year but not in the previous year.
Route	A link in the USAN, which connects the original city (node) to a destination city (node) in the binary directed network, e.g., one route may have one or more airlines operating on it.

records in the case of information loss, say the missing value of important fields including original city and destination city. The second step intends to obtain the WGS84 geo-referenced coordinate (latitude and longitude) of each city via the Google Geocoding API. Lastly, the third step is conducted to extract the network model from each table according to the year. It is necessary to note that in the USAN the nodes denote cities and the links refer to airlines operated between two cities, which is different from some previous studies [6,13,16–18]. Moreover, for the simplicity of description, some terms related to the USAN are defined in Table 2 from the perspective of analysis.

2.2. Measurements

Before conducting the explorative analysis, several measurements are defined to characterize the property of the USAN. Without loss of generality, the fundamental concepts in network theory are elaborated firstly and then this is followed by the physical meaning in this context. In this study, the USAN at time period t is modeled as both a binary directed network and a weighted directed network. The former can be denoted as $BDN(t) = \{l_{ij}(t),\ i \neq j\}$, where $l_{ij}(t)$ is 1 when there exists a link from node i to node j and 0 when there is no link. The latter refers to $WDN(t) = \{l_{ij}(t) \times w_{ij}(t),\ i \neq j\}$, where $w_{ij}(t)$ is simply the weight value attached, such as passenger or freight in this case.

2.2.1. Indegree and outdegree

From the aspect of network theory, indegree (k_{in}) is defined as the number of nodes pointing directly to the current node, whereas outdegree (k_{out}) is defined as the number of nodes pointed directly by the current node. As important metrics to represent the structural property of a binary directed network, they reflect the importance of the current node [19]. In this study, at time t, $k_{\text{in}}(t)$ refers to the number of cities having flights to the current city, while $k_{\text{out}}(t)$ refers to the number of cities having flights from the current city. For instance, the indegree and outdegree of a city i at time t can be calculated as $k_{\text{in}}(i, t) = \sum_j l_{ji}(t)$ and $k_{\text{out}}(i, t) = \sum_j l_{ij}(t)$.

2.2.2. Betweenness

Betweenness (B) is defined as the number of shortest paths between any two nodes that pass through the current node. It is used to measure the extent to which the current node lies in the network [19]. Obviously, a node acting as a bridge tends to have a high value. Hence, in this context, it is used to measure the influence of the current city on transiting traffic between other cities. For instance, at time t, the Betweenness of a city i can be calculated as $B_i(t) = \sum_{m\neq n\neq i} \text{Path}(m, i, n, t)/\text{Path}(m, n, t)$, where $\text{Path}(m, i, n, t)$ is the number of shortest paths from city m to n passing through city i and $\text{Path}(m, n, t)$ is the number of shortest paths from city m to n.

2.2.3. Clustering coefficient and average shortest path

Clustering coefficient (CC) is used to characterize the extent to which nodes in the network are clustered together, while average shortest path (ASP) measures the average shortest number of steps among all pairs of nodes [20]. CC can characterize the local cohesiveness of the current node, while ASP can characterize the efficiency of information circulating on the network. In this context, CC reflects the ease of air traffic among the neighboring cities of the current one, while ASP reveals the ease of air traffic among all cities [6]. For instance, the CC of a city i at time t can be calculated as $CC_i(t) = R_i(t)/[k_n(i, t)(k_n(i, t) - 1)]$, where $R_i(t)$ is the actual number of routes among the neighboring cities and $k_n(i, t)$ is the number of neighboring cities. ASP at time t can be expressed as $ASP_i(t) = \sum_{i\neq j} d_{ij}(t)/N(t) * (N(t) - 1)$, where $d_{ij}(t)$ is the shortest distance between city i and j and $N(t)$ is the number of cities at time t.

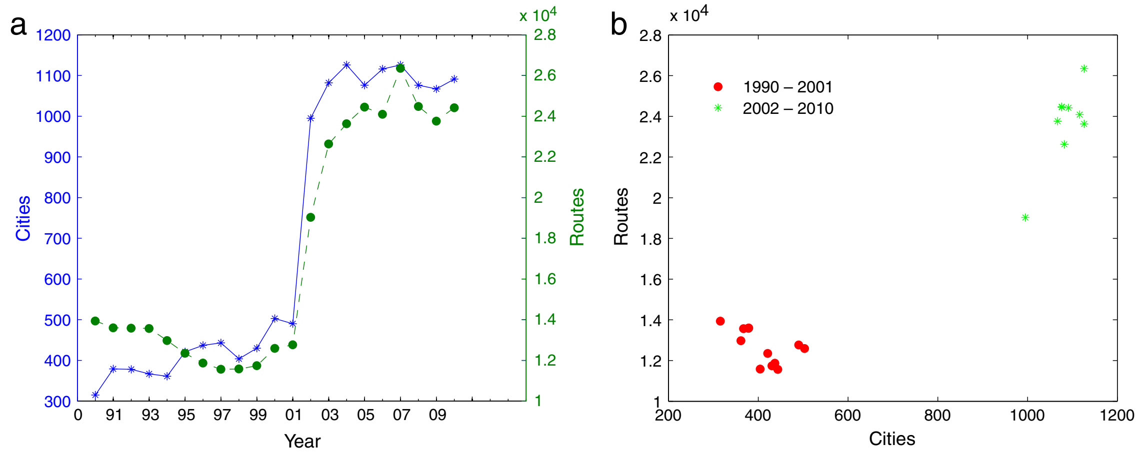

Fig. 1. Evolution of the number of cities and routes in the USAN. (Note: (a) shows the number of cities and routes changing with time; (b) displays a two-stage evolution symbolized with red dot and green asterisk.) (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

2.2.4. Network symmetry

Network symmetry (R) is devised to quantify the symmetry of the directed network. It is defined as the ratio of the number of links to the number of edges in the network. In this context, it is used to characterize the extent of reciprocity of air traffic among pairs of cities. For instance, the network R at time t can be calculated with $R(t) = \sum_{i \neq j} l_{ij}(t)/N(e, t)$, where $N(e, t)$ is the number of edges in the network at time t. Note that the values of $R(t)$ fluctuate between 1 and 2, and to make it simple, we subtract it by 1 to obtain a new range from 0 to 1. Hence, the value of 0 indicates an extremely asymmetric network, whereas the value of 1 indicates a complete reciprocal network.

2.2.5. Node similarity and network similarity

Node similarity (S) is proposed to quantify the extent of structural change of the current node compared with a previous one. Here, the structural change is measured with the proportion of common links. In this context, it measures the proportion of common routes of the current city between two successive years, and hence it can be used to characterize the evolution of individual cities. For instance, the S of a city i at time t can be calculated as $S_i(t) = |A(i, t) \cap A(i, t-1)|/|A(i, t) \cup A(i, t-1)|$, where $A(i, t)$ is the set of routes from or to city i at time t and $|\cdot|$ denotes the magnitude of the set. Consequently, the S of the network at time t is defined as $S(t) = \sum_{i=1}^{N(t)} S_i(t)/N(t)$, where $N(t)$ is the number of cities at time t.

3. Evolution of the whole USAN

Based on the metrics elaborated above, we present the traffic and structural evolution of the USAN in this section. Findings are mainly focused on three aspects. First, we report the traffic evolution of the USAN including the number of cities, routes, flights, passengers, freight and mails. Second, we show the structural evolution of the USAN, such as scale-free and small-world properties. Lastly, mixing patterns of the USAN over time is revealed.

3.1. Traffic properties

We examine the traffic properties of the USAN in the period 1990–2010. They include the number of cities, routes, flights, passengers, freight and mails. As shown in Fig. 1(a), we can see that a drastic increase in the number of cities and routes occurred in 2002, which demarcates the whole stage into two evolutional periods, namely 1990–2001 and 2002–2010. The first period witnessed a slow growth in the number of cities and decrease in the number of routes, while the second period displayed their fluctuation over time. This finding can be further observed in Fig. 1(b), where the two periods are symbolized with red dot and green asterisk respectively. The turning point in 2002 is probably due to the 9/11 terrorist attack, which induced the enactment of stringent policies on airline management and stimulated the construction of new airports to make air transportation more robust. However, this growth pattern is different from observations in other regions: the Brazilian airport network displays a gradual decreasing pattern [11], while the Chinese airport network shows an exponential growth pattern [14].

Similarly, the evolution of other traffic properties, such as flights, passengers, freight, and mails, is shown in Fig. 2. The values of the four properties are divided by the corresponding maximum values, which leads to normalized values from 0 to 1. In Fig. 2, the number of flights experiences a sharp growth in 2002 which is consistent with the growth of routes in Fig. 1(a), while the number of passengers keeps a relatively stable growth. As for the number of freight, it displays an exponential

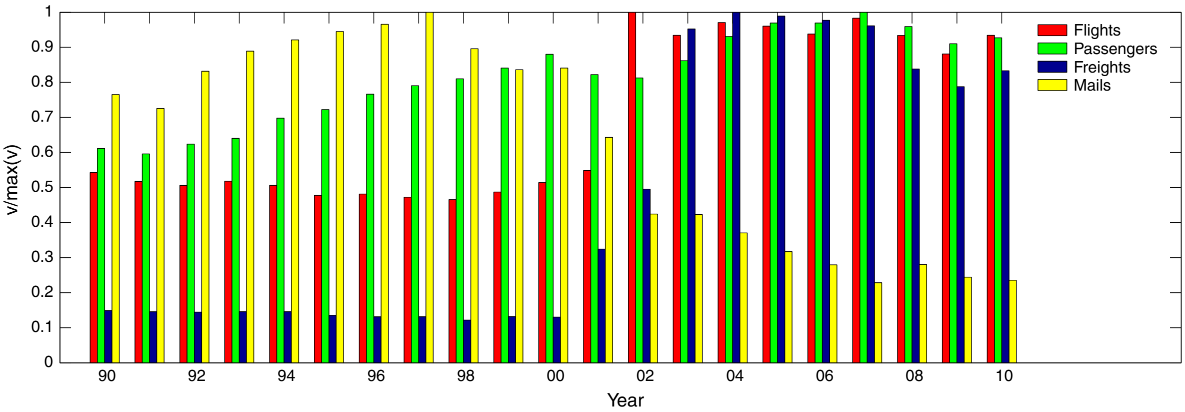

Fig. 2. (Color online) Evolution of the number of flights, passengers, freight, and mails in the USAN.

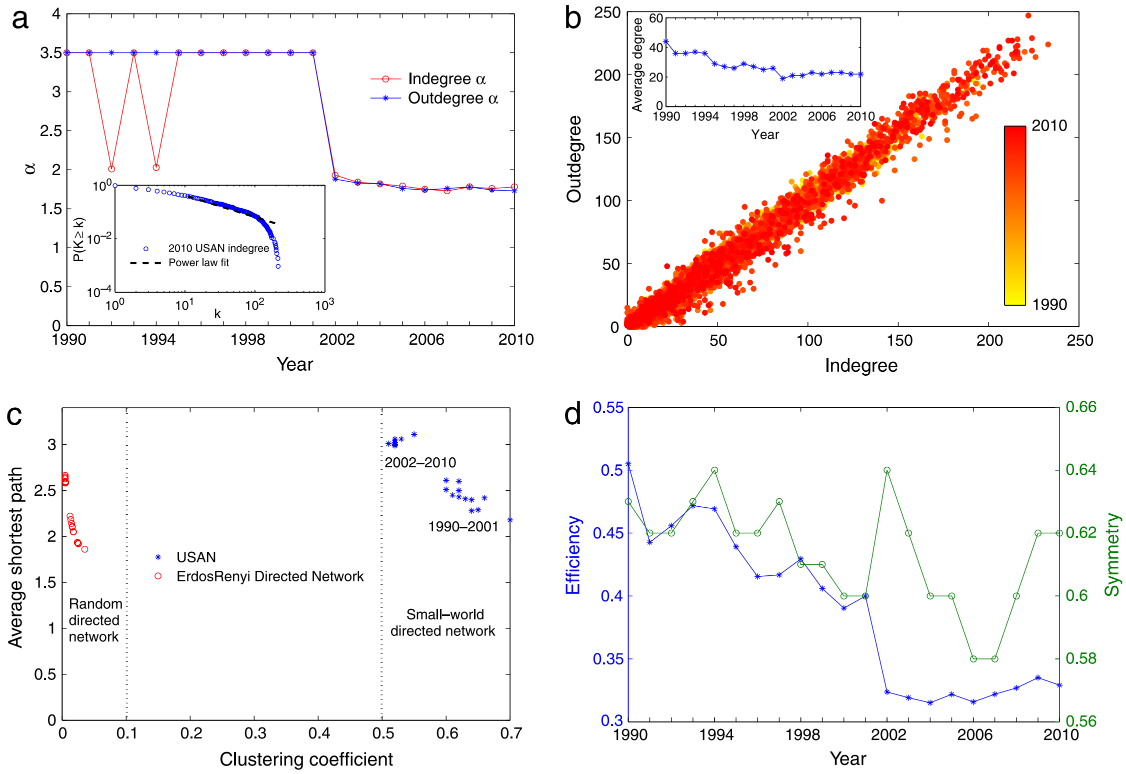

Fig. 3. (Color online) (a) Shows the scale-free property with inset displaying the power law distribution of indegree in 2010; (b) plots the linear relationship between indegree and outdegree with inset showing the evolution of average degree value; (c) presents the small-world property compared with the average result from 100 simulated Erdos–Renyi directed networks with the same number of nodes and edges for every year; and (d) displays the properties of network efficiency and symmetry.

growth from 2000 to 2003, but fluctuates around this value in the subsequent years. Besides, it is not so surprising to find that the number of mails shows a slow growth from 1990 to 1997 and then encounters a gradual decrease until 2010, because people are more likely to use e-mail instead of paper mail due to the popularity of the Internet.

3.2. Scale-free and small-world properties

A network is a scale-free network if its degree follows a power law distribution [20]. A network is a small-world network [21] if it has a large value of clustering coefficient (*CC*) and a small value of average shortest path (*ASP*). Here, we explore the distribution of both indegree and outdegree of the USAN and find that both metrics follow a power law distribution with truncations (cf. Fig. 3(a)), which differentiates from other studies, such as a stretched exponential

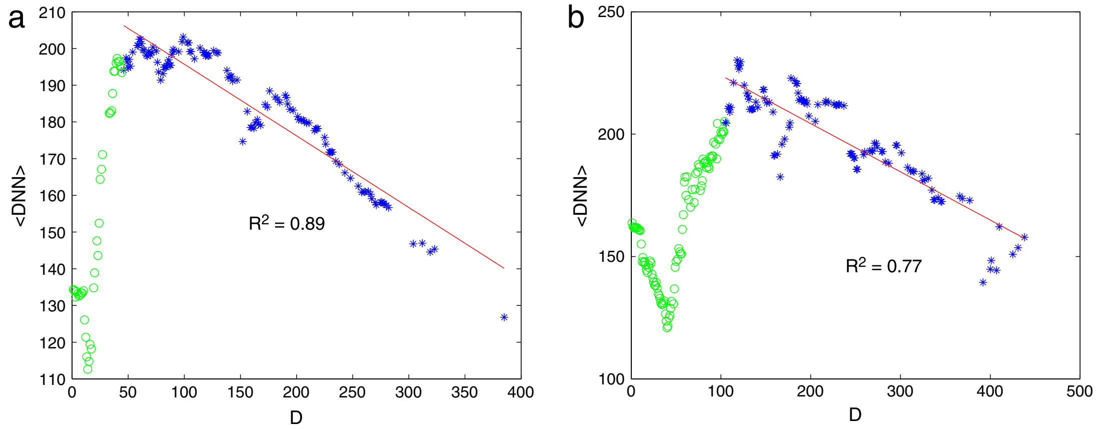

Fig. 4. (Color online) Mixing patterns in the USAN for the years (a) 1991 and (b) 2010.

distribution for Brazilian airport network [11] and a two-regime power-law distribution for Chinese airport network [14]. Importantly, we observe that the two values α_{in} and α_{out} do not deviate from each other too much except for the year 1992 and 1994, and they decrease dramatically in 2002. This finding implies that airports connections in the USAN are much more heterogeneous in the last decade. Another finding is that indegree is highly linearly correlated with outdegree irrespective of the year and that the average degree value tends to decline over years (cf. Fig. 3(b)) [11].

To verify whether the USAN exhibits the property of small-world, two structural metrics are investigated, namely clustering coefficient (*CC*) and average shortest path (*ASP*). We find that the USAN has a large value of *CC* and a small value of *ASP* compared with the ones of random directed network with the same number of nodes and edges (cf. Fig. 3(c)), which indicates the small-world property of the USAN irrespective of the year. This finding is consistent with most of the previous studies [6,11,14,17]. Moreover, the value of *CC* is gradually decreased from 0.70 in 1990 to 0.52 in 2010, while the value of *ASP* is gradually increased from 2.18 in 1990 to 3.02 in 2010.

To quantify how efficient the USAN is, we explore its efficiency coefficient over years. Efficiency in a network is highly inversely related to the value of shortest path length. Here, it is defined as the average of inverse shortest path length among all pairs of nodes. As shown in Fig. 3(d), we find that the efficiency of the USAN is gradually dropping down until it reaches a stable status in 2002. This finding coincides with the results from the analysis of small-world property and is probably due to the growth of USAN. Furthermore, we take a look at the symmetry (*R*) of the USAN or the extent of reciprocity of air traffic between any two cities. It reports that *R* fluctuates from 1990 to 2010 with relatively small values compared with the Brazilian airport network (cf. Fig. 3(d)) [11], which suggests that one flying to a city may have a 40% of chance to fly back using the same route. This finding may be useful for airport network modeling.

3.3. Mixing patterns

We continue to explore the evolution of mixing patterns in the USAN. Mixing patterns can be assortative mixing or disassortative mixing [22]. Assortative mixing refers to the situation that large degree nodes tend to be connected by large degree nodes. It can be described by the famous rich-club phenomena [23], which is commonly observed in society where individuals with similar interests are more likely to be clustered together [24]. Disassortative mixing means that large degree nodes tend to be connected by small degree nodes, which is typically found in the field of technology or biology [22].

Mixing pattern in the USAN is examined by the correlation of neighboring cities, namely the average nearest neighbor degree ($\langle DNN \rangle$) and the degree (note that degree is the sum of indegree and outdegree). We find that the USAN reflects a pattern of disassortative mixing with values ranging from −0.16 to −0.28 in the time period, which is consistent with several previous studies [6,16,25,26]. However, this mixing value is calculated with certain truncated degree, namely cities with degree value larger than the truncated degree contribute to the mixing value. Particularly, the truncated degree is around 45 for the network in the period 1990–2001, whereas the one is around 104 for the network in the period 2002–2010. Again, the year 2002 acts as a turning point in determining the truncated degree value. To make it clear, we show the mixing patterns of the USAN in 1991 and 2010 with respect to the two periods in Fig. 4.

4. Evolution of the USAN from a perspective of stable cities

The evolution of the entire USAN has been investigated in the above section. However, few attentions have been paid to the evolution of the USAN from the perspective of stable cities. Stable cities refer to the ones in the USAN that never disappear in the period 1990–2010, and they are assumed to form the backbone of the evolution of the USAN. To test the assumption, we examine their role in the USAN in terms of traffic share and structural function. Then, we explore structural evolution of stable cities, which indicates a hidden regularity.

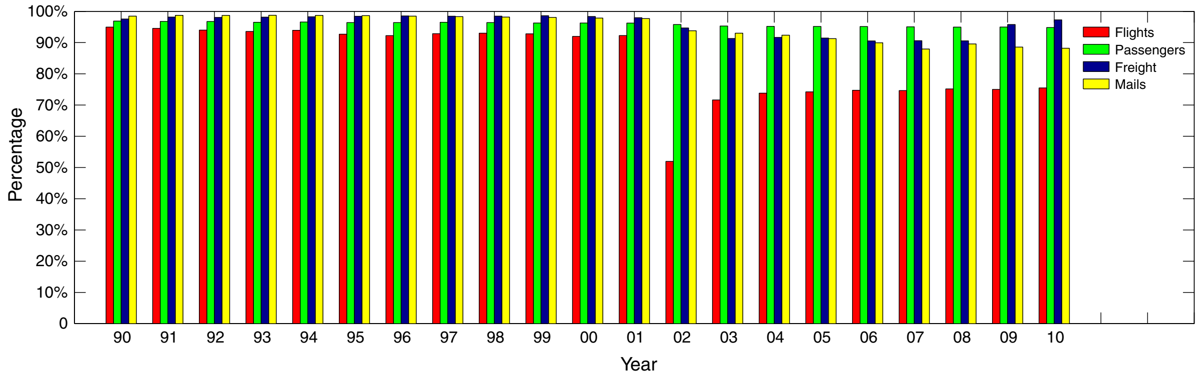

Fig. 5. (Color online) Evolution of traffic share of the stable cities.

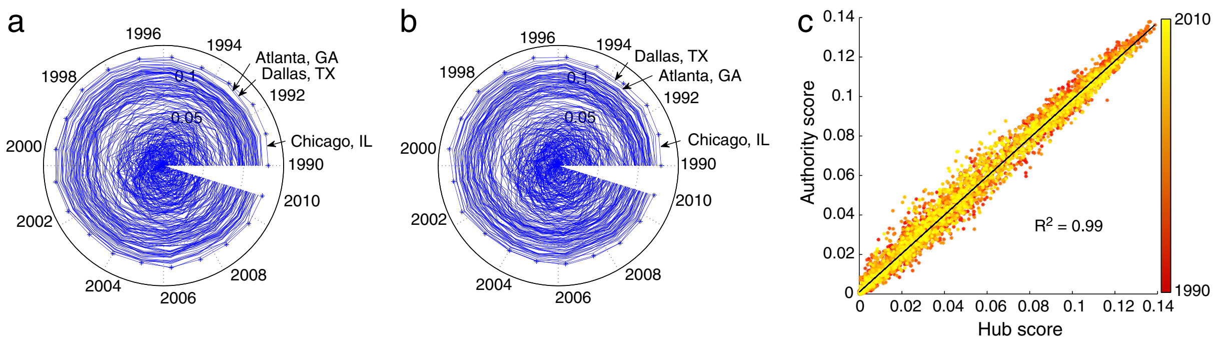

Fig. 6. (Color online) Evolution of structural position of the stable cities: (a) hub score, (b) authority score, and (c) their relationship.

4.1. Roles of stable cities over time

It is our assumption that stable cities might form the backbone of the USAN in both traffic share and structural function. To verify our assumption, we take a look at the traffic share of stable cities in the USAN, which include the proportion of flights, passengers, freight and mails. As shown in Fig. 5, we can observe that passengers, freight and mails managed or circulated by the stable cities constitute almost 90% of the total traffic in the USAN over years. However, flights operated on the stable cities show a different pattern. That is, it constitutes almost 90% of the total flights in the USAN from the year 1990 to 2001, but it encounters a drastic decrease to 50% in 2002 and thereafter a gradual growth to maintain a level of 70%. Two reasons can be supplied. One is marginal effect of 9/11 terrorist attack, which might lead to the drastic decrease in 2002, and the other one is the increasing number of new airports sharing the flights market, which might lead to the percentage of 70%.

Apart from the traffic share, we further examine the structural function of stable cities in the USAN. Structural function is measured using the hub score and authority score proposed in Jon Kleinberg's [27] algorithm HITS (Hyperlink Induced Topic Search). A higher hub score occurs if a city has flights to many other cities with high authority scores, while a higher authority score occurs if a city has flights from many cities with high hub scores. The evolution of hub scores and authority scores of stable cities are plotted respectively in Fig. 6. Most of the stable cities maintain relatively robust hub scores or authority scores over years, and the top three cities identified are Chicago, Dallas and Atlanta. Besides, the result shown in Fig. 6(c) demonstrates a remarkable linear relationship between hub score and authority score. In other words, a stable city with a high hub score tends to have a high authority score.

4.2. Structural evolution of stable cities

Individual stable cities in the USAN have experienced certain degree of structural change in terms of the routes to or from them. Here, we employ the similarity (S) measurement proposed in Section 2 to quantify them from 1990 to 2010. The result can be observed in Fig. 7(a), where the similarity of a stable city between two consecutive years is encoded in a pixel with red representing high value and blue representing low value. A high value implies a small structural change, while a low value represents a large one. Statistical analysis shows that around 43% of the stable cities have an average similarity value over this time period less than 0.5, which indicates that a considerable number of stable cities encounter at least 50% of structural change.

Besides, the evolution of structural similarity of individual stable cities shows a hidden regularity. This is examined by calculating the standard deviation and average value for each stable city during the time period. A stable city with a high

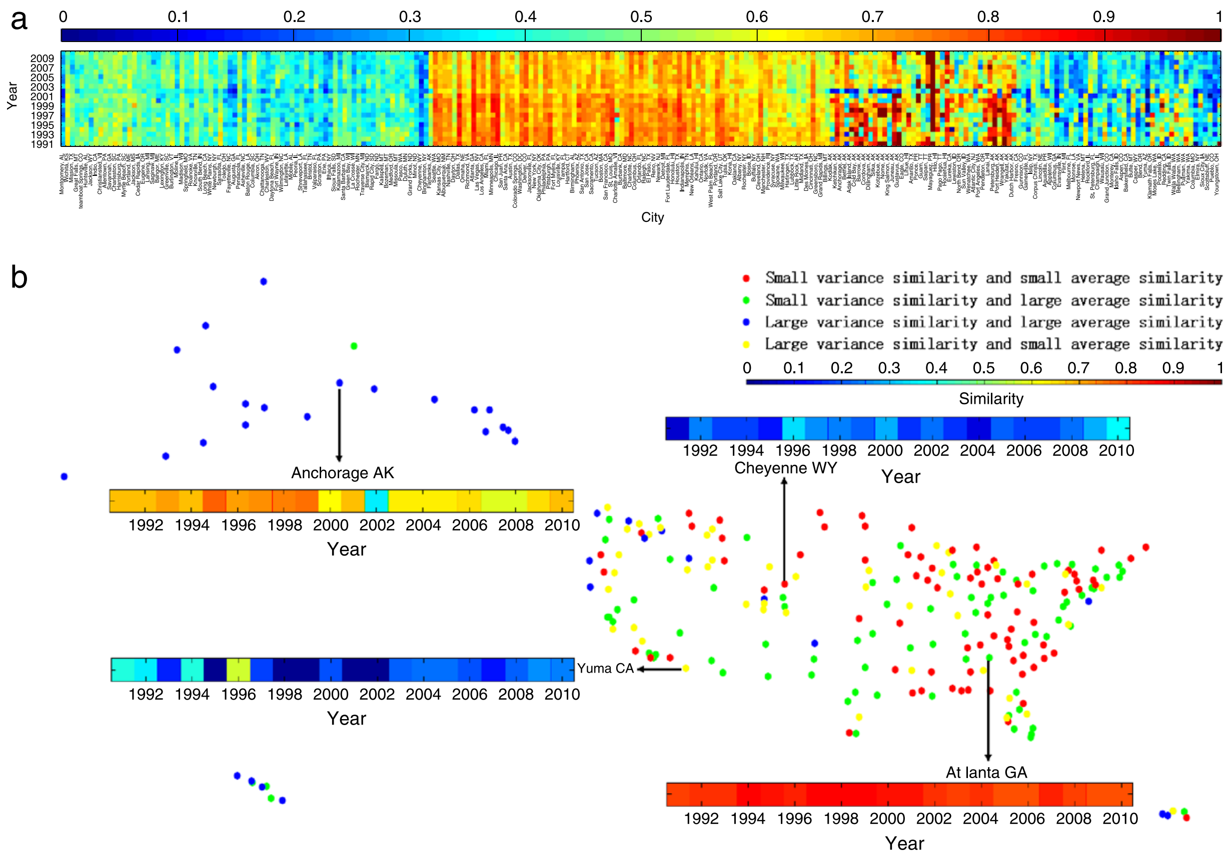

Fig. 7. (a) Evolution of similarity values for all stable cities and (b) the derived typology map. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

standard deviation value is much more spread out over a large range of similarity values than the one with a low standard deviation value, while a stable city with a low average value suggests a higher degree of structural change than the one with a high average value. In this way, stable cities are demarcated into four types using the mean values of both standard deviation and average similarity values (cf. Fig. 7). The first type refers to stable cities with narrow yet large structural changes, and typical examples are small cities, such as Cheyenne. The second type denotes the ones with narrow yet small structural changes, and large cities tend to belong to this type, such as Atlanta and Chicago. The third type indicates the ones with wide yet small structural changes, and typical examples tend to act as bridges in the USAN, such as Anchorage. The last type includes the ones with wide yet large structural changes, and small cities tend to belong to this type, such as Yuma.

5. Evolution of the USAN from a perspective of new cities

Apart from the evolution of stable cities, this section concentrates on the evolution of new cities. New cities denote the ones in the USAN appearing in the current year but not in the previous year. They have impacts on the USAN not only in traffic change but also in structural change. Hence, two aspects are to be examined. First, the dynamics of traffic change is demonstrated. Second, the influences imposed by new cities on the entire structure of the USAN over time are explored.

5.1. Evolution of traffic change in new cities

Traffic change in the USAN means the appearance of new routes and the associated flights, passengers, freight, and mails but not found in the previous year. New routes can be appeared in three types: (1) between two new cities, (2) one new city and one old city, or (3) two old cities. New routes with type (1) and (2) refer to traffic change due to new cities, while new routes with type (3) refer to traffic change within old cities. Obviously, the former traffic change tends to explore the USAN, while the latter one is likely to densify the USAN. As shown in Fig. 8, the proportion of the traffic change in new cities reaches a maximum in 1991 and 2002, whereas it is less than 15% in other years. This pattern can be also observed in other traffic, such as flights, passengers, freight and mails, but with a slightly high proportion. From the point of evolution, it hints that the USAN has experienced an exploration process in 1991 and 2002 while a densification process in other years.

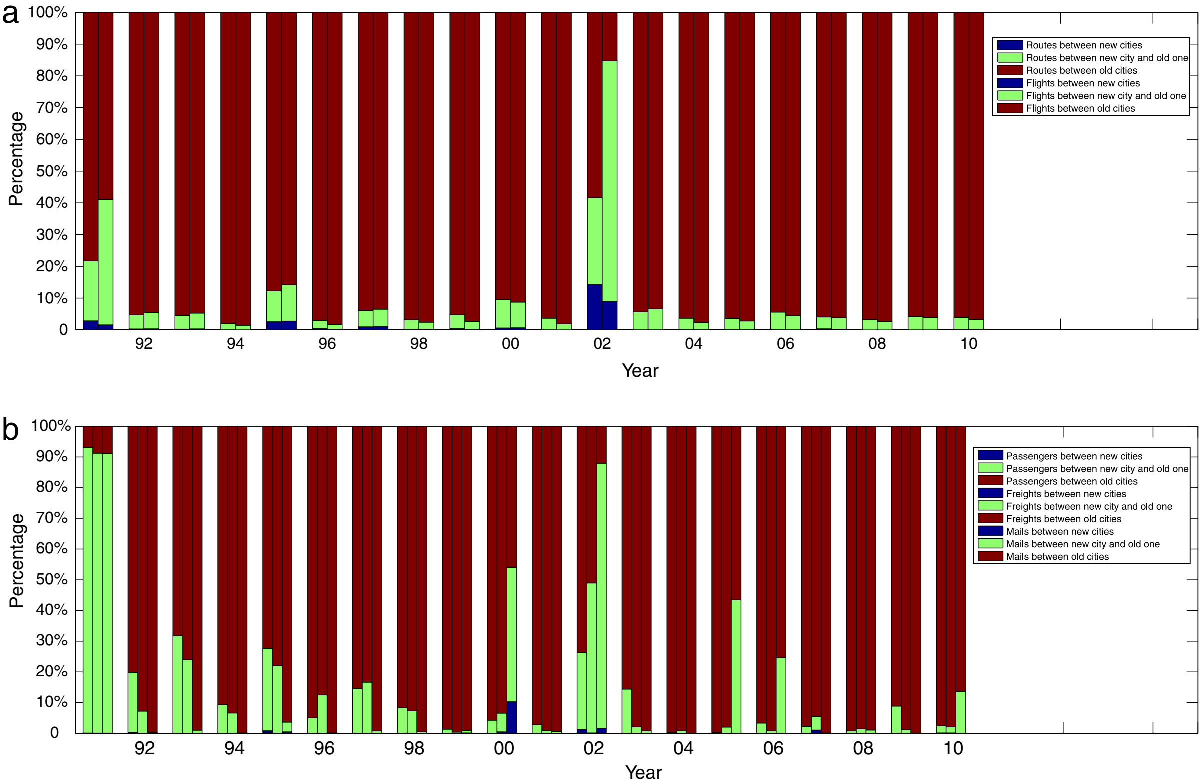

Fig. 8. (Color online) Proportion of traffic change among cities over years: (a) routes and flights, and (b) passengers, freight, and mails.

To vividly depict this evolution process, we visualize the dynamics of traffic change among cities in Fig. 9. From Fig. 9(a), we can clearly observe an exploration process with traffic change due to new cities colored in red and green, which mainly occurred in Alaska and near the Great Lakes. On the other hand, from Fig. 9(b), we can see a densification process with traffic change within old cities colored in blue, which occurred nearly across the entire continent. In general, the evolution of the USAN can be described as a process of continuous densification intertwined with a small degree of exploration. Indeed, we measure the change rate of network density among old cities between two consecutive years (the network density is defined as, $\rho = (\mathrm{Den}(\mathrm{year}) - \mathrm{Den}(\mathrm{year} - 1))/\mathrm{Den}(\mathrm{year})$ and $\mathrm{Den}(\mathrm{year}) = n_{\mathrm{routes}}/(n_{\mathrm{cities}} \times (n_{\mathrm{cities}} - 1))$), and we find that ρ gradually increases from 25% in 1991 to 43% in 2010. Not surprisingly, it coincides with the above findings.

5.2. Evolution of structural change in new cities

It is assumed that each new city might play a role in the USAN, and a structural change of the USAN might be encountered if one city is removed. To investigate the evolution of such structural change, network Betweenness (B) value is adopted, which is the average value of B of all cities and can reflect the transiting capability of the USAN. Hence, the structural change resulted from one city i can be defined as $\tau(i) = (B(N) - B_i(N))/B(N)$ [8], where $B(N)$ is the network Betweenness value and $B_i(N)$ is the Betweenness value of network without city i.

We find that the distribution of τ can be roughly approximated by a uniform distribution regardless of the year, which indicates an equal number of new cities with respect to different roles. To characterize this uniform distribution, we obtain the values such as the minimum, the maximum and the average, and plot them with respect to time in Fig. 10. The evolution of τ can be roughly classified into three time periods, where (a) time period from 1991 to 2001 experiences a relatively wide range of τ values with the maximum around 32% and the minimum around 0, and (b) time period in 2002 shows an extreme large gap among τ values with the maximum around 61% and the minimum around 0, and (c) time period from 2003 to 2010 displays a relatively small range of τ values with the maximum around 14% and the minimum 0. These findings in general reflect the evolution of structural changes from new cities, and particularly concur two facts: (1) some new cities in 2002 are considered as the most influential ones; and (2) most new cities after 2002 do not play crucial roles because of the stability of the USAN. From this point of view, this stability might be related to the densification process elaborated above.

Next, we visualize the spatial distribution of new cities with τ values with respect to three time periods, namely 1991, 2002, and 2010. As shown in Fig. 11, a rough trend can be observed for the distribution of τ values in geographic space with time. In 1991, new cities with high τ values are mainly concentrated on Alaska with a few scattered in the main continent.

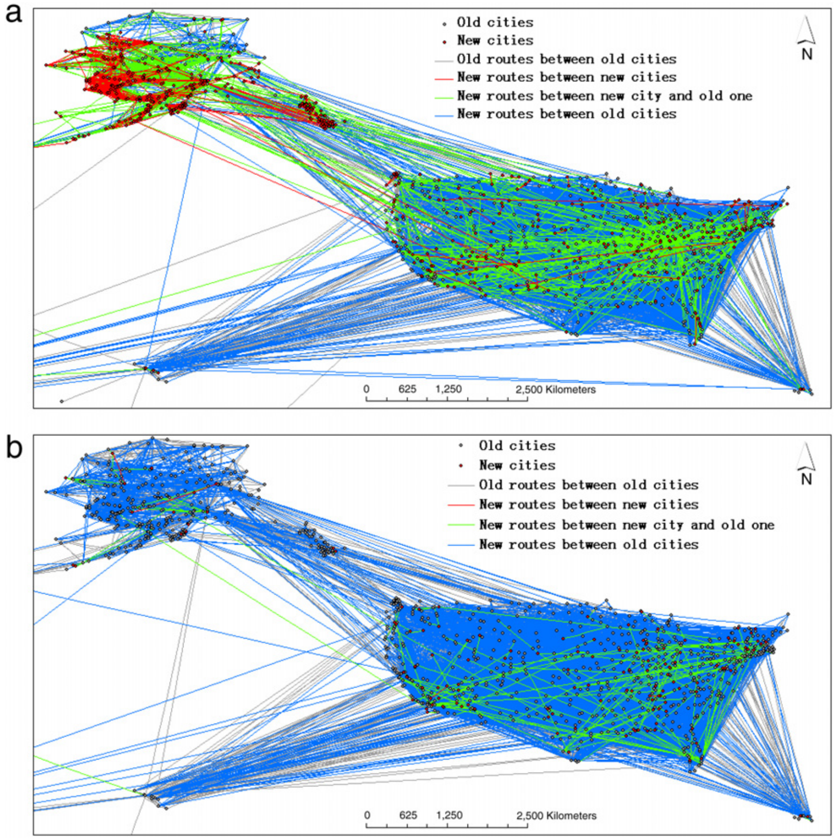

Fig. 9. Map of the USAN: (a) exploration in 2002 and (b) densification in 2010. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

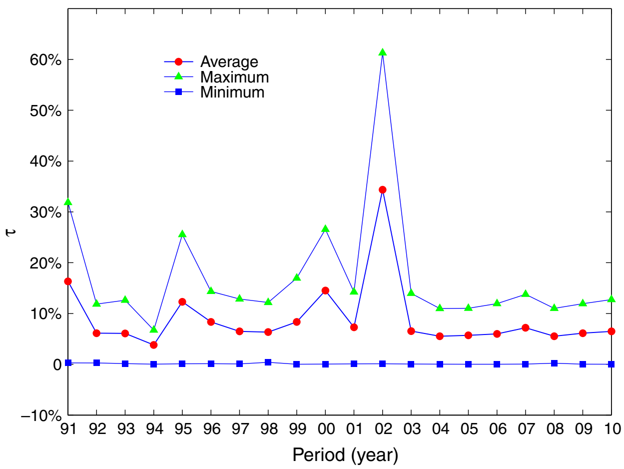

Fig. 10. (Color online) Evolution of structural change values (τ) from new cities.

In 2002, most of the new cities with high τ values are distributed nearly evenly in the main continent with a few scattered around other regions, while most of the new cities with low τ values are concentrated on Alaska with a few scattered in other regions. Lastly until 2010, new cities seem to be evenly distributed around the entire region with relatively low τ values. However, it needs further investigation as to how the evolution of τ values in geographic space can benefit the work of sustainable air transportation design and management. Nonetheless, this finding is consistent with aforementioned findings that the USAN has experienced a process of intense exploration in 1991 and 2002 and a continuous densification until 2010, which consequently leads to a stable USAN.

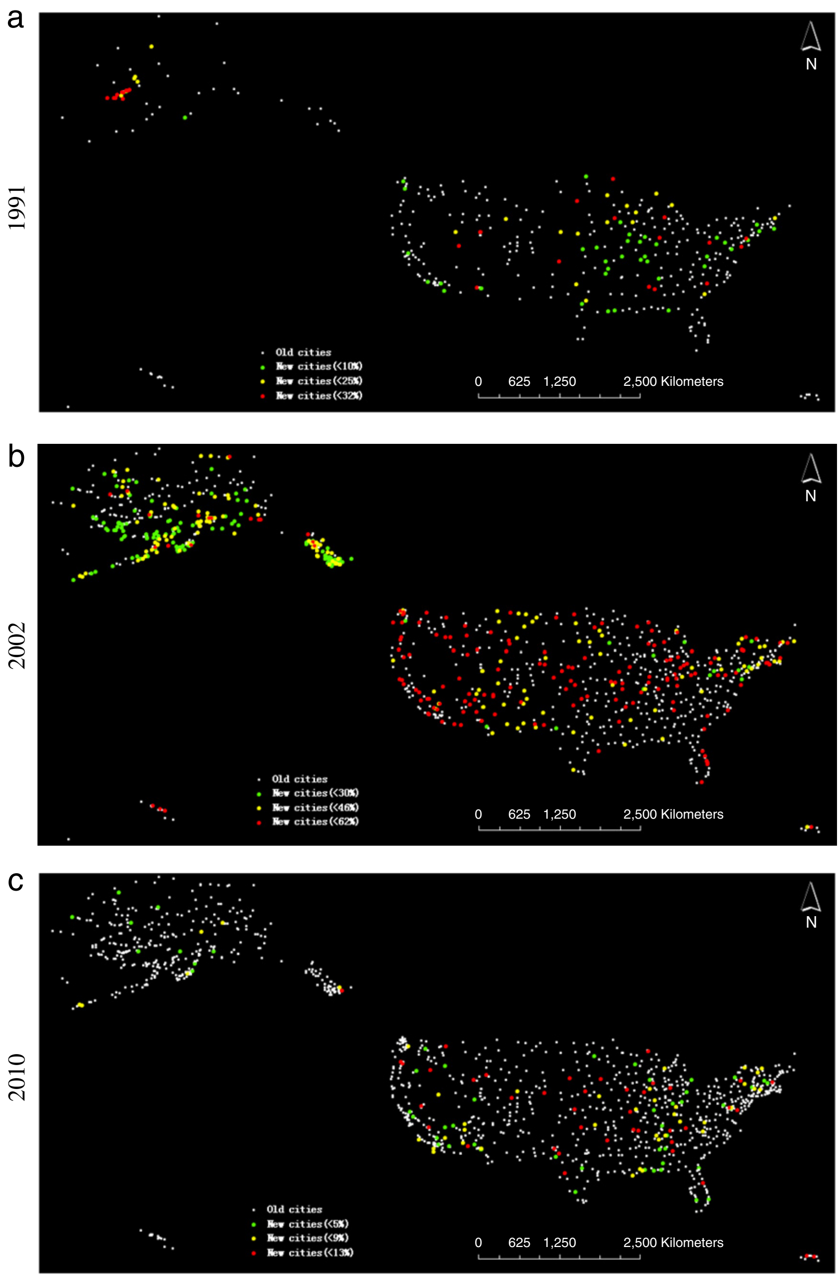

Fig. 11. Map of geographical distribution of new cities with τ values colored in green, yellow, and red for three time periods: (a) 1991, (b) 2002, and (c) 2010. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

6. Discussions

First, it is well known that the evolution of airport network might be subject to several factors, such as planning strategy [12], political policy [28], or geographical constraint [28]. The geographical constraint seems to play a vital role in shaping the uniqueness of airport network in terms of its structure and function. A common way is to correlate degree value with Betweenness value of each node, and typical result is the Anchorage city, which acts as a bridge to connect Alaska with the main continent but having a small number of connections [6,28]. Besides, modular structure in airport network means clusters of highly interconnected nodes that are less connected with nodes in other clusters, and each cluster suggests a certain function of the network. In this respect, the uniqueness of the entire USAN (including the main continent plus the Alaska and Hawaii) can be probably understood through the spatial distribution of modular structure. This argument puts forward an open question on whether modular structure in airport network can be constrained by geography. Using the

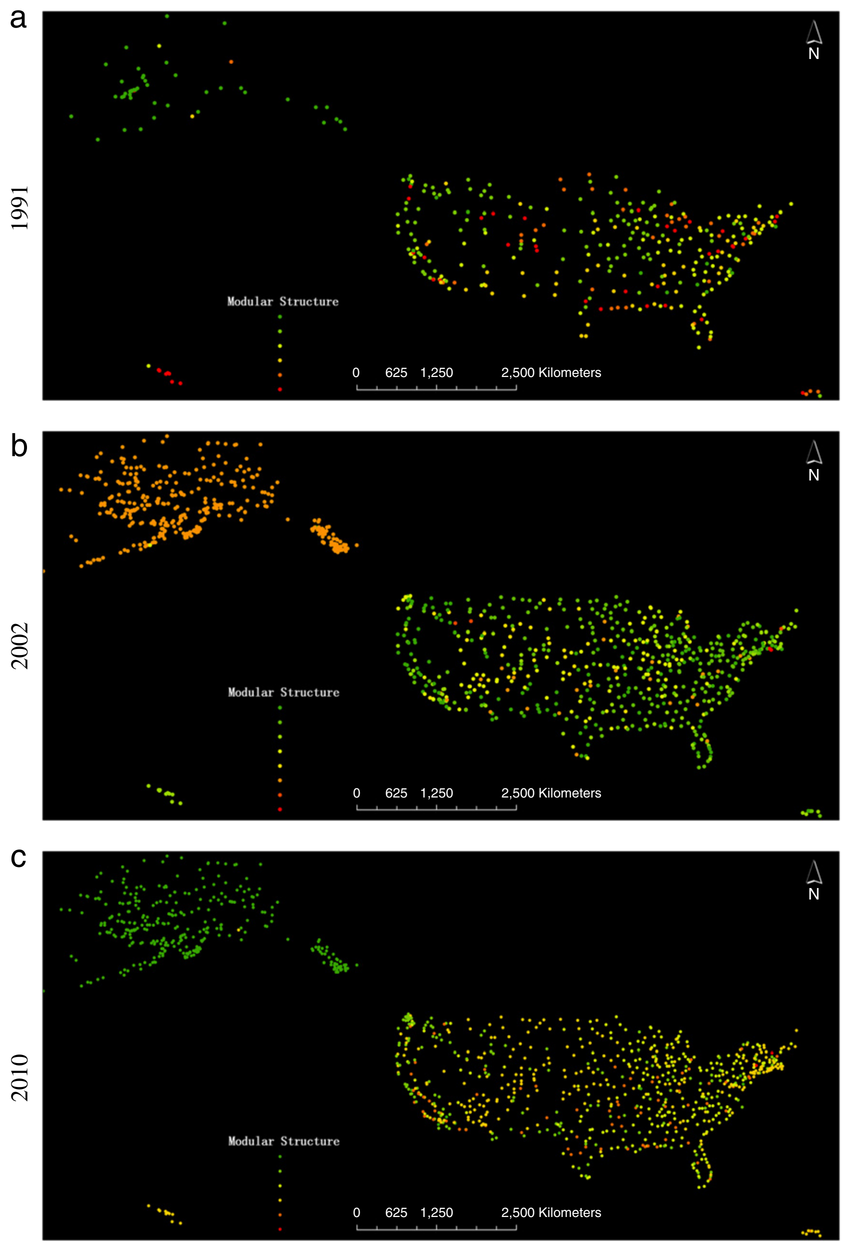

Fig. 12. (Color online) Map of geographical distribution of modular structure in all cities for three time periods: (a) 6 communities in 1991, (b) 8 ones in 2002, and (c) 6 ones in 2010.

Louvain's method for community detection [29], this study suggests that the entire USAN indeed displays a unique spatial pattern of modular structure over time (cf. Fig. 12): modular structure in the main continent displays a mixing pattern with many communities, whereas modular structure in Alaska and Hawaii shows a unique pattern with only one community respectively.

Second, it is necessary to think about the way to characterize the evolution of airport network. The most common way is to treat the evolving network as a series of snapshots with each one representing a static network in a particular timescale. Properties of the successive static networks, such as the average degree, can then be examined to uncover their trends in space and time. However, a problem of this way is how to define the time step for demarcating the evolving network. Obviously, a large time step will hide the spatio-temporal pattern within a static network, while a small time step will obscure wide trends visible over long timescale. This study adopts the time step as one year, and hence it fails to report the seasonal pattern of the evolving USAN, which has been presented in a previous study [14]. Another potential way is to look at the inner dynamics of the evolving networks in terms of birth/death of a node/link and splitting/merging of a community.

This study misses the findings related to the evolving modular structure in terms of splitting/merging communities, but it focuses on the evolving properties of stable cities and new cities. The introduction of stable cities and new cities opens a new vista on studies of evolving networks, which not only allows analysis on the backbone of the USAN with time, but also permits exploration on the dynamics of cities and their associated socioeconomic or geographic factors, such as population size or proximity to major hubs.

Third, the evolution of the USAN displays a small degree of similarity to the evolution of road network in a previous study [8], which also indicates an evolution of exploration and densification. However, airport network is different from road network in three main aspects. (1) Airport network is more likely to be subject to the intervention from transportation planning or zoning than the road network which may grow in a self-organized way. (2) The study extent of airport network tends to span a larger geographical region than the one of road network, for instance, country versus city. (3) Airport network can be intensively densified with routes among cities, but road network can only be slightly densified among street nodes because of the use of urban space. These aspects undoubtedly suggest a large degree of dissimilarity of the evolution of airport network to the one of road network.

7. Conclusions

This paper presents a vivid exploration on the evolution of the USAN, which employs the concept of evolving network studying the networks changing as a function of time. Airport network plays an important role in shaping the development of a country or region, whereas its evolution characteristics can benefit decision makers in different fields and researchers in network modeling. To enrich our knowledge in this field, this paper has empirically explored the evolution of the USAN in the time period 1990–2010. Generally, three aspects related to its evolution are investigated, namely the entire USAN, stable cities, and new cities. Common finding among the three aspects is that the USAN has experienced a drastic change in both its structural properties and traffic amount in the year 2002.

Findings from the first perspective suggest that the USAN preserves the scale-free, small-world, and disassortative mixing properties over time. Findings from the second perspective indicate that stable cities form the backbone of the USAN over time in both traffic share and structural function, and that evolution of individual structural similarity implies a typology of four categories of stable cities. Finally, findings from the last perspective demonstrate that the USAN has undergone a process of continuous densification intertwined with intense exploration in 1991 and 2002, which consequently leads to a stable USAN. However, how this knowledge on the evolution of the USAN can be employed by the policy makers or integrated into the network modeling requires further efforts, which definitely points out our future work.

Acknowledgments

We would like to thank the constructive comments from the anonymous referees, whose efforts greatly improved the quality of this paper. We also thank Prof. Bin Jiang and Mr. Manley Edward for providing us the way to download the data. Lastly, we appreciate the financial supports from the Key Laboratory for National Geographic State Monitoring of National Administration of Surveying, Mapping and Geoinformation (No. 213363014), the Research Fund for the Doctoral Program of Higher Education of China (No. 20130141120075), the Scientific Research Foundation of Wuhan University (No. 274196), and National Natural Science Foundation of China (No. 61172175).

References

[1] G. Bell, T. Hey, A. Szalay, Beyond the data deluge, Science 323 (2009) 1297–1298.
[2] R. Albert, H. Jeong, A.L. Barabasi, Diameter of the World Wide Web, Nature 401 (1999) 130–131.
[3] G.A. Pagani, M. Aiello, The Power Grid as a complex network: a survey, Physica A 392 (2013) 2688–2700.
[4] E. Bullmore, O. Sporns, Complex brain networks: graph theoretical analysis of structural and functional systems, Nat. Rev. Neurosci. 10 (2009) 186–198.
[5] M.E.J. Newman, The structure of scientific collaboration networks, Proc. Natl. Acad. Sci. USA 98 (2001) 404–409.
[6] T. Jia, B. Jiang, Building and analyzing US airport network based on en-route location information, Physica A 391 (2012) 4031–4042.
[7] Y.H. Hu, D.L. Zhu, Empirical analysis of the worldwide maritime transportation network, Physica A 388 (2009) 2061–2071.
[8] E. Strano, V. Nicosia, V. Latora, S. Porta, M. Barthelemy, Elementary processes governing the evolution of road networks, Sci. Rep. 2 (2012) 1–8.
[9] J. Wang, F.J. Jin, H.H. Mo, F.H. Wang, Spatiotemporal evolution of China's railway network in the 20th century: an accessibility approach, Transport Res. A-Pol. 43 (2009) 765–778.
[10] H. Soh, S. Lim, T.Y. Zhang, X.J. Fu, G.K.K. Lee, T.G.G. Hung, P. Di, S. Prakasam, L. Wong, Weighted complex network analysis of travel routes on the Singapore public transportation system, Physica A 389 (2010) 5852–5863.
[11] L.E.C.D. Rocha, Structural evolution of the Brazilian airport network, J. Stat. Mech. Theory Exp. (2009) P04020.
[12] J.R. Meyer, T.R. Menzies, The continuing vigil: maintaining competition in deregulated airline markets, J. Transp. Econ. Policy 34 (2000) 1–20.
[13] G. Burghouwt, J. Hakfoort, The evolution of the European aviation network, 1990–1998, J. Air Transp. Manag. 7 (2001) 311–318.
[14] J. Zhang, X. Cao, W. Du, K. Cai, Evolution of Chinese airport network, Physica A 389 (2010) 3922–3931.
[15] A. Gautreau, A. Barrat, M. Barthelemy, Microdynamics in stationary complex networks, Proc. Natl. Acad. Sci. 106 (2009) 8847–8852.
[16] W. Li, X. Cai, Statistical analysis of airport network of China, Phys. Rev. E 69 (2004) 046106.
[17] M. Guida, M. Funaro, Topology of the Italian airport network: a scale-free small-world network with a fractal structure, Chaos Solitons Fractals 31 (2007) 527–536.
[18] B. Jiang, T. Jia, Exploring human mobility patterns based on location information of US flights, 2011. arXiv:1104.4578v2.
[19] L.C. Freeman, Centrality in social networks: conceptual clarification, Social Networks 1 (1979) 215–239.
[20] A.L. Barabasi, E. Bonabeau, Scale-free networks, Sci. Am. 288 (2003) 60–69.
[21] D.J. Watts, S.H. Strogatz, Collective dynamics of small world networks, Nature 393 (1998) 440–442.

[22] M.E.J. Newman, Assortative mixing in networks, Phys. Rev. Lett. 89 (2002) 208701.
[23] V. Colizza, A. Flammini, M.A. Serrano, A. Vespignani, Detecting rich-club ordering in complex networks, Nat. Phys. 2 (2006) 110–115.
[24] A. Grabowski, R. Kosinski, Mixing patterns in a large social network, Acta Phys. Polon. B 39 (2008) 1291–1300.
[25] G. Bagler, Analysis of the airport network of India as a complex weighted network, Physica A 387 (2008) 2972–2980.
[26] G. Bagler, Analysis of the airport network of India as a complex weighted network, Physica A 387 (12) (2008) 2972–2980.
[27] J.M. Kleinberg, Authoritative sources in a hyperlinked environment, J. ACM 46 (1999) 604–632.
[28] R. Guimerà, S. Mossa, A. Turtschi, L.A.N. Amaral, The worldwide air transportation network: anomalous centrality, community structure, and cities' global roles, Proc. Natl. Acad. Sci. USA 102 (22) (2005) 7794–7799.
[29] V.D. Blondel, J.-L. Guillaume, R. Lambiotte, E. Lefebvre, Fast unfolding of community hierarchies in large networks, J. Stat. Mech. (10) (2008) P10008.