Transportation Research Part E 82 (2015) 55–78

Contents lists available at ScienceDirect

Transportation Research Part E

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

Evolution of the international air transportation country network from 2002 to 2013

Sebastian Wandelt [a,b], Xiaoqian Sun [a,*]

[a] School of Electronic and Information Engineering, Beihang University, No. 37 Xueyuan Road, 100191 Beijing, China
[b] Department of Computer Science, Humboldt-University Berlin, Unter den Linden 6, 10099 Berlin, Germany

A R T I C L E I N F O

Article history:
Received 10 January 2015
Received in revised form 5 August 2015
Accepted 6 August 2015
Available online 15 August 2015

Keywords:
Air transportation
Country network
Network evolution
Criticality

A B S T R A C T

In this research, we analyze the evolution of the international air transportation country network from 2002 to 2013 with two perspectives: The network's physical topology and the functional network with traffic information. Our analysis shows that the network is scale-free and has the small-world property. The evolution of triadic properties suggests that the network gears towards symmetric, transitive closure. We find that United States, Great Britain, and France are critical from both perspectives; Surprisingly, South Africa is particularly critical from topological point of view. Furthermore, topological and functional criticality are highly correlated to the GDP of a country.

1. Introduction

Air transportation is a complex socio-technical system and its function is to transfer passengers/cargos over long distances across countries or continents. With increased demand of air traffic, air transportation affects national or international economies significantly. Complex network theory can help us to understand the structure and dynamics of air transportation system. Previous studies on air transportation networks mainly focused on centrality measures of individual airports (Kotegawa et al., 2014; Zanin and Lillo, 2013), network robustness (Janic, 2015; Wei et al., 2014; Lordan et al., 2014), delay propagation (Baumgarten et al., 2014; Zhao et al., 2014; Zou and Hansen, 2014; Fleurquin et al., 2013), epidemic spreading (Gomes et al., 2014), route network similarity analysis (Sun and Wandelt, 2014), and temporal evolution (Jia et al., 2014; Sun et al., 2015; Azzam et al., 2013). Furthermore, Burghouwt and Redondi (2013) compare and classify different connectivity models for airport networks, for instance, shortest path length centrality (Malighetti et al., 2008), quickest path length centrality (Paleari et al., 2010), and weighted number of connections (Burghouwt, 2007).

Instead of looking at specific airports, as done in related work, we suggest to analyze air transportation at country level to identify the roles of whole countries in international air transportation and also to understand the network properties induced by the aggregation. While the idea of aggregating the airport network is not new, Guimera et al. (2005) and Bonnefoy (2008) aggregated the airport network to the city level, in order to identify the city's global roles, we are the first to look at the passenger air transportation at country level.

Country networks have been studied in other fields recently. Hawelka et al. (2014) constructed a country-to-country mobility network based on geo-located Twitter messages, with the countries as nodes and the number of Twitter users exchanging tweets between two countries as the link weight. The results showed that there is increased mobility in the

* Corresponding author. Tel.: +86 10 8231 6306.
E-mail addresses: wandelt@informatik.hu-berlin.de (S. Wandelt), qqian.sun@gmail.com (X. Sun).

http://dx.doi.org/10.1016/j.tre.2015.08.002
1366-5545/

developed countries and the Twitter mobility network is spatially connected and well aligned with common socio-geographical regions. Kaltenbrunner et al. (2014) built a social network for sister cities at country level; a link between two countries exists if a city of one country is twinned with a city of the other country. It is found that the impact of the geographical distance on the sister city country network is negligible and the cities with similar degree are preferentially connected. Moreover, Deguchi et al. (2014) analyzed the world trade network, where the nodes are countries; the links are exports and imports among the countries, weighted by the annual amounts of trade. Variants of the HITS (Hyperlink Induced Topic Search) algorithm were used to investigate the economic influences of the countries in the world trade network.

The structure and function of complex networks often interact with each other (Newman, 2003) and it has been shown that critical nodes in both networks are often different. Thus, the conclusions for structural networks cannot be directly extended to functional networks, and vice versa (Zhang and Sterbenz, 2014; Lehner, 2013). Hereby, we give a clear definition of what is topological criticality and what is functional criticality in air transportation networks:

Topological criticality is investigated from the properties of the physical network structure, independently from the actual passenger traffic on top of the network. From this topological view, connections with a small number of passengers are considered equally important as connections with a large number of passengers.

Functional criticality is identified from the properties of the network, when taking into account the actual passenger traffic on top of the network. From the functional point of view, connections with a large number of passengers are considered more important for the network, than connections with only few passengers.

Therefore, we refer to the physical network with passenger traffic data as a *functional network* (Newman, 2003), since one major function of air transportation systems is to deliver passengers from their origins to destinations. In this research, we investigate the temporal evolution of international air transportation country network from two perspectives separately: (1) the network's physical topology and (2) the functional network with passenger traffic data.

This paper is organized as follows. Section 2 discusses the state-of-art in the evolutionary analysis of air transportation networks. In Section 3, we build the international air transportation network at country level. Section 4 presents the evolution of the physical country network from 2002 to 2013, with focus on unweighted network properties and topologically critical nodes/links. Section 5 presents the evolution of the country network with passenger traffic data, focusing on traffic properties, weighted network properties, and functionally critical nodes/links. We discuss our results in Section 6 and conclude the paper with Section 7.

2. Related work

This section provides a literature review of the network evolution analysis in air transportation systems. Most research focused on airport networks, with airports as nodes and links exist if there is at least one direct flight connection between two airports. Azzam et al. (2013) studied the evolution of the worldwide airport network using Official Airline Guide (OAG) flight schedules data between 1979 and 2007. The authors found that the degree distribution is non-stationary and is subject to accelerated growth; the average degree increases while the average shortest path length decreases; the average clustering coefficient decreases for growing node degrees.

Several researchers investigated the evolution of the US airport network. Jia et al. (2014) examined the evolution of the US airport network from 1990 to 2010, based on a dataset provided by Bureau of Transportation Statistics (BTS). The results showed that the US airport network preserves the scale-free, small-world, and disassortative mixing properties; the evolution of stable cities and new cities has also been examined. Based on the same dataset, Lin and Ban (2014) studied the evolution of topological and spatial characteristics of the US airline network. They found that the dynamics of the US airline work is stable, distance becomes more significant with the passage of time, and the network efficiency decreases with the growth of the network. Kotegawa et al. (2014) presented a network restructuring algorithm in order to capture the evolutionary behavior of the US air transportation network. Gautreau et al. (2009) studied the evolution of the US airport network between 1990 and 2000 with the BTS data as well. The authors showed that although statistical distributions of most indicators are stationary, there exist several dynamics at the microscopic level, with many appearing/disappearing connections between airports. Neal (2013) presented the evolution of the business air travel network in the US from 1993 to 2011 and revealed that the business travel among US cities is becoming more symmetric and evenly dispersed. Bounova (2009) studied the evolution of the airline networks in US from 1990 to 2007 and showed that there are topology transitions; most airline networks have similar topology and historical patterns, with the exception of Southwest Airlines.

The evolution of European airport networks has also been widely studied. Burghouwt and Hakfoort (2001) analyzed the evolution of the European air traffic according to different airport groups, based on a weekly OAG data for the years 1990–1998. The authors showed that there is no clear trend of concentration of intra-European traffic on the primary hubs and a type of hub-and-spoke route structure has been developed. Jimenez et al. (2012) studied the evolution of the Portuguese airport network between 2001 and 2010. The analysis showed that the network is less concentrated and the low-cost carriers have a great impact on the evolution of the network. Papatheodorou and Arvanitis (2009) explored the evolution of the airport network in Greece over the period 1978–2006. The analysis showed that the spatial concentration and asymmetry