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Robustness of airline alliance route networks

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ABSTRACT

The aim of this study is to analyze the robustness of the three major airline alliances' (i.e., Star Alliance, oneworld and SkyTeam) route networks. Firstly, the normalization of a multi-scale measure of vulnerability is proposed in order to perform the analysis in networks with different sizes, i.e., number of nodes. An alternative node selection criterion is also proposed in order to study robustness and vulnerability of such complex networks, based on network efficiency. And lastly, a new procedure – the inverted adaptive strategy – is presented to sort the nodes in order to anticipate network breakdown. Finally, the robustness of the three alliance networks are analyzed with (1) a normalized multi-scale measure of vulnerability, (2) an adaptive strategy based on four different criteria and (3) an inverted adaptive strategy based on the efficiency criterion. The results show that Star Alliance has the most resilient route network, followed by SkyTeam and then oneworld. It was also shown that the inverted adaptive strategy based on the efficiency criterion – inverted efficiency – shows a great success in quickly breaking networks similar to that found with betweenness criterion but with even better results.

1. Introduction

The restructuring of airline activities into alliances has been one of the major traits of this industry since the beginning of the 90s, and over the last decade most Full-Service Carriers and regional airlines have participated in an airline alliance. Airlines join alliances for several reasons [7]. First, alliance members can benefit from economies of scale and density: without having to increase investment in aircraft, alliance members can extend their route network and offer a wider range of frequency to customers on selected routes. Furthermore, alliance members can explore easier ways to collaborate with other members through codesharing, joint-ventures or even merger and acquisitions. Finally, alliance members can benefit from the joint venture by offering benefits to customers (e.g., frequent-flyer programs) or from the joint purchase of supplies such as fuel. In respect to consumer welfare, airline alliances lower the fares of interline flights, which compensates for the fare increases on interhub flights [4,5]. However, it must be noted that the competence of alliance members to coordinate routes and fares is an important requirement for passengers to realize these benefits [18].

When an airline joins an alliance, the reliability of its services offered to customers not only depends on the flights the airline operates, but also on the operations of the rest of the alliance members, since most of the routes offered by alliances are operated on a hub-and-spoke basis. Although airline alliances have been formed for operational and competitive reasons, the attachment to an alliance can determine the robustness of the airline network.

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The *Airline alliance route networks* (AARNs) are constructed as an aggregation of the airlines' route networks belonging to the alliance. These networks can be considered as a multilayered network [6], and constitute an intermediate level of analysis of air transport networks, between airline route networks and global or regional networks [14]. The aim of the present study is to analyze the vulnerability of AARNs to errors (i.e., the random isolation of an airport) and attacks (i.e., isolation of well-connected airports with the aim of causing the maximum damage to the route network). This assessment is performed by two different approaches: first, using a multi-scale measure of vulnerability [2], and second, examining the effect of the disconnection of a fraction f of well-connected nodes on the size of the overall giant component. This study can shed light on the robustness of real networks not only for the special case of airline alliances but also for networks sharing similar topological properties.

2. Methods

2.1. Vulnerability

In [2], a multi-scale measure of the vulnerability of a graph G is defined by introducing the coefficient p to the characteristic formula of the average edge betweenness as:

$$b_p(G) = \left(\frac{1}{|E|}\sum_{l\in E} b_l^p\right)^{1/p} \tag{1}$$

where $|E|$ is the number of edges, and b_l is the betweenness of the edge l calculated as:

$$b_l = \sum_{i\neq j}\frac{n_{ij}(l)}{n_{ij}} \tag{2}$$

where $n_{ij}(l)$ is the number of geodesics (i.e., shortest paths) from node i to node j that contain the edge l, and n_{ij} is the total number of shortest paths. The scale parameter $p > 0$ acts as an exponent of each value of edge betweenness, and its inverse value as an exponent of the sum of all (powered) edge betweenness. For instance, $b_2(G)$ is the square root of the average square edge betweenness of the graph G.

To compare the vulnerability of two networks G and G' with similar structural properties, the first step is to compute b_1 for both graphs. If $b_1(G) < b_1(G')$, then G is more robust (less vulnerable) than G'. If $b_1(G) = b_1(G')$, then the values of b_p for values of $p > 1$ must be computed until $b_p(G) \neq b_p(G')$. Then, the network with the smallest value of b_p will be the most robust one. In general, the full multi-scale sequence of betweenness coefficients $(b_p(G))_{p\geqslant 1}$ must be considered in order to get an accurate approach to the robustness of the network [2].

This procedure can be used to assess differences in vulnerability between airline alliance route networks (AARNs). As shown in Table 1, AARNs have really different numbers of nodes and edges, so the measures of vulnerability have to be normalized in order to be able to compare graphs. One possible normalization procedure can be defined by using the graphs of N nodes with minimum and maximum vulnerability: the complete and the string graphs, respectively. A *complete graph* of N nodes is a fully connected graph where each node has $N-1$ edges. It is easy to see that the complete graph has a minimum vulnerability, which is $b(G_{complete}) = 1$. On the other hand, a *path graph* of N nodes can be defined as a string of nodes attached to its neighbors. Each node has two edges, except the two end nodes of the string that just have one. This graph has the highest vulnerability among all graphs of N nodes. Mishkovski et al. [16] proposed a normalization for $b(G)$ as:

$$b_{nor}(G) = \frac{b(G) - b(G_{complete})}{b(G_{path}) - b(G_{complete})} = \frac{b(G) - 1}{\frac{N(N+1)}{6} - 1} \tag{3}$$

This normalization can be extended for other scales of vulnerability where $p \neq 1$. Considering the multi-scale approach on a complete graph, one can easily see that $(b_p(G_{complete}))_{p\geqslant 1} = 1$. For the path graph, although it is known that $b_1(G_{path}) = \frac{N(N+1)}{6}$, this simplification cannot be extended for $p > 1$. Despite that, it is easy to see that $b_p(G_{complete}) \leqslant b(G) \leqslant b_p(G_{path})$. As a consequence, the normalization of the multi-scale measure of the vulnerability of a graph is defined as:

$$b_{p_{nor}}(G) = \frac{b_p(G) - b_p(G_{complete})}{b_p(G_{path}) - b_p(G_{complete})} = \frac{b_p(G) - 1}{b_p(G_{path}) - 1} \tag{4}$$

Table 1
Main topological properties of AARNs. The quantities measured are: number of vertices N, number of edges E, characteristic path length L, clustering coefficient C, average degree $\langle k\rangle$, and type of correlations.

	N	E	$\langle k\rangle$	L	C	ν
Star Alliance	1150	4240	7.37	3.24	0.77	<0
SkyTeam	896	3226	7.20	3.13	0.74	<0
oneworld	741	1670	4.51	3.28	0.71	<0