



NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

THESIS

**A NETWORK THEORETIC INVESTIGATION INTO
THE TOPOLOGICAL CHARACTERISTICS OF U.S.
AIRLINE ROUTE NETWORK GROWTH**

by

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June 2018

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REPORT DOCUMENTATION PAGE			<i>Form Approved OMB No. 0704-0188</i>	
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instruction, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188) Washington, DC 20503.				
1. AGENCY USE ONLY (Leave blank)		2. REPORT DATE June 2018	3. REPORT TYPE AND DATES COVERED Master's thesis	
4. TITLE AND SUBTITLE A NETWORK THEORETIC INVESTIGATION INTO THE TOPOLOGICAL CHARACTERISTICS OF U.S. AIRLINE ROUTE NETWORK GROWTH			5. FUNDING NUMBERS	
6. AUTHOR(S) Kenneth A. Hicks				
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Naval Postgraduate School Monterey, CA 93943-5000			8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) N/A			10. SPONSORING / MONITORING AGENCY REPORT NUMBER	
11. SUPPLEMENTARY NOTES The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government.				
12a. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release. Distribution is unlimited.			12b. DISTRIBUTION CODE A	
13. ABSTRACT (maximum 200 words) Commercial airline networks are complex, dynamic systems that have become critical components of infrastructure, and understanding the nature and evolution of these networks is necessary in order to maximize their benefits. In this thesis we model the U.S. domestic air transportation system as a temporal multilayer directed network and investigate the route network structure of different U.S. airlines. We apply a network theoretic framework to the evolution of these airlines, represented as layers of the network. We identify the topological properties of these layers as airports are added to and dropped from the airline route networks during years of growth. From this framework we develop a model based upon centralities for identifying airports that make good candidates for addition to or removal from an airline network, and assess how our model aligns with historical decisions made by the airlines. We find the model to be more successful in identifying airports (1) for removal from, rather than addition to, a layer, and (2) for addition by low-cost carriers rather than full-service carriers.				
14. SUBJECT TERMS network science, airline network, multilayer network model, network evolution			15. NUMBER OF PAGES 187	
			16. PRICE CODE	
17. SECURITY CLASSIFICATION OF REPORT Unclassified	18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT Unclassified	20. LIMITATION OF ABSTRACT UU	

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Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN APPLIED MATHEMATICS

from the

**NAVAL POSTGRADUATE SCHOOL
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ABSTRACT

Commercial airline networks are complex, dynamic systems that have become critical components of infrastructure, and understanding the nature and evolution of these networks is necessary in order to maximize their benefits. In this thesis we model the U.S. domestic air transportation system as a temporal multilayer directed network and investigate the route network structure of different U.S. airlines. We apply a network theoretic framework to the evolution of these airlines, represented as layers of the network. We identify the topological properties of these layers as airports are added to and dropped from the airline route networks during years of growth. From this framework, we develop a model based upon centralities for identifying airports that make good candidates for addition to or removal from an airline network, and assess how our model aligns with historical decisions made by the airlines. We find the model to be more successful in identifying airports (1) for removal from, rather than in addition to, a layer, and (2) for addition by low-cost carriers rather than full-service carriers.

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Executive Summary

An important component of the nature of airline networks is how they evolve in time. The growth of airline networks is a complex and dynamic process. A variety of economic, geographic, and political factors must be considered by an airline as it chooses the airports that it will fly into and out of. A mathematical tool with the capability to model this process might allow airlines to make better and more efficient decisions as they grow.

In this work we model the U.S. domestic air transportation system from 1990 to 2017 as a temporal multilayer directed network and study individual airlines represented as layers of the network. We investigate the structural evolution of three prolific U.S. airlines: American Airlines, Delta Airlines, and Southwest Airlines. We focus on how the networks of these airlines change following mergers and acquisitions. We map and characterize the route network of each of these airlines through a variety of global properties for each year in which they are involved in a merger or acquisition. We then identify the sets of all U.S. airports with potential to be added to or removed from that airline's route network, and calculate their centralities within our multilayer network model. Ranking these airports by their centrality values, we designate the top-ranked airports in each set to be candidates for addition to, or removal from, the airline network.

We take the airports that are actually added to or removed from the networks of the airlines that we study in the years following each merger or acquisition to be ground truth. We evaluate the potential usefulness of our method by determining the extent to which the sets of candidate airports generated for each merger or acquisition align with the corresponding sets of ground truth airports. We find in our work that our method is consistently more successful in identifying airports historically removed from airline networks than airports added to them. We also find that airports identified by our method align significantly better with those historically added by Southwest Airlines than those added by American Airlines and Delta Airlines. Throughout the period of study, Southwest Airlines exhibits structural characteristics generally associated with low-cost carrier networks, whereas both American Airlines and Delta Airlines exhibit characteristics associated with full-service carrier networks. We therefore surmise that our method is of greater use to airlines that operate as low-cost carriers than to full-service carriers. We conclude that our approach shows potential value in planning airline

network growth, and suggest several improvements to be made in future work.

Acknowledgments

I would like to thank my advisor Ralucca Gera for introducing me to, and instructing me in, both graph theory and network science, and for accepting me as a thesis student. Nearly all of the work in this thesis stems directly from what she taught me. I must also thank her for all of her patience, assistance, and guidance throughout this work.

I would also like to thank my advisor Michelle Isenhour for her patience, assistance, and guidance, and for agreeing to join my project. Her advice and constructive criticism greatly improved this work, and her expertise in writing code is what made much of this thesis possible.

I would like to thank my academic associate Bard Mansager for working with me to craft a schedule that made the completion of this thesis possible, and for his guidance throughout my time at NPS.

I would like to thank all of my professors at Naval Postgraduate School for all of their work and guidance, and for greatly expanding my horizons in mathematics. I would also like to thank the entire Naval Postgraduate School Applied Mathematics department for everything they have done for me to help get me to graduation.

Finally, I would like to thank the Bowman Scholarship program for giving me the chance to study at the Naval Postgraduate School in the first place.

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CHAPTER 1:

Introduction

Since its development in the early 20th century, commercial aviation has grown to become a primary means of transportation and a central component of the world economy. In 2014, civilian aviation composed 5.1 percent of the U.S. GDP, accounting for \$1.6 trillion in total economic activity. In the same year, more than 64.1 billion revenue ton-miles of freight passed through U.S. airports. Air carriers operating in U.S. airspace transported 871.8 million passengers in 2014, enabling \$310 billion in visitor expenditures on goods and services. From 1997 to 2014, the airline industry had the second highest multifactor productivity average annual growth, behind only the computer and electronic products industry [1].

The aviation industry is only projected to grow in importance in coming years. In its 2017 current market outlook, Boeing estimates that commercial aviation will experience an average 4.8 percent passenger traffic growth over the next 20 years. Within North America, commercial airline fleet sizes are projected to surpass 10,000 aircraft by 2036 [2]. These figures illustrate the vitality of the airline industry and its global economic significance. Understanding the patterns of growth within this industry is important for predicting the future economic and social impact of aviation.

With over nine million scheduled passenger flights per year and 521 airports large enough for traffic control towers in the United States alone [3], airline traffic is a prime candidate to be modeled as a network. Within the young and rapidly growing field of network science, several tools have been developed with the potential to deepen our understanding of how airlines operate. Through a network theoretic approach, useful insight can be gained from relatively low complexity computation. Data on the U.S. airline industry from 1990 to 2017 is currently available via the United States Department of Transportation Bureau of Transportation Statistics. If airports are modeled as nodes, and flight routes between those airports are modeled as edges, a historical view on the U.S. commercial airline industry forms a very dense, complex network. In order to perform a focused temporal analysis of the airline data, the overall network can be divided into smaller networks of individual airlines. Measurements taken on both the entire complex network and the smaller airline

networks provide insight into the nature of U.S. commercial aviation.

When an airline merges with or acquires another airline, it comes into possession of new resources and must make decisions as to how to best utilize those resources. Depending upon the amount and type of resources gained and on the existing structure of an airline’s network, the best ways to utilize those resources can be a complex problem. There are many economic and practical factors to be considered in the growth of an airline. This growth can be modeled by a temporal network theoretic approach, which can offer quantitative measures of the ways in which an airline network expands.

By investigating the networks of historically successful airlines, insights can be gained as to what topological properties of an airline’s network can lead to possible economic success and further expansion. A good example of such an airline is Southwest Airlines. As Southwest grew from a midsize regional carrier to a large nationwide airline from 1990 to 2017, its network structure evolved [4]. Other growing carriers might profit from a study of this successful growth, as we propose in this work.

What is a complex network? The idea stems from the “simple networks” in graph theory. Graph theory is a branch of discrete mathematics concerned with the study of mathematical structures called graphs, which are composed of sets of nodes (also called vertices), and edges (also called arcs or links). Within a graph, each edge connects two of the nodes. Graphs can be used to represent relationships and can be highly useful in understanding a wide variety of phenomena in many fields of study. Systems can often be generalized such that the nodes of a graph represent people, users or objects within the system, and edges represent relationships or interactions between them.

1.1 Research Questions and Contributions

Within the network of all U.S. airports and flight routes, individual airlines can be thought of as individual layers of the same multilayer network. These layers expand as new flight routes are added to airports outside the airline’s existing coverage, and grow denser as more routes are added between airports already within the airline network. We examine the network theoretic properties of how these layers expand from year to year by focusing on airline growth following the acquisition of another airline. By identifying network theoretic indicators of how successful airlines have chosen to allocate their resources in the past, we

aim to develop guidelines for success in future airline growth.

Often the best ways to understand the nature of a complex network is by determining its structural properties, such as its degree distribution, density, or clustering coefficient. We investigate the structural properties of some of the largest domestic airline networks within the United States, and how these properties change as the airlines grow. By identifying trends in the overall structure of airline networks, we develop a framework for understanding their decisions regarding expansion.

1.2 Problem Description

After compiling the U.S. flight route data from 1990 to 2017, we analyze its network properties for years of interest. We then decompose the data into subnetworks of interest for deeper analysis. These subnetworks are composed of three of the largest U.S. domestic airlines: American Airlines, Delta Airlines, and Southwest Airlines.

When investigating the network theoretic properties of airline community growth, we study airports that are added to airline networks, as well as airports that are removed from them. Sets of possible airports for addition or removal are identified, and different measures of centrality are calculated for each airport within these sets. We analyze the airline networks using Gephi [5] and NetworkX [6], network analysis tools. The airports that were historically added to and dropped from an airline's network in the years following a merger or acquisition are taken to be ground truth. We compare these airports to those identified as good candidates for addition to or removal from the same network via measures of centrality for the same years.

While examining the network structure of American, Delta, and Southwest, various global properties are calculated for each airline community network in several years of interest through the algorithms in NetworkX. Determinations are made regarding the structural nature of the network, and the meaning of these results is analyzed in the context of the airline industry.

1.3 Thesis Structure

This thesis is organized as follows. Chapter 2 presents a background in network science and reviews the current literature related to the airline industry in network science and economics. In Chapter 3 we detail the source and refining of the data we use in our analysis, followed by our research methodology in Chapter 4. Chapter 5 presents the results of our analysis and our inferences with conclusions and further extensions in Chapter 6.

CHAPTER 2: Background

In this chapter we present a background in network science required for understanding the analysis in subsequent chapters. We conclude this chapter with a review of previous works which have applied network science to airline networks, as well as works related to airline economics and airline mergers and acquisitions.

2.1 Network Science

Network science focuses on the holistic study of data through complex networks. With its beginnings in the 1990s, it is one of the newest major scientific disciplines, complementing other tools needed to study extremely large and complex data that have emerged in modern history. Network science is rapidly growing and changing, with new research in the field constantly taking place around the world.

The first step in a network theoretic analysis of any system is understanding exactly what a network is. First developed in graph theory, a network is mathematically identical to a graph. A graph is defined:

A graph is an ordered pair of finite disjoint sets (V, E) such that E is a subset of the set V^2 of unordered pairs of V . The set V is the set of vertices and E is the set of edges. If G is a graph, then $V = V(G)$ is the vertex set of G , and $E = E(G)$ is the edge set of G . An edge $\{x, y\}$ is said to join the vertices x and y and is denoted by xy . Thus xy and yx means exactly the same edge; the vertices x and y are the end vertices of this edge [7].

The properties of a network are formed through combinations of its most elemental units: nodes and edges. Walks, paths, and trails are some network elements formed by simple combinations of nodes and edges. These elements are defined as follows:

A walk of length k is a sequence $v_0, e_1, v_1, e_2, \dots, e_k, v_k$ of vertices and edges such that $e_i = v_{i-1}v_i$ for all i . A trail is a walk with no repeated edge. A path

is a walk with no repeated vertex. A u, v - walk is a walk with the first vertex u and the last vertex v ; these are its *endpoints*, and it is *closed* if $u = v$ [8].

Several other fundamental characteristics of a network based upon the relationship of its constituent nodes and edges are defined as follows:

The *degree* of a vertex v within a graph G , written $d_G(v)$ or $d(v)$, is the number of non-loop edges containing v plus twice the number of loops containing v . The maximum degree of a vertex in G is $\Delta(G)$; the minimum such degree is $\delta(G)$. A graph is *regular* if $\Delta(G) = \delta(G)$; *k-regular* if $\Delta(G) = \delta(G) = k$. A vertex of degree k is *k-valent*. The *neighborhood* of v , written $N_G(v)$ or $N(v)$ is $\{x \in V(G) : \{v, x\} \in E(G)\}$; x is a neighbor of v if $x \in N(v)$. An *isolated vertex* has degree 0 [8].

In small graphs, it is possible to formulate closed mathematical relations concerning these elements. The formulation and study of such relations is the focus of much of graph theory. As technology advances, the systems to be modeled by graphs become larger and more complex. Many graphs have become far too big to be analyzed by hand, and so computer algorithms have been developed to quantify graph properties. Generally, the term network is used for those graphs that have several types of nodes and edges, weights and attributes assigned to them, or are too complex to be analyzed without the use of a computer.

As graphs become larger and more complex, it can become more difficult to perform meaningful analysis or extract meaningful information from them. Perhaps the simplest way to avoid this problem is to focus only on the smaller part of a complex graph that you are interested in, known as a subgraph or subnetwork. A subgraph is defined as follows:

A *subgraph* of a graph G is a graph H such that $V(H) \subseteq V(G)$ and $E(H) \subseteq E(G)$ and the assignment of endpoints to edges in H is the same as in G . We then write $H \subseteq G$ [9].

In its most elementary form, a network modeling a system represents entities within the network (people, computers, animals, websites) as nodes, and relationships between those

entities (friendship, correspondence, web links) as edges. However, there exist systems in which node i influences node j , but node j has no influence on node i . Such systems are better represented by directed network. A directed network is defined as:

A directed network or directed graph is a network in which each edge has a direction, pointing from one vertex to another. Such edges are themselves called directed edges, and can be represented by lines with arrows on them [10].

Traditional graphs are binary in nature; either an edge exists between two vertices or it does not. However, there are systems that can be more naturally represented if multiple edges are allowed to exist between pairs of nodes. Networks or graphs in which this is present are known as multigraphs, which are defined as follows:

A multigraph M consists of a finite nonempty set V of vertices and set E of edges, where every two vertices of M are joined by a finite number of edges (possibly zero). If two or more edges join the same pair of (distinct) vertices, then those edges are known as parallel edges [11].

A useful way of mathematically representing a network is through what is known as an adjacency matrix. An adjacency matrix for a network with n edges is an $n \times n$ matrix defined such that

$$A_{ij} = \begin{cases} 1 & \text{if there exists an edge between node } i \text{ and node } j \\ 0 & \text{otherwise.} \end{cases}$$

The adjacency matrix of a simple network must always be symmetric. However, the adjacency matrix of a directed graph is generally not symmetric [10].

It is often valuable to examine characteristics of the individual nodes within a network. One characteristic that is commonly calculated in network analysis is centrality. Defined broadly, centrality is a measure of a node's importance within a network. There are various types of centralities, which measure the importance of a node in different ways. Some of

the most common types of centrality measurements include closeness centrality, harmonic centrality, betweenness centrality, PageRank centrality, and eigenvector centrality. Each of these measures can be quickly calculated algorithmically, making them useful tools for analyzing even very large networks.

A node's closeness centrality is the reciprocal of the summation of the lengths of the shortest paths between that node and all other nodes in the network. The closeness centrality C_i of node i in a network of n nodes is defined as

$$C_i = \frac{1}{\sum_{j=1}^n d(i, j)},$$

where $d(i, j)$ is the length of the shortest path between nodes i and j [12]. This measure obviously depends upon the number of nodes, n , in the network, therefore a normalized closeness centrality was developed to allow comparison between nodes in different sized networks. Normalized closeness centrality is defined in [12] as:

$$C_i = \frac{n - 1}{\sum_{j=1}^n d(i, j)}$$

Normalized closeness centrality is a measure of the average length of the shortest path between the node i and all other nodes in the network instead of the summation of their lengths.

In an unconnected network, the length of the shortest path between two nodes of different components is taken to be infinity by convention. Because there must be at least two components in an unconnected network, this guarantees a closeness centrality value of zero for every node in an unconnected network. In order to account for this, harmonic centrality [13] is proposed. Harmonic centrality is defined by

$$H_i = \sum_{j \neq i} \frac{1}{d(i, j)}.$$

Harmonic centrality is generally very similar to closeness centrality within connected networks, and will generate meaningful values for each node within an unconnected network, making it more robust than closeness centrality.

Another important measure of centrality is betweenness centrality. Both closeness centrality and harmonic centrality are measures of the path lengths from a node to all other nodes. On the other hand, betweenness centrality measures the number of shortest paths in a network that include a node. More formally, betweenness centrality of node i in a network of n nodes is defined as

$$B_i = \frac{2 \sum \sum \frac{g_{jk}(i)}{g_{jk}}}{(n-1)(n-2)},$$

where g_{jk} are the shortest paths from node j to node k , and $g_{jk}(i)$ are shortest paths from node j to node k that include node i . The double sum is calculated for all pairs of nodes (j, k) such that $j \neq k \neq i$, and $j < k$ [13].

Another series of approaches to the definition of the centrality of a node are based on the idea of defining it recursively as the sum of the centralities of that node's neighbors. The best known of these methods is eigenvector centrality. The eigenvector centrality of node i in a network is defined as $E_i = x_i$, the i th component of the vector $\mathbf{x}$, which in turn is defined by the matrix equation

$$\mathbf{Ax} = \lambda \mathbf{x},$$

where A is the adjacency matrix of the network and λ is the largest eigenvalue of A [14]. An equivalent and perhaps more intuitive definition of eigenvector centrality is

$$x_i = \frac{1}{\lambda} \sum_j a_{ij} x_j.$$

A node's eigenvector centrality will be high if it is attached to other nodes with high centrality.

PageRank centrality is an extension of eigenvector centrality developed primarily for use by a search engine on the world wide web, which is applicable to other directed networks as well. Using standard eigenvector centrality there is potential for an undesirable imbalance in a directed network. Within a directed network there can exist pairs of nodes i and j such that i is a neighbor of j but j is not a neighbor of i . Therefore, there can exist a node with high centrality that has many neighbors, and such a node would inflate the centralities of its neighbors. This inflation of centrality can unrealistically reflect the importance of the neighboring nodes within the network. In order to avoid this imbalance, PageRank

centrality divides a node's centrality by its out degree when calculating its contribution to its neighbors' centrality. The PageRank centrality of a node i is then defined as

$$PR_i = \alpha \sum_j \frac{PR_j}{outdeg(j)} + \beta,$$

where α and β are selected constants and $outdeg(j)$ is defined to be $\max(1, \text{out degree of node } j)$ [10].

There are various other properties measured at each node or community that are useful in understanding the nature of a network. Such properties are often called local properties, whereas network properties that are measured at the network level are known as global properties [15]. All of the above measures of centrality are local properties. Another important local property is a node's clustering coefficient. Clustering coefficient is a measure of how "cliquish" a node and its neighbors are. More formally, clustering coefficient cc_i of a node i is defined as follows:

Suppose a vertex i has k_i neighbors; then at most $\frac{k_i(k_i-1)}{2}$ edges can exist between them. Let cc_i denote the fraction of these allowable edges that actually exist [15].

In some cases global properties of a network are obtained by taking an average of a local property over all the network's nodes. A network's clustering coefficient is defined in this manner: if cc_i is the clustering coefficient of node i , then the clustering coefficient for the entire network is defined to be the average of cc_i over all i [15]. It is the overall clustering coefficient that is generally used in analyzing the structure of a network.

One global property of a network that is not a network average of a local property is network density. Network density is the fraction of edges that exist within a network divided by the number of possible edges that could exist within that network, and quantifies how well connected a network is. Network density is defined mathematically as

$$d = \frac{2m}{n(n-1)}$$

for simple networks. Because each edge is only incident upon one node in a directed

network, the density of a directed network is defined to be

$$d = \frac{m}{n(n-1)},$$

where m is the number of edges in the network and n is the number of nodes [10]. A network with a low density is known as a sparse network. Because high density is often associated with high cost, a common goal in network design is finding a sparse network that performs well in some desired measure [4].

One of the most widely used tools in network analysis is the global property of degree distribution. Degree distribution is a measure of how many nodes within a network have a degree k , where k ranges from the minimum degree to the maximum degree node. Then p_k is defined to be the fraction of nodes in a network of degree k . A network's degree distribution is the collection of the fractions p_k for every value of k within the network [16]. Degree distribution is very useful in determining the nature of a network. An important classification of networks based on degree distribution is whether the network is scale-free. A scale-free network is one in which the fraction of nodes with degree k follows a power law, decaying like $k^{-\alpha}$, often with $2 < \alpha < 3$ [17]. A great deal of work has been done in understanding the nature of scale-free networks under the belief that most real world networks are at least partially scale-free [16], however, recent work has shown that truly scale-free networks are much more uncommon than previously thought [17].

There are many aspects to consider when modeling data as a complex network, and one important such aspect is the temporal nature of the network. A static network does not have a temporal aspect. Such a network often represents a snapshot of a complex system at one moment in time. However, many networks do have temporal aspects and evolve as time progresses. There are a variety of ways in which networks can evolve: new nodes can appear, old nodes can disappear, new edges between nodes can be formed and other edges can be severed.

2.2 Literature Review

Commercial airline networks are transportation systems that cover the planet, linking people, economies and cultures. Air transportation systems are not governed by any unified entity,

but instead are influenced by a variety of geographic, economic and political factors. These systems are composed of various component systems that operate independently, but interact at various levels, and can be classified as systems-of-systems [18]. As a result, airline networks are highly complex. However, airline networks have become a critical infrastructure, both economically and culturally, and understanding these systems is necessary in order to maximize their potential benefits [4], [18], [19]. To this end, focused study of airline networks is required. Due to the linked nature of air transport systems, network science is a natural tool to employ in their study. Applications of network theory and system-of-system approaches to airline networks include modeling airline systems for optimizing aircraft design [20] and modeling airline route network evolution to project the future impact of yet-to-be-designed aircraft [21].

Research into air transportation systems includes works from many other fields of study, notably economics. This research is very diverse, but a common theme is investigation of what makes an airline successful. From an economic perspective, Southwest Airlines represents a prime candidate for study due to its transformation from a smaller regional airline around 1990 to one of the dominant service providers in the U.S. market. Borenstein et al. perform an economic analysis of market power in the U.S. airline industry in 1989, in which they characterize the economic conditions and business environment in commercial aviation [22]. Many economic analysts recognize the emergence of Southwest Airlines, and investigate its success. Richards et al. analyze the effect of Southwest Airlines on the domestic airline market. They find that pricing strategies on a route differ based upon whether or not Southwest is a competitor, a potential competitor, or not a competitor, and that the presence of Southwest on a flight route is a better indicator of its competitiveness than flight concentration [23]. Boguslaski et al. investigate how Southwest Airlines was so successful in the 1990s, when other airlines suffered major losses. They research Southwest's effect on the domestic market, the vulnerability of other airlines to Southwest expansion, and Southwest's entry patterns over the 1990s. They find that Southwest's strategy changed over the time period. They identify two primary types of airline network structures: point-to-point and hub-and-spoke. In a point-to-point network, almost all of the airports have direct flight routes to almost every other airport. In a hub-and-spoke network, only a few large degree airports have direct flight routes to many other airports, while the majority of airports have few direct flight routes, which are mostly to hubs. Point-to-point

route networks are traditionally utilized by low-cost carriers, while hub-and-spoke networks are traditionally utilized by the larger full-service carriers. In the early 1990s Southwest can be characterized as a purely low-cost carrier with point-to-point characteristics, but by the end of the decade Southwest begins to adopt some characteristics of a hub-and-spoke style full-service carrier [24]. De Witt et al. analyze the historical business models of low-cost carriers such as Southwest Airlines in both the U.S. and European markets. While the direct network model has been extremely successful, there are limits to growth within such a model due to route densities. As a result, the largest low-cost carriers must adopt full-service carrier routes in order to continue to expand [25].

There has been a great deal of research into the network structure of airline networks for a variety of reasons, from understanding the spread of epidemics [26] to understanding vulnerabilities to natural disaster [27]. The earliest network theoretic approaches were conducted as network science was just emerging as its own field of study, and are most notable for recognizing the potential of network science to airline networks [28]. These works are primarily studies of simplified, idealized models of hypothetical airlines that result in highly theoretical conclusions [29]–[31]. However, even with relatively simple approaches, these early works made important discoveries. It is determined that the hub-and-spoke system, which had long been the dominant airline network architecture in the United States, was not always the optimal design [30], [31].

As the discipline of network science is maturing, so are network theoretic studies of airline networks. After these early mostly theoretical works on air transportation systems, the focus of research in the area shifts to studying real world airline networks. The first studies of real airline systems model them as large, single layer networks in which nodes represent airports or urban areas and edges represent flight routes between these airports [26], [32]–[42]. Bagler et al. study the Air Network of India [33], Li et al. study the airport network of China [38], and Guimera et al. study the world-wide airport network [34], [37]. Many studies investigate the U.S. air transportation system (ATS) [32], [35], [36], [39], [40]. Results of this research include important discoveries about the topological structure of airline networks. Many air transportation systems are found to be small-world networks that display scale-free properties. However, they might not be purely scale-free due to a multitude of factors including physical limitations at airports, geopolitical pressures, economic drivers, and regional ties, and are sometimes classified as broad-scale [32]–[35],

[37]–[39]. Some more sophisticated approaches based on single layer networks include variations of edge weighting to investigate the topological structure of a network [41], incorporation of spatial distance to a network to observe more realistic properties [42], and investigation of network evolution [40], [43]

An important advancement in network science is the the development of multilayer and multiplex networks to represent complex systems in a more realistic manner [44]–[50]. In such networks, nodes and edges can belong to one or more distinct layers that have different properties. For example, a person within a social network of friends might have connections to a group of friends (one layer) as well social connections to work associates (another layer). He may behave differently within these different groups, or share different information with members of each group, which in turn affects the properties of the entire network [46]. When such a framework is applied to airline networks, nodes still represent airports and edges still represent flight routes between those airports, but each route is organized into a different layer based on which airline operates those routes. This more sophisticated approach allows for the identification of network properties that would likely be missed with a single layer approach [46]. Several studies investigate the U.S. ATS with this approach [4], [51], [52]. Others take a multilayer network approach to research the European Air Transportation Network [27], [45], [48], [53]. Da Rocha et al. conduct a multilayer network study of the Brazilian air network [54], and Du et al. use a multilayer network model to study the airport network of China [55]. These studies reveal a great deal about the topological structures of airline networks, such as their resilience to lost nodes or edges [27], [52], or the nature of their temporal evolution [48], [51], [54]. A common finding among these studies is that subnetworks and layers of air transportation systems differ markedly from the overall network in their structure [4], [48], [53], [55].

In this chapter, we have covered a background in network science that will be useful in understanding the analysis within later chapters. We have also reviewed the academic works most related to this investigation. In the next section we discuss the data that we work with.

CHAPTER 3:

Data

In this chapter we discuss the data used in subsequent analysis. We identify the source, as well as describe the procedures with which it is processed. We conclude with a discussion of the limitations of our data.

3.1 Description of Airline Data

Air traffic data is available via the T-100 domestic market subset of the Air Carrier Statistics database on the United States Department of Transportation Bureau of Transportation Statistics website [56]. The data analyzed in this project are flight routes within the United States from 1990 to 2017, including the airline operating the route, the airport of departure, the airport of arrival, the International Air Transport Association (IATA) identifier code for each airport, and the month and year for which the route is flown. These data are downloaded in the form of 28 Microsoft Excel comma-separated value (csv) files, one file per year.

In order to generate the temporal aspect of the air transport network, we construct a time interval for each of the flight routes. This is achieved by consecutively numbering the months from January 1990 to July 2017. A given flight route in month i of year j is tagged with a month number m , and it is defined by $m = 12(j - 1990) + i$. Our study is comprised of 331 months, such that January 1990 is month 1 and July 2017 is month 331.

In the source data, two flights operated by the same airline between the same two airports on different days of the same month are considered to be the same flight route. However, two identical routes that are flown in two different months are considered to be two unique routes. Therefore, the interval for a route that takes place in month m , must be constructed such that it begins at month m and ends at month $m + 1$. The interval in which the flight route is said to exist is then defined to be $\{m, m + 1\}$. If the same airline operated the same route between the same two airports in both January and February of 1990 for example, those routes are considered in the airline network to be two separate routes with intervals $\{1, 2\}$ and $\{2, 3\}$ respectively. This results in a total of 5,920,139 independent flight routes

from January 1990 to July 2017.

In the interest of this interval construction, a column is added to each year's csv file that calculates the number of the month to be $m = 12(j - 1990) + i$. A second column is then added to each file, which calculates $m + 1$. These csv files are then saved as gephi files. The interval for each flight route is then constructed in the data laboratory function of Gephi.

A geographic layout is useful in gaining an initial understanding of an airline network's structure. Towards this end, we create an additional csv file that contains 537 airports within the U.S. domestic network, including every airport we study, defined by their three-digit IATA code. The latitude and longitude for each airport is then identified and entered into the csv such that each row represents an individual airport and contains its latitude and longitude in separate columns. The flight network for year j is then constructed in Gephi by uploading the geographic airport csv as the node set and the year j flight routes as an edge set. The Gephi plugin Geo Layout [5], which displays the network as a Mercator projection based on the longitude and latitude of each node, can then be applied to these networks. Two examples of the geographic network layout produced by Gephi are shown in Figures 3.1 and 3.2.

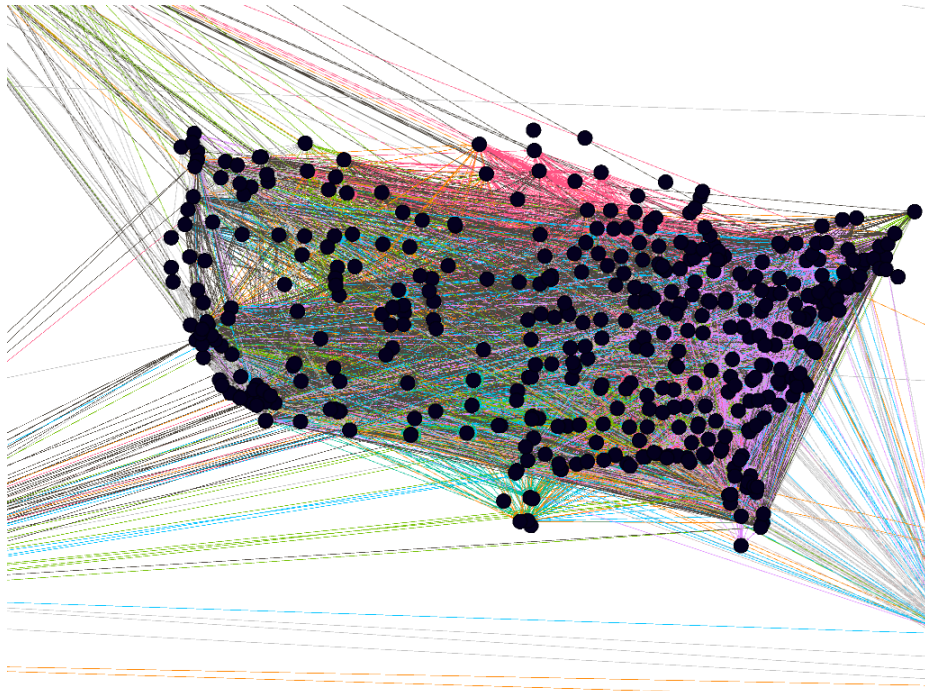


Figure 3.1. Continental U.S. domestic airline network in 1990. Edges are colored by airline operating the flight route.

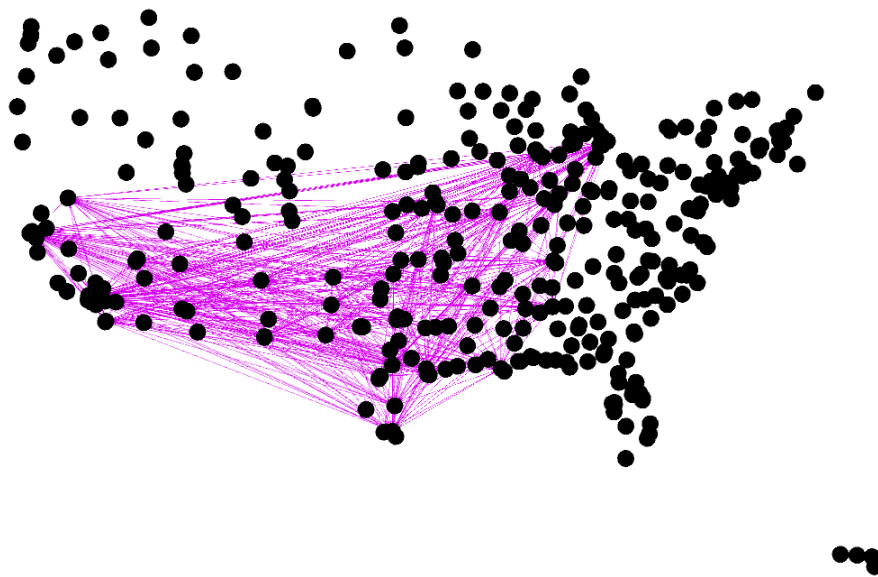


Figure 3.2. Southwest Airlines route network in 1990

3.2 Airline Mergers and Acquisitions

The U.S. domestic market network data over the entire interval from 1990 to 2017 can then be refined by the three airlines studied. This is achieved through the use of a Python script that searches through the 28 flight route csv files, and copies only the flights operated by a desired airline into a new csv. In the interest of investigating airline mergers and acquisitions over this period, this script is run for American Airlines, Delta Airlines, and Southwest Airlines for each year in which they are involved in a merger or acquisition, and the 4 following years.

Table 3.1. American Airlines, Delta Airlines, and Southwest Airlines mergers and acquisitions from 1990 to 2017.

Airline Studied	Airlines merged with or acquired	Year
American Airlines	Reno Air	1998
	TWA Airlines	2001
	US Airways	2013
Delta Airlines	Pan American Airlines	1991
	Comair	1999
	Atlantic Southeast Airlines	1999
	Northwest Airlines	2009
Southwest Airlines	Morris Airlines	1993
	ATA Airlines	2008
	AirTran Airlines	2011

Table 3.1 shows every merger and acquisition studied in this work. In the time period from 1990 to 2017, both American Airlines and Delta Airlines are involved with mergers or acquisitions that primarily involve their international routes. Due to the focus on the U.S. domestic flight route network, these events are not included in the mergers and acquisitions that we study. Data on airline mergers and acquisitions can be found at [57].

American Airlines acquires Reno Air in 1998, TWA Airlines in 2001, and merges with US Airways in 2013. Delta Airlines acquires Pan American Airlines in 1991, both Comair and Atlantic Southeast Airlines in 1999, and merges with Northwest Airlines in 2009. Southwest Airlines acquires Morris Air in 1993, ATA Airlines in 2008, and AirTran Airlines in 2011.

3.3 Limitations

One of the core principles of network science is the simplification of a given complex system in order to represent it as a network. A result of this simplification is the ability to analyze the topological structure of the system, and often the discovery of information that is not readily apparent within the system. However, as a consequence it may become impossible to make conclusions about the full nature of the system. The analysis of data without contextual understanding can lead to problems [58]. In order to mitigate this risk, it is important to fully understand the limitations of a data set.

The primary limitation of this data is its sparse nature. There is information not included in the data set that would allow for a more realistic understanding of the U.S. domestic air transportation system. The two ways in which the data analysis could be most improved are a finer temporal interval and volume information along each flight. Because different flight routes are recorded monthly, any changes to the air transportation network that occur on a time scale shorter than one month are not discernible.

By focusing only on U.S. domestic flight routes, this study does not entirely capture the airlines under investigation. An airline with many international flight routes will be under represented within the data, while an entirely domestic airline would be fully represented. Furthermore, it is possible that resources acquired from a merger with a domestic airline might be allocated to an airline's international flight routes, or that resources from an international merger might be allocated to domestic flight routes. Thus it would be useful to include international routes for the networks studied.

Additionally, more information on the flights operated along the flight routes might allow for network modeling that more accurately reflects the importance of that route. The volume of flights along a specific route might give greater insight into the importance of a route. Flights operated along the same route may be either passenger flights or cargo flights. An ability to discern between types of flights along a route might provide useful information. For passenger flights, the number of passengers per flight could add further meaning to the volume of the route. These pieces of information could be represented through edge weighting.

The data we analyze in this work is divided into two categories. First, the flight routes of the

U.S. domestic air transportation system for each individual year over the same time period. Second, the flight routes of specific airlines operating within the U.S. domestic market for each year. Our methodology is laid out in the following chapter.

CHAPTER 4:

Methodology

Broadly speaking, there are two different ways in which airlines grow, characterizable as either regular growth or irregular growth. Regular growth for airlines entails the purchasing or leasing of aircraft from an aircraft production company and hiring new personnel [59]–[61]. Irregular growth entails an airline’s acquisition of resources that is not regular, a great deal of which is comprised of mergers or acquisitions of other airlines [62]–[64]. This study focuses on periods of irregular growth for three of the largest U.S. domestic carriers: American Airlines, Delta Airlines, and Southwest Airlines. Irregular growth is studied in particular because a large influx of new resources can result in significant growth in an airline’s route network.

For each airline that we study, we use the same methodology to extract and analyze its network structure in the years that it was involved in a merger or acquisition as well as the years immediately following. That generalized methodology is as follows.

Each year, y , in which airline, A , is involved in a merger or acquisition is identified from data in [57]. For a merger in year y , flight route data for the U.S. domestic market in year y is isolated from the larger data set. The flight route network of airline A in year y is then extracted from this larger network. This process is repeated to obtain the flight route data for airline A in each of the years $y + 1$, $y + 2$, $y + 3$, and $y + 4$.

Once the data for a given year is established, two programs are used in its analysis. The first is the NetworkX [6] program in Python. Flight route data for year y is compiled via the csv file for each year, and a Python script using NetworkX functionality is run on these data as a network. This script models the route network of airline A in year y as both a directed graph and as a multigraph and calculates global properties of the network, including network density, network clustering coefficient, and degree distribution. The second program used in analyzing the data is Gephi. We generate graph files for the entire U.S. domestic market and for airline A within Gephi by importing flight route data csv files. Gephi is used to visualize the network of airline A in year y , and to calculate local properties of the entire U.S. flight route network in the same years, including closeness centrality (C_i), harmonic

centrality (H_i), betweenness centrality (B_i), PageRank centrality (PR_i), and eigenvector centrality (E_i).

After the local properties of the nodes of the domestic route network are calculated, this information is exported from Gephi to Microsoft Excel. The data set is in the form of a table including each airport in the United States active during year y and its closeness centrality (C_i), harmonic centrality (H_i), betweenness centrality (B_i), PageRank centrality (PR_i), and eigenvector centrality (E_i). An example piece of the data set from 1993 is shown in Table 4.1.

Table 4.1. Airports in the United States with the fifteen highest values of eigenvector centrality (E_i) in 1993, and their associated values of closeness (C_i), harmonic (H_i), betweenness (B_i), and PageRank (PR_i) centrality.

i	C_i	H_i	B_i	PR_i	E_i
ORD	0.661	0.754	0.063	0.004	1.000
LAX	0.587	0.667	0.015	0.001	0.993
DFW	0.654	0.748	0.053	0.002	0.923
BOS	0.599	0.684	0.012	0.001	0.918
DEN	0.606	0.688	0.014	0.001	0.846
SFO	0.586	0.665	0.028	0.002	0.838
LAS	0.572	0.646	0.001	0.001	0.835
PHX	0.582	0.653	0.002	0.001	0.828
EWR	0.603	0.691	0.008	0.001	0.807
LGA	0.590	0.673	0.005	0.001	0.779
SAN	0.568	0.633	0.002	0.001	0.767
ATL	0.631	0.728	0.035	0.002	0.764
MCO	0.573	0.647	0.003	0.001	0.758
SEA	0.600	0.681	0.041	0.002	0.750
STL	0.606	0.703	0.028	0.001	0.737

Each active airport in the United States in year y is then ranked by its value in each measure of centrality, from highest to lowest. An example of the resulting table for the 1993 data set can be seen in Table 4.2.

We then extract two lists from the network data of airline A for year y : (1) the departure airport for every flight route operated by airline A that year and (2) the arrival airports of the same routes. Because there is an independent set of routes for each month, there are

Table 4.2. The top fifteen airports in the U.S. in 1993 as ranked (R) by eigenvector centrality (E_i) and their associated value and ranking by closeness (C_i), harmonic (H_i), betweenness (B_i), and PageRank (PR_i) centrality.

i	C_i	R_C	H_i	R_H	B_i	R_B	PR_i	R_{PR}	E_i	R_E
ORD	0.661	1	0.754	1	0.063	1	0.004	1	1.000	1
LAX	0.587	14	0.667	16	0.015	11	0.001	16	0.993	2
DFW	0.654	2	0.748	2	0.053	2	0.002	4	0.923	3
BOS	0.599	10	0.684	9	0.012	13	0.001	35	0.918	4
DEN	0.606	6	0.688	7	0.014	12	0.001	13	0.846	5
SFO	0.586	16	0.665	18	0.028	8	0.002	8	0.838	6
LAS	0.572	27	0.646	30	0.001	54	0.001	66	0.835	7
PHX	0.582	20	0.653	27	0.002	49	0.001	69	0.828	8
EWR	0.603	7	0.691	5	0.008	15	0.001	27	0.807	9
LGA	0.590	12	0.673	13	0.005	24	0.001	42	0.779	10
SAN	0.568	29	0.633	42	0.002	43	0.001	74	0.767	11
ATL	0.631	3	0.728	3	0.035	5	0.002	6	0.764	12
MCO	0.573	26	0.647	29	0.003	37	0.001	78	0.758	13
SEA	0.600	9	0.681	11	0.041	4	0.002	5	0.750	14
STL	0.606	5	0.703	4	0.028	7	0.001	11	0.737	15

many duplicates in these lists of departure and arrival. Once these duplicates have been removed, the result is a list of all the airports that a flight operated by airline A departed from in year y , and a list of all the airports that a flight operated by airline A arrived at in year y . Because these lists are not necessarily identical, we take the union of the two. This results in a list of every airport that a flight operated by airline A either departed from or arrived at in year y . We define these to be the airports in the route network of airline A for year y . An identical procedure is then used to determine the airports in the network of airline A for year $y + 1$, $y + 2$, $y + 3$, and $y + 4$.

By determining airports in the network of airline A in year $y + 1$ that are not in the network in year y we determine the airports added to the network of airline A in year $y + 1$. Additionally, by identifying the airports in the network of airline A in year y that are not in the network in year $y + 1$, we determine the airports that are removed from the network of airline A in year $y + 1$. This process is repeated to find the airports that are added and removed in each subsequent year $y + 2$, $y + 3$, and $y + 4$. However, it is often the case that an airport added to the network of airline A in year $y + i$, is removed in one of the immediately following

years. Similarly there are airports that are removed from the network of A in year $y + i$ that are added back in one of the following years. We consider such additions and removals of airports to be intermediary, and not true changes to the network of A following the merger or acquisition in year y .

In order to account for intermediary additions, the airports added the network of A in each year $y + i$ are compared to the airports removed from the network of A in each year $y + j$, where $1 \leq i \leq 3$ and $i < j \leq 4$. A list of airports added to the network of airline A in year $y + i$ that are not removed in one of the following years is compiled for each year, where $1 \leq i \leq 3$. The union of these lists is taken to be the airports that are added to the network of airline A following the merger or acquisition in year y .

Intermediary removals are accounted for in a similar manner. Airports removed from the network of A in each year $y + i$ are compared to the airports added to the network of A in each year $y + j$, where $1 \leq i \leq 3$ and $i < j \leq 4$. A list of airports removed from the network of A in year $y + i$ that are not added back to the network in one of the following years is compiled for each year where $1 \leq i \leq 3$. The union of these lists is then taken. Because it is possible for there to exist within this union an airport that is an intermediary addition in one of the years $y + i$, the union is then compared to the airports that belong to the network of A in year y , and any airports that did not belong to the network of A in year y are removed. The result of this filtered union is taken to be the airports that are dropped from the network of airline A following the merger or acquisition in year y .

By comparing these lists of added and dropped airports to the table of centralities and rankings of every airport in the U.S. for year y , we obtain a network theoretic ranking based on the importance of the airports that A chose to add and drop from its network at the time when it would have chosen to do so. An example of the airports added to the Southwest network after 1993 (Table 4.3) and of the airports dropped from the Southwest network after 1993 (Table 4.4) following Southwest's acquisition of Morris airlines is shown.

We then identify the airports that are not a part the network of airline A for year y , which display good potential to be added to that network based on their values of each measure of centrality that we use. We take the difference of the list of airports in the network of airline A for year y and the table of all active airports in the United States for year y . This results in a table of U.S. airports that are not in the A network in year y , including their

Table 4.3. Airports added to the Southwest network following the 1993 merger with Morris Airlines and their rankings within the entire U.S. domestic network in 1993 by each measure of centrality

Added Airports	R_C	R_H	R_B	R_{PR}	R_E
MCO	26	29	37	78	13
SEA	9	11	4	5	14
TPA	52	43	60	67	22
PDX	17	23	10	15	25
SLC	18	24	17	39	30
FLL	57	60	59	38	36
SNA	80	80	90	90	41
TUS	50	61	96	111	57
OMA	40	40	67	33	58
PVD	54	54	76	64	71
GEG	39	50	18	10	79
BOI	61	72	30	57	90

Table 4.4. Airports dropped from the Southwest network following the 1993 merger with Morris Airlines and their rankings within the entire U.S. domestic network in 1993 by each measure of centrality

Dropped Airports	R_C	R_H	R_B	R_{PR}	R_E
DET	173	167	259	272	129

centrality values and rankings. Sorting this table by values of centrality, we identify the top ten percent of airports for each measure of centrality. The result is the top ten percent of airports that are not a part of the network of airline A in year y , as ranked by each measure of centrality. An example can be seen in Table 4.5, in which the top quarter of the top ten percent of airports that are not in the Southwest network in 1993 are shown.

We utilize a similar procedure to identify the airports within the A network in year y that show good potential to be dropped based on their centrality values. We take the intersection of the list of airports in the network of airline A for year y and the table of all active airports in the United States for year y . This results in a table of U.S. airports that are in the A network in year y , including their centrality values and rankings. We then sort this table in

Table 4.5. Top 2.5% of airports not in the Southwest network in 1993 as ranked by closeness (C_i), harmonic (H_i), betweenness (B_i), PageRank (PR_i), and eigenvector (E_i) centrality

Top 2.5% potential (C_i)	Top 2.5% potential (H_i)	Top 2.5% potential (B_i)	Top 2.5% potential (PR_i)	Top 2.5% potential (E_i)
ORD	ORD	ORD	ORD	ORD
ATL	ATL	ANC	EKO	BOS
MSP	EWR	SEA	ANC	DEN
DEN	MSP	ATL	SEA	EWR
EWR	DEN	EKO	ATL	LGA
SEA	BOS	HNL	HNL	ATL
BOS	PHL	PDX	GEG	MCO
PHL	SEA	DEN	COU	SEA
LGA	LGA	BOS	DEN	DCA
MKE	CVG	MSP	JFK	MIA
PDX	PIT	EWR	PDX	PHL
SLC	MKE	SLC	MSP	MSP
CVG	PDX	GEG	GRR	TPA

Excel by values of each measure of centrality ranking from highest to lowest, and record the top 50 percent of airports sorted in this manner. The result is a table of the bottom 50 percent of airports that are a part of the network of airline A in year y , as ranked by each measure of centrality. An example can be seen in Table 4.6, which displays half of the bottom 50 percent of airports that are in the Southwest network in 1993.

Taking the airports that are actually added to, and dropped from, the network of airline A following a merger or acquisition in year y to be ground truth, we evaluate each centrality as a measure of potential network action on an airport with two methods. First, the average ranking of the ground truth airports, both those added and dropped, are calculated for each measure of centrality and are compared to the overall median of U.S. airports for year y . An example of this can be seen in Tables 4.7 and 4.8.

Next, the airports actually added to the A 's network following the merger or acquisition in year y are compared to the top ten percent of airports not in the network in year y ; the airports in the intersection of the lists, as well as the number of such airports, is recorded.

Table 4.6. Bottom 25% of airports within the Southwest network in 1993 as ranked by closeness (C_i), harmonic (H_i), betweenness (B_i), PageRank (PR_i), and eigenvector (E_i) centrality

Top 25% droppable (C_i)	Top 25% droppable (H_i)	Top 25% droppable (B_i)	Top 25% droppable (PR_i)	Top 25% droppable (E_i)
DET	DET	DET	DET	DET
DAL	DAL	DAL	DAL	DAL
LBB	LBB	MAF	MAF	MAF
MAF	MAF	LBB	AMA	LBB
HRL	HRL	HRL	LBB	HRL
AMA	AMA	AMA	HRL	AMA
CRP	BUR	CRP	CRP	CRP
BUR	CRP	BUR	ELP	BUR
ELP	ELP	ELP	BHM	BHM
RNO	RNO	BHM	RNO	SDF

Table 4.7. The average ranking by each measure of centrality of the airports added to the Southwest network following the Morris merger as well as all airports not in the Southwest network in 1993

Average Centrality Ranking					
	$\bar{R}_C$	$\bar{R}_H$	$\bar{R}_B$	$\bar{R}_{PR}$	$\bar{R}_E$
Added to SW Network 1994-1996	41.917	45.583	47.000	50.583	44.667
Not in SW Network in 1993	296.482	296.528	295.033	294.404	297.056

We define the number of the airports in the intersection divided by the number of airports actually added to be the alignment of a centrality with ground truth. A similar comparison is done for the airports that are dropped from the A network in years $y + 1$ through $y + 3$ with the bottom half of airports within the network in year y , and the alignment is recorded in the same way. Examples of the alignments for the airports added and dropped from the Southwest network after the Morris merger are shown in Tables 4.9 and 4.10.

These procedures are used to process and analyze the data for American Airlines, Delta Airlines, and Southwest Airlines. Data is collected for the year of, and year after, every merger or acquisition in which American, Delta, or Southwest is involved. Our results and their interpretation are shown in full in Chapter 5.

Table 4.8. The average ranking by each measure of centrality of the airports dropped from the Southwest network following the Morris merger as well as all airports in the Southwest network in 1993

Average Centrality Ranking					
	$\bar{R}_C$	$\bar{R}_H$	$\bar{R}_B$	$\bar{R}_{PR}$	$\bar{R}_E$
Dropped from SW Network 1994-1996	173.00	167.00	259.00	272.00	129.00
In SW Network in 1993	53.05	52.45	71.78	79.90	45.63

Table 4.9. Alignment between the airports actually added to the Southwest network after the Morris merger and the top ten percent of potential airports in 1993 based on closeness (C_i), harmonic (H_i), betweenness (B_i), PageRank (PR_i), and eigenvector (E_i) centrality rank

Alignment of Airports Added in 1993				
C_i	H_i	B_i	PR_i	E_i
12 of 12	12 of 12	10 of 12	9 of 12	12 of 12
SEA	SEA	SEA	SEA	MCO
PDX	PDX	PDX	GEG	SEA
SLC	SLC	SLC	PDX	TPA
MCO	MCO	GEG	OMA	PDX
GEG	OMA	BOI	FLL	SLC
OMA	TPA	MCO	SLC	FLL
TUS	GEG	FLL	BOI	SNA
TPA	PVD	TPA	PVD	TUS
PVD	FLL	OMA	TPA	OMA
FLL	TUS	PVD		PVD
BOI	BOI			GEG
SNA	SNA			BOI

Table 4.10. Alignment between the airports actually dropped from the Southwest network after the Morris merger and the bottom 50 percent of Southwest airports in 1993 based on closeness (C_i), harmonic (H_i), betweenness (B_i), PageRank (PR_i), and eigenvector (E_i) centrality rank

Alignment of Airports Dropped in 1993				
C_i	H_i	B_i	PR_i	E_i
1 of 1	1 of 1	1 of 1	1 of 1	1 of 1
DET	DET	DET	DET	DET

CHAPTER 5:

Results and Analysis

In this chapter we present the results of our investigation into the growth of airline route networks during periods of irregular growth. We analyze the structural evolution of our airline route networks through the measurement of their global properties during years of interest. We find that the airline networks we study can be characterized as either hub-and-spoke or point-to-point in nature. The characteristics of a point-to-point route network include a high network density, a high average degree, and a high clustering coefficient, and the characteristics of a hub-and-spoke network include a low network density, a small average degree, and a low clustering coefficient. We also find that the most important indicator of a network's structure to be its degree distribution. A point-to-point degree distribution includes the majority of airports in a cluster near the maximum degree of the network. A hub-and-spoke degree distribution includes the majority of airports over a range of smaller degrees, with a small number of high degree "hub" airports.

We take the airports which are actually chosen by the airlines we study for addition to and removal from their networks in the years following a merger or acquisition to be ground truth. We then evaluate the potential usefulness of our method by determining the extent to which the sets of candidate airports generated for each merger or acquisition align with the corresponding sets of ground truth airports.

5.1 Southwest Acquisitions

The first airline that we study over the period from 1990 to 2017 is Southwest Airlines. Southwest is of particular interest due to its notable economic success and rapid expansion during this time. Additionally, as Southwest expands from a regional to a nationwide air carrier, its route network structure evolves, developing notable hub-and-spoke characteristics alongside its traditional point-to-point network. From 1990 to 2017, Southwest acquires three other airlines: Morris Air, ATA Airlines, and AirTran Airlines. Southwest finalizes its acquisition of Morris Air in 1993, and of ATA Airlines in 2008. The acquisition of AirTran Airlines takes place in 2011.

We find that for airports added to a route network, our method had the highest alignment with ground truth for Southwest Airlines. For airports dropped from the network, our method had the second highest alignment with ground truth. In 1993, Southwest Airlines has route network characteristics indicative of a point-to-point network structure. Over the time period studied, Southwest builds upon this point-to-point structure and develops some hub-and-spoke characteristics.

5.1.1 Southwest Airlines – Morris Air Acquisition

A summary of the Southwest Airlines network in 1993 is shown in Table 5.1. Changes to the Southwest network following its acquisition of Morris Air in 1993 are summarized in Tables 5.2, 5.3, 5.4, and 5.5.

Several global network statistics are measured on Southwest route network in 1993. These statistics include the total number of nodes in the network, the number of edges in the network, the average degree of nodes in the network, the network density, and the network clustering coefficient. These statistics are shown in Table 5.1.

Table 5.1. Global statistics of the Southwest Airlines route network in 1993

Southwest Network 1993 Global Statistics	
Nodes	40
Edges	660
Average Degree	33
Density	0.846
Clustering Coefficient	0.928

In 1993 the Southwest route network is relatively small, consisting of only 40 airports. Throughout the year, there are a total of 660 flight routes between these airports. With only 40 airports, the average degree of airports in the network is 33, which is highly indicative of a point-to-point network. The network density is 0.846, which reflects that almost all the possible flight routes between the network airports are actually flown in 1993. The clustering coefficient 0.928, which reflects that in the Southwest network in 1993 almost every possible edge between a node and all its neighbors exist. All of these properties are indicative of a point-to-point structure.

In the three years following Southwest Airline's acquisition of Morris Air there are 12 airports added to the Southwest route network that are not removed in subsequent years. A list of these airports can be found in Appendix A. The average ranking of these airports in each measure of centrality is shown in Table 5.2. For comparison, the average rankings for all U.S. airports that are not in the route network of Southwest in 1993 in each measure of centrality are also shown.

Table 5.2. Average ranking of airports added to the Southwest route network following the acquisition of Morris Air and average ranking of all airports not in the Southwest route network in 1993 by each measure of centrality

Average Centrality Ranking					
	$\bar{R}_C$	$\bar{R}_H$	$\bar{R}_B$	$\bar{R}_{PR}$	$\bar{R}_E$
Added to SW Network 1994-1996	41.917	45.583	47.000	50.583	44.667
Not in SW Network in 1993	296.482	296.528	295.033	294.404	297.056

In Table 5.2 the average rankings of the airports that are actually added to the Southwest network are significantly better than the average for possible U.S. airports in 1993. This supports the idea that an airport's centrality has value as an indicator of whether it will be added to the Southwest network.

When the acquisition of Morris Air by Southwest Airlines occurs in 1993, there are 517 active U.S. airports that are not a part of the Southwest route network. We rank these airports by their values of closeness, harmonic, betweenness, PageRank, and eigenvector centrality. We consider the 52 top ranked airports by each measure of centrality to be those identified as good candidates for addition to the Southwest network. The full list of these airports can be found in Appendix A. These 52 candidate airports for each measure of centrality are compared to the 12 ground truth airports that are actually added to the Southwest network following the acquisition of Morris. The alignment with ground truth for each measure of centrality is shown in Table 5.3.

Table 5.3 shows that three of the five measures of centrality we use have 100 percent alignment with this ground truth. All of the airports added to the Southwest route network following the acquisition of Morris Air are also among the top ten percent of active U.S. airports in 1993 as identified by closeness, harmonic, and eigenvector centrality. For the same period, 10 of the 12 added airports are among the top ten percent of potential airports

Table 5.3. The airports added to the Southwest network following the Morris Air acquisition that are among the top 10% of U.S. airports in 1993 in each measure of centrality

Alignment of Airports Added in 1994-1996				
C_i	H_i	B_i	PR_i	E_i
12 of 12	12 of 12	10 of 12	9 of 12	12 of 12
SEA	SEA	SEA	SEA	MCO
PDX	PDX	PDX	GEG	SEA
SLC	SLC	SLC	PDX	TPA
MCO	MCO	GEG	OMA	PDX
GEG	OMA	BOI	FLL	SLC
OMA	TPA	MCO	SLC	FLL
TUS	GEG	FLL	BOI	SNA
TPA	PVD	TPA	PVD	TUS
PVD	FLL	OMA	TPA	OMA
FLL	TUS	PVD		PVD
BOI	BOI			GEG
SNA	SNA			BOI

as identified by betweenness centrality. In this case, PageRank centrality has the least alignment with ground truth as only 9 of the 12 actually added airports are among the top 10 percent of potential airports as identified by PageRank centrality.

Although Southwest Airlines' decisions regarding the addition of airports to its network are influenced by a variety of other factors, on average 91.7% of the airports selected for addition by Southwest Airlines following the acquisition of Morris Air are present within the candidate lists which comprise only 10% of all possible airports. This demonstrates the potential value to airlines of using a centrality based analysis in selecting airports to add to their network.

Following Southwest Airline's acquisition of Morris Air there is only one airport dropped from the Southwest route network that is not added back in subsequent years, the Coleman A. Young International Airport (DET) located in the city of Detroit, Michigan. The ranking of this airport in each measure of centrality is shown in Table 5.4. For comparison, the average ranking for all U.S. airports in the route network of Southwest in 1993 in each measure of centrality is also shown.

Table 5.4. Average ranking of airports dropped from the Southwest route network in following the acquisition of Morris and average ranking of all airports in the Southwest route network in 1993 by each measure of centrality

Average Centrality Ranking					
	$\bar{R}_C$	$\bar{R}_H$	$\bar{R}_B$	$\bar{R}_{PR}$	$\bar{R}_E$
Dropped from SW Network 1994-1996	173.00	167.00	259.00	272.00	129.00
In SW Network in 1993	53.05	52.45	71.78	79.90	45.63

Table 5.4 shows that on average the rankings of the dropped airport is considerably worse than the average for airports in the Southwest network in 1993 in every measure of centrality. This indicates that centrality rankings have value for indicating which airports will be removed from the Southwest network.

In 1993 there are 40 U.S. airports that are a part of the Southwest route network. We rank these airports by their values of closeness, harmonic, betweenness, PageRank, and eigenvector centrality. We consider the 20 bottom ranked airports by each measure of centrality to be those identified as good candidates for removal from the Southwest network. The full list of these airports can be found in Appendix A. These 20 candidate airports for each measure of centrality are compared to the one ground truth airport that is actually dropped from the Southwest network following the acquisition of Morris Air. The alignment with ground truth for each measure of centrality is shown in Table 5.5.

Table 5.5. The airports dropped from the Southwest network following the Morris Air acquisition that are among the bottom 50% of U.S. airports in 1993 in each measure of centrality.

Alignment of Airports Dropped in 1994-1996				
C_i	H_i	B_i	PR_i	E_i
1 of 1	1 of 1	1 of 1	1 of 1	1 of 1
DET	DET	DET	DET	DET

Table 5.5 shows that all five measures of centrality are in 100 percent alignment with this ground truth. The airport dropped from the Southwest route network following the acquisition of Morris Air is also among the bottom fifty percent of airports in the Southwest network in 1993 as identified by every measure of centrality.

Although Southwest Airlines' decisions regarding the removal of airports from its network are influenced by a variety of other factors, 100% of the airports selected for removal by Southwest Airlines following the acquisition of Morris Air are present within the candidate lists which comprise 50% of all possible airports. This demonstrates the potential value to airlines of using a centrality based analysis in selecting airports to remove from their network.

5.1.2 Southwest Airlines – ATA Airlines Acquisition

A summary of the Southwest Airlines route network in 2008 is shown in Table 5.6. Changes to the Southwest network following its acquisition of ATA Airlines in 2008 are shown in Tables 5.7, 5.8, 5.9, and 5.10.

Global statistics are used to understand the nature of the Southwest route network in 2008. These statistics include the total number of nodes in the network, the number of edges in the network, the average degree of nodes in the network, the network density, and the network clustering coefficient. These statistics are shown in Table 5.6.

Table 5.6. Global statistics of the Southwest Airlines route network in 2008

Southwest Network 2008 Global Statistics	
Nodes	114
Edges	1865
Average Degree	32.719
Density	0.290
Clustering Coefficient	0.600

By 2008 the Southwest route network has grown considerably, consisting of 114 airports and 1865 flight routes. In 2008 the Southwest route network's global properties are similar to those of the American network and the Delta network. The average degree has remained fairly constant, dropping slightly to 32.719. However, the network density and clustering coefficient both decrease significantly, measuring 0.29 and 0.6 respectively. The drop in density and clustering coefficient suggest a shift toward a hub-and-spoke structure. However, the constant average degree indicates that at least some point-to-point characteristics have been maintained.

Following Southwest Airline's acquisition of ATA Airlines in 2008 there are 18 airports added to the Southwest network that are not subsequently removed. A complete list of these airports can be found in Appendix B. The average ranking of these airports in each measure of centrality is shown in Table 5.7. For comparison, the average ranking for all U.S. airports not in the route network of Southwest in 2008 in each measure of centrality is also shown.

Table 5.7. Average ranking of airports added to the Southwest route network following the acquisition of ATA and average ranking of all U.S. airports not in the Southwest route network in 2008 by each measure of centrality

Average Centrality Ranking					
	$\bar{R}_C$	$\bar{R}_H$	$\bar{R}_B$	$\bar{R}_{PR}$	$\bar{R}_E$
Added to SW Network 2009-2011	196.278	193.333	245.611	206.111	203.722
Not in SW Network in 2008	650.415	650.542	641.666	641.546	649.915

Table 5.7 shows that on average the airports that are selected for addition to the Southwest network are ranked better than the average of all airports which could be added in 2008. This further supports the idea that an airport's centrality has value as an indicator of whether it will be added to the Southwest network.

When the acquisition of ATA by Southwest occurs in 2008, there are 1085 active U.S. airports that are not a part of the Southwest route network. We rank these airports by their values of closeness, harmonic, betweenness, PageRank, and eigenvector centrality. We consider the 108 top ranked airports by each measure of centrality to be those identified as good candidates for addition to the Southwest network. The full list of these candidate airports can be found in Appendix B. These 108 candidate airports for each measure of centrality are compared to the 18 ground truth airports that are actually added to the Southwest network in the three years following the acquisition of ATA. The alignment with ground truth for each measure of centrality is shown in Table 5.8.

Table 5.8 shows that three of the five measures of centrality achieve 50 percent alignment for this ground truth. Nine out of the 18 airports added to the Southwest route network following the acquisition of ATA Airlines are also among the top ten percent of active U.S. airports in 2008 as identified by closeness, PageRank, and eigenvector centrality. For the same period harmonic centrality performs slightly better, with 10 of the 18 added airports among the top ten percent of potential airports as identified by harmonic centrality. Only 6

Table 5.8. The airports added to the Southwest network following the ATA Airlines acquisition that are among the top 10% of U.S. airports in 2008 in each measure of centrality

Alignment of Airports Added in 2009-2011				
C_i	H_i	B_i	PR_i	E_i
9 of 18	10 of 18	6 of 18	9 of 18	9 of 18
BOS	BOS	BOS	GSP	BOS
LGA	LGA	LGA	BOS	LGA
CHS	CHS	GSP	LAN	CHS
CAE	CAE	CHS	CHS	GSP
GRK	GSP	CAE	ILG	CAE
XNA	XNA	LAN	LGA	XNA
GSP	LAN		CAE	LAN
LAN	FAR		ACT	FAR
FAR	GRK		GRK	MGM
	ACT			

of the 18 added airports were among the top ten percent of potential airports as identified by betweenness centrality.

Although Southwest Airlines' decisions regarding the addition of airports to its network are influenced by a variety of other factors, on average 47.8% of the airports selected for addition by Southwest Airlines following the acquisition of ATA Airlines are present within the candidate lists which comprise only 10% of all possible airports. Although this alignment is not as high as for Southwest's acquisition with Morris Air, it still shows value in a centrality based analysis for selecting airports to add to an airline network. With larger candidate lists, for example 20%, a higher alignment could be achieved while still greatly reducing the number of potential airports that need to be considered.

Following Southwest Airline's acquisition of ATA Airlines there are also 18 airports that are dropped from the Southwest route network that are not added back in subsequent years. A complete list of these airports can be found in Appendix B. The average ranking of these airports in each measure of centrality is shown in Table 5.9. For comparison, the average ranking for all U.S. airports in the route network of Southwest in 2008 in each measure of centrality is also shown.

Table 5.9. Average ranking of airports dropped from the Southwest route network following the ATA acquisition and average ranking of all airports in the Southwest route network in 2008 by each measure of centrality

Average Centrality Ranking					
	$\bar{R}_C$	$\bar{R}_H$	$\bar{R}_B$	$\bar{R}_{PR}$	$\bar{R}_E$
Dropped from SW Network in 2009-2011	220.833	221.833	350.278	345.556	247.889
In SW Network in 2008	120.175	118.965	203.439	204.588	124.930

Table 5.9 shows that the average rankings of the airports dropped from the network are significantly higher the average of an airport in the Southwest network in 2008. This also demonstrates the value of centrality as an indicator of which airports will be dropped from the Southwest network.

When the acquisition of ATA by Southwest occurs in 2008, there are 114 active U.S. airports that are a part of the Southwest route network. We rank these airports by their values of closeness, harmonic, betweenness, PageRank, and eigenvector centrality. We consider the 57 bottom ranked airports by each measure of centrality to be those identified as good candidates for removal from the Southwest network. A complete list of these candidate airports can be found in Appendix B. These 57 candidate airports for each measure of centrality are compared to the 18 ground truth airports that are actually dropped from the Southwest network in the three years following the acquisition of ATA. The alignment with ground truth for each measure of centrality is shown in Table 5.10.

Table 5.10 shows that three of the five measures of centrality achieve 94.4 percent alignment for this ground truth. Seventeen out of the 18 airports dropped from the Southwest route network following the acquisition of ATA Airlines are also among the bottom 50 percent of Southwest network airports in 2008 as identified by harmonic, PageRank, and eigenvector centralities. For the same period closeness and betweenness perform only slightly worse; 16 of the 18 added airports among the bottom 50 percent of potential airports as identified by both closeness and betweenness centrality.

Although Southwest Airlines' decisions regarding the removal of airports from its network are influenced by a variety of other factors, on average 92.2% of the airports selected for removal by Southwest Airlines following the acquisition of ATA Airlines are present within

Table 5.10. The airports dropped from the Southwest network following the ATA Airlines acquisition that are among the bottom 50% of U.S. airports in the Southwest network in 2008 in each measure of centrality

Alignment of Airports Dropped in 2009-2011				
C_i	H_i	B_i	PR_i	E_i
16 of 18	17 of 18	16 of 18	17 of 18	17 of 18
OGD	OGD	OGD	SMX	OGD
SMX	SMX	SMX	DRO	PAE
PUB	PUB	PUB	YKM	YKM
DRO	PAE	DRO	OGD	PUB
LBE	DRO	YKM	SBA	SMX
PAE	YKM	SBA	LBE	LBE
YKM	LBE	TRI	PAE	GNV
GNV	GNV	PIA	PUB	DRO
CHO	CHO	LBE	PIA	MSO
TRI	TRI	CHO	TRI	CHO
ROA	PIA	MSO	MSO	TRI
PIA	ROA	SGF	ROA	SBA
SGF	SBA	ROA	ICT	PIA
SBA	SGF	GNV	GNV	ROA
MSO	MSO	ICT	CVG	SGF
ICT	ICT	PAE	SGF	ICT
	HNL		CHO	HNL

the candidate lists which comprise 50% of all possible airports. This represents a significant reduction in the number of airports which must be considered when selecting airports for removal from a network.

5.1.3 Southwest Airlines – AirTran Airlines Acquisition

A summary of the Southwest Airlines route network in 2011 is shown in Table 5.11. Changes to the Southwest network following its acquisition of AirTran Airlines in 2011 are shown in Tables 5.12, 5.13, 5.14, and 5.15.

Global statistics are used to understand the nature of the Southwest route network in 2011. These statistics include the total number of nodes in the network, the number of edges in the network, the average degree of nodes in the network, the network density, and the network

clustering coefficient. These statistics are shown in Table 5.11.

Table 5.11. Global statistics of the Southwest Airlines route network in 2011

Southwest Network 2011 Global Statistics	
Nodes	116
Edges	2395
Average Degree	41.293
Density	0.359
Clustering Coefficient	0.645

In 2011 the Southwest route network properties indicate a shift back toward point-to-point structure. The number of airports in the network increased slightly to 116, but the number of flight routes increased significantly to 2,395. As a result, the average degree is 41.293, the highest of all the airlines for every year studied. The network density increases to 0.359, and the clustering coefficient also increases to 0.645. All of these changes to the properties of the Southwest route network in 2011 reflect the development of a point-to-point structure.

In the three years following Southwest's acquisition of AirTran Airlines, there are 19 airports added to the Southwest route network that are not subsequently removed. A complete list of these airports can be found in Appendix C. The average ranking of these airports in each measure of centrality is shown in Table 5.12. For comparison, the average rankings for all U.S. airports not in the route network of Southwest in 2011 in each measure of centrality are also shown.

Table 5.12. Average ranking of airports added to the Southwest route network following the acquisition of AirTran and average ranking of all U.S. airports not in the Southwest route network in 2011 by each measure of centrality

Average Centrality Ranking					
	$\bar{R}_C$	$\bar{R}_H$	$\bar{R}_B$	$\bar{R}_{PR}$	$\bar{R}_E$
Added to SW Network 2012-2014	149.263	138.053	205.526	202.947	125.421
Not in SW Network in 2011	697.234	697.755	689.982	688.955	698.081

Table 5.12 shows that on average the airports that are selected for addition to the Southwest network are ranked significantly better than the average of all airports which could possibly

be added in 2011. This also supports centrality as an indicator of whether Southwest will add an airport to its route network.

When the Southwest acquisition of AirTran occurs in 2011, there are 1,174 active U.S. airports that are not a part of the Southwest route network. We rank these airports by their values of closeness, harmonic, betweenness, PageRank, and eigenvector centrality. We consider the 117 top ranked airports by each measure of centrality to be those identified as good candidates for addition to the Southwest network. The full list of these airports can be found in Appendix C. These 117 candidate airports for each measure of centrality are compared to the 19 ground truth airports that are actually added to the Southwest network in the three years following the acquisition of AirTran. The alignment with ground truth for each measure of centrality is shown in Table 5.13.

Table 5.13. The airports added to the Southwest network following the AirTran Airlines acquisition that are among the top 10% of U.S. airports in 2011 in each measure of centrality

Alignment of Airports Added in 2012-2014				
C_i	H_i	B_i	PR_i	E_i
13 of 19	13 of 19	10 of 19	7 of 19	14 of 19
ATL	ATL	ATL	MIA	ATL
MIA	MIA	MIA	ATL	CLT
DCA	DCA	CLT	CLT	DCA
CLT	CLT	SJU	DCA	MIA
ICT	ICT	DCA	CAK	GRR
GRR	GRR	GRR	FNT	ROC
SJU	DAY	FNT	GRR	DAY
DAY	SJU	DAY		SJU
ROC	ROC	CAK		ICT
FSD	FSD	PWM		PWM
CAK	CAK			FSD
PWM	PWM			CAK
PNS	PNS			PNS
				FNT

Table 5.13 shows that in this case the measure of centrality with the greatest alignment to ground truth is eigenvector centrality, as 14 of the 19 airports added to the Southwest network following the acquisition of AirTran are also among the top 10 percent of active U.S.

airports that are not a part of the Southwest network in 2011 as identified by eigenvector centrality. Both closeness and harmonic centralities have an alignment that is nearly as good, 13 of the 19 added airports are among the top 10 percent of potential airports as measured by each of these. Ten of the 19 added airports are among the top 10 percent of potential airports as identified by betweenness centrality. For this acquisition, PageRank centrality has the lowest alignment with ground truth. Seven out of the 19 added airports are among the top 10 percent of possible airports as measured by PageRank centrality.

Although Southwest Airlines' decisions regarding the addition of airports to its network are influenced by a variety of other factors, on average 60% of the airports selected for addition by Southwest Airlines following the acquisition of AirTran Airlines are present within the candidate lists which comprise only 10% of all possible airports. If only the top three centralities were considered, this alignment would be even higher. This further demonstrates the value in a centrality based analysis for selecting airports to add to an airline network.

Following Southwest Airline's acquisition of AirTran Airlines there are 11 airports that are dropped from the Southwest route network that are not added back in subsequent years. A complete list of these airports can be found in Appendix C. The average ranking of these airports in each measure of centrality is shown in Table 5.14. For comparison, the average rankings for all U.S. airports in the route network of Southwest in 2011 in each measure of centrality are also shown.

Table 5.14. Average ranking of airports dropped from the Southwest route network following the acquisition of AirTran and average ranking of all U.S. airports in the Southwest route network in 2011 by each measure of centrality

Average Centrality Ranking					
	$\bar{R}_C$	$\bar{R}_H$	$\bar{R}_B$	$\bar{R}_{PR}$	$\bar{R}_E$
Dropped from SW Network in 2012-2014	218.909	217.091	294.000	267.818	220.727
In SW Network in 2011	121.914	116.647	195.310	205.707	113.345

Table 5.14 shows that the average rankings of the airports dropped from the network are higher the average of the Southwest network in 2011, again demonstrating the value of centrality as an indicator of airports to be dropped.

In 2011, there are 116 active U.S. airports that are a part of the Southwest route network. We rank these airports by their values of closeness, harmonic, betweenness, PageRank, and eigenvector centrality. We consider the 58 bottom ranked airports by each measure of centrality to be those identified as good candidates for removal from the Southwest network. The full list of these airports can be found in Appendix C. These 58 candidate airports for each measure of centrality are compared to the 11 ground truth airports that are actually dropped from the Southwest network in the three years following the acquisition of AirTran. The alignment with ground truth for each measure of centrality is shown in Table 5.15.

Table 5.15. The airports dropped from the Southwest network following the AirTran Airlines acquisition that are among the bottom 50% of U.S. airports in 2011 in each measure of centrality

Alignment of Airports Dropped in 2012-2014				
C_i	H_i	B_i	PR_i	E_i
10 of 11	10 of 11	9 of 11	7 of 11	10 of 11
LAR	LAR	LAR	LAR	TCL
GRI	GRI	DLH	LWS	LAR
ALO	ALO	LFT	DLH	LWS
LFT	LWS	ALO	GRI	GRI
LWS	LFT	GRI	LFT	ALO
TCL	TCL	LWS	ALO	CMI
DLH	CMI	ABE	ABE	LFT
CMI	DLH	CMI		DLH
ABE	ABE	TCL		ABE
CAE	CAE			CAE

Table 5.15 shows that for airports dropped from the Southwest network following the AirTran acquisition, the three measures of centrality with the greatest alignment to ground truth are closeness, harmonic, and eigenvector centralities. Ten of the 11 airports dropped from the Southwest network following the acquisition of AirTran are also among the bottom 50 percent of active U.S. airports that are a part of the Southwest network in 2011 as identified by these three types of centrality. Nine of the 11 dropped airports are among the bottom 50 percent of potential airports as identified by betweenness centrality. PageRank centrality again has the lowest alignment with ground truth. Seven out of the 11 added airports are among the bottom 50 percent of possible airports as measured by PageRank centrality.

Although Southwest Airlines’ decisions regarding the removal of airports from its network are influenced by a variety of other factors, on average 83.6% of the airports selected for removal by Southwest Airlines following the acquisition of AirTran Airlines are present within the candidate lists which comprise 50% of all possible airports. This again demonstrates the potential usefulness of a centrality based analysis for selecting airports to remove from an airline network.

5.1.4 Southwest Overview

For identifying candidates for addition to a flight route network, our approach of centrality based identification had the greatest alignment with the ground truth for the Southwest Airlines route network. The average alignment of every measure of centrality with ground truth for every Southwest acquisition is shown in Table 5.16.

Table 5.16. The average alignment for Southwest acquisitions between airports identified as good candidates for addition to or removal from an airline and ground truth

	Airports Added	Airports Dropped
Southwest Average	66.48%	91.95%

Shown in Table 5.16, the average alignment between airports selected by our method of centrality based identification and ground truth added airports for Southwest Airlines is 66.48%. This is significantly higher than the corresponding alignments of American and Delta, which can be seen in Tables 5.32 and 5.48. The average alignment for ground truth dropped airports for Southwest Airlines is 91.95%, which is the second greatest alignment of the three airlines studied for dropped airports.

The growth of the Southwest Airlines route network from 1990 to 2017 is shown in Figures 5.1 – 5.5. Figure 5.1 shows a trend of steady increase in the number of airports within the Southwest route network over the time period from 1990 to 2017. There are periods of more rapid growth and periods of decline in the number of airports, but overall the trend of growth is fairly consistent.

Figure 5.2 shows an overall trend of increase in the average degree of the airports within the Southwest network when the network is isolated for each year. Two distinct periods

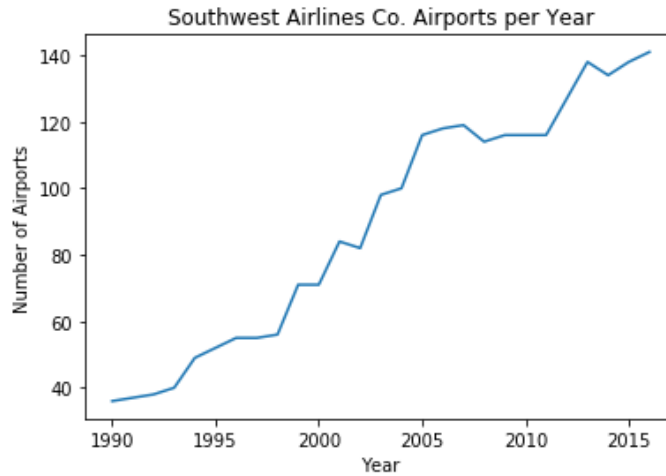


Figure 5.1. The number of airports within the Southwest route network per year from 1990 to 2017

emerge within the data over the interval from 1990 to 2017. From 1990-2005 there is an overall negative trend in the average degree of the Southwest network airports, with periods of inconsistency in which there are significant spikes or declines. From 2005-2017 there is a strongly positive trend in the average degree of the Southwest network airports. This period is also fairly consistent.

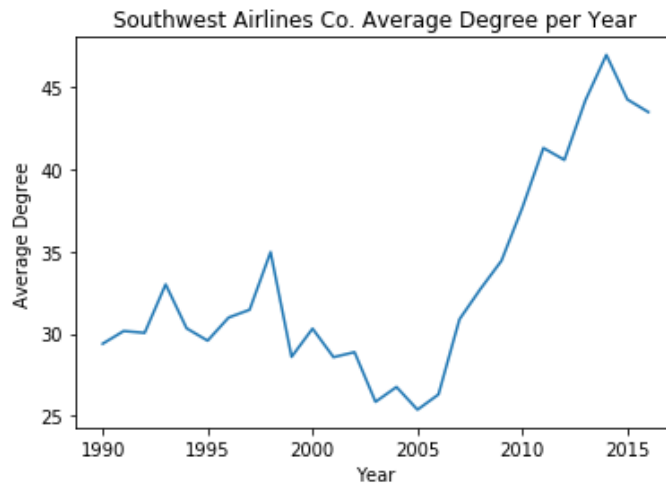


Figure 5.2. The average degree of all the airports within the Southwest route network per year from 1990 to 2017

Figures 5.3, 5.4, and 5.5 show a geographical layout and the degree distribution of the

Southwest network in 1993, 2008, and 2011 respectively. In Figures 5.3, 5.4, and 5.5, nodes are colored from dark to light by degree from high to low, and edges are colored by the source node.

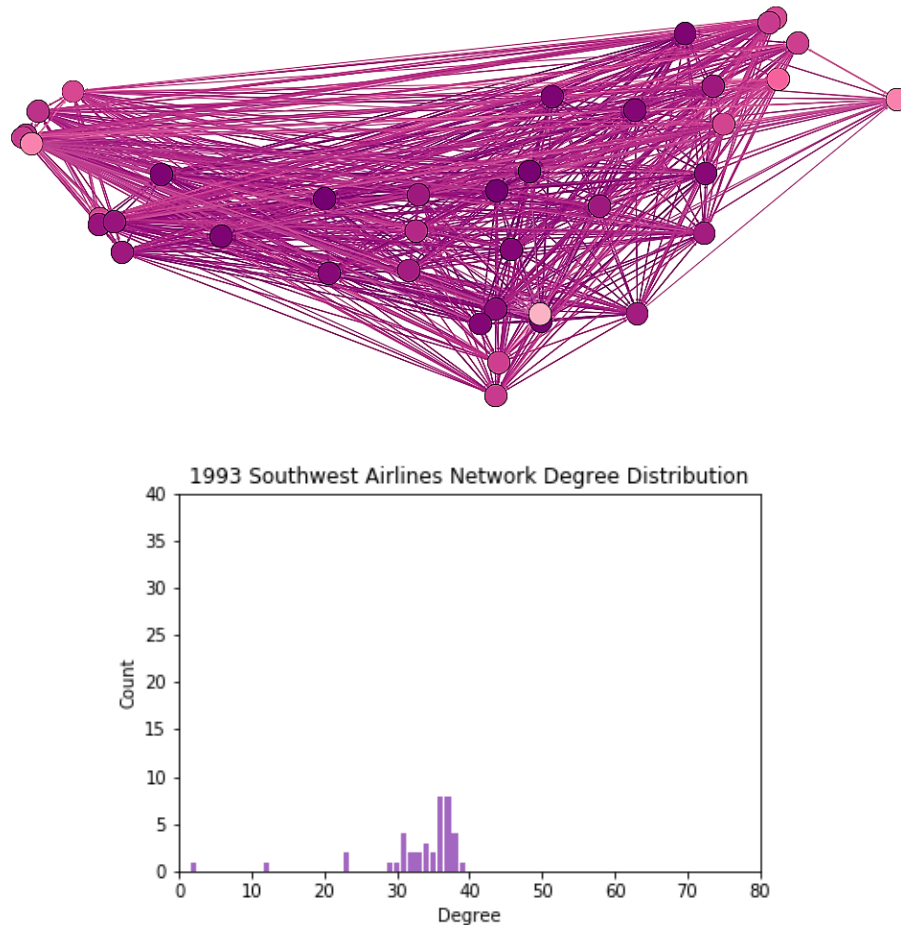


Figure 5.3. The Southwest Airlines route network and corresponding degree distribution in 1993

Shown in Figure 5.3, the Southwest route network in 1993 is point-to-point in nature. Nearly every airport in the network is connected by a flight route to the majority of the other airports in the network. As a result, almost every node in network is a dark color. As can be seen in the degree distribution of Figure 5.3, in 1993 the Southwest route network consists almost entirely of airports with a degree between 30 and 40. This is indicative of a network in which every airport has routes to almost every other airport within the network.

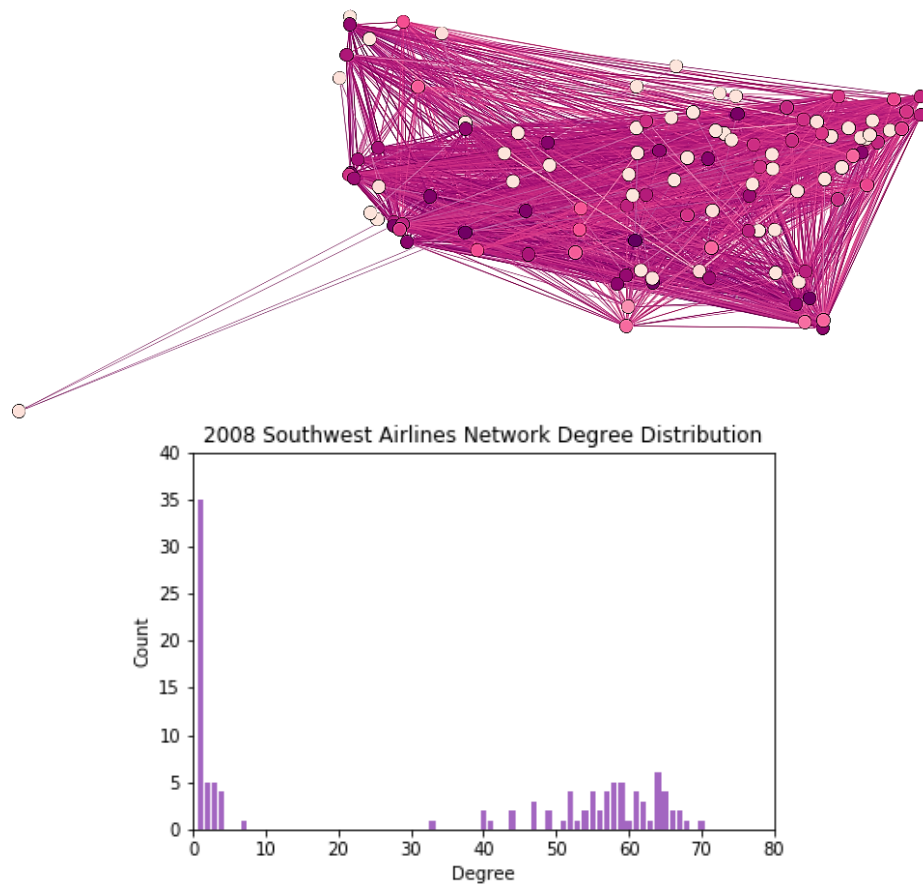


Figure 5.4. The Southwest Airlines route network and corresponding degree distribution in 2008

Figure 5.4 shows the expansion of Southwest Airlines from a regional carrier to a nationwide carrier. There are very light nodes in the network, which represent the low degree airports that are added. However, the majority of the nodes remain darkly colored, indicating that the point-to-point core of the Southwest network is still intact. As shown by the degree distribution in Figure 5.4, the majority of Southwest airports have a relatively high degree, however a large number of low degree airports have been added. The high degree airports have degrees that span from 40 to 70, which indicates the addition of new high degree airports and the growth of the direct network structure. However, the presence of many low degree airports is a characteristic of a hub-and-spoke structure.

In 2011 the Southwest route network appears to be very similar to the Southwest network

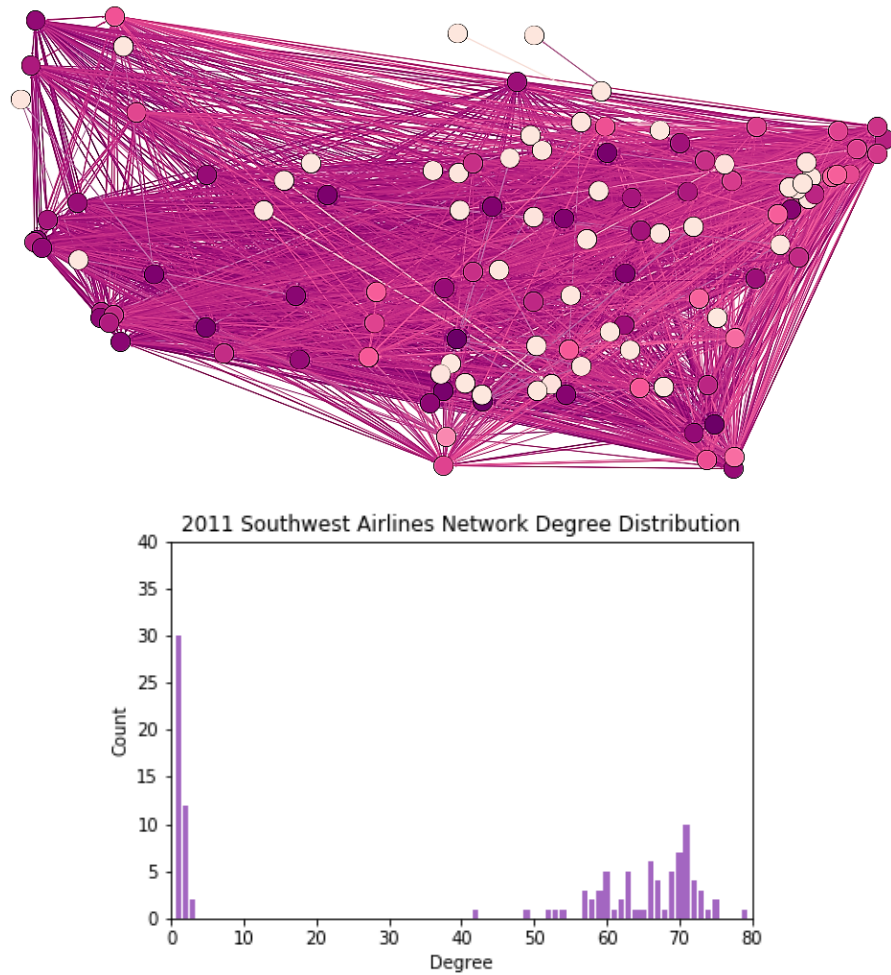


Figure 5.5. The Southwest Airlines route network and corresponding degree distribution in 2011

in 2008, as can be seen in Figure 5.5. One notable difference is the removal of a Hawaiian airport. The number of darkly colored nodes has also increased, while the number of lightly colored nodes has slightly decreased. Seen in the degree distribution, the number of higher degree nodes has increased, and the majority of high degree airports have degrees that span from 50 to 80 with a peak around degree 70, which indicates further growth of the direct network structure. The number of low degree airports have dropped slightly while the total number of airports has slightly increased from 2008. This could indicate the addition of previously low degree airports to the point-to-point structure.

5.2 American Mergers and Acquisitions

The next airline that we study from 1990 to 2017 is American Airlines. American is of interest because of the prominent place it has held among the U.S. commercial aviation industry for decades. Additionally, American is a good example of a traditional hub-and-spoke structure airline network. In addition to some international expansion, American acquires Reno Air and TWA Airlines and merges with US Airways during the 1990 to 2017 time frame. American's acquisition of Reno Air occurs in 1998, and its acquisition of TWA is finalized in 2001. The merger of American Airlines and US Airways takes place in 2013.

We find that our method aligns slightly better with American Airlines' decisions in terms of added airports than it does with Delta Airlines. However, this alignment is far lower than the corresponding alignment of Southwest Airlines. For airports dropped from the American route network, our methodology has the lowest alignment with ground truth. In 1998, the American Airlines route network has characteristics that are indicative of a hub-and-spoke structure. Over the remainder of the time period studied, the American network continues to develop a hub-and-spoke structure.

5.2.1 American Airlines – Reno Air Acquisition

A summary of the American Airlines route network in 1998 is shown in Table 5.17. Changes to the American network following its acquisition of Reno Air in 1998 are summarized in Tables 5.18, 5.19, 5.20, and 5.21.

We model the American route network in 1998 as a directed graph and as a directed multigraph, and measure global statistics on both. The direct graph represents the existence of all flight routes operated by American Airlines in 1998, and the multigraph includes weighting to reflect how many months of the year each route is flown. The statistics we take include the total number of nodes in the network, the number of edges in the network, the average degree of nodes in the network, the network density, and the network clustering coefficient. These statistics are shown in Table 5.17.

In 1998 the American route network consists of 102 airports with 1126 flight routes. The network's average degree is 22.078, which is smaller than the smallest average degree measured for Southwest Airlines, which is indicative of a hub-and-spoke structure. The network density is 0.219, which reflects that a relatively small number of the possible flight

Table 5.17. Global statistics of the American Airlines route network in 1998

American Network 1998 Global Statistics	
Nodes	102
Edges	1126
Average Degree	22.078
Density	0.219
Clustering Coefficient	0.489

routes between American network airports are flown in 1998. The clustering coefficient is 0.489, which shows that on average about half the possible edges between a node and all of its neighbors exist in the American network.

In the three years following American's acquisition of Reno Air there are seven airports added to American's route network that are not removed in subsequent years. A list of these airports can be found in Appendix D. The average ranking of these airports in each measure of centrality is shown in Table 5.18. For comparison, the average rankings for all U.S. airports not in the route network of American in 1998 in each measure of centrality are also shown.

Table 5.18. Average ranking of airports added to the American Airlines (AA) route network following the acquisition of Reno Air and average ranking of all U.S. airports not in the AA route network in 1998 by each measure of centrality

Average Centrality Ranking					
	$\bar{R}_C$	$\bar{R}_H$	$\bar{R}_B$	$\bar{R}_{PR}$	$\bar{R}_E$
Added to AA Network 1999-2001	122.429	123.714	132.714	179.286	156.571
Not in AA Network in 1998	353.559	353.512	349.638	345.874	353.868

Table 5.18 shows that airports that are selected for addition to the American network are ranked significantly better than the average of all possible airports in 1998. This result supports the idea that an airport's centrality has value as an indicator of whether it will be added to the American network.

In 1998 there are 508 active U.S. airports recorded that are not a part of the American route network. We rank these airports by their values of closeness, harmonic, betweenness,

PageRank, and eigenvector centrality. We consider the 51 top ranked airports by each measure of centrality to be those identified as good candidates for addition to the American network. The full list of these airports can be found in Appendix D. The 51 candidate airports for each measure of centrality are compared to the seven ground truth airports that are actually added to the American network in the three years following the acquisition of Reno Air. The alignment with ground truth for each measure of centrality is shown in Table 5.19.

Table 5.19. The airports added to the American network following the Reno Air acquisition that are among the top 10% of U.S. airports in 1998 in each measure of centrality

Alignment of Airports Added in 1999-2001				
C_i	H_i	B_i	PR_i	E_i
4 of 7	4 of 7	4 of 7	3 of 7	4 of 7
MKE	MKE	ANC	ANC	MKE
ANC	ANC	MKE	MKE	ANC
TYS	TYS	KOA	SHV	TYS
SHV	SHV	SHV		SHV

Table 5.19 shows that for airports added to the American network following the acquisition of Reno Air, the alignment is fairly consistent across each measure of centrality. Four out of seven of the airports actually added to the American network are also among the top ten percent of airports as ranked by closeness, harmonic, betweenness, and eigenvector centralities. For PageRank centrality, three out of the seven added airports are among the top 10 percent of possible airports as measured by PageRank.

Although American Airlines' decisions regarding the addition of airports to its network are influenced by a variety of other factors, on average 54.3% of the airports selected for addition by American Airlines following the acquisition of Reno Air are present within the candidate lists which comprise only 10% of all possible airports. Although this alignment is not as high as any for Southwest Airlines acquisitions, it still shows there is value in a centrality based analysis for selecting airports for addition to an airline network.

Following American Airline's acquisition of Reno Air there are four airports that are dropped from the American route network that are not added back in subsequent years. A complete list of these airports can be found in Appendix D. The average ranking of these airports in

each measure of centrality is shown in Table 5.20. For comparison, the average rankings for all U.S. airports in the route network of American in 1998 in each measure of centrality are also shown.

Table 5.20. Average ranking of airports dropped from the American Airlines (AA) route network following the acquisition of Reno Air and average ranking of all U.S. airports within the AA route network in 1998 by each measure of centrality

Average Centrality Ranking					
	$\bar{R}_C$	$\bar{R}_H$	$\bar{R}_B$	$\bar{R}_{PR}$	$\bar{R}_E$
Dropped from AA Network 1999-2001	153.500	159.500	193.500	243.250	156.500
In AA Network in 1998	66.147	66.382	85.676	104.422	64.608

Table 5.20 shows that the average rankings of the airports dropped from the network are again inferior to the average airport in the American network in 1998. This demonstrates the value of centrality as an indicator of airports with good potential for removal from the American network.

In 1998, there are 102 active U.S. airports that are a part of the American route network. We rank these airports by their values of closeness, harmonic, betweenness, PageRank, and eigenvector centrality. We consider the 51 bottom ranked airports by each measure of centrality to be those identified as good candidates for removal from the American network. The full list of these candidate airports can be found in Appendix D. The 51 candidate airports for each measure of centrality are compared to the four ground truth airports that are actually dropped from the American network in the three years following the acquisition of Reno Air. The alignment with ground truth for each measure of centrality is shown in Table 5.21.

Table 5.21 shows that for airports dropped from the American network following the acquisition of Reno Air the three measures of centrality with the greatest alignment to ground truth are closeness, harmonic, and eigenvector centralities. Four of the four airports dropped from the American network following the Reno Air acquisition are also among the bottom 50 percent of active U.S. airports that are a part of the American network in 1998 as identified by these three measures of centrality. Three of the four dropped airports are among the bottom 50 percent of potential airports as identified by betweenness and

Table 5.21. The airports dropped from the American network following the Reno Air acquisition that are among the bottom 50% of U.S. airports in 1998 in each measure of centrality

Alignment of Airports Dropped in 1999-2001				
C_i	H_i	B_i	PR_i	E_i
4 of 4	4 of 4	3 of 4	3 of 4	4 of 4
BFL	BFL	BFL	BFL	BFL
ISP	ISP	ISP	ISP	GTF
GTF	GTF	GTF	GTF	ISP
MAF	MAF			MAF

PageRank centralities.

Although American Airlines' decisions regarding the removal of airports from its network are influenced by a variety of other factors, on average 90% of the airports selected for removal by American Airlines following the acquisition of Reno Air are present within the candidate lists which comprise 50% of all possible airports. This represents a significant reduction in the number of potential airports to be considered when selecting airports for removal from an airline network.

5.2.2 American – TWA Airlines Acquisition

A summary of the American Airlines route network in 2001 is shown in Table 5.22. Changes to the American network following its acquisition of TWA Airlines in 2001 are summarized in Tables 5.23, 5.24, 5.25, and 5.26.

Global statistics are measured in order to understand the nature of the American route network in 2001. These statistics include the total number of nodes in the network, the number of edges in the network, the average degree of nodes in the network, the network density, and the network clustering coefficient. These statistics are shown in Table 5.22.

In 2001 the American route network is structurally very similar to the American network in 1998. It consists of 111 airports, between which there are 1275 flight routes. The average degree has increased slightly to 22.973 since, indicating the addition of higher degree airports. The network density has remained almost constant, dropping slightly to 0.209. The clustering coefficient also shows little change, rising slightly 0.503. That the

Table 5.22. Global statistics of the American Airlines route network in 2001

American Network 2001 Global Statistics	
Nodes	111
Edges	1275
Average Degree	22.973
Density	0.209
Clustering Coefficient	0.503

American route networks properties change so little between 1998 and 2001 suggest that nature of the network has not changed, and remains primarily hub-and-spoke in nature.

In the three years following American's acquisition of TWA Airlines there are 31 airports added to the American route network that are not removed in subsequent years. A list of these airports can be found in Appendix E. The average ranking of these airports in each measure of centrality is shown in Table 5.23. For comparison, the average rankings for all U.S. airports not in the route network of American in 2001 in each measure of centrality are also shown.

Table 5.23. Average ranking of airports added to the American Airlines (AA) route network following the acquisition of TWA Airlines and average ranking of all U.S. airports not in the AA route network in 2001 by each measure of centrality

Average Centrality Ranking					
	$\bar{R}_C$	$\bar{R}_H$	$\bar{R}_B$	$\bar{R}_{PR}$	$\bar{R}_E$
Added to AA Network 2002-2004	297.387	294.355	275.710	276.129	319.323
Not in AA Network in 2001	386.547	386.543	379.737	375.112	386.924

Table 5.23 shows that on average the airports that are selected for addition to the American network are better ranked than the average possible airport in 2001. This further supports centrality as an indicator of whether an airport will be selected for addition to the American route network.

When the American acquisition of TWA occurs in 2001, there are 556 active U.S. airports recorded that are not a part of the American route network. We rank these airports by their values of closeness, harmonic, betweenness, PageRank, and eigenvector centrality. We

consider the 55 top ranked airports by each measure of centrality to be those identified as good candidates for addition to the American network. The full list of these airports can be found in Appendix E. These 55 candidate airports for each measure of centrality are compared to the 31 ground truth airports that are actually added to the American network in the three years following the acquisition of Reno Air. The alignment with ground truth for each measure of centrality is shown in Table 5.24.

Table 5.24. The airports added to the American network following the TWA Airlines acquisition that are among the top 10% of U.S. airports in 2001 in each measure of centrality

Alignment of Airports Added in 2002-2004				
C_i	H_i	B_i	PR_i	E_i
3 of 31	2 of 31	5 of 31	7 of 31	4 of 31
CAE LAN BFI	CAE LAN	WRI AEX NTD BFI CAE	NTD WRI BFI CAE AEX CLL RIV	CAE LAN GPT LIH

Table 5.24 shows that for airports added to the American network following the acquisition of TWA, the alignment is inconsistent between each measure of centrality. Additionally, the alignment for all measures of centrality are significantly lower than for other acquisitions studied. Seven out of 31 of the airports actually added to the American network are among the top ten percent of airports as ranked by PageRank centrality, in this case the highest performing measure. Five of the 31 airports added are among the top ten percent potential airports as identified by betweenness centrality, and four of the 31 are among those identified by eigenvector centrality. Three of the 31 are among the top potential airports as listed by closeness centrality. Harmonic centrality performs poorly for this acquisition, identifying only two of the 31 added airports.

On average 13.5% of the airports selected for addition by American Airlines following the acquisition of TWA Airlines are present within the candidate lists which comprise only 10% of all possible airports. While this alignment is significantly lower than any previous, it still represents a reduction in the number of airports to be considered for addition to a

route network.

Following American Airline's acquisition of TWA there are seven airports that are dropped from the American route network that are not added back in subsequent years. A complete list of these airports can be found in Appendix E. The average ranking of these airports in each measure of centrality is shown in Table 5.25. For comparison, the average rankings for all U.S. airports in the route network of American in 2001 in each measure of centrality are also shown.

Table 5.25. Average ranking of airports dropped from the American Airlines (AA) route network following the acquisition of TWA Airlines and average ranking of all U.S. airports within the AA route network in 2001 by each measure of centrality

Average Centrality Ranking					
	$\bar{R}_C$	$\bar{R}_H$	$\bar{R}_B$	$\bar{R}_{PR}$	$\bar{R}_E$
Dropped from AA Network 2002-2004	156.286	154.429	184.286	179.143	154.857
In AA Network in 2001	70.793	70.811	104.901	128.072	68.901

Table 5.25 shows that the average rankings of the airports dropped from the network are again higher than the average of the American network in 2001. This again shows that the centrality of an airport is a good indicator of whether it will be dropped from the American network.

In 2001, there are 111 active U.S. airports that are a part of the American route network. We rank these airports by their values of closeness, harmonic, betweenness, PageRank, and eigenvector centrality. We consider the 55 bottom ranked airports by each measure of centrality to be those identified as good candidates for removal from the American network. The full list of these candidate airports can be found in Appendix E. The 55 candidate airports for each measure of centrality are compared to the seven ground truth airports that are actually dropped from the American network in the three years following the acquisition of TWA. The alignment with ground truth for each measure of centrality is shown in Table 5.26.

Table 5.26 shows that for airports dropped from the American network following the acquisition of TWA Airlines four of the five measures of centrality identify 100% of the airports dropped. All of the seven airports dropped are also among those identified as candidates

Table 5.26. The airports dropped from the American network following the TWA Airlines acquisition that are among the bottom 50% of U.S. airports in 2001 in each measure of centrality

Alignment of Airports Dropped in 2002-2004				
C_i	H_i	B_i	PR_i	E_i
7 of 7	7 of 7	7 of 7	4 of 7	7 of 7
DRO	DRO	SUX	ACY	DRO
SUX	SUX	ACY	SUX	SUX
ACY	ACY	MDT	MDT	ACY
CAK	CAK	AMA	AMA	CAK
AMA	AMA	BIL		AMA
MDT	MDT	DRO		BIL
BIL	BIL	CAK		MDT

for removal by closeness, harmonic, betweenness, and eigenvector centralities. Four of the seven airports dropped from the American network following the TWA acquisition are also among the bottom 50 percent of active U.S. airports that are a part of the American network in 2001 as identified by PageRank centrality.

Although American Airlines' decisions regarding the removal of airports from its network are influenced by a variety of other factors, on average 91.4% of the airports selected for removal by American Airlines following the acquisition of TWA Airlines are present within the candidate lists which comprise 50% of all possible airports. The list of candidate airports generated with PageRank centrality shows significantly lower alignment than those of the other four centralities. If PageRank were not considered, the average alignment of the candidate lists with the same removed airports would improve to 100%.

5.2.3 American – US Airways Merger

A summary of the American Airlines route network in 2013 is shown in Table 5.27. Changes to the American network following its merger with US Airways in 2013 are summarized in Tables 5.28, 5.29, 5.30, and 5.31.

Global statistics are used to quantify the American route network in 2013. These statistics include the total number of nodes in the network, the number of edges in the network, the average degree of nodes in the network, the network density, and the network clustering

coefficient. These statistics are shown in Table 5.27.

Table 5.27. Global statistics of the American Airlines route network in 2013

American Network 2013 Global Statistics	
Nodes	136
Edges	922
Average Degree	13.559
Density	0.100
Clustering Coefficient	0.411

In 2013 the American route network remains a characteristically hub-and-spoke network. Since 2001, it has grown to 136 airports, but the number of flight routes have fallen to 922. As a result, the average degree has fallen significantly to 13.559. The network density and clustering coefficient have also both decreased to 0.1 and 0.411 respectively. Smaller values in a network's average degree, density and clustering coefficient are all indicative of hub-and-spoke networks. Therefore, the decrease of these three values for the American route network between 2001 and 2013 is indicative of further development of the hub-and-spoke structure of the American Airlines route network.

In the three years following American's merger with US Airways there are 28 airports added to the American route network that are not removed in subsequent years. A list of these airports can be found in Appendix F. The average ranking of these airports in each measure of centrality is shown in Table 5.28. For comparison, the average rankings for all U.S. airports not in the route network of American in 2013 in each measure of centrality are also shown.

Table 5.28. Average ranking of airports added to the American Airlines (AA) route network following the merger with US Airways and average ranking of all U.S. airports not in the AA route network in 2013 by each measure of centrality

Average Centrality Ranking					
	$\bar{R}_C$	$\bar{R}_H$	$\bar{R}_B$	$\bar{R}_{PR}$	$\bar{R}_E$
Added to AA Network 2014-2016	153.393	148.607	252.321	290.536	150.643
Not in AA Network in 2013	678.323	678.213	667.382	663.047	675.428

Table 5.28 shows that on average the airports that are selected for addition to the American network are ranked significantly better than the average of airports that could be added in 2013. This again demonstrates the value of centrality as an indicator of whether an airport will be added to the American Airlines network.

In 2013 there are 1085 active U.S. airports recorded that are not a part of the American route network. We rank these airports by their values of closeness, harmonic, betweenness, PageRank, and eigenvector centrality. We consider the 109 top ranked airports by each measure of centrality to be those identified as good candidates for addition to the American route network. The full list of these airports can be found in Appendix F. These 109 candidate airports for each measure of centrality are compared to the 28 ground truth airports that are actually added to the American network in the three years following the merger with US Airways. The alignment with ground truth for each measure of centrality is shown in Table 5.29.

Table 5.29 shows non-trivial inconsistencies between centrality measures in the alignment with ground truth. Eighteen out of 28 of the airports actually added to the American network following the US Airways merger are among the top ten percent of airports as ranked by eigenvector centrality, in this case the highest performing measure. Sixteen of the 28 airports added are among the top ten percent potential airports as identified by closeness and harmonic centralities. Nine of the 28 are among those identified by betweenness centrality. Only four of the 28 added airports are among the top potential airports as identified by PageRank centrality.

Although American Airlines' decisions regarding the addition of airports to its network are influenced by a variety of other factors, on average 45% of the airports selected for addition by American Airlines following the merger with US Airways are present within the candidate lists, which comprise only 10% of all possible airports. Although this alignment is not as high as any for Southwest Airlines acquisitions, it still represents a significant reduction in the number of airports to be considered for addition to a route network.

Following American Airline's merger with US Airways there are 19 airports that are dropped from the American route network that are not added back in subsequent years. A complete list of these airports can be found in Appendix F. The average ranking of these airports in each measure of centrality is shown in Table 5.30. For comparison, the average rankings

Table 5.29. The airports added to the American network following the US Airways merger that are among the top 10% of U.S. airports in 2013 in each measure of centrality

Alignment of Airports Added in 2014-2016				
C_i	H_i	B_i	PR_i	E_i
16 of 28	16 of 28	9 of 28	4 of 28	18 of 28
CVG	CVG	HPN	HPN	CVG
ROC	ROC	ALB	GSP	ALB
ALB	ALB	CVG	ALB	ROC
GSP	GSP	PWM	CPS	GSO
MDT	HPN	FWA		GSP
BZN	MDT	MDT		MDT
GSO	GSO	ILM		PWM
HPN	TYS	GSO		SAV
PWM	PWM	ROC		TYS
TYS	BZN			ILM
SAV	SAV			HPN
ILM	ILM			BZN
FWA	FWA			SGF
SGF	SGF			AVL
CPS	AVL			FWA
AVL	DAB			EVV
				DAB
				AZO

for all U.S. airports in the route network of American in 2013 in each measure of centrality are also shown.

Table 5.30 shows that the average rankings of the airports dropped from the network are higher than the average airport in the American route network in 2013. This finding further supports the idea that an airport's centrality has value as an indicator of whether it will be dropped from the American network.

In 2013, there are 143 active U.S. airports that are a part of the American route network. We rank these airports by their values of closeness, harmonic, betweenness, PageRank, and eigenvector centrality. We consider the 72 bottom ranked airports by each measure of centrality to be those identified as good candidates for removal from the American network.

Table 5.30. Average ranking of airports dropped from the American route network following the merger with US Airways and average ranking of all U.S. airports within the American route network in 2013 by each measure of centrality

Average Centrality Ranking					
	$\overline{R}_C$	$\overline{R}_H$	$\overline{R}_B$	$\overline{R}_{PR}$	$\overline{R}_E$
Dropped from AA Network 2014-2016	280.895	279.105	387.842	366.579	441.421
In AA Network in 2013	130.252	131.084	213.259	246.154	152.217

The full list of these candidate airports can be found in Appendix F. The 72 candidate airports for each measure of centrality are compared to the 19 ground truth airports that are actually dropped from the American network in the three years following the merger with US Airways. The alignment with ground truth for each measure of centrality is shown in Table 5.31.

Table 5.31 shows a fairly strong alignment between all centrality measures and ground truth. All of the 19 airports dropped are also among those identified as good candidates for removal by eigenvector centrality. Seventeen of the 19 airports dropped are also among those identified as candidates for removal by closeness and harmonic centralities. Among those identified as good candidates for removal by betweenness centrality are 16 of the 19 airports dropped. PageRank centrality performs only slightly worse, as 15 of the 19 airports dropped from the American network following the US Airways merger are also among the bottom 50 percent of active U.S. airports that are a part of the American network in 2013 as identified by PageRank centrality.

Although American Airlines' decisions regarding the removal of airports from its network are influenced by a variety of other factors, on average 88.4% of the airports selected for removal by American Airlines following the merger with US Airways are present within the candidate lists which comprise 50% of all possible airports. Again, the alignments of the candidate lists generated by PageRank centrality and betweenness centrality are the lowest of all the centralities. If only closeness centrality, harmonic centrality, and eigenvector centrality are considered, the average alignment increases significantly. This further demonstrates the value of centrality analysis in the selection of airports to remove from an airline network.

Table 5.31. The airports dropped from the American network following the US Airlines merger that are among the bottom 50% of U.S. airports in 2013 in each measure of centrality

Alignment of Airports Dropped in 2014-2016				
C_i	H_i	B_i	PR_i	E_i
17 of 19	17 of 19	16 of 19	15 of 19	19 of 19
SKF	SKF	SKF	SKF	MIB
OCF	OCF	OCF	RST	BAD
TUP	LAW	MIB	BIF	SKF
LAW	TUP	RST	LAW	BIF
YKM	YKM	BIF	OCF	OCF
BIF	BIF	LAW	BFM	NGU
NGU	NGU	BFM	GTF	TCL
BFM	BFM	NGU	TUP	LAW
TCL	TCL	ACT	NGU	TUP
ACT	ACT	TUP	YKM	YKM
RST	RST	YKM	ACT	BFM
GTF	GTF	CID	CID	ACT
BGR	BGR	GTF	BIL	SFB
SFB	CID	BAD	GPT	RST
CID	SFB	BGR	BGR	GTF
GPT	BIL	TCL		BGR
BIL	GPT			GPT
				BIL
				CID

5.2.4 American Overview

The alignment of our method of centrality based identification of potential airports and ground truth for the additions to the American Airlines route network is far behind that of Southwest. The average alignment of every measure of centrality for every American Airlines acquisition and merger is shown in Table 5.32.

As can be seen in Table 5.32, the average alignment between airports selected by our method and ground truth added airports for American Airlines is 37.61%. This is the second highest alignment for added airports of the three airlines studied, Tables 5.16 and 5.48, only slightly higher than the corresponding alignment for Delta. The average alignment with ground truth dropped airports for American Airlines is 89.95%, which is slightly behind that of

Table 5.32. The average alignment for American mergers and acquisitions between airports identified as good candidates for addition to or removal from an airline and ground truth

	Added Airports	Airports Dropped
American Average	37.61%	89.95%

Southwest Airlines and Delta Airlines.

The growth of the American Airlines route network from 1990 to 2017 is shown in Figures 5.6 – 5.10. Figure 5.6 shows an increasing trend in the number of airports within the American route network over the time period from 1990 to 2017. However, this trend is rather weak, as there are intermittent, multi-year long periods of sharp increase as well as of sharp decrease.



Figure 5.6. The number of airports within the American route network per year from 1990 to 2017

Figure 5.7 shows an overall trend of decrease in the average degree of the airports within the American network from 1990 to 2017. This downward trend is far more consistent than the increasing trend in the number of airports per year in the American network. With the exception of several small upward spikes, the average degree of airports of the American Airlines route network when studied in isolation has trended steadily downward.

Figures 5.8, 5.9, and 5.10 show a geographical layout and the degree distribution of the

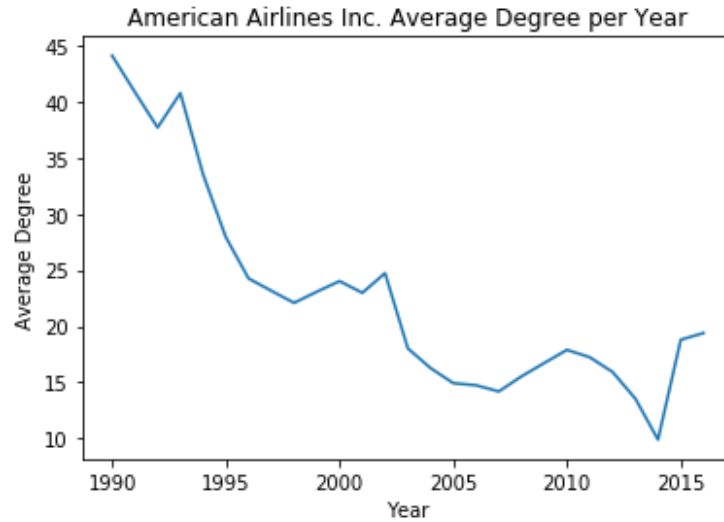


Figure 5.7. The average degree of all the airports within the American route network per year from 1990 to 2017

American route network for 1998, 2001, and 2013 respectively. In Figures 5.8, 5.9, and 5.10, nodes are again colored from dark to light by degree from high to low, and edges are colored by the source node.

Figure 5.8 shows the American Airlines route network in 1998. It does not display the point-to-point characteristics of the Southwest network. There is only one node that is darkly colored, Dallas/Fort Worth International Airport (DFW). The majority of other nodes are either white or lightly colored. These are the spokes in the hub-and-spoke structure of the American route network. In 1998 the degree distribution of the American route network consists of a fairly even distribution of airports over a wide range of degrees from 1 to nearly 50. In general the number of airports as a function of degree decreases as degree increases, with a small peak around degree 45. The two airports with the highest degree are the aforementioned DFW, with a degree of 94, and the Chicago O'Hare International Airport (ORD), with a degree 66.

With the exception of the addition of a flight route to Alaska, the American route network shown in Figure 5.9 is almost the same as the American route network in 1998. It displays the same hub-and-spoke statistics, in which there are only a few dark nodes and many lightly colored nodes. The degree distribution of the American Airlines route network in 2001 is

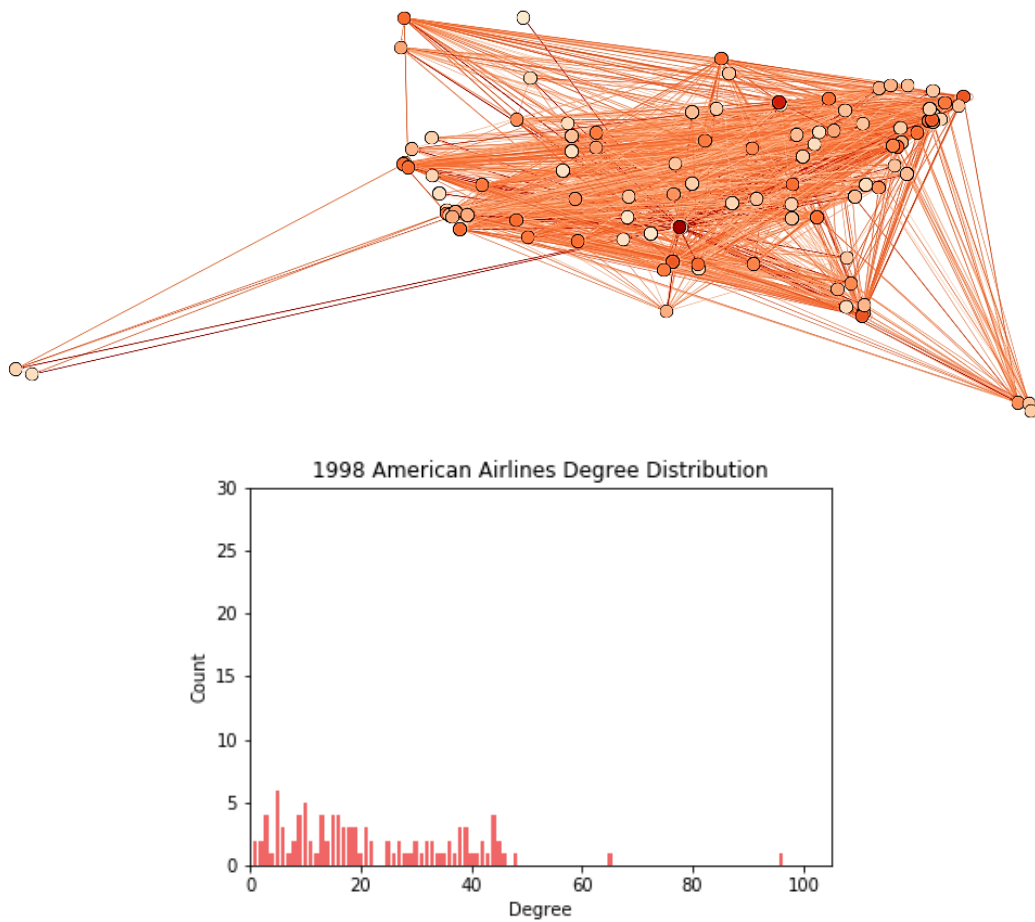


Figure 5.8. The American Airlines route network and corresponding degree distribution in 1998

very similar to its degree distribution in 1998. The majority of airports in the American route network have a degree between 1 and 50, and the same two hubs stand out with the highest degrees. The number of airports with a degree of less than 10 as well as the number of airports with a degree around 50 have increased. The degree of both hubs have also increased, DFW to over 100.

Figure 5.10 shows some notable differences from that of 2001. The number of lightly colored nodes has increased significantly since 2001. The darkest nodes remain the same: DFW and ORD. In the degree distribution of the American Airlines network in 2013 the

majority of airports fall within a range of degrees from 1 to approximately 30. There are still some airports with degrees ranging from 30 to 60, but the number of such airports has significantly declined. The number of airports with a degree less than 10 has significantly increased. The most common degree is 1. The airports with the two largest degrees remain DFW and ORD, however the degree of both of these has dropped. Overall the network more strongly exhibits hub-and-spoke characteristics.

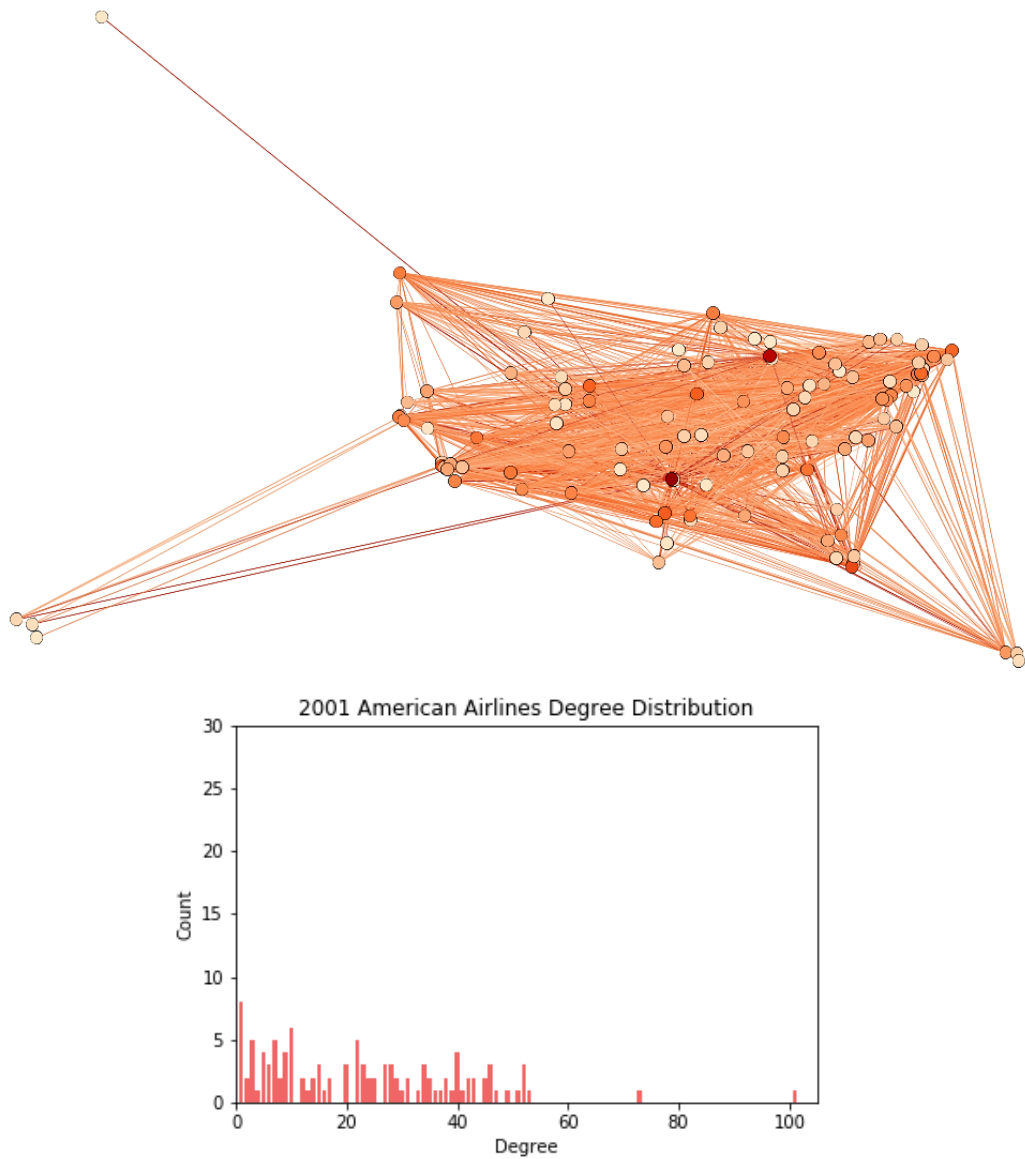


Figure 5.9. American route network and corresponding degree distribution in 2001

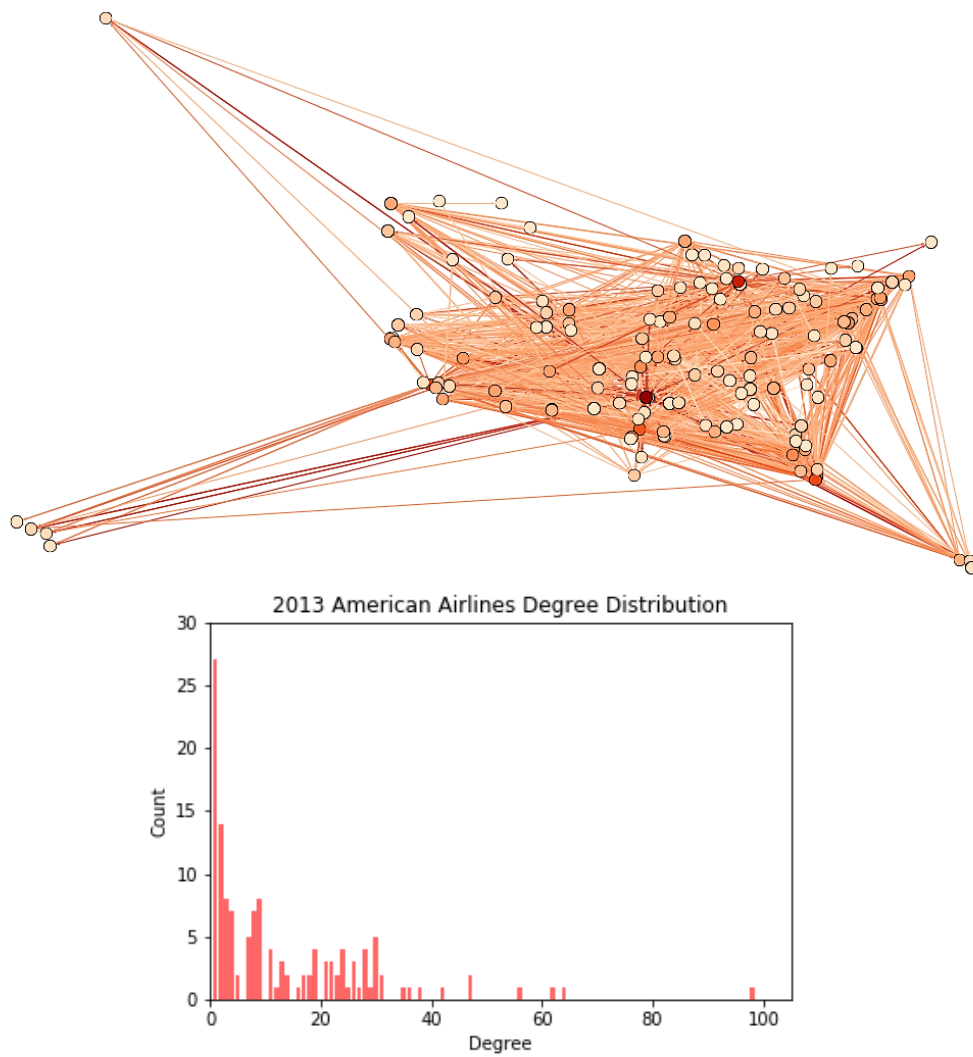


Figure 5.10. American route network and corresponding degree distribution in 2013

5.3 Delta Mergers and Acquisitions

The final airline that we study from 1990 to 2017 is Delta Airlines. Along with American Airlines, Delta is of interest because of its status as a major American service provider and its traditional hub-and-spoke structure. Over the time period from 1990 to 2017, Delta merges with or acquires four other airlines: Pan American Airlines, Atlantic Southeast Airlines, Comair, and Northwest Airlines. The acquisition of Pan American takes place in 1991. In 1999, Delta acquires both Atlantic Southeast Airlines and Comair. Lastly, Delta finalizes its merger with Northwest Airlines in 2009.

We find that our method has the poorest performance for Delta Airlines out of all the airlines studied in terms of alignment with added airports. On the other hand, for airports dropped from the networks, our method has higher alignment with ground truth for Delta Airlines than for Southwest Airlines and American Airlines. In 1991, the Delta Airlines route network also displays a hub-and-spoke structure. Over the remainder of the time period studied, the Delta Airlines route network evolves in a similar manner to the American Airlines network, developing stronger hub-and-spoke characteristics.

5.3.1 Delta – Pan American Airlines Acquisition

A summary of the Delta Airlines route network in 1991 is shown in Table 5.33. Changes to the Delta network following its acquisition of Pan American Airlines in 1991 are summarized in Tables 5.34, 5.35, 5.36, and 5.37.

Global statistics are measured in order to understand the nature of the Delta route network in 1991. These statistics include the total number of nodes in the network, the number of edges in the network, the average degree of nodes in the network, the network density, and the network clustering coefficient. These statistics are shown in Table 5.33.

In 1991 the Delta route network consists of 140 airports and 2,455 flight routes, the most flight routes of all the networks in all the years we study. The average degree is 35.071, which is higher even than the highly point-to-point Southwest network of 1993. This large average degree suggests that the Delta route network in 1991 is at least partially point-to-point in nature, however, the low network density of 0.252 is characteristic of a hub-and-spoke structure. The clustering coefficient of 0.569 is higher than any clustering coefficient measured for the American route network, but smaller than any measured for

Table 5.33. Global statistics of the Delta Airlines route network in 1991

Delta Network 1991 Global Statistics	
Nodes	140
Edges	2455
Average Degree	35.071
Density	0.252
Clustering Coefficient	0.569

the Southwest network. These statistics suggest that in 1991, the Delta network is neither purely hub-and-spoke nor point-to-point in nature, but somewhere in between the two.

In the three years following Delta's acquisition of Pan American Airlines there are four airports added to the Delta route network that are not removed in subsequent years. A list of these airports can be found in Appendix G. The average ranking of these airports in each measure of centrality is shown in Table 5.34. For comparison, the average rankings for all U.S. airports not in the route network of Delta in 1991 in each measure of centrality are also shown.

Table 5.34. Average ranking of airports added to the Delta route network following the acquisition of PanAm and average ranking of all U.S. airports not in the Delta route network in 1991 by each measure of centrality

Average Centrality Ranking					
	$\bar{R}_C$	$\bar{R}_H$	$\bar{R}_B$	$\bar{R}_{PR}$	$\bar{R}_E$
Added to Delta Network 1992-1994	170.750	173.000	217.500	248.750	163.000
Not in Delta Network in 1991	320.989	321.094	315.946	306.876	321.092

In Table 5.34 the average ranking of the airports added to the Delta network are significantly better than the average ranking of all the airports which could possibly be added in 1991. This finding supports the value of centrality in indicating an airports potential for addition to the Delta network.

When the Delta acquisition of Pan American Airlines occurs in 1991, there are 371 active U.S. airports recorded that are not a part of the Delta route network. We rank these airports by their values of closeness, harmonic, betweenness, PageRank, and eigenvector centrality.

We consider the 37 top ranked airports by each measure of centrality to be those identified as good candidates for addition to the Delta network. The full list of these airports can be found in Appendix G. The 37 candidate airports for each measure of centrality are compared to the four ground truth airports that are actually added to the Delta network in the three years following the acquisition of Pan American. The alignment with ground truth for each measure of centrality is shown in Table 5.35.

Table 5.35. The airports added to the Delta network following the PanAm acquisition that are among the top 10% of U.S. airports in 1991 in each measure of centrality

Alignment of Airports Added in 1992-1994				
C_i	H_i	B_i	PR_i	E_i
1 of 4	1 of 4	0 of 4	1 of 4	2 of 4
AVP	AVP		SBN	SBN AVP

Table 5.35 shows that for airports added to the Delta network following the acquisition of Pan American Airlines, there is little alignment with ground truth for any measure of centrality. One of four of the airports actually added to the Delta network are also among the top ten percent of airports as ranked by closeness, harmonic, and PageRank centralities. Two of the four added airports are also among the top potential airports as identified by eigenvector centrality. None of the airports identified by betweenness centrality are actually added to the Delta network following the acquisition of Pan American.

On average 25% of the airports selected for addition by Delta Airlines following the acquisition of Pan American Airlines are present within the candidate lists, which comprise only 10% of all possible airports. Although this alignment is again not as high as the alignment for Southwest Airlines acquisitions, it still represents a moderate reduction in the number of airports to be considered for addition to a route network, and therefore demonstrates the value of centrality based analysis in selecting airports for addition to an airline network.

Following Delta Airline's acquisition of Pan American there are six airports that are dropped from the Delta route network that are not added back in subsequent years. A complete list of these airports can be found in Appendix G. The average ranking of these airports in each measure of centrality is shown in Table 5.36. For comparison, the average rankings for all

U.S. airports in the route network of Delta in 1991 in each measure of centrality are also shown.

Table 5.36. Average ranking of airports dropped from the Delta route network following the acquisition of PanAm and average ranking of all U.S. airports within the Delta route network in 1991 by each measure of centrality

Average Centrality Ranking					
	$\bar{R}_C$	$\bar{R}_H$	$\bar{R}_B$	$\bar{R}_{PR}$	$\bar{R}_E$
Dropped from Delta Network 1992-1994	140.167	143.167	162.500	211.500	158.167
In Delta Network in 1991	83.779	83.500	97.143	121.179	83.507

Table 5.36 shows that the average rankings of the airports dropped from the network are inferior the average airport in the Delta network, supporting the idea that an airport's centrality has value as an indicator of its potential for removal from the Delta route network.

In 1991, there are 140 active U.S. airports that are a part of the Delta route network. We rank these airports by their values of closeness, harmonic, betweenness, PageRank, and eigenvector centrality. We consider the 70 bottom ranked airports by each measure of centrality to be those identified as good candidates for removal from the Delta network. The full list of these candidate airports can be found in Appendix G. These 70 candidate airports for each measure of centrality are compared to the six ground truth airports that are actually dropped from the Delta route network in the three years following the acquisition of Pan American Airlines. The alignment with ground truth for each measure of centrality is shown in Table 5.37.

In Table 5.37 the alignment between the top candidates for removal and the airports dropped following the Pan American acquisition is fairly good. All six of the dropped airports are also among those listed as top candidates for removal based on closeness, harmonic, and PageRank centralities. Five of the six dropped airports were among the candidates for removal as identified by betweenness and eigenvector centralities.

Although Delta Airlines' decisions regarding the removal of airports from its network are influenced by a variety of other factors, on average 93.3% of the airports selected for removal by Delta Airlines following the acquisition of Pan American Airlines are present within the

Table 5.37. The airports dropped from the Delta network following the PanAm acquisition that are among the bottom 50% of U.S. airports in 1991 in each measure of centrality

Alignment of Airports Dropped in 1992-1994				
C_i	H_i	B_i	PR_i	E_i
6 of 6	6 of 6	5 of 6	6 of 6	5 of 6
OGD	OGD	OGD	OGD	OGD
ILM	ILM	ILM	ILM	BIS
BIS	BIS	BIS	LGB	ILM
AMA	AMA	AMA	AMA	LGB
BUR	LGB	BUR	BIS	AMA
LGB	BUR		BUR	

candidate lists which comprise 50% of all possible airports. This again demonstrates the value of centrality analysis in the selection of airports to remove from an airline network.

5.3.2 Delta – Comair and Atlantic Southeast Airlines Acquisitions

A summary of the Delta Airlines route network in 1999 is shown in Table 5.38. Changes to the Delta Airlines route network following its acquisitions of Comair and Atlantic Southeast Airlines in 1999 are summarized in Tables 5.39, 5.40, 5.41, and 5.42.

Global statistics are used to quantify the Delta route network in 1999. These statistics include the total number of nodes in the network, the number of edges in the network, the average degree of nodes in the network, the network density, and the network clustering coefficient. These statistics are shown in Table 5.38.

Table 5.38. Global statistics of the Delta Airlines route network in 1999

Delta Network 1999 Global Statistics	
Nodes	121
Edges	1952
Average Degree	32.364
Density	0.269
Clustering Coefficient	0.511

Between 1991 and 1999, the Delta network shrinks considerably. In 1999, it consists of

121 airports and 1952 flight routes. The network density remains fairly constant, increasing slightly to 0.269. However, the average degree and the clustering coefficient of the network both decrease, to 32.364 and 0.511 respectively, which is indicative of a shift towards a more hub-and-spoke network structure.

In the three years following Delta's acquisitions of Comair and Atlantic Southeast Airlines there are 24 airports added to the Delta route network that are not removed in subsequent years. A list of these airports can be found in Appendix H. The average ranking of these airports in each measure of centrality is shown in Table 5.39. For comparison, the average rankings for all U.S. airports not in the route network of Delta in 1999 in each measure of centrality are also shown.

Table 5.39. Average ranking of airports added to the Delta route network following the acquisitions of Comair and Atlantic Southeast Airlines and average ranking of all U.S. airports not in the Delta route network in 1999 by each measure of centrality

Average Centrality Ranking					
	$\bar{R}_C$	$\bar{R}_H$	$\bar{R}_B$	$\bar{R}_{PR}$	$\bar{R}_E$
Added to Delta Network 2000-2002	215.875	213.750	251.208	270.708	210.833
Not in Delta Network in 1999	369.667	369.709	364.705	357.061	370.463

In Table 5.39 the average centrality rankings of the airports added to the Delta network are significantly better than the average of all the possible airports in 1999, further supporting the idea that an airport's centrality has value as an indicator as to whether an airport will be added to the Delta network.

In 1999 there are 505 active U.S. airports recorded that are not a part of the Delta route network. We rank these airports by their values of closeness, harmonic, betweenness, PageRank, and eigenvector centrality. We consider the 50 top ranked airports by each measure of centrality to be those identified as good candidates for addition to the Delta network. The full list of these airports can be found in Appendix H. The 50 candidate airports for each measure of centrality are compared to the 24 ground truth airports that are actually added to the Delta network in the three years following the acquisitions of Comair and Atlantic Southeast Airlines. The alignment with ground truth for each measure of centrality is shown in Table 5.40.

Table 5.40. The airports added to the Delta network following the Comair and Atlantic Southeast Airlines acquisitions that are among the top 10% of U.S. airports in 1999 in each measure of centrality

Alignment of Airports Added in 2000-2002				
C_i	H_i	B_i	PR_i	E_i
8 of 24	8 of 24	2 of 24	0 of 24	10 of 24
MSN	MSN	CAK		MHT
MHT	MHT	MSN		MSN
PSP	PSP			PSP
EUG	EUG			LBB
FAT	CAK			EUG
CAK	LBB			CAK
VPS	VPS			FAT
LBB	FAT			ROA
				XNA
				VPS

In Table 5.40 there is notable variation among the centrality measures in alignment with ground truth airports. Ten of the 24 airports added following the acquisitions of Comair and Atlantic Southeast Airlines are also among those identified as good candidate airports by eigenvector centrality. Eight of the 24 added airports are among the top potential airports identified by both closeness and harmonic centralities. Only two of the added airports are among the top potential airports as identified by betweenness centrality, and none of the added airports are among the candidates identified by PageRank.

Although Delta Airlines' decisions regarding the addition of airports to its network are influenced by a variety of other factors, on average 23.3% of the airports selected for addition by Delta Airlines following the acquisitions of Comair and Atlantic Southeast Airlines are present within the candidate lists, which comprise only 10% of all possible airports. The candidate lists generated by both PageRank centrality and betweenness centrality have significantly lower alignment with the added airports than those of the other three centralities. If only closeness centrality, harmonic centrality, and eigenvector centrality were considered, the average alignment would be significantly higher.

Following Delta Airline's acquisitions of Comair and Atlantic Southeast Airlines there are three airports that are dropped from the Delta route network that are not added back in

subsequent years. A complete list of these airports can be found in Appendix H. The average ranking of these airports in each measure of centrality is shown in Table 5.41. For comparison, the average rankings for all U.S. airports in the route network of Delta in 1999 in each measure of centrality are also shown.

Table 5.41. Average ranking of airports dropped from the Delta route network following the acquisitions of Comair and Atlantic Southeast Airlines and the average ranking of all U.S. airports within the Delta route network in 1999 by each measure of centrality

Average Centrality Ranking					
	$\bar{R}_C$	$\bar{R}_H$	$\bar{R}_B$	$\bar{R}_{PR}$	$\bar{R}_E$
Dropped from Delta Network 2000-2002	147.667	149.667	214.000	307.000	146.333
In Delta Network in 1999	79.083	78.909	99.793	131.694	75.760

In Table 5.41 the average rankings of the airports dropped from the network are significantly higher the average of airports in the Delta network in 1999. This demonstrates that an airports centrality is also a good indicator of whether it will be dropped from the Delta network.

In 1999, there are 121 active U.S. airports that are a part of the Delta route network. We rank these airports by their values of closeness, harmonic, betweenness, PageRank, and eigenvector centrality. We consider the 60 bottom ranked airports by each measure of centrality to be those identified as good candidates for removal from the Delta network. The full list of these candidate airports can be found in Appendix H. These 60 candidate airports for each measure of centrality are compared to the three ground truth airports that are actually dropped from the Delta route network in the three years following the acquisitions of Comair and Atlantic Southeast Airlines. The alignment with ground truth for each measure of centrality is shown in Table 5.42.

In Table 5.42 the alignment between the top candidates for removal and the airports dropped following the Comair and Atlantic Southeast Airlines acquisitions is fairly good. All three of the dropped airports are also among those listed as top candidates for removal based on harmonic, betweenness, and PageRank centralities. Two of the three dropped airports were among the candidates for removal as identified by closeness and eigenvector centralities.

Although Delta Airlines' decisions regarding the removal of airports from its network are

Table 5.42. The airports dropped from the Delta network following the Comair and Atlantic Southeast Airlines acquisitions that are among the bottom 50% of U.S. airports in 1999 in each measure of centrality

Alignment of Airports Dropped in 2000-2002				
C_i	H_i	B_i	PR_i	E_i
2 of 3	3 of 3	3 of 3	3 of 3	2 of 3
GUC	GUC	GUC	GUC	GUC
STX	STX	STX	STX	STX
	RNO	RNO	RNO	

influenced by a variety of other factors, on average 86.7% of the airports selected for removal by Delta Airlines following the acquisitions of Comair and Atlantic Southeast Airlines are present within the candidate lists which comprise 50% of all possible airports. This again represents a significant reduction in the number of airports to be considered in the selection of airports to remove from an airline's network.

5.3.3 Delta – Northwest Airlines Merger

A summary of the Delta Airlines route network in 2009 is shown in Table 5.43. Changes to the Delta Airlines route network following its merger with Northwest Airlines in 2009 are summarized in Tables 5.44, 5.45, 5.46, and 5.47.

Global statistics are used to quantify the Delta route network in 2009. These statistics include the total number of nodes in the network, the number of edges in the network, the average degree of nodes in the network, the network density, and the network clustering coefficient. These statistics are shown in Table 5.43.

Table 5.43. Global statistics of the Delta Airlines route network in 2009

Delta Network 2009 Global Statistics	
Nodes	153
Edges	1547
Average Degree	20.222
Density	0.133
Clustering Coefficient	0.480

From 1999 to 2009, the Delta route network properties shift significantly toward those of a hub-and-spoke network. The number of the airports in the Delta network increase to 153, but the number of flight routes decrease to 1547. As a result, the average degree drops to 20.222. The network density falls to 0.133, and the clustering coefficient drops to 0.48. The decreases in average degree, density, and clustering coefficient all indicate a shift toward a hub-and-spoke structure.

In the three years following Delta's merger with Northwest Airlines there are 45 airports added to the Delta route network that are not removed in subsequent years. A list of these airports can be found in Appendix I. The average ranking of these airports in each measure of centrality is shown in Table 5.44. For comparison, the average rankings for all U.S. airports not in the route network of Delta in 2009 in each measure of centrality are also shown.

Table 5.44. Average ranking of airports added to the Delta route network following the merger with Northwest Airlines and average ranking of all U.S. airports not in the Delta route network in 2009 by each measure of centrality

Average Centrality Ranking					
	$\bar{R}_C$	$\bar{R}_H$	$\bar{R}_B$	$\bar{R}_{PR}$	$\bar{R}_E$
Added to Delta Network 2010-2012	220.267	214.556	333.800	331.022	239.333
Not in Delta Network in 2009	693.765	694.038	682.455	679.877	694.233

In Table 5.44 the average ranking of the airports added to the Delta network are again better than the average of all airports which could be added in 2009. This again demonstrates that centrality can indicate whether an airport will be added to the Delta route network.

In 2009 there are 1091 active U.S. airports recorded that are not a part of the Delta route network. We rank these airports by their values of closeness, harmonic, betweenness, PageRank, and eigenvector centrality. We consider the 109 top ranked airports by each measure of centrality to be those identified as good candidates for addition to the Delta network. The full list of these airports can be found in Appendix I. These candidate airports for each measure of centrality are compared to the 45 ground truth airports that are actually added to the Delta network in the three years following the merger with Northwest. The alignment with ground truth for each measure of centrality is shown in Table 5.45.

In Table 5.45 there is variation among the centrality measures in alignment with ground truth airports. Thirty-five of the 45 airports added to the Delta network following the merger with Northwest Airlines are also among those identified as good candidate airports by harmonic centrality. Both closeness and eigenvector centralities also perform fairly well. Thirty-three of the 45 added airports are among the top potential airports as identified by closeness centrality, and 32 of the 45 are also identified by eigenvector centrality. There is a sharp drop in alignment for betweenness and PageRank centralities. Fifteen of the 45 added airports are among the top potential airports as identified by betweenness centrality, and 13 of the 45 added airports are also identified by PageRank centrality.

Although Delta Airlines' decisions regarding the addition of airports to its network are influenced by a variety of other factors, on average 56.9% of the airports selected for addition by Delta Airlines following the merger with Northwest Airlines are present within the candidate lists, which comprise only 10% of all possible airports. This alignment is the best of the three periods studied for Delta Airlines. Again, if betweenness centrality and PageRank centrality were not considered, the alignment would be even higher.

Following Delta Airlines' merger with Northwest Airlines there are five airports that are dropped from the Delta route network that are not added back in subsequent years. A complete list of these airports can be found in Appendix I. The average ranking of these airports in each measure of centrality is shown in Table 5.46. For comparison, the average rankings for all U.S. airports in the route network of Delta in 2009 in each measure of centrality are also shown.

In Table 5.46 the average rankings of the airports dropped from the network are significantly higher the average of the Delta network in 2009. This finding supports the usefulness of centrality in indicating airports to be removed from the Delta network.

In 2009 there are 153 active U.S. airports that are a part of the Delta route network. We rank these airports by their values of closeness, harmonic, betweenness, PageRank, and eigenvector centrality. We consider the 77 bottom ranked airports by each measure of centrality to be those identified as good candidates for removal from the Delta network. The full list of these candidate airports can be found in Appendix I. These candidate airports for each measure of centrality are compared to the five ground truth airports that are actually dropped from the Delta route network in the three years following the merger

with Northwest Airlines. The alignment with ground truth for each measure of centrality is shown in Table 5.47.

In Table 5.47 there is strong alignment between the top candidates for removal and the airports dropped following the Northwest Airlines merger. All five of the dropped airports are also among those identified as top candidates for removal by all five measures of centrality.

Although Delta Airlines' decisions regarding the removal of airports from its network are influenced by a variety of other factors, 100% of the airports selected for removal by Delta Airlines following the merger with Northwest Airlines are present within the candidate lists which comprise 50% of all possible airports. This is a strong indicator of the usefulness of this centrality based analysis in the selection of airports for removal from an airline network.

5.3.4 Delta Overview

Our method of centrality based identification of potential airports for additions to the Delta Airlines route network has the least alignment with ground truth. The average alignment of every measure of centrality for every Delta Airlines merger or acquisition is shown in Table 5.48.

As can be seen in Table 5.48, the average alignment between airports selected by our method and ground truth added airports for Delta Airlines is 35.07%. This is the least alignment for added airports of the three airlines that we study, (tables 5.16 and 5.32) slightly worse than the corresponding alignment for American. The average alignment with ground truth dropped airports for Delta Airlines is 93.33%, which is the highest of the three airlines studied.

The growth of the Delta Airlines route network from 1990 to 2017 is shown in Figures 5.11 – 5.15. Figure 5.11 shows an increasing trend in the number of airports within the Delta route network over the time period from 1990 to 2017. Similar to the American route network over the same period, the number of airports in the Delta network increases in sharp spikes, and for long periods shows relatively little change or slight decrease. The most significant spikes are within the time periods we study, following Delta's acquisitions of Comair and Atlantic Southeast and its merger with Northwest Airlines.

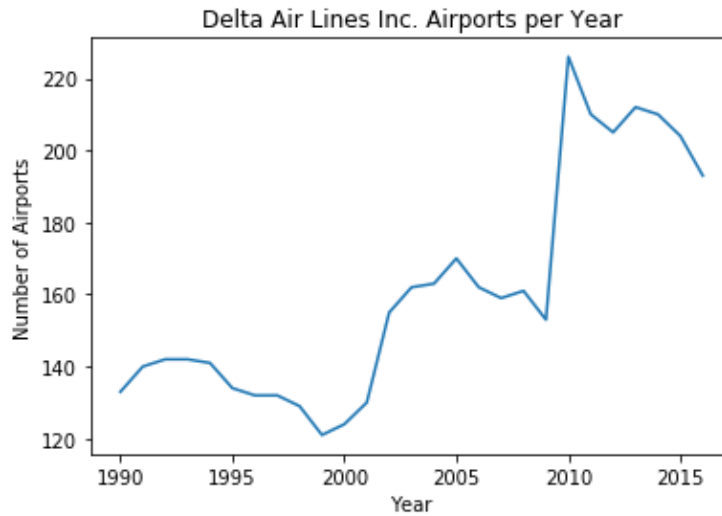


Figure 5.11. The number of airports within the Delta route network per year from 1990 to 2017

Figure 5.12 shows an overall trend of decrease in the average degree of the airports within the Delta network from 1990 to 2017. While the trend over the entire period is clearly negative, from year to year the average degree of airports in the Delta network sharply rise and fall. Again, the largest of these spikes follow Delta’s acquisitions and merger.

Figures 5.13, 5.14, and 5.15 show a geographical layout and the degree distribution of the Delta route network for 1991, 1999, and 2009 respectively. In Figures 5.13, 5.14, and 5.15, nodes are again colored from dark to light by degree from high to low, and edges are colored by the source node.

Figure 5.13 shows the Delta Airlines route network in 1991. It is the most expansive of the early networks of the three airlines we study. It also displays hub-and-spoke structure as the American network does. The four hub airports are clearly visible as the darkest nodes. The majority of the other nodes are lightly colored spoke airports. The degree distribution consists of a fairly even distribution of airports over wide range of degrees from 1 to approximately 70, similar to that of American Airlines in 1998. The most dense portions of this range fall between the degrees of 10 and 20 and the degrees of 41 and 45. Delta has four high degree hub airports. Hartsfield-Jackson Atlanta International Airport (ATL), with a degree over 120, is the largest hub. The next second largest is Dallas/Fort Worth International Airport (DFW), followed by Salt Lake City International Airport (SLC), and

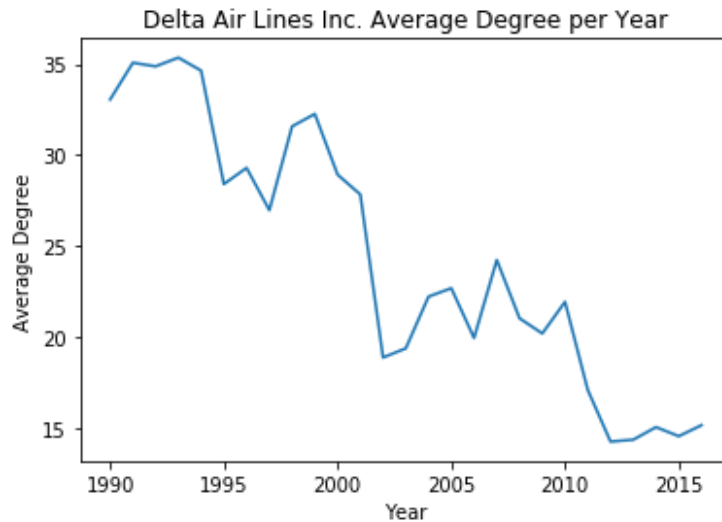


Figure 5.12. The average degree of all the airports within the Delta route network per year from 1990 to 2017

Cincinnati/Northern Kentucky International Airport (CVG).

Figure 5.14 shows the Delta Airlines route network in 1999. While a hub-and-spoke structure is still visible, the number of lightly colored nodes has clearly dropped from 1991. The number of airports in the Delta route network drops from 140 in 1991 to 121 in 1999, and the majority of the dropped airports have a low degree.

The degree distribution in 1999 remains similar to that of Delta's network in 1991, with airports fairly evenly spread over a wide range of degrees. In 1999 this range is from 1 to about 60. The number of airports with a degree less than 20 has declined since 1991, while the number of airports with a degree between 40 and 60 has increased. These changes indicate an increase in the point-to-point capacity of the Delta route network. Additionally, the degrees of all of the major Delta hubs drop. The only Delta hub with a degree over 100 in 1999 is ATL, while the others are clustered between 80 and 90.

This hub-and-spoke structure can also be seen in the geographical layout of the Delta network in 2009, shown in Figure 5.15. The number of lightly colored nodes has increased dramatically from 1999. Additionally, three of the darkest nodes in 1999, CVG, DFW, and SLC, have lightened considerably. This leaves ATL as the only true hub remaining in the network. The degree distribution of the Delta route network in 2009 shows significant

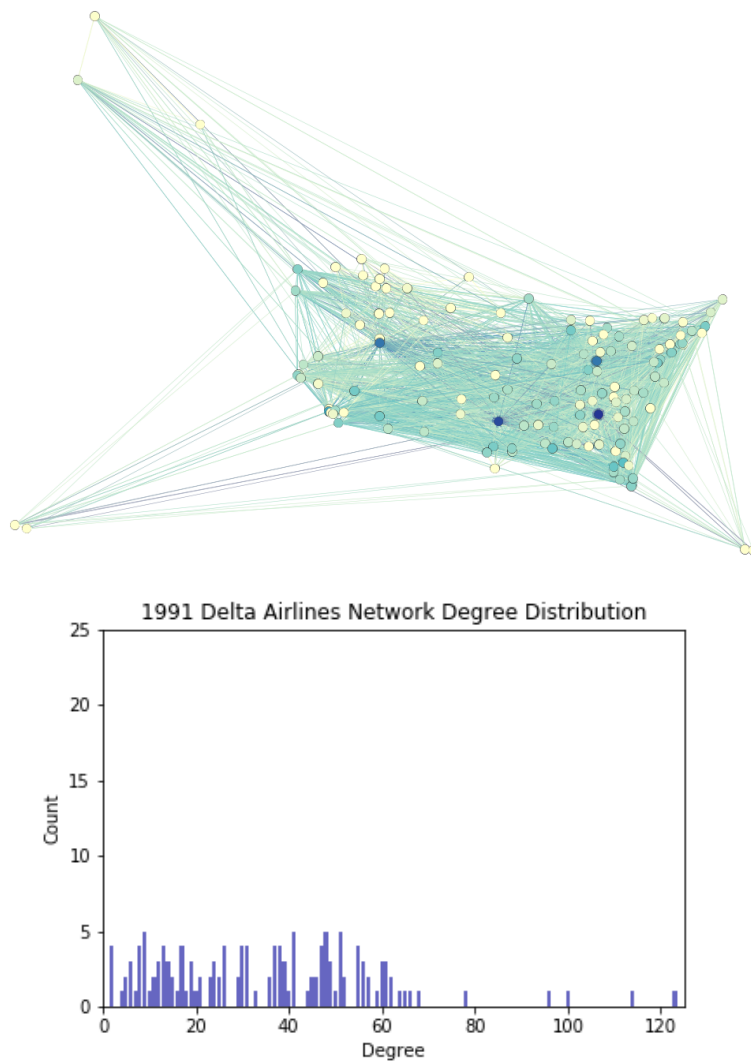


Figure 5.13. Delta route network and corresponding degree distribution in 1991

changes since 1999. There has been a large increase in the number of airports with a degree less than 10. Additionally, the degree of the three smaller hubs have dropped to around 60, and they are almost indistinguishable from the rest of the Delta network airports. However, ATL has increased in degree to almost 120. Similar to that of the American Airlines network in 2013, the Delta network degree distribution in 2009 shows a primarily hub-and-spoke network.

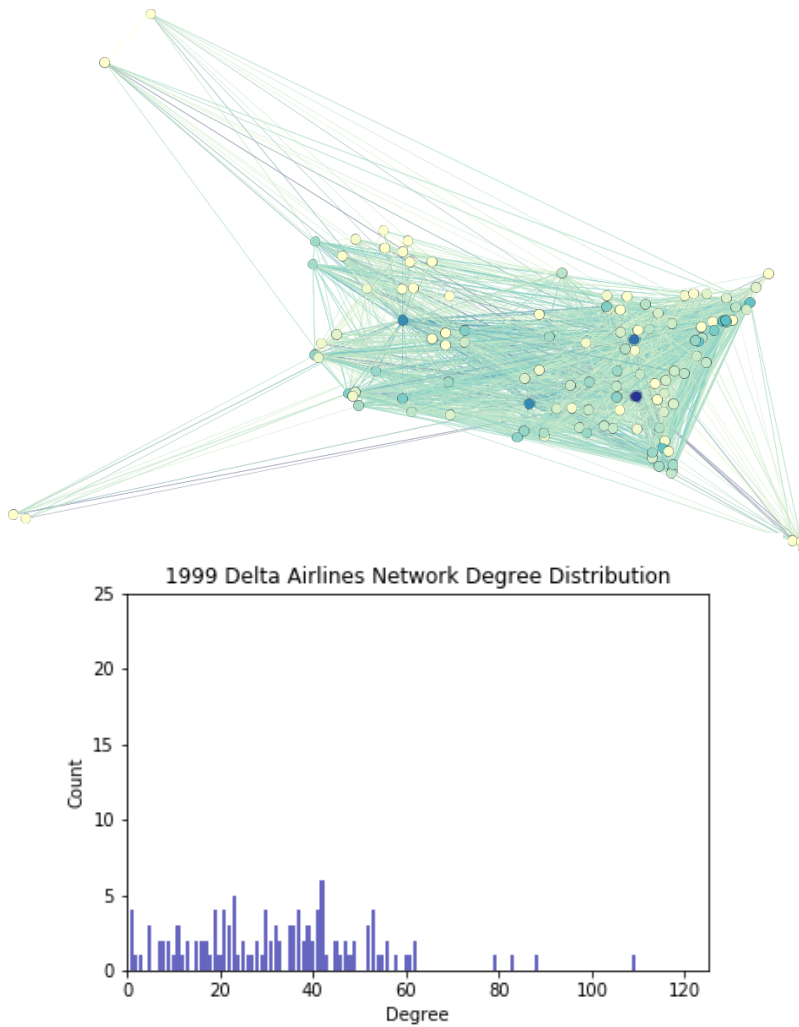


Figure 5.14. Delta route network and corresponding degree distribution in 1999

Table 5.45. The airports added to the Delta network following the Northwest Airlines merger that are among the top 10% of U.S. airports in 2009 in each measure of centrality

Alignment of Airports Added in 2010-2012				
C_i	H_i	B_i	PR_i	E_i
33 of 45	35 of 45	15 of 45	13 of 45	32 of 45
FAI	FAI	FAI	FAI	MHT
DSM	DSM	GUM	LBB	GRR
BIS	MHT	BIL	ICT	DSM
MHT	GRR	LBB	DSM	MYR
LGB	ICT	DSM	SCE	ICT
GRR	LGB	GRR	FRG	TOL
BIL	BIL	ICT	LAN	LGB
ICT	FSD	FNT	GRR	ISP
FSD	BIS	LGB	MYR	FSD
MOT	TOL	FRG	ADW	BIL
LBB	LBB	MYR	BIL	LBB
TOL	MYR	SCE	GUM	ROA
ISP	ISP	TOL	FNT	ILM
PSP	LAN	TVC		FNT
MYR	PSP	ROA		PSP
MSO	FAR			FAR
FAR	MOT			CRW
LAN	MSO			TVC
ADW	ROA			LAN
ROA	FNT			BIS
FNT	ADW			TRI
TVC	SCE			FAI
FRG	ILM			AVL
SCE	FRG			BMI
CRW	TVC			MSO
AVL	AVL			SCE
BMI	CRW			FAY
ILM	BMI			LSE
MHK	FAY			CMI
FAY	MHK			MOT
LSE	FOE			FRG
FOE	CMI			ACT
CMI	LSE			
	ACT			
	TRI			

Table 5.46. Average ranking of airports dropped from the Delta route network following the merger with Northwest Airlines and the average ranking of all U.S. airports within the Delta route network in 2009 by each measure of centrality

Average Centrality Ranking					
	$\bar{R}_C$	$\bar{R}_H$	$\bar{R}_B$	$\bar{R}_{PR}$	$\bar{R}_E$
Dropped from Delta Network 2010-2012	364.400	375.800	534.200	657.000	422.600
In Delta Network in 2009	114.327	112.386	194.980	213.359	110.993

Table 5.47. The airports dropped from the Delta network following the Northwest merger that are among the bottom 50% of U.S. airports in 2009 in each measure of centrality

Alignment of Airports Dropped in 2010-2012				
C_i	H_i	B_i	PR_i	E_i
5 of 5	5 of 5	5 of 5	5 of 5	5 of 5
UST	UST	UST	UST	UST
GUC	NZY	GUC	GUC	NZY
NZY	GUC	AMA	LWS	LWS
LWS	LWS	LWS	AMA	GUC
AMA	AMA	NZY	NZY	AMA

Table 5.48. The average alignment for Delta mergers and acquisitions between airports identified as good candidates for addition to or removal from an airline and ground truth

	Added Airports	Airports Dropped
Delta Average	35.07%	93.33%

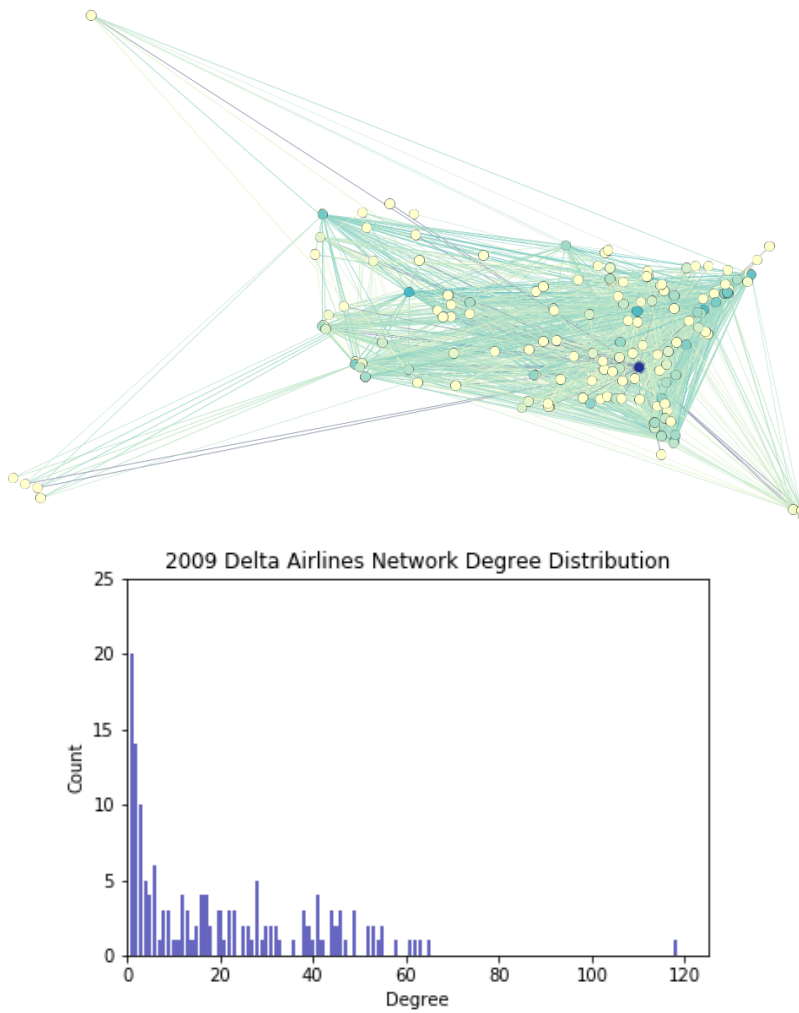


Figure 5.15. Delta route network and corresponding degree distribution in 2009

5.4 Overview

Across every acquisition or merger studied, there is higher alignment with ground truth for airports identified as good candidates for removal from a network than there is for airports identified as good candidates for addition to a network. The average alignments for airports added to and dropped from the airline networks of interest are shown in Table 5.49.

Table 5.49. The average alignment for each merger between airports identified as good candidates for addition to or removal from an airline and ground truth

Merger	Average percent alignment added (%)	Average percent alignment dropped (%)
AA-Reno	54.29	90.00
AA-TWA	13.55	91.43
AA-US Airways	45.00	88.42
Delta-PanAm	25.00	93.33
Delta-Comair&ASA	23.33	86.67
Delta-NW	56.89	100.00
SW-Morris	91.67	100.00
SW-ATA	47.78	92.22
SW-AirTran	60.00	83.64
Overall Average	46.39	91.75
Standard Deviation	22.31	5.22

From Table 5.49 it can be seen that the overall average alignment for added airports for each measure of centrality across every merger or acquisition studied is 46.39%, with a standard deviation of 22.31%. The overall average alignment for dropped airports is 91.75%, with a standard deviation of 5.22%. Our technique is much more successful at identifying airports that are good candidates for removal from an airline network than it is at identifying good candidates for addition.

There are differences in the alignment between the potential airports identified by each measure of centrality and ground truth. The average alignment of each measure of centrality for added and dropped airports for every merger studied is presented in Table 5.50.

Two tiers emerge from the five measures of centrality that we study. In the first tier is closeness, harmonic, and eigenvector centralities, each of which perform similarly and above the overall averages for both added and dropped airports. Betweenness and PageRank

Table 5.50. Average alignments of each measure of centrality for airports added to and dropped from the airline networks for every merger studied.

Centrality Type	Added average alignment (%)	Dropped average alignment (%)
Closeness	52.66	91.89
Harmonic	53.72	94.59
Betweenness	32.45	87.84
PageRank	28.19	82.43
Eigenvector	55.85	95.95
Overall Average	46.39	91.75
Standard Deviation	11.76	4.91

centralities form the second tier, each of which perform well below the overall averages for added and dropped airports. Eigenvector centrality stands out as the highest performing measure of centrality, followed by harmonic centrality, then closeness centrality. PageRank centrality shows the least alignment with ground truth of any measure, and betweenness centrality on average only performs slightly better than PageRank. The rankings of the average alignment of each measure of centrality is the same for added airports and for dropped airports.

Our methodology uses airport centralities within the U.S. flight route network to identify candidate airports with good potential for addition to or removal from an airline's route network. In order to test the validity of these candidate airports, we compare them with the ground truth: airports that actually have been chosen by successful airlines to be added to or dropped from their route networks. We find that the alignment of the identified candidate airports with ground truth varies between airlines and between the mergers and acquisitions studied. When considering airports to be added to an airline's network, we find that the candidate airports identified by our methodology align significantly better with the decisions made by Southwest Airlines than those of American Airlines and Delta Airlines. We also find that our methodology aligns better with the decisions of all three studied airlines on airports to be removed from their networks than with airports to be added. We then classify the structure and growth of the airlines studied, finding that Southwest Airlines develops primarily as a point-to-point network, while American Airlines and Delta Airlines develop primarily as hub-and-spoke networks. Our conclusions are presented in the following chapter.

CHAPTER 6:

Conclusion

Using different measures of centrality to rank airports, our method identifies potential airports for addition to or removal from an airline route network. We test the method on Southwest Airlines, American Airlines, and Delta Airlines for the years following each merger or acquisition in which these airlines were involved from 1990 to 2017. We take the airports that are historically chosen by these airlines to be added to or removed from their networks to be ground truth. In order to test the validity of the candidate airports identified in our methodology, we compare them with the ground truth airports for each merger or acquisition.

We define the alignment for each centrality type to be the extent to which the set of potential airports identified by that centrality overlaps with the set of ground truth airports. We then measure the alignment for each measure of centrality for every merger or acquisition studied. We find that alignment varies significantly between added and dropped airports, between types of centrality, and between airlines.

We find that the average rankings of airports chosen for addition to an airline network are significantly better than the average rankings of the corresponding set of possible airports. We also find that the average rankings of airports chosen for removal from an airline network are significantly worse than the average rankings of all airports the network. Both of these findings hold true for every merger and acquisition studied for each airline. This is an indicator that a correlation exists between airport centralities and these airlines' decisions regarding the suitability for both addition to and removal from their network.

6.1 Centralities

The types of centralities that we study are closeness centrality, harmonic centrality, betweenness centrality, PageRank centrality, and eigenvector centrality. When the alignments for each measure of centrality is averaged across every merger and acquisition, eigenvector centrality has the highest alignment, followed by harmonic centrality, then by closeness centrality, and by betweenness centrality. PageRank centrality has the least alignment.

The alignments of closeness centrality, harmonic centrality, and eigenvector centrality are all within 4% of one another for airports added the airline networks. The alignments of these centralities are within 5% of one another for dropped airports. The similarity in results between closeness centrality and harmonic centrality is somewhat expected, as harmonic centrality is an extension of closeness centrality and is designed to perform similarly. However, PageRank centrality is similarly an extension of eigenvector centrality, but the alignment of eigenvector centrality are more than two standard deviations better than the alignment of PageRank centrality, for both added and dropped airports.

We hypothesize that this disparity is due to the intended application of PageRank centrality. PageRank centrality was initially designed to rank web pages on the Google search engine based on votes that pages give to each-other. Closeness centrality, harmonic centrality, and eigenvector centrality are all generalized measures of centrality. Because the networks on which we calculate these centralities are simplified abstractions of the real-world flight route data, it stands to reason that a measure of centrality designed for a specific, real-world purpose might not perform as well as generalized measures.

6.2 Airline Structure

The airlines we study are American Airlines, Delta Airlines, and Southwest Airlines. All of these airlines also operate international flight routes during the time period studied, but we study only the domestic aspects of their route networks. In order to compare the performance of our method for each of these airlines, we average the alignments of each measure of centrality for every merger or acquisition, and average all of the resulting values. We determine that the potential airports identified for Southwest Airlines have by far the highest alignment with ground truth for added airports. The corresponding alignments for American Airlines and Delta Airlines are both significantly below that of Southwest Airlines, with American slightly outperforming Delta. The alignments for airports removed are all within a range of 4% of one another.

The alignments of our method are very similar for both American Airlines and Delta Airlines, but the alignment with Southwest Airlines differs significantly from both. Similarly, the structural evolution of the American Airlines route network and the Delta Airlines route network are highly similar to one another, but differ from that of Southwest Airlines. These

differences in structural evolution may reflect different priorities considered when selecting airports for addition to the network.

The first acquisitions for which American Airlines and Delta Airlines are studied, both display hub-and-spoke properties, in which there are a few high degree hubs with direct routes to many airports, and many small degree airports that are primarily connected through hubs and do not have direct routes to one another. This is most clearly seen in the earliest degree distribution and network map of both airlines, in which a few high degree airports are distinguishable, and the majority of airports fall into a range of lower degrees. For each subsequent merger or acquisition studied, the hub-and-spoke nature of both American Airlines and Delta Airlines seems to solidify. The hub airports become more distinct from the lower degree airports, and airports of the lowest degrees become the most common.

At the time of the first acquisition for which Southwest is studied, it is essentially a purely point-to-point network, in which almost every airport in the network has direct flight routes to almost every other network airport. This network structure is commonly utilized by low-cost carriers. The point-to-point nature of the network is best seen in the degree distribution and the network map, in which almost every airport within the network exist in a cluster within a range of 10 degrees from the maximum degree. Over the next two acquisitions, a large number of low degree airports are added to the Southwest network, as in the American and Delta networks. However, there are also a significant number higher degree airports added, which can be seen by growth of the high degree cluster in the Southwest network degree distribution and the increase in the number of darkly colored nodes in the network map. While the addition of very low degree airports is indicative of a shift towards a hub-and-spoke structure, the addition of higher degree airports indicates a continued focus on point-to-point structure. Over the time period studied, Southwest seems to strive to adopt some hub-and-spoke characteristics while maintaining the point-to-point core of its network.

All three airlines studied develop properties indicative of a hub-and-spoke network, while only Southwest also develops a point-to-point network structure. The significantly higher alignment of airports identified by the centralities with the airports added by Southwest Airlines indicates that our methodology identifies airports that are better suited for addition to a point-to-point network than to a hub-and-spoke network.

6.3 Added Versus Dropped Airports

The alignments between airports identified for addition to the airline networks and between airports identified for removal from the airline networks with their respective ground truths show significant differences. For every merger or acquisition studied, the alignments for removed airports are higher than for added airports. When every measure of centrality is averaged over every merger and acquisition studied, the average alignment for removed airports is 91.75%, and the average alignment for added airports is 46.39%. We believe the imbalance in alignment between added and dropped airports is due to two factors: a difference in the way potential airports are identified for addition and removal, and the difference in the nature of the centrality ranking for added and dropped airports.

In order to be considered for addition to an airline route network, an airport must not be a part of that network. Similarly, an airport considered for removal from an airline route network must belong to that network. However, the number of airports in even the largest single airline network is significantly smaller than the number of active airports in the United States. As a result, if our method identifies the top 10% of potential airports for both addition and removal, the number of identified airports for addition is significantly greater than the number of potential airports for removal. In order to generate a more balanced number of identified airports in both categories, the top 10% of potential airports are identified for addition to a network, and the top 50% of potential airports are identified for removal from a network. Because airports identified for removal from a network compose a greater percentage of the potential airports, it stands to reason that the alignment with airports actually removed is higher as well.

Additionally, because the sets of potential airports are different for added and removed airports, the centrality rankings of these sets have different meanings. Potential airports for addition to an airline network must not belong to that network. As a result, the centrality rankings of these airports give a somewhat abstract measure of their importance to that airline, as the centrality is calculated based on the networks of other airlines. However, the potential airports for removal from an airline network must belong to that network. Therefore, the centrality rankings of these airports give a more concrete measure of their importance to that airline, as their own network is taken into consideration in the ranking. The more concrete centrality ranking of the potential airports for removal from a network may contribute to the higher alignment of removed airports.

6.4 Overall Conclusion

There are a great deal of practical and economic factors that must be taken into consideration by an airline as it plans its flight route network. The purpose of this work is to determine whether the method of calculating centralities upon mathematical abstractions of existing flight route networks has value as a tool in this planning process. The value of this method is derived through the production of significantly smaller sets of airports with strong potential for addition or removal from an airline network from the entire set of possible airports. This could reduce the amount of work required to choose the best airports for addition or removal, or bring good potential airports to attention that otherwise might have been missed.

Based upon the high level of alignment of the airports identified for removal from the route networks of our studied airlines and those actually removed, the method certainly seems to have value as a tool for identifying good airports for removal from an airline network. Based upon the alignment of airports identified for addition to the Southwest Airlines network and those actually added, our method shows value in identifying airports for addition to a point-to-point route network.

6.5 Future Work

Our results show that making mathematical models of airline flight route networks and using these models to calculate the centralities of nodes within them could be useful in planning basic airline expansion, but additional information will improve them. There is a great deal of work that can be done to determine how best to utilize this technique.

Airports in the top 10% of the entire U.S. flight route network seem to make good candidates for addition to a point-to-point route network. However, our data set is made up of only one point-to-point airline network and two hub-and-spoke networks. In order to confirm that a point-to-point structure generally results in stronger alignments, the growth of more airlines need to be studied with this approach.

Although the intention of this work is to utilize simple models of flight route networks to identify airports for addition or removal, it is possible to make these models better reflect reality. The edges within a model network can be weighted to reflect the volume of traffic

along a flight route. The models we use have no edge weighting, showing only if an flight route exists between two airports in a given year. This represents a route flown once in a year as just as important as a route flown hundreds of times.

Additionally, in this work the unit of time for which network changes are evaluated is one year. For this reason, any network fluctuation that occurs over a shorter time span may not be captured. The U.S. Department of Transportation Bureau of Transportation Statistics produces data that reflects monthly changes [56]. Evaluating airline network evolution on a monthly basis may reveal more subtle patterns of growth. An Airline network modeled on a monthly basis will be different than the same network modeled on a yearly basis, and the correlation between these two approaches should be studied.

Based upon the differences between the alignments of the five measures of centrality used, we determine that PageRank centrality and betweenness centrality do not perform as well as closeness centrality, harmonic centrality, and eigenvector centrality. There are many other measures of centrality that can be tested in the same way, or created for this purpose.

When determining the number of potential airports to identify as candidates for addition or removal, in this work we prioritize consistency in the percentage of potential airports used. Increasing the percentage of potential airports used as candidates would likely increase the alignments measured. However, an approach that may more accurately reflect the effectiveness of centrality ranking might be to base the number of identified candidate airports on the number of airports actually added or dropped. If in the years following a merger, airline A adds x airports to its route network and drops y airports from it, then the top $3x$ possible airports for addition can be considered candidates for addition, and the top $3y$ potential airports for removal can be considered candidates for removal.

Finally, this work focused on windows of irregular growth throughout the period from 1990 to 2017. While much significant network growth was captured in this manner, there is notable growth that occurs outside windows. In order to study this growth, the method used in this work can be adapted to to study year-to-year or even month-to-month growth over shorter time periods.

APPENDIX A:

Southwest Airlines – Morris Air Acquisition

Table A1. Airports added to and dropped from the Southwest route network following the Morris acquisition in 1993.

All added	All dropped
PDX	DET
SEA	
SNA	
GEG	
SLC	
TUS	
BOI	
OMA	
FLL	
TPA	
MCO	
PVD	

Table A2. Airports added to the Southwest route network following the Morris acquisition and their ranking among all active U.S. airports in 1993 by each measure of centrality.

Added Airports	R_C	R_H	R_B	R_{PR}	R_E
MCO	26	29	37	78	13
SEA	9	11	4	5	14
TPA	52	43	60	67	22
PDX	17	23	10	15	25
SLC	18	24	17	39	30
FLL	57	60	59	38	36
SNA	80	80	90	90	41
TUS	50	61	96	111	57
OMA	40	40	67	33	58
PVD	54	54	76	64	71
GEG	39	50	18	10	79
BOI	61	72	30	57	90

Table A3. Top 10% of U.S. airports not in the Southwest network in 1993, as ranked by closeness, harmonic, betweenness, PageRank, and eigenvector centrality.

Top 10% potential (C_i)	Top 10% potential (H_i)	Top 10% potential (B_i)	Top 10% potential (PR_i)	Top 10% potential (E_i)
ORD	ORD	ORD	ORD	ORD
ATL	ATL	ANC	EKO	BOS
MSP	EWR	SEA	ANC	DEN
DEN	MSP	ATL	SEA	EWR
EWR	DEN	EKO	ATL	LGA
SEA	BOS	HNL	HNL	ATL
BOS	PHL	PDX	GEG	MCO
PHL	SEA	DEN	COU	SEA
LGA	LGA	BOS	DEN	DCA
MKE	CVG	MSP	JFK	MIA
PDX	PIT	EWR	PDX	PHL
SLC	MKE	SLC	MSP	MSP
CVG	PDX	GEG	GRR	TPA
MEM	SLC	PIT	DAY	PDX
IAD	MEM	GUM	MIA	JFK

Table A3. (continued)

MCO	IAD	JON	PIT	SLC
DCA	MCO	PHL	IAD	PIT
PIT	DCA	LGA	PHL	MKE
MIA	MIA	MIA	LAN	FLL
GEG	RDU	JFK	EWR	IAD
OMA	CLT	SPI	DSM	BDL
RDU	OMA	IAD	GUM	SNA
CLT	BDL	BOI	OMA	CVG
BDL	TPA	CLT	PSM	RDU
TUS	ORF	MKE	BOS	CLT
JFK	GEG	SJU	JON	PBI
TPA	DAY	DCA	FLL	MEM
ORF	PVD	MCO	SLC	BUF
PVD	BUF	LAN	MKE	TUS
COS	SYR	FAT	SPN	OMA
FLL	FLL	HIK	LGA	RSW
DAY	TUS	CVG	RIC	JAX
ANC	RIC	GRR	CVG	SJU
BOI	GSO	OGG	DCA	COS
BUF	JFK	MEM	COS	HNL
SYR	EKO	COU	CLT	ROC
DSM	ROC	ACV	RDU	SYR
RIC	COS	PIH	BDL	ORF
JAX	JAX	FLL	SBN	PVD
GSO	ALB	TPA	BOI	ALB
ROC	ANC	BDL	FAT	RIC
ALB	BOI	RDU	SGF	DAY
ICT	DSM	OMA	CID	ANC
EKO	ICT	RIC	HIK	GSO
PBI	RSW	DAY	PVD	SRQ
HNL	PBI	ADK	MSN	GRR
RSW	MSN	PVD	TPA	GEG
SNA	SNA	FAI	CMI	DSM
EUG	GRR	SYA	SPI	ICT
MSN	MDT	SYR	ORF	PWM
MDT	TYS	ALB	LNK	CHS
PWM	PWM	HPN	MEM	BOI

Table A4. Airports dropped from the Southwest route network following the Morris acquisition and their ranking among all active U.S. airports in 1993 by each measure of centrality.

Dropped Airports	R_C	R_H	R_B	R_{PR}	R_E
DET	173	167	259	272	129

Table A5. Bottom 50% of U.S. airports in the Southwest network in 1993, as ranked by closeness, harmonic, betweenness, PageRank, and eigenvector centrality.

Top 50% droppable (C_i)	Top 50% droppable (H_i)	Top 50% droppable (B_i)	Top 50 droppable (PR_i)	Top 50% droppable (E_i)
DET	DET	DET	DET	DET
DAL	DAL	DAL	DAL	DAL
LBB	LBB	MAF	MAF	MAF
MAF	MAF	LBB	AMA	LBB
HRL	HRL	HRL	LBB	HRL
AMA	AMA	AMA	HRL	AMA
CRP	BUR	CRP	CRP	CRP
BUR	CRP	BUR	ELP	BUR
ELP	ELP	ELP	BHM	BHM
RNO	RNO	BHM	RNO	SDF
LIT	LIT	LIT	LIT	LIT
HOU	HOU	HOU	SJC	ELP
BHM	BHM	OKC	AUS	TUL
OKC	OKC	AUS	BUR	OAK
ABQ	ABQ	TUL	OKC	MDW
TUL	MDW	OAK	OAK	HOU
AUS	OAK	RNO	SAN	RNO
BWI	TUL	ABQ	HOU	OKC
MDW	SJC	SAT	SAT	SMF
MSY	SMF	SDF	PHX	SJC

APPENDIX B:

Southwest Airlines – ATA Airlines Acquisition

Table B1. Airports added to and dropped from the Southwest route network following the ATA acquisition in 2008.

All added	All dropped
BOS	LBE
LGA	DRO
LAN	SBA
MLU	SGF
GRK	SMX
ACT	TRI
ECP	ICT
ILG	CVG
CMI	PAE
MSN	YKM
CLL	MSO
GSP	ROA
CHS	PIA
EWR	GNV
FAR	PUB
MGM	CHO
XNA	OGD
CAE	HNL

Table B2. Airports added to the Southwest route network as a result of the merger with ATA and their ranking among all active U.S. airports in 2008 by each measure of centrality.

Added Airports	R_C	R_H	R_B	R_{PR}	R_E
EWB	10	10	28	95	9
BOS	27	26	13	34	20
LGA	32	30	73	117	21
CHS	45	53	111	84	74
GSP	133	110	77	32	85
CAE	86	78	113	123	89
MSN	104	93	165	187	90
XNA	127	119	291	212	104
LAN	139	134	146	47	134
FAR	166	149	301	227	144
CLL	222	223	138	83	195
MGM	225	216	451	311	200
MLU	314	305	361	265	209
GRK	121	156	177	159	217
CMI	219	218	428	332	225
ACT	200	194	240	133	260
ILG	247	250	192	109	387
ECP	1116	1116	1116	1160	1204

Table B3. Top 10% of U.S. airports not in the Southwest network in 2008, as ranked by closeness, harmonic, betweenness, PageRank, and eigenvector centrality.

Top 10% potential (C_i)	Top 10% potential (H_i)	Top 10% potential (B_i)	Top 10% potential (PR_i)	Top 10% potential (E_i)
JGC	JGC	ANC	HPN	ORD
JXN	JXN	FAI	ANC	CLT
ANC	ANC	ORD	TEB	DFW
ORD	ORD	ADQ	FAI	BOS
DFW	DFW	BET	OXC	LGA
DCA	MIA	KTN	ADQ	DCA
MIA	BOS	BOS	MIA	JFK
BOS	DCA	HPN	JVL	MIA
LGA	LGA	AKN	YIP	RIC
ILN	CLT	DFW	RFD	GSO
JFK	JFK	JNU	ACK	ROC
BFI	ILN	TEB	NGU	ILN
CHS	CHS	JFK	RIC	SYR
RFD	IFP	HOM	AKN	ANC
CLT	FAI	MIA	MCG	CHS
FAI	RFD	OME	MMU	DAY
AZA	BFI	BFI	PSM	GRR
AFW	CAE	CLT	WFB	TYS
OGG	RIC	OTZ	DET	SJU
IFP	GRR	WFB	HOM	SAV
CAE	GSO	DLG	TOL	GSP
GRR	DAY	RFD	GSP	CAE
GRB	AZA	OXC	BOS	HSV
LGB	TYS	LKE	LKE	TOL
RIC	SYR	MCG	HTO	PWM
GSO	UTM	LRD	LRD	COS
RIV	HPN	FRD	CLT	MYR
DAY	GPT	SJU	ORD	HPN
SBN	COS	ANI	ACY	BTV
COS	GRB	MMU	LAN	SRQ
TOL	AFW	RIC	FOK	RFD
SYR	SBN	ILI	LSV	XNA
BIL	OGG	LGA	HIK	ACY
PSP	TOL	BIL	PTK	ABE

Table B3. (continued)

BZN	LGB	BRW	DUT	GPT
HPN	GSP	IFP	JFK	PNS
GPT	PNS	GSP	OME	MLI
UTM	ACY	DUT	INT	GRB
TYS	BIL	BGR	SFB	CAK
VCV	SHV	PTK	BED	FNT
SUU	ROC	VGT	BLV	ILM
BLI	YIP	NGU	DFW	OGG
PIE	XNA	STT	WRI	LGB
GRK	PIE	DCA	SJU	SBN
PNS	INT	HTO	JZT	IFP
AEX	TEB	GUM	ANI	UTM
XNA	HSV	YIP	SLN	CHA
BED	BED	GCN	SYR	BIL
GFK	LRD	SIG	CHS	PSP
HSV	PWM	ACY	NKT	FWA
GSP	SAV	GRR	FRG	VPS
YIP	BZN	ILN	GRR	MOB
SHV	MYR	ACK	ILI	LAN
ACY	SRQ	PGA	BTB	SHV
INT	LAN	SFB	FNT	CRW
LAN	PSP	FLG	IFP	PHF
ROC	SJU	SIT	POB	ATW
SAV	CAK	JVL	VGT	SWF
LCK	BTB	FNT	VBG	FAR
SRQ	SFB	TOL	JQF	STT
TEB	BGR	TYS	BET	BZN
BIS	RIV	CHS	GCN	PIE
GTF	GFK	SLN	TYS	JAC
CAK	RAP	CAE	TIK	RAP
LRD	ILM	SCC	BIL	MBS
SJU	FAR	MVW	BRW	DAB
JAC	AEX	GKN	SUU	KOA
RAP	ABE	CDB	HFD	BGR
DOV	JAC	OGG	ILG	TVC
FCA	VPS	BED	FWA	AVL
PWM	GRK	GFK	BFT	LFT
MYR	FNT	CLM	LGA	AFW
BGR	ENV	PSM	SCC	RST

Table B3. (continued)

BTV	LCK	WRG	LMT	AZO
ADQ	GTF	BLI	BTI	EVV
ENV	DLH	BDR	JNU	EYW
MKC	DAB	SUU	CAE	FAI
PSC	FWA	INT	TCL	DLH
DLH	BIS	NUW	ASE	BFI
KOA	SWF	LSV	VOK	BIS
FAR	VCV	SYR	BDR	CWA
SFB	SUU	MBS	MKC	MFR
VPS	FCA	BTV	SIT	EGE
ILM	FRG	FOK	HOP	AEX
HLN	NGU	DET	ACT	LIH
NGU	CHA	HIK	PHF	LRD
ABE	ADQ	SPN	KOZ	IDA
IDA	EVV	SVA	AZA	GTF
EVV	MOB	TIK	PIE	MFE
DAB	BLI	KOZ	NPT	FCA
FNT	MLI	LAN	BGR	MRY
FRG	CRW	NKT	GSO	BFL
FWA	MKC	NYL	SVA	BET
MFR	PSC	UTM	BFI	LCK
SWF	RST	FRG	GPT	MTJ
SSC	MFE	AZA	OUN	GFK
MOB	MBS	GTF	UTM	AGS
MFE	HLN	GPT	MLY	BED
MLI	CPR	TKJ	SUA	ERI
NIP	KOA	KEH	RBG	CPR
EGE	BET	COS	NJK	FAY
MHR	ACT	UNK	MXE	INT
MRY	ATW	EWN	MVY	MGM
EIL	IDA	HTS	GRK	ASE
CHA	PSM	BVU	BAD	SFB
CPR	DOV	JQF	DLG	BQN
CRW	JQF	GSO	WVL	RDM
RST	TVC	DAY	PNE	ENV

Table B4. Airports dropped from the Southwest route network following the ATA merger and their ranking among all active U.S. airports in 2008 by each measure of centrality.

Dropped Airports	R_C	R_H	R_B	R_{PR}	R_E
CVG	35	33	63	174	19
HNL	56	88	27	58	79
ICT	91	97	241	204	96
SGF	157	143	290	171	115
ROA	192	165	282	219	120
PIA	185	180	319	302	143
SBA	128	154	398	396	150
TRI	210	192	358	264	151
CHO	217	202	308	161	164
MSO	117	138	297	228	170
DRO	302	298	505	726	214
GNV	234	211	267	175	220
LBE	291	278	310	361	290
SMX	382	381	682	807	298
PUB	349	337	555	313	323
YKM	260	285	504	684	324
PAE	284	329	202	347	669
OGD	485	482	697	630	917

Table B5. Bottom 50% of U.S. airports in the Southwest network in 2008, as ranked by closeness, harmonic, betweenness, PageRank, and eigenvector centrality.

Top 50% droppable (C_i)	Top 50% droppable (H_i)	Top 50% droppable (B_i)	Top 50 droppable (PR_i)	Top 50% droppable (E_i)
ANB	RDG	RDG	RDG	OGD
RDG	ANB	ANB	SMX	PAE
OGD	OGD	OGD	ANB	ANB
BWG	BWG	BWG	DRO	BWG
SMX	LNS	LNS	BWG	RDG
LNS	SMX	SMX	LNS	LNS
PUB	PUB	SWO	YKM	SWO
DRO	PAE	PUB	OGD	YNG
LBE	DRO	DRO	SWO	YKM

Table B5. (continued)

PAE	YKM	YKM	ISP	PUB
YNG	LBE	HDN	CRP	SMX
YKM	YNG	CRP	HDN	COU
BMI	SWO	GJT	AMA	LBE
GNV	BMI	COU	SBA	MHK
COU	COU	CMI	COU	CMI
SCE	CLL	SCE	LBE	GNV
CLL	CMI	BMI	PAE	DRO
CMI	SCE	SBA	GJT	CLL
CHO	GNV	AMA	CMI	HDN
SWO	MHK	ISP	JAN	LNK
TRI	CHO	TRI	PUB	CRP
MHK	HDN	JAN	PIA	SCE
AVP	TRI	PIA	SCE	MSO
ROA	LNK	TLH	EUG	BMI
LNK	AVP	LNK	BMI	CHO
HDN	PIA	LBE	MHT	EUG
PIA	CRP	CHO	TRI	GJT
CRP	EUG	YNG	BUR	TRI
TLH	ROA	FAT	MDT	SBA
EUG	SBA	MSO	RSW	PIA
SGF	GJT	BTR	FAT	BTR
BTR	SGF	SGF	MSO	AMA
HRL	TLH	ROA	HOU	FAT
SBA	FAT	MDT	TLH	MAF
GJT	MSO	EUG	ROA	AVP
FAT	HRL	GNV	BTR	HRL
CID	AMA	CID	LNK	LBB
MSO	BTR	RSW	ORF	ROA
MDT	MAF	HRL	CID	ISP
AMA	LBB	HOU	ICT	SGF
LBB	CID	PBI	YNG	FSD
MSN	FSD	ICT	FSD	TLH
MAF	MDT	DSM	GEG	CID
FSD	ISP	JAX	HRL	LEX
LEX	ICT	PAE	PBI	JAN
ISP	MSN	AVP	TUS	ICT
ICT	JAN	MHT	JAX	MSN
MHT	BUR	BUF	MSN	MDT

Table B5. (continued)

JAN	BOI	SNA	LBB	BUR
BUR	HNL	DAL	MSY	BOI
BOI	LEX	BUR	SAN	DAL
LIT	MHT	FSD	GNV	GEG
RSW	RSW	MSN	CVG	HNL
DSM	LIT	RNO	DSM	LIT
TUS	TUS	SJC	SGF	DSM
HOU	HOU	LEX	LEX	HOU
ELP	PBI	MSY	BUF	PBI
SJC	SJC	TUL	SMF	ELP
ALB	ALB	MAF	CHO	TUS
BHM	ELP	LBB	RNO	TUL
ABQ	DAL	CLL	TUL	RNO
PBI	BHM	ORF	AUS	MHT
DAL	DSM	LIT	BDL	ALB
PVD	PVD	BOI	SJC	SNA
RNO	ABQ	MDW	OMA	ONT
SMF	BUF	TUS	MCO	MDW
BDL	SMF	PVD	SNA	BHM
BUF	RNO	RDU	DAL	RSW

APPENDIX C:

Southwest Airlines – AirTran Airlines Acquisition

Table C1. Airports added to and dropped from the Southwest route network following the AirTran acquisition in 2011.

All added	All dropped
ATL	ALO
DCA	GRI
CAK	LAR
DAY	DLH
SWO	TCL
FSD	LFT
ICT	LWS
CLT	CAE
FNT	CMI
PWM	IAH
ROC	ABE
SJU	
GRR	
PIB	
TLH	
PNS	
RIC	
MIA	
GTR	

Table C2. Airports added to the Southwest route network following the merger with AirTran and their ranking among all active U.S. airports in 2011 by each measure of centrality.

Added Airports	R_C	R_H	R_B	R_{PR}	R_E
ATL	8	7	9	10	5
CLT	64	49	37	27	11
DCA	50	45	65	58	18
MIA	22	23	33	9	44
GRR	91	87	113	183	58
RIC	85	74	128	85	59
ROC	100	102	209	218	69
DAY	93	91	125	215	75
SJU	92	101	59	296	86
ICT	90	86	290	241	89
PWM	161	142	178	222	90
FSD	117	107	291	276	99
CAK	130	127	143	99	112
PNS	164	152	461	487	113
FNT	222	215	115	118	133
TLH	197	173	354	269	143
GTR	406	358	419	396	277
PIB	450	377	318	188	340
SWO	294	307	558	459	562

Table C3. Top 10% of U.S. airports not in the Southwest network in 2011, as ranked by closeness, harmonic, betweenness, PageRank, and eigenvector centrality.

Top 10% potential (C_i)	Top 10% potential (H_i)	Top 10% potential (B_i)	Top 10% potential (PR_i)	Top 10% potential (E_i)
WA6	WA6	ANC	HPN	ORD
WA7	WA7	FAI	TEB	ATL
ANC	ORD	ORD	FAI	CLT
ORD	ANC	HPN	ANC	CVG
ATL	ATL	ATL	HTO	DFW
DFW	DFW	ADQ	ACK	DCA
MIA	MIA	BET	MIA	JFK
JFK	CVG	KTN	ATL	MIA
CVG	JFK	AKN	YIP	GRR
COS	DCA	DFW	ADQ	SYR
HNL	CLT	HOM	WFB	ROC
LGB	COS	JNU	AKN	DAY
RFD	FAI	WFB	MCG	GSO
BFI	IFP	TEB	JQF	HNL
DCA	RFD	OME	HOM	ANC
BIL	HNL	JFK	BVY	SJU
HSV	HPN	BFI	LRD	TYS
FAI	LGB	MIA	BFI	SAV
CLT	BFI	HNL	CLT	ICT
OGG	ICT	CLT	OXC	PWM
IFP	GRR	ACK	OME	HSV
VNY	BIL	DLG	VNY	MYR
ICT	DAY	MCG	JFK	COS
GRR	HSV	PGA	ACY	MLI
SJU	TYS	CVG	DXR	FSD
DAY	OGG	HTO	MVY	SBN
HPN	SJU	OTZ	GCN	OGG
ROC	ROC	SJU	PGA	HPN
TOL	TOL	YIP	LKE	BTB
ASE	ACY	LRD	FRG	TOL
TYS	LRD	DCA	ORD	BIL
TEB	FSD	ACY	DFW	ACY
PSP	TEB	LKE	GYY	CAK
BZN	SYR	ANI	PTK	PNS

Table C3. (continued)

BED	YIP	GCN	CFT	ILM
ACY	GSO	OGG	DCA	ROA
FSD	SAV	BLI	CT1	GPT
LRD	UTM	OXC	ZXU	ATW
RAP	BED	GUM	FOK	PSP
SYR	VNY	ILI	BRW	IFP
SAV	ASE	WRG	MUO	LGB
PIE	PSP	BIL	KTN	SGF
SBA	GPT	VNY	PYM	CRW
YIP	CAK	BRW	BET	KOA
GSO	BZN	BVY	JNU	RFD
CAK	PIE	JQF	VIS	BZN
FWA	RAP	IFP	BED	AVL
BFL	ROA	LEB	PUB	FWA
JAC	SFB	RFD	NC3	FNT
UTM	MYR	FRD	MMU	PIA
AZA	AZA	PWT	FYV	JAC
MTJ	SBA	PTK	RKD	SRQ
BGR	FWA	MVY	KEH	RAP
MKC	PWM	GSO	DOV	AFW
EGE	JAC	YAK	BHB	LIH
AFW	SBN	TYS	GSO	EVV
BLI	MLI	DXR	BDR	CHA
FRG	SGF	FRG	CAK	PHF
GTF	BGR	SCC	DRT	BMI
MLI	BFL	PSG	BKL	STT
GPT	SCE	DUT	ANI	BIS
ROA	ENV	ORH	FRY	TVC
MYR	AFW	GRR	TYS	BGR
FCA	PNS	CDB	SAD	SBA
SCE	ILM	FNT	EEN	RST
SGF	FRG	BED	HYA	SWF
SFB	MFE	TOL	SDM	SHV
SWF	EGE	GTF	SHD	AZO
SBN	SWF	UNK	NKX	MFE
MFR	ATW	DAY	FNT	BFI
MSO	GTF	GKN	OWD	LRD
MFE	BIS	MTN	LGU	UTM
PWM	PIA	HYA	BLD	VPS

Table C3. (continued)

LCK	MTJ	COS	IFP	BFL
ATW	PTK	SIT	PSM	CWA
PNS	LCK	STX	GFL	PSC
PSC	FCA	KEH	MBS	MTJ
ILM	MKC	PYM	STP	CHO
PTK	MSO	SPN	GTF	MFR
HOM	BET	CAK	ILI	LCK
BIS	PSC	PUB	SCF	SCE
KOA	MFR	EDF	PGV	AGS
ENV	SHV	PSM	COS	MRY
MRY	AVL	SHD	CKD	FAI
SUU	MRY	VIS	HVN	TRI
PIA	BLI	ZXU	APA	RDM
RDM	BTM	HII	ORH	EYW
RIV	ADS	BDR	TKE	GTF
PAE	ACK	EEN	LBF	ASE
PHF	CHA	LGU	LKP	BET
ADS	RDM	CFT	CVG	MSO
ACK	KOA	MZJ	MYR	PIE
AVL	PHF	WBQ	WSX	MBS
SHV	DAB	TKE	JAC	AZA
OTH	HOM	WST	MQY	DAB
CHA	SRQ	STS	PWA	EGE
LMT	ADW	MYR	PGC	MOT
FOE	STT	CXO	RFD	LSE
HLN	CPR	CLM	KEB	GFK
PUW	FOE	SFB	GUM	DRO
STT	CHO	GYG	SUA	AEX
ADW	JQF	CTI	TNC	FCA
IDA	OTH	SIG	SBA	SFB
CPR	ACV	ILM	STS	ELM
BTM	IDA	FOK	KOY	DOV
MVY	MVY	SOV	HLM	MOB
ACV	HLN	NYL	MI2	FAY
CHO	SUS	LGB	MZJ	BLI
SUS	GFK	ESD	AZA	YIP
SIT	LMT	PIA	DLG	OAJ
DAB	CRW	MRI	OTZ	CPR
KTN	AKN	PWM	UTM	IDA

Table C3. (continued)

RST	AGS	MFE	SBD	ITH
CLD	DRO	AVL	ILM	ENV
SRQ	EVV	RME	ADS	CSG
LIH	RST	N1C	AIK	MLB
SMX	MOT	MVW	GRR	EWN

Table C4. Airports dropped from the Southwest route network following the AirTran merger and their ranking among all active U.S. airports in 2011 by each measure of centrality.

Dropped Airports	R_C	R_H	R_B	R_{PR}	R_E
IAH	17	15	13	12	17
CAE	115	112	102	76	94
ABE	170	158	313	167	105
DLH	216	210	409	351	156
LFT	253	229	401	308	187
CMI	214	211	207	93	240
ALO	285	294	396	272	271
GRI	287	300	383	350	275
LWS	236	242	326	461	285
LAR	383	397	498	770	365
TCL	232	220	186	86	433

Table C5. Bottom 50% of U.S. airports in the Southwest network in 2011, as ranked by closeness, harmonic, betweenness, PageRank, and eigenvector centrality.

Top 50% droppable (C_i)	Top 50% droppable (H_i)	Top 50% droppable (B_i)	Top 50 droppable (PR_i)	Top 50% droppable (E_i)
LNS	LNS	LNS	LNS	ILG
RDG	RDG	MWA	RDG	RDG
MWA	MWA	MHK	LAR	MWA
PIB	LAR	ECP	MGM	LNS
LAR	PIB	HTS	MWA	TCL
ILG	ILG	LAR	ECP	YNG
MLU	GRI	AVP	MHK	LAR
HTS	ALO	COU	CRP	PIB
GRK	HTS	YNG	HTS	COU
GRI	MLU	AMA	LWS	LWS
ALO	GRK	CRP	HRL	GRI
COU	COU	ILG	EUG	ALO
LFT	MHK	MGM	AMA	MHK
ACT	LWS	DLH	AVP	ACT
MHK	ACT	LFT	GRB	CMI
CLL	LFT	GRB	YNG	GRK
LWS	MGM	ALO	DLH	MGM
YNG	YNG	RDG	GRI	HTS
TCL	TCL	GRI	MLU	CLL
MGM	CLL	CLL	RSW	HDN
DLH	CMI	MAF	XNA	MLU
CMI	DLH	ACT	JAX	LFT
AVP	HDN	XNA	GJT	BTR
TLH	AVP	TLH	LFT	CRP
HDN	TLH	MLU	JAN	EUG
LAN	LAN	JAN	ILG	DLH
BTR	BTR	EUG	COU	LNK
ABE	ABE	MHT	MAF	GJT
XNA	GJT	LWS	MHT	TLH
GJT	EUG	PIB	ALO	ECP
ECP	CRP	ABE	GEG	LAN
CID	ECP	CID	TLH	AVP
GRB	XNA	JAX	BOI	AMA
FAR	CID	BTR	TUS	FAR

Table C5. (continued)

EUG	GRB	FAT	CLL	FAT
CRP	FAR	LNK	ACT	MAF
CAE	FAT	RSW	SMF	ISP
FAT	LNK	HRL	CID	LBB
LNK	CAE	ISP	BTR	JAN
MAF	AMA	BOI	FAT	GRB
HRL	MAF	GJT	ISP	ABE
AMA	HRL	HDN	MSN	HRL
MSN	ISP	CMJ	BUF	XNA
LEX	JAN	GRK	ORF	LEX
MDT	MDT	LBB	RNO	CAE
JAN	MSN	LIT	SAN	CID
GSP	LBB	TCL	TUL	MDT
ISP	LEX	MSN	CHS	GEG
LBB	GSP	TUL	PIB	PBI
MHT	MHT	MDW	LNK	GSP
RNO	RSW	FAR	LBB	MSN
RIC	RNO	MDT	MDW	LIT
LIT	PBI	SNA	GRK	DAL
TUS	JAX	DAL	TPA	HOU
HOU	HOU	BUF	ABE	BOI
JAX	TUS	LAN	SEA	DSM
RSW	RIC	TUS	ABQ	TUS
ORF	ORF	BHM	HDN	MHT

APPENDIX D: American Airlines – Reno Air Acquisition

Table D1. All airports added to and dropped from the American route network following the Reno Air acquisition in 1998.

All Added	All Dropped
ANC	ISP
TYS	BFL
SHV	MAF
MTJ	GTF
XNA	
KOA	
MKE	

Table D2. All airports added to the American route network following the Reno Air merger and their ranking among all active U.S. airports in 1998 by each measure of centrality.

Added Airports	R_C	R_H	R_B	R_{PR}	R_E
MKE	37	34	57	86	42
ANC	50	66	7	38	72
TYS	91	88	133	134	89
SHV	115	114	123	113	107
KOA	149	153	122	329	147
MTJ	187	188	198	166	212
XNA	228	223	289	389	427

Table D3. Top 10% of U.S. airports not in the American network in 1998 , as ranked by closeness, harmonic, betweenness, PageRank, and eigenvector centrality.

Top 10% potential (C_i)	Top 10% potential (H_i)	Top 10% potential (B_i)	Top 10% potential (PR_i)	Top 10% potential (E_i)
MKE	MKE	FAI	FAI	MKE
ANC	GEG	ANC	NRR	GEG
GEG	ANC	EKO	EKO	ANC
BOI	EKO	GUM	YIP	BOI
EKO	GRR	YIP	HUS	GRR
GRR	MSN	BFI	TAL	MHT
MSN	BOI	NRR	GUM	MSN
PWM	PWM	OPF	BFI	JAN
JAN	JAN	BOI	FYU	CID
CRP	MHT	HUS	TOL	TYS
BIL	TYS	HSL	CMI	GSP
TYS	BIL	FYU	ATW	EKO
MHT	CRP	MKE	PTK	CHS
FSD	CID	LRD	ANC	SRQ
CID	ABE	TOL	MXF	MYR
SRQ	FSD	ATW	EAA	ABE
MBS	GSP	CMI	HSL	PWM
ABE	SRQ	PTK	CHP	PNS
BTR	MBS	TAL	OPF	SAV
GSP	PNS	EAA	VEE	MBS
GRB	BTR	HRL	UTO	SBN
BZN	GRB	SUS	GAL	FSD
BMI	YIP	NGU	ABE	SHV
PNS	CHS	SBD	BSM	CAE
FAI	MYR	SUU	VBG	BIL
BTV	BZN	CHP	BWG	LEX
MYR	CAE	WBQ	WBQ	GRB
YIP	LNK	GPT	IPL	MLI
CAE	FAI	GEG	ILN	BTR
MLU	BTV	PIE	TYR	BTV
SHV	SHV	UTO	CAK	AZO
SBN	SBN	VEE	FWA	CRP
FNT	FNT	RMP	MKE	LAN
CHS	BMI	FWA	SGF	SGF

Table D3. (continued)

LAN	SAV	ROA	GJT	CAK
LNK	LEX	CAK	GRR	LNK
LEX	LAN	SGF	GPT	BMI
RAP	AZO	MSN	PIE	FWA
SAV	HRL	LWS	RMP	EUG
AZO	MOB	PSC	GEG	FAI
DAB	RAP	ABE	BOI	ATW
MSO	MLU	JNU	GGG	MOB
FAR	FWA	GJT	JNU	FAR
LFT	FAR	KOA	MWO	FNT
HRL	LFT	SHV	CYS	LFT
SGF	SGF	GRR	SHV	ROA
DLH	DAB	CHS	MBS	DLH
EUG	DLH	SBN	COU	BZN
FWA	MSO	EVV	NIP	PIA
CAK	EUG	GRB	ROA	AVP
MOB	MLI	AZO	CLL	SBA

Table D4. All airports dropped from the American route network following the Reno Air merger and their ranking among all active U.S. airports in 1998 by each measure of centrality.

Dropped Airports	R_C	R_H	R_B	R_{PR}	R_E
MAF	107	107	66	32	93
ISP	180	182	281	345	159
GTF	118	133	140	247	163
BFL	209	216	287	349	211

Table D5. Bottom 50% of U.S. airports in the American network in 1998 , as ranked by closeness, harmonic, betweenness, PageRank, and eigenvector centrality.

Top 50% droppable (C_i)	Top 50% droppable (H_i)	Top 50% droppable (B_i)	Top 50 droppable (PR_i)	Top 50% droppable (E_i)
DRO	DRO	BFL	BFL	DRO
ABI	BFL	ISP	ISP	GUC
BFL	ABI	ABI	FAT	ABI
GUC	GUC	GUC	ABI	BFL
ISP	ISP	PSP	PSP	GTF
STX	STX	DRO	SWF	ISP
SWF	SWF	STX	STX	LGB
FAT	FAT	EGE	GUC	STX
JAC	JAC	DAL	EGE	HDN
LGB	LGB	FAT	DRO	JAC
OGG	OGG	RST	AMA	SWF
STT	STT	SWF	GTF	DAL
DAL	EGE	HSV	MFE	FAT
HSV	DAL	LBB	HSV	EGE
RST	GTF	JAC	OGG	RST
EGE	RST	MDT	BUR	STT
LBB	HDN	BUR	LBB	HSV
GTF	HSV	ALB	DAL	MFE
HDN	LBB	AMA	ONT	AMA
MAF	MAF	GTF	HPN	HPN
AMA	AMA	HPN	ALB	LBB
MDT	HPN	HDN	RNO	PSP
HPN	MDT	MFE	MDT	MAF
MFE	PSP	SYR	TUS	OGG
PSP	MFE	ROC	LIT	MDT
ICT	BUR	RIC	SNA	ICT
ALB	HNL	ORF	SMF	SYR
LIT	ICT	LIT	OAK	DSM
BUR	LIT	SMF	PBI	DAY
RIC	SJU	BUF	TUL	ALB
TUL	ALB	ONT	RSW	RIC
SJU	TUL	PVD	BHM	BUR
GSO	RIC	ICT	RIC	LIT
HNL	DSM	JAX	RST	ROC

Table D5. (continued)

DSM	RSW	BHM	PVD	ORF
SYR	GSO	PBI	JAC	GSO
BUF	RNO	OMA	ABQ	BHM
RSW	SYR	GSO	ICT	RSW
ROC	SNA	RNO	OMA	TUL
OAK	OAK	TUL	SYR	BUF
PVD	BUF	SNA	ORF	ELP
DAY	DAY	RDU	HNL	JAX
BHM	PVD	ABQ	JAX	HNL
SNA	ROC	COS	ROC	COS
PBI	PBI	HOU	MSY	HOU
JAX	COS	DAY	PHX	PBI
HOU	ABQ	MSY	BUF	OKC
COS	HOU	FLL	FLL	SDF
ABQ	TUS	OGG	SJC	PVD
ORF	BHM	CMH	GSO	SJU
OKC	JAX	BNA	DAY	OAK

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APPENDIX E:

American Airlines – TWA Airlines Acquisition

Table E1. All airports added to and dropped from the American route network following the TWA Airlines acquisition in 2001.

All Added	All Dropped
LIH	AMA
BMG	MDT
LWB	DRO
MHK	SUX
LAN	ACY
FOE	CAK
GNV	BIL
ACT	
SPS	
CLL	
BFI	
WRI	
EFD	
PIE	
BED	
CAE	
NKT	
AEX	
VOK	
GRK	
VCV	
TYS	
NTD	
SVN	
GPT	
BIF	
CRP	
RIV	
LBB	
TCM	
HOP	

Table E2. All airports added to the American route network following the TWA acquisition and their ranking among all active U.S. airports in 2001 by each measure of centrality.

Added Airports	R_C	R_H	R_B	R_{PR}	R_E
CAE	94	88	58	53	87
TYS	89	85	131	82	91
LBB	168	162	195	155	114
LAN	117	114	176	151	125
GPT	160	158	241	345	126
CRP	108	101	200	217	132
LIH	180	184	183	394	147
PIE	167	167	170	129	158
AEX	179	171	46	70	184
BFI	149	157	54	33	185
EFD	203	210	267	238	190
CLL	223	207	188	100	191
ACT	188	192	184	135	204
SPS	266	254	277	315	221
GNV	260	243	335	312	267
LWB	222	228	196	459	309
FOE	357	338	390	452	358
BED	345	339	391	466	362
MHK	335	332	384	366	382
BMG	478	478	486	524	407
BIF	371	366	414	472	418
SVN	484	484	491	403	453
NTD	251	271	51	21	497
WRI	488	487	34	25	498
HOP	494	493	499	172	509
RIV	500	501	255	104	517
VCV	387	383	253	160	520
NKT	407	393	426	514	528
GRK	406	396	429	515	529
TCM	567	567	567	585	591
VOK	576	576	576	593	599

Table E3. Top 10% of U.S. airports not in the American network in 2001, as ranked by closeness, harmonic, betweenness, PageRank, and eigenvector centrality.

Top 10% potential (C_i)	Top 10% potential (H_i)	Top 10% potential (B_i)	Top 10% potential (PR_i)	Top 10% potential (E_i)
GEG	YIP	FAI	FAI	MHT
GRR	GRR	YIP	YIP	BOI
YIP	GEG	EKO	GUM	GEG
MHT	MHT	SUU	EKO	GSP
BOI	EKO	BRW	FWA	GRR
FAI	BOI	WRI	SUU	PWM
CID	CAE	GSP	FFO	CAE
RFD	CID	AEX	NTD	JAN
EKO	FAI	GRR	LRD	ISP
CAE	RFD	GUM	WRI	RFD
ABE	PWM	PIZ	UAM	CHS
PNS	ABE	NTD	ROA	CID
PWM	GSP	HUS	BFI	MYR
CHS	CHS	BFI	PAM	SAV
FSD	PNS	CAE	PIZ	BTV
GSP	JAN	LNK	LSV	EKO
BTR	SAV	SCE	NZY	SRQ
FAR	FSD	AGS	LNK	RAP
JAN	MBS	ADW	SCC	PNS
BTV	BTR	LCH	GRR	BTR
MBS	BTV	EAA	AGS	ABE
SAV	ISP	FWA	ADW	MAF
ISP	FAR	ROA	CAE	FSD
GRB	GRB	LRD	SCE	SBN
LCK	LAN	SCC	GSP	GRB
RAP	LEX	LSV	AVL	EUG
LAN	LRD	OME	EAA	MLI
TOL	TOL	CID	FNT	LEX
LEX	LCK	MBS	LCH	MBS
LRD	RAP	LCK	BGR	LAN
MOB	SRQ	BGR	HIK	GPT
BZN	MYR	JAN	FSM	FWA
LNK	LNK	AVL	PAE	LFT
MSO	MOB	FNT	CWA	AZO

Table E3. (continued)

MYR	SBN	BOI	AEX	ATW
SRQ	BZN	ATW	JVL	LNK
SBN	MSO	MHR	FLO	TOL
FCA	ATW	CWA	AKP	FAR
DLH	FWA	FFO	LEX	BFM
ATW	LFT	NZY	WBQ	YIP
MLI	MLI	FSM	CSG	MLB
BIS	BIS	FLO	BTT	FAI
EUG	ROA	JVL	ATK	ROA
ROA	EUG	UAM	CLL	HRL
MLU	MAF	AKN	ADS	BMI
VPS	SGF	OTZ	RFD	MOB
FWA	DLH	GCK	RIV	PIA
LFT	FCA	IFP	LUF	SGF
BMI	GFK	MCG	HIF	LIH
GFK	MLU	LMA	NUQ	FNT
MAF	VPS	HTS	GEG	TVC
PIA	BRO	CDB	CID	BZN
SGF	BMI	MHM	PWM	DLH
BFI	TRI	HIK	GAL	DAB
BRO	PIA	PGV	MKG	VPS

Table E4. Airports dropped from the American route network following the TWA merger and their ranking among all active U.S. airports in 2001 by each measure of centrality.

Dropped Airports	R_C	R_H	R_B	R_{PR}	R_E
MDT	91	91	203	199	97
BIL	86	89	119	84	105
AMA	126	121	153	157	110
CAK	177	173	90	65	153
ACY	190	190	295	356	171
SUX	198	196	327	318	207
DRO	226	221	103	75	241

Table E5. Bottom 50% of U.S. airports in the American network in 2001 , as ranked by closeness, harmonic, betweenness, PageRank, and eigenvector centrality.

Top 50% droppable (C_i)	Top 50% droppable (H_i)	Top 50% droppable (B_i)	Top 50 droppable (PR_i)	Top 50% droppable (E_i)
ABI	DRO	SUX	GUC	DRO
DRO	ABI	GUC	STX	GUC
SUX	STX	STX	MTJ	ABI
STX	SUX	ACY	KOA	SUX
GUC	GUC	MTJ	STT	STX
ACY	ACY	EGE	ACY	MTJ
MTJ	MTJ	LGB	FAT	HDN
CAK	KOA	XNA	ABI	ACY
KOA	FAT	ABI	SUX	SWF
JAC	CAK	HDN	SWF	FAT
FAT	JAC	PSP	LGB	JAC
RST	RST	JAC	XNA	CAK
LBB	LBB	STT	PSP	RST
XNA	XNA	MDT	EGE	EGE
SWF	SWF	CRP	OGG	CRP
STT	STT	HSV	JAC	XNA
OGG	OGG	LBB	SNA	MFE
SHV	SHV	FAT	CRP	KOA
EGE	EGE	HPN	HSV	LGB

Table E5. (continued)

AMA	HDN	PBI	RST	LBB
LGB	AMA	SNA	HOU	STT
HDN	LGB	KOA	MDT	HSV
DAL	PSP	RSW	RSW	AMA
CRP	DAL	MSN	BUR	PSP
HPN	HSV	SMF	PBI	BIL
HSV	HPN	SWF	ALB	DAL
PSP	CRP	SYR	SHV	HPN
MDT	MDT	JAX	HPN	MDT
TYS	MFE	RIC	GSO	TYS
MFE	BIL	ALB	HDN	MSN
BIL	HNL	AMA	SJC	SHV
SJU	BUR	ICT	RIC	OGG
ICT	TYS	BUR	SYR	SYR
HNL	ICT	SHV	SAN	DAY
ALB	SJU	OMA	SMF	BUR
HOU	HOU	DSM	MSN	ORF
GSO	ALB	OAK	AMA	ALB
MSN	MSN	PVD	LBB	DSM
SYR	SYR	TYS	OAK	ROC
BUR	RSW	OGG	BHM	COS
PBI	PBI	ORF	JAX	ICT
ROC	LIT	BDL	BDL	TUL
RNO	TUS	MKE	OMA	HOU
DAY	RNO	MFE	MDW	RSW
TUS	SMF	DAY	MKE	ANC
SMF	ROC	LIT	DCA	BHM
LIT	GSO	BIL	AUS	RIC
RSW	SNA	RST	LGA	OKC
SNA	DAY	DCA	SFO	HNL
TUL	TUL	DRO	BOS	JAX
RIC	OKC	MDW	DSM	PBI
OKC	DSM	TUS	MCO	GSO
DSM	RIC	CAK	ICT	SJU
BHM	PVD	DAL	IAD	TUS
PVD	COS	TUL	PHL	BUF

APPENDIX F:

American Airlines – US Airways Merger

Table F1. All airports added to and dropped from the American route network following the US Airways acquisition in 2013.

All Added	All Dropped
CVG	SKF
TYS	ACT
GSP	BAD
LAF	TCL
ALB	MIB
ROC	TUP
MDT	LAW
AZO	CID
CHS	SFB
FWA	GPT
GEG	BGR
GSO	RST
ILM	GTF
LEX	YKM
MDW	OCF
PWM	BIL
EVV	NGU
LSE	BIF
SAV	BFM
SWF	
HPN	
AVL	
BZN	
CRP	
SGF	
DAB	
LAL	
CPS	

Table F2. All airports added to the American route network following the US Airways merger and their ranking among all active U.S. airports in 2013 by each measure of centrality.

Added Airports	R_C	R_H	R_B	R_{PR}	R_E
CVG	55	53	84	203	26
ALB	75	74	77	178	56
MDW	77	68	99	88	59
ROC	60	62	172	281	60
CHS	56	56	82	181	61
GSO	111	101	167	246	77
GEG	63	65	57	110	79
GSP	89	81	249	105	83
MDT	107	100	117	290	86
PWM	118	112	108	213	88
SAV	134	121	243	234	90
TYS	124	111	259	210	91
ILM	142	130	161	190	98
LEX	132	117	202	107	105
HPN	113	86	6	1	107
BZN	110	113	283	376	109
SGF	197	190	325	363	138
AVL	217	191	326	283	139
FWA	166	162	115	237	142
SWF	199	188	285	120	164
EVV	300	302	540	615	170
DAB	243	202	445	386	181
AZO	302	324	588	873	182
CRP	96	109	211	399	191
LSE	208	218	474	678	210
CPS	213	227	286	183	341
LAF	245	243	512	367	452
LAL	343	355	592	618	633

Table F3. Top 10% of U.S. airports not in the American network in 2013, as ranked by closeness, harmonic, betweenness, PageRank, and eigenvector centrality.

Top 10% potential (C_i)	Top 10% potential (H_i)	Top 10% potential (B_i)	Top 10% potential (PR_i)	Top 10% potential (E_i)
FTY	FTY	FAI	HPN	CVG
RNT	RNT	HPN	BUR	ALB
SPB	SPB	BUR	ACK	ROC
SSB	SSB	ADQ	FAI	MHT
BUR	BUR	BET	YIP	GSO
CVG	CVG	KTN	TEB	BUR
ROC	ROC	ACK	MVY	GSP
SRQ	ALB	JNU	WFB	MDT
LGB	FAI	WFB	LKE	MYR
YIP	GSP	FRD	LRD	PWM
ALB	YIP	HOM	ADQ	SAV
LRD	SRQ	TEB	BFI	TYS
FAI	HPN	LKE	OME	BTM
GSP	IFP	OME	PTK	ILM
BFI	MHT	AKN	MCG	FSD
MHT	LRD	PGA	ANI	IFP
IFP	LGB	BFI	BED	JAN
ISP	MDT	MCG	HOM	HPN
RME	GSO	OTZ	BMI	ACY
MDT	ISP	DLG	TKJ	BZN
BZN	BFI	YIP	ILI	GRB
GSO	JAN	MVY	OXR	SBN
JAN	TYS	LRD	OXC	ISP
HPN	PWM	ANI	GYG	LGB
FSD	BZN	SIT	JQF	PNS
PWM	FSD	GCN	VNY	ROA
EYW	SAV	VQS	LMT	ABE
WRI	SBN	ILI	FOK	FAR
TYS	TEB	BED	TOL	SRQ
BIS	EYW	TKJ	FRG	HRL
OSC	AZA	ALB	LSV	EYW
SBA	UTM	IFP	EDE	FNT
SBN	BED	FRG	BET	CRW
BED	ILM	LSV	YNG	CHA

Table F3. (continued)

ABE	RME	MRI	LGB	UTM
ILN	ACY	PTK	OTZ	SGF
SAV	HRL	CVG	ITH	AVL
TEB	ECP	GUM	HYA	RAP
AZA	PNS	BRW	PGA	AVP
ECP	MYR	LGB	UKI	FWA
HRL	SBA	OXC	EEN	TLH
ILM	FNT	TTN	IFP	GJT
PNS	ABE	PSG	EDF	LAN
BQN	ENV	BLD	BLD	ECP
FNT	TOL	GKN	BVY	ATW
EUG	LAN	PIE	CCR	BMI
UTM	BTV	WRG	CGF	AFW
MKC	BIS	ILG	RME	AZA
LAN	WRI	PWM	AKN	EUG
GRB	OSC	TOL	NKX	BIS
BTV	EUG	ITH	APF	TVC
ENV	AFW	FWA	LAN	FAI
ACY	PIE	ESD	ADW	MOT
MYR	TLH	MDT	SMO	FAY
MSO	ACK	HYA	PLN	LRD
FCA	SCE	BMI	DLG	SBA
AFW	FWA	SBA	OWD	CHO
FWA	BET	BTV	TCT	PSC
TOL	PTK	NKX	ILG	LNK
TLH	BQN	CDB	AEX	AGS
PTK	FAR	YNG	RIV	ITO
SCE	GRB	BLI	GSP	BLI
PSC	ILN	PAE	ADS	EVV
FAR	MKC	BVU	JNU	DLH
KTN	JQF	SMO	MQY	MFR
BMI	LNK	LMT	MBS	PHF
LNK	GFK	EYW	GRI	VPS
FRG	MSO	UKI	UTO	MSO
LWS	MVY	MBS	NPT	DRO
GFK	BMI	BVY	BFF	SCE
PIE	ROA	GAI	GAI	AEX
ADQ	PHF	SPN	MRY	TOL
GUM	FRG	OWD	MKC	DAB

Table F3. (continued)

JQF	FCA	EEN	GCN	AZO
PHF	ADQ	ADW	OTH	ACK
HLN	LCK	OXR	VIS	LCK
LCK	PSC	EDE	HKS	CWA
MVY	SGF	ASE	RDV	GFK
ACK	AVL	OPF	ROW	BFI
PAE	AKN	OTH	RDD	BET
ILG	KTN	CON	FCA	MOB
GJT	BRO	LAN	BFL	RDM
SGF	LWS	SCC	JZT	PIE
ROA	AVP	JQF	ASE	FCA
BRO	AEX	ACY	FYU	BFL
AKN	ILG	AZA	PNE	OAJ
ASE	GJT	ILM	SCC	TTN
MFR	DAB	LEB	MFI	MRY
AEX	PSM	FYU	SQV	ELM
BLI	CMI	VNY	PIE	ASE
CMI	TTN	GSO	CON	IDA
JNU	PVU	UNK	FXE	LFT
TTN	CHA	TYE	AZA	YIP
SUS	CRW	ROC	SBA	TRI
PVU	FAY	BID	GON	BQN
CPS	JNU	GYG	OPF	ITH
CDV	HLN	FOK	KEH	MBS
VNY	GUM	KTB	UNK	EWN
TVC	AGS	DRT	ENV	ENV
AVL	TRI	LBE	FRY	PBG
ATW	ASE	FLG	RKD	HLN
CRW	DOV	IRC	SC5	ERI
PSM	VNY	AFW	ROA	SAF
AVP	OME	PDT	ALB	MLU
DOV	ADS	AEX	BRW	BRO
CHA	CHO	CDC	CPS	OME
TRI	BFL	UTO	EUG	CPR
YAK	MFR	EDF	LUK	JNU
MHR	TVC	PSM	ACY	CSG

Table F4. Airports dropped from the American route network following the US Airways merger and their ranking among all active U.S. airports in 2013 by each measure of centrality.

Dropped Airports	R_C	R_H	R_B	R_{PR}	R_E
CID	138	133	307	295	92
BIL	114	116	42	241	96
GPT	117	114	135	196	119
BGR	147	140	205	180	135
GTF	179	195	268	507	166
RST	232	244	581	715	185
SFB	144	119	129	165	186
ACT	257	250	408	306	335
BFM	311	313	464	527	342
YKM	419	472	381	320	343
TUP	559	475	400	357	379
LAW	458	476	504	567	427
TCL	270	254	178	67	482
NGU	339	359	434	333	582
OCF	608	576	733	536	621
BIF	344	370	516	644	737
SKF	698	694	813	998	971
BAD	1	1	233	5	1086
MIB	2	2	638	6	1103

Table F5. Bottom 50% of U.S. airports in the American network in 2013, as ranked by closeness, harmonic, betweenness, PageRank, and eigenvector centrality.

Top 50% droppable (C_i)	Top 50% droppable (H_i)	Top 50% droppable (B_i)	Top 50% droppable (PR_i)	Top 50% droppable (E_i)
SKF	SKF	SKF	NTD	MIB
NTD	NTD	NTD	SKF	BAD
OCF	OCF	OCF	GGG	SKF
TUP	GGG	GGG	EFD	BIF
GGG	STX	SPS	GUC	NTD
STX	LAW	SWO	STX	FYV
LAW	TUP	EFD	SPS	OCF

Table F5. (continued)

YKM	YKM	GUC	SWO	EFD
SPS	SPS	MTJ	MTJ	SWO
SWO	BIF	MIB	RST	NGU
FYV	SWO	ABI	LIH	TCL
BIF	FYV	RST	LSE	LAW
NGU	NGU	BIF	BIF	GGG
LWB	LWB	MGM	EGE	TUP
BFM	BFM	JAC	STT	SPS
GNV	EFD	LAW	ABI	FOE
ABI	ABI	LIH	LAW	YKM
GUC	GUC	LSE	OCF	BFM
TCL	GNV	BFM	JAC	ACT
MGM	MGM	FOE	BFM	LWB
ACT	FOE	NGU	KOA	ABI
COU	TCL	HDN	GTF	PUB
EFD	ACT	PUB	HDN	STX
FOE	RST	ACT	PUB	MHK
GRK	GRK	TUP	MGM	GUC
RST	COU	YKM	FOE	COU
LSE	LSE	XNA	PIA	GRK
MHK	MHK	STX	CRP	MGM
SWF	MTJ	EGE	PSP	LSE
MTJ	GTF	LWB	TUP	HDN
PIA	PIA	GNV	MAF	GNV
BTR	SWF	FAT	NGU	EGE
GTF	EGE	GRK	YKM	CRP
MLI	BTR	BTR	XNA	SFB
EGE	LIH	CID	FYV	RST
SHV	MLI	PSP	ACT	MTJ
STT	HDN	SYR	LWB	BTR
MFE	PUB	STT	CID	GTF
CAE	SHV	LIT	RSW	SWF
BGR	STT	MFE	PBI	MFE
LIH	MFE	CAK	SJU	SHV
SFB	BGR	KOA	OGG	STT
HDN	XNA	SWF	LIT	BGR
XNA	FAT	MSN	SYR	RFD
CID	JAC	COS	MFE	FAT
SYR	CAE	AMA	GNV	LIH

Table F5. (continued)

LEX	CID	BOI	AMA	MAF
PUB	KOA	GTF	ICT	JAC
FAT	PSP	PBI	PVD	PIA
JAC	SYR	MHK	RNO	AMA
MSN	SFB	RSW	BIL	GPT
GPT	LEX	OKC	MLI	PSP
PSP	BIL	HOU	JAX	LBB
BIL	MSN	BAD	MSN	KOA
MAF	GPT	FYV	BDL	MLI
LBB	MAF	CRP	BTR	LEX
CAK	CRP	BGR	LBB	XNA
KOA	AMA	LEX	ORF	CAK
AMA	LBB	PIA	CAK	HSV
DAY	OGG	TUS	PDX	OGG
TUS	CAK	MLI	CAE	BIL
RNO	HSV	MAF	GPT	COS
HOU	RNO	TCL	BOI	CAE
CRP	DAY	SHV	FAT	CID
ORF	TUS	JAX	HOU	ICT
TUL	COS	BDL	TUS	DAY
RIC	HNL	CAE	ABQ	TUS
ELP	TUL	DSM	CHS	MSN
JAX	RFD	ICT	BGR	LIT
LIT	HOU	DAY	MHK	GEG
HSV	ORF	COU	MSY	SJU
BHM	LIT	LBB	OKC	ELP

APPENDIX G:

Delta Airlines – Pan American Airlines Acquisition

Table G1. Airports added to and dropped from the Delta route network following the PanAm Airways acquisition in 1991.

All Added	All Dropped
SBN	AMA
STX	BIS
AVP	BUR
EGE	LGB
	ILM
	OGD

Table G2. Airports added to the Delta route network following the PanAm acquisition and their ranking among all active U.S. airports in 1991 by each measure of centrality.

Added Airports	R_C	R_H	R_B	R_{PR}	R_E
SBN	169	168	156	63	134
AVP	155	151	199	259	154
STX	173	177	237	326	163
EGE	186	196	278	347	201

Table G3. Top 10% of U.S. airports not in the Delta network in 1991, as ranked by closeness, harmonic, betweenness, PageRank, and eigenvector centrality.

Top 10% potential (C_i)	Top 10% potential (H_i)	Top 10% potential (B_i)	Top 10% potential (PR_i)	Top 10% potential (E_i)
DSM	DSM	EKO	EKO	MDW
MSN	MDW	BET	BET	DSM
MDW	MSN	GUM	KWK	MAF
CID	EKO	WRI	KKH	HRL
BTV	BTV	SPI	WRI	DAL
ISP	ISP	KWT	KWT	ISP
EUG	CID	DSM	TLT	MSN
LNK	LNK	KKH	AKI	DET
MHT	EUG	NKT	KWN	BTV
EKO	MHT	OSH	DSM	CID
HRL	HRL	SYA	KKI	EUG
CAK	MAF	LFT	MCG	MHT
SBA	CAK	EFD	EEK	SBA
MAF	SBA	ADW	WTL	MLI
GJT	MBS	TIK	SYA	CAK
MLI	MLI	LSF	PKA	HPN
BFI	HPN	KWN	OSH	AZO
MFE	MFE	MDW	NKT	MYR
BFL	GJT	GRB	WNA	LNK
FAR	AZO	SPN	KPN	LAN
HPN	GRB	MSN	FOE	SBN
MBS	FAR	BMI	BMI	ROA
SGF	LAN	PIA	SBN	RST
GRB	FAY	CID	PSM	MBS
MFR	SGF	SGF	KMC	FAY
PUB	BFL	EUG	HCR	FAR
PIA	ROA	SBA	AZO	BLI
AZO	CRW	ISP	RFD	MFE
SUX	MYR	LNK	GRB	CRW
MYR	SUX	FOE	ADK	MRY
FAY	PIA	CAK	BQN	EVV
CRW	DAL	BFL	COU	SUX
GFK	MFR	GJT	MSN	AVP
MOT	AVP	RFD	TCM	GJT

Table G3. (continued)

LSE	RST	MAF	AKN	BFL
KOA	MOT	CWA	SGF	GRB
AVP	PUB	BQN	SBA	MFR

Table G4. Airports dropped from the Delta route network following the PanAm acquisition and their ranking among all active U.S. airports in 1991 by each measure of centrality.

Dropped Airports	R_C	R_H	R_B	R_{PR}	R_E
BUR	85	84	97	140	71
AMA	108	110	116	162	89
LGB	82	93	61	171	93
ILM	139	136	189	255	152
BIS	127	135	186	154	156
OGD	300	301	326	387	388

Table G5. Bottom 50% of U.S. airports in the Delta network in 1991, as ranked by closeness, harmonic, betweenness, PageRank, and eigenvector centrality.

Top 50% droppable (C_i)	Top 50% droppable (H_i)	Top 50% droppable (B_i)	Top 50 droppable (PR_i)	Top 50% droppable (E_i)
OGD	OGD	OGD	OGD	OGD
PFN	PFN	GUC	GUC	TWF
TWF	TWF	PFN	PFN	CSG
CPR	GUC	CPR	CPR	GUC
GUC	JNU	JAC	JAC	CPR
JNU	CPR	STT	STT	PFN
CSG	CSG	CSG	MLU	HLN
GNV	IDA	MLU	CSG	JNU
MLU	MLU	TWF	ILM	GNV
IDA	GNV	MLB	BZN	MLU
AGS	PSC	HLN	MGM	MGM
PSC	STT	BTM	AGS	IDA
CHA	MGM	ILM	TWF	BTM
TRI	JAC	AGS	MLB	PSC
JAC	AGS	BIS	HSV	FCA
STT	FCA	GNV	CRP	AGS
TOL	BTM	HSV	BTR	CHA
MGM	OGG	MGM	AVL	TRI
AVL	TRI	SWF	IDA	BIS
FWA	FAI	PWM	CHA	JAC
TLH	TOL	TOL	BTM	ILM
FCA	CHA	FCA	TOL	TOL
BTM	HLN	BZN	PWM	GTF
HLN	TLH	FWA	HLN	STT
OGG	FWA	AVL	GNV	TLH
LEX	AVL	IDA	TRI	AVL
MLB	ILM	CHA	JAN	RAP
ILM	BIS	TRI	OGG	MSO
DAB	LEX	JAN	FWA	BZN
FAI	MLB	SAV	SWF	FWA
JAN	BZN	SRQ	SAV	FAI
BZN	BGR	TLH	MOB	SHV
BIS	GTF	GTF	FCA	MLB
GTF	DAB	CAE	PBI	SWF

Table G5. (continued)

PNS	MSO	CRP	LGB	LEX
BGR	JAN	LEX	GTF	BGR
BTR	SJU	ALB	LEX	BIL
SWF	HSV	BTR	GSP	DAB
LBB	RAP	MSO	MSO	FSD
MSO	LBB	LBB	AMA	ABE
HSV	PNS	CHS	SRQ	PNS
SJU	AMA	RSW	LBB	MDT
RAP	SWF	GRR	BIS	OGG
AMA	SHV	JNU	PNS	MOB
SHV	BTR	RAP	RSW	JAN
FSD	BIL	MOB	PSP	HSV
BIL	FSD	PNS	TLH	FAT
MOB	FAT	FSD	RAP	BOI
FAT	HNL	PBI	FAI	BTR
ABE	MOB	GSP	CHS	TYS
PWM	ABE	ROC	BHM	GSP
SAV	LGB	PVD	PSC	LGB
BOI	BOI	AMA	SHV	SAV
MDT	PWM	SHV	BUR	PSP
CHS	SAV	PSC	CAE	CAE
GSP	GSP	TYS	MDT	AMA
SRQ	SRQ	BIL	ALB	PWM
BUR	MDT	ICT	JNU	CHS
TYS	CHS	BUF	ROC	GEG
LGB	BUR	COS	PVD	LBB
CAE	CRP	ELP	HOU	ANC
PVD	TYS	MDT	BIL	CRP
SNA	PSP	BUR	TYS	RIC
HNL	SNA	JAX	SJU	ALB
RSW	CAE	BHM	ICT	GRR
ELP	RSW	HOU	JAX	SJU
ALB	PVD	GSO	GRR	GSO
RNO	ELP	RIC	FSD	ICT
JAX	ICT	RNO	ELP	COS
GRR	ALB	PSP	RNO	PVD

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APPENDIX H:

Delta Airlines – Comair and ASA Airlines Acquisitions

Table H1. Airports added to and dropped from the Delta route network following the Comair and Atlantic Southeast Airlines acquisitions in 1999.

All Added	All Dropped
MHT	RNO
GNV	STX
LBB	GUC
VPS	
CAK	
GTR	
CSG	
TRI	
XNA	
ROA	
SBN	
GRR	
MSN	
EFD	
EUG	
BED	
TCL	
PGV	
CHO	
JAC	
PSP	
CMI	
PIH	
FAT	

Table H2. Airports added to the Delta route network following the Comair and Atlantic Southeast acquisitions and their ranking among all active U.S. airports in 1999 by each measure of centrality.

Added Airports	R_C	R_H	R_B	R_{PR}	R_E
MHT	90	90	189	195	71
GRR	75	73	75	39	80
MSN	83	84	128	134	85
PSP	99	102	183	282	101
LBB	153	144	179	287	103
SBN	128	121	135	188	110
EUG	129	134	221	310	131
CAK	146	142	122	172	133
FAT	143	153	203	319	137
ROA	178	165	166	163	142
XNA	192	187	204	262	144
VPS	148	151	223	329	147
TRI	184	183	241	227	163
JAC	162	166	239	228	166
CMI	199	199	175	225	193
GTR	217	209	267	346	196
CSG	248	243	305	169	230
GNV	291	270	320	305	246
EFD	207	213	298	142	269
PIH	368	369	392	332	335
PGV	342	333	365	355	385
BED	435	435	435	468	470
CHO	446	446	446	476	478
TCL	518	518	518	544	545

Table H3. Top 10% of U.S. airports not in the Delta network in 1999, as ranked by closeness, harmonic, betweenness, PageRank, and eigenvector centrality.

Top 10% potential (C_i)	Top 10% potential (H_i)	Top 10% potential (B_i)	Top 10% potential (PR_i)	Top 10% potential (E_i)
NGU	NGU	EKO	LRD	MHT
NUQ	NUQ	YIP	BRW	BUR
AOH	AOH	LRD	GAL	DSM
DSM	DSM	BRW	HSL	ICT
ICT	ICT	MMI	EKO	MSN
MSN	EKO	GAL	OPF	CID
EKO	MSN	TAL	KYU	MYR
CID	YIP	OPF	EAA	MAF
MHT	MHT	GUM	HUS	EKO
YIP	CID	ACK	NUL	AMA
MFE	MFE	ACY	TAL	FSD
BUR	BUR	YUM	CXF	MBS
CRP	CRP	BFI	MMI	PSP
FSD	FSD	PFN	ACY	LBB
PSP	MBS	EAA	ACK	HPN
BTV	LNK	GYG	AIN	GRB
LNK	BTV	HSL	RST	MFE
AMA	PSP	GPT	MBS	MLI
MBS	AMA	MBS	GUM	BMI
BMI	HPN	RST	PFN	FNT
HPN	GRB	BRO	COD	CRP
FAR	FAR	TVL	DRO	LAN
GRB	MLI	DRO	NRR	PIA
MLI	BMI	COD	TVL	AZO
LGB	FNT	CXF	TIX	FAR
LAN	AZO	NUL	BWG	LNK
MYR	LAN	ERI	YUM	LGB
FNT	LGB	CHP	MHV	DLH
AZO	MYR	WCR	KAL	RST
GPT	DLH	KAL	YIP	GPT
EUG	GPT	SFB	FYU	DAL
DLH	MAF	FWA	BFI	EUG
SGF	SGF	BTT	FWA	BTV
GFK	EUG	AVL	GYG	CAK

Table H3. (continued)

MOT	RST	PIZ	HYA	ATW
BIS	BIS	ATK	PIZ	FWA
RST	DAL	ICT	VEE	SGF
PIA	GFK	SVS	MCN	FAT
HDN	PIA	VEE	WCR	DET
MAF	CAK	DSM	BTT	LFT
FAT	HRL	CAK	BRO	SBA
AVP	LBB	LWS	SFB	ROA
LSE	MOT	FSD	CYS	XNA
CAK	ILM	CRP	YKM	VPS
FWA	AVP	MSN	AVL	SWF
VPS	HDN	EVV	TOL	MRY
ILM	LSE	MYR	MVY	HDN
HRL	FWA	BQN	CHA	TVC
SWF	VPS	AMA	DRT	AVP
LBB	FAT	GRB	BGS	ACY

Table H4. Airports dropped from the Delta route network following the Comair and Atlantic Southeast Airlines acquisitions and their ranking among all active U.S. airports in 1999 by each measure of centrality.

Dropped Airports	R_C	R_H	R_B	R_{PR}	R_E
RNO	64	69	116	176	49
STX	174	177	261	352	176
GUC	205	203	265	393	214

Table H5. Bottom 50% of U.S. airports in the Delta network in 1999 , as ranked by closeness, harmonic, betweenness, PageRank, and eigenvector centrality.

Top 50% droppable (C_i)	Top 50% droppable (H_i)	Top 50% droppable (B_i)	Top 50 droppable (PR_i)	Top 50% droppable (E_i)
CPR	CPR	CPR	GUC	IDA
IDA	IDA	HLN	EGE	CPR
HLN	HLN	GUC	MLB	GUC
GUC	GUC	TLH	STX	BGR
AGS	AGS	STX	DAB	GJT
TLH	TLH	MLB	HLN	HLN
GJT	GJT	EGE	TLH	AGS
STX	STX	AGS	MGM	TLH
MLB	MLB	DAB	STT	STX
PSC	PSC	JAC	MLU	GTF
MGM	BGR	GJT	BGR	JAC
DAB	JAC	MGM	MOB	PSC
BGR	MGM	MOB	IDA	FCA
OGG	DAB	SRQ	PSC	BZN
JAC	OGG	STT	MSO	DAB
MLU	MLU	MLU	BZN	MLB
ISP	FCA	SAV	AGS	MGM
FCA	STT	IDA	JAN	MLU
STT	ISP	PNS	GTF	MSO
GTF	EGE	CHS	OGG	MOB
MOB	GTF	PWM	GJT	FAI
LEX	MOB	FCA	PWM	EGE
EGE	BZN	ABE	FCA	STT
SBN	LEX	BTR	JAC	BTR
BZN	SBN	ROC	SRQ	SAV
CAE	MSO	MSO	PNS	HSV
HSV	FAI	JAN	CHS	LEX
GSP	CAE	MDT	BTR	CAE
ABE	SAV	GTF	SAV	SBN
SAV	SHV	ALB	LIT	SHV
SHV	ABE	BZN	LEX	CHS
FAI	HSV	LEX	CPR	BIL
PNS	PNS	GSP	SBN	PNS
MSO	BTR	SYR	SNA	ABE

Table H5. (continued)

BTR	GSP	SBN	SMF	ISP
CHS	CHS	PSC	SHV	SRQ
SRQ	SRQ	TYS	RNO	GSP
PWM	HNL	LIT	ABE	OGG
HNL	BIL	SNA	ROC	PWM
BIL	PWM	RIC	TUS	TYS
LIT	JAN	ORF	ALB	MDT
MDT	MDT	PBI	MDT	JAN
JAN	LIT	BHM	SYR	SYR
TYS	TYS	SMF	TYS	ALB
GEG	GEG	RNO	RSW	GRR
BOI	BOI	ONT	BOI	DAY
PBI	PBI	RSW	PBI	LIT
ROC	ROC	JAX	BHM	ANC
GSO	RSW	TUS	ISP	BOI
SYR	SYR	GSO	GSP	ROC
GRR	ANC	ISP	RIC	GSO
SMF	SMF	CAE	FLL	RIC
ALB	GRR	OAK	ONT	GEG
TUL	ALB	OKC	GSO	RSW
RSW	SJU	FLL	GEG	ORF
ORF	GSO	OGG	ORF	TUL
SJU	RNO	COS	JAX	HNL
HOU	TUL	HOU	OAK	BHM
RIC	JFK	BDL	JFK	PBI
JAX	SNA	GEG	CAE	BUF

APPENDIX I:

Delta Airlines – Northwest Airlines Merger

Table I1. Airports added to and dropped from the Delta route network following the Northwest merger in 2009.

All Added	All Dropped
GRR	GUC
BIS	NZY
MHT	AMA
BIL	UST
FSD	LWS
FNT	
MYR	
SCE	
FAI	
FAR	
CMI	
TVC	
PSP	
FAY	
DSM	
ECP	
LAN	
MSO	
MOT	
FRG	
LGB	
TOL	
ROA	
PGV	
FOE	
OCF	
ICT	
ISP	
PVU	
CRW	
ADW	
MHK	
BMG	
AVL	
ILM	
MIE	
TRI	
YNG	
COU	
EFD	
LBB	
LSE	
ACT	
BMI	
GUM	

Table I2. Airports added to the Delta route network following the Northwest Merger and their ranking among all active U.S. airports in 2009 by each measure of centrality.

Added Airports	R_C	R_H	R_B	R_{PR}	R_E
MHT	89	85	274	293	67
GRR	94	88	102	100	74
DSM	84	71	101	65	77
MYR	129	113	151	102	91
ICT	101	98	109	57	94
TOL	107	110	186	285	95
LGB	93	100	146	240	108
ISP	109	121	427	434	111
FSD	102	107	245	229	112
BIL	97	103	93	157	115
LBB	106	112	98	52	116
ROA	172	151	197	247	118
ILM	221	177	270	341	123
FNT	174	164	130	178	125
PSP	123	137	290	415	126
FAR	144	138	278	299	132
CRW	200	199	501	517	138
TVC	181	184	192	326	141
LAN	149	135	292	99	147
BIS	87	108	315	342	157
TRI	272	248	480	351	158
FAI	57	59	2	2	163
AVL	207	198	286	414	167
BMI	215	205	390	385	172
MSO	133	147	382	481	173
SCE	187	171	172	80	180
FAY	230	208	486	485	196
LSE	233	231	614	717	206
CMI	237	229	338	323	217
MOT	104	146	277	380	223
FRG	183	178	148	88	234
ACT	261	244	384	324	248
MHK	223	213	301	217	254
ADW	164	166	306	148	256
GUM	599	572	72	161	262
PGV	330	328	624	566	287
COU	295	276	532	386	329
EFD	232	255	696	748	349
FOE	234	222	307	330	360
YNG	420	345	516	462	502
BMG	252	253	595	387	511
PVU	298	304	233	318	574
MIE	496	459	636	719	605
OCF	339	348	698	467	666
ECP	1149	1149	1149	1179	1211

Table I3. (continued)

Table I3. Top 10% of U.S. airports not in the Delta network in 2009, as ranked by closeness, harmonic, betweenness, PageRank, and eigenvector centrality.

Top 10% potential (C_i)	Top 10% potential (H_i)	Top 10% potential (B_i)	Top 10% potential (PR_i)	Top 10% potential (E_i)
JGC	JGC	FAI	FAI	MHT
MVN	MVN	ADQ	TEB	GRR
AOH	AOH	KTN	OXC	DSM
OCE	OCE	AKN	OCE	MYR
NJ3	NJ3	BET	NJ3	ICT
ILN	FAI	JNU	HOM	TOL
RFD	IFP	HOM	WFB	BTB
FAI	ILN	TEB	HTO	MLI
IFP	DSM	WFB	RFD	LGB
DSM	RFD	OME	LKE	RFD
BIS	MHT	OTZ	GCN	UTM
MHT	GRR	LKE	ADQ	ISP
DLH	ICT	DLG	AKN	FSD
LGB	LGB	BLI	GMU	ACY
GRR	TEB	RFD	MVY	BIL
AFW	BIL	OXC	VNY	LBB
BIL	FSD	FRD	MCG	HRL
ICT	BIS	CLM	LSV	ROA
FSD	UTM	MCG	NGU	SGF
MOT	TOL	GCN	OTZ	ILM
LBB	LBB	GUM	HIF	IFP
TOL	MYR	MRI	LBB	FNT
TEB	DLH	IFP	OME	PSP
ISP	ISP	ANI	JNU	ILN
TCM	HRL	BRW	ICT	FWA
HRL	AFW	ILI	DSM	MAF
MAF	ACY	PSM	TCM	FAR
PSP	MAF	HTO	AFP	FAT
FAT	LAN	DUT	ACK	AVP
MYR	FAT	LRD	BLD	CRW
AZA	PSP	PGA	BRW	PIA
MSO	FAR	BIL	SCE	TVC

Table I3. (continued)

SUU	AZA	LBB	LRU	LFT
WRI	SFB	MVY	WRI	LAN
BLI	MOT	DSM	XWF	MBS
SBA	MSO	GRR	PSM	DLH
FAR	LRD	VGT	FRG	SBA
UTM	SGF	GFK	HYA	BIS
LAN	ROA	YUM	PWT	TRI
ACY	INT	MMU	AZA	CWA
PSC	TCM	ICT	BAD	CRP
PAE	ENV	ESD	LAN	FAI
ENV	SBA	VNY	GRR	MFE
SGF	GFK	CDB	MYR	RST
ADW	BTW	GKN	UKI	AVL
SFB	FNT	AZA	IFP	EVV
LCK	MFE	CDV	BET	AFW
MLI	ADW	WRG	SBP	BMI
GFK	MLI	MBS	NEW	MSO
PIA	SCE	DMA	LRD	LCK
BTW	PSC	NYL	HMN	AEX
ROA	PIA	SIT	NKX	BET
FNT	FWA	FNT	DUT	MFR
MFE	JQF	MVM	VCV	LRD
PSM	ILM	SPN	FRD	SCE
TVC	FRG	LMT	MMU	MRY
CPR	PSM	LGD	KLN	ERI
FRG	CRP	SIG	UTM	AZO
INT	LCK	KLN	PDK	GFK
NKX	TVC	LRU	FTW	PSC
SCE	SUU	XWF	DRO	OAJ
CRP	BET	HYA	LEB	RDM
LRD	BLI	HHH	DMA	CPR
FWA	WRI	BAD	CNM	FAY
MBS	MBS	RQR	SYA	MLU
MWH	CPR	GMU	BFF	IDA
JQF	EVV	KY3	JQF	ITH
DOV	AVL	GCK	VGT	CLL
SUS	CRW	LGB	PWK	ENV
IDA	SUS	MQJ	HHH	BQN
CRW	RST	FRG	GFK	BLI

Table I3. (continued)

ASE	AVP	MYR	FYU	LSE
EVV	BMI	NGU	ADW	SFB
ADQ	LFT	ACK	BHB	ASE
RST	CWA	CGA	YUM	HTS
AVL	FAY	LSV	GYU	SPI
GRK	PAE	HTS	HFD	DRO
SIT	GRK	GAL	MRY	ELM
AVP	ADQ	SUU	BIL	BFL
HOM	MHK	BLD	CDV	DOV
HLN	AEX	HIK	MVM	CMI
MFR	MRY	WRI	RQR	OME
BMI	ASE	KSM	GUM	INT
LFT	DOV	UNK	CEC	JQF
MRY	MLU	SBP	VRB	HLN
KTN	IDA	SCE	FWH	GRK
CWA	FOE	PSG	ONP	MOT
ILM	CLL	NUW	MCF	MQT
CYS	HOM	TCM	LMT	BGM
MHK	MFR	EMK	FWS	LCH
AEX	BFL	SCC	KY3	TEB
MLU	CMI	TOL	DQP	FSM
JNU	LSE	FSM	HIK	WRI
FAY	NKX	FWH	AEX	FRG
LSE	AKN	HRL	DTO	OTZ
FOE	KTN	ABI	FNT	PFN
BFL	CYS	TVC	EDF	EWN
CMI	HTS	ACY	ILI	KTN
BET	HLN	ENV	PGA	ANI
STS	AZO	MRY	EIL	JNU
CLL	NGU	ROA	MFR	FLG
PUW	SIT	CYS	ACY	SBP
NGU	MWH	DRO	SUN	ACV
LFI	JNU	UTM	FOK	ACK
RDM	ACT	NKX	GBR	CYS
LUK	ADS	POB	DOV	GCC
AZO	TRI	PWK	PAM	ACT
RDD	SLN	VOK	FBK	HHH
HTS	OME	RST	ANI	STS

Table I4. Airports dropped from the Delta route network following the Northwest merger and their ranking among all active U.S. airports in 2009 by each measure of centrality.

Added Airports	R_C	R_H	R_B	R_{PR}	R_E
AMA	120	130	423	376	131
GUC	321	318	697	869	266
LWS	239	251	308	679	281
NZY	280	320	304	250	660
UST	862	860	939	1111	775

Table 15. Bottom 50% of U.S. airports in the Delta network in 2009 , as ranked by closeness, harmonic, betweenness, PageRank, and eigenvector centrality.

Top 50% droppable (C_i)	Top 50% droppable (H_i)	Top 50% droppable (B_i)	Top 50 droppable (PR_i)	Top 50% droppable (E_i)
UST	UST	UST	UST	UST
TUP	TUP	GUC	GUC	NZY
GTR	NZY	EFD	EGE	TCL
GUC	GUC	GTR	EFD	LAF
EYW	GTR	MTJ	MTJ	EFD
NZY	EYW	MLB	HDN	BKL
TCL	CKB	TUP	LWS	TUP
MLB	TCL	EGE	GTR	CKB
CKB	STX	AGS	KOA	LWS
AGS	EFD	JAC	JAC	MKC
STX	LIH	CKB	MLB	GTR
CSG	LWS	HDN	CKB	GUC
LWS	MTJ	GNV	STX	YIP
GNV	MLB	SRQ	GJT	GNV
MTJ	CSG	GJT	EYW	MLB
EFD	AGS	EYW	AGS	PTK
PHF	HDN	CSG	SRQ	CSG
LIH	BKL	BKL	DAB	STX
HDN	GNV	DAB	TUP	MGM
MGM	STT	BZN	BZN	EYW
STT	PHF	AMA	BKL	HDN
CHA	EGE	LAF	GRB	AGS
BKL	MGM	GRB	EUG	BED
CHO	EUG	MOB	LIH	FCA
SWF	CHA	FCA	ATW	EGE
ATW	ATW	CHO	OGG	MTJ
DAB	GTF	TCL	AMA	LNK
EGE	CHO	LNK	LNK	GTF
LNK	SWF	BTR	CSG	BFI
EUG	KOA	RAP	LAF	EUG
BGR	DAB	LIH	MOB	PIE
GTF	GJT	ATW	FCA	LIH
MOB	LNK	SBN	TCL	CHO
ABE	PTK	TLH	GNV	DAB

Table I5. (continued)

SRQ	MKC	XNA	PIE	BTR
PTK	LAF	PIE	RAP	MOB
GJT	BGR	ABE	PWM	GJT
PWM	MOB	LWS	BOI	BGR
TLH	JAC	NZY	CHA	SWF
YIP	RAP	PWM	ABE	VPS
KOA	ABE	KOA	MKC	KOA
GPT	SRQ	MSN	CHO	JAC
VPS	PWM	DAY	STT	RAP
GSP	BZN	BOI	XNA	STT
PNS	PIE	SHV	HOU	CHA
MKC	VPS	MDT	MGM	PHF
PIE	FCA	SYR	RSW	ATW
RAP	BED	EUG	BTR	BZN
BED	TLH	SWF	SBN	AMA
JAC	YIP	CID	NZY	SHV
SJU	AMA	HSV	MDT	SBN
SAV	GPT	CAE	GSO	GRB
LEX	PNS	TUS	PHF	OGG
BZN	GRB	CHA	DCA	CAK
CID	CAK	PNS	TLH	TLH
XNA	SJU	MGM	SJU	SRQ
LAF	GSP	BHM	DAY	LEX
CAK	SBN	PBI	CID	PNS
FCA	BTR	SAV	SAV	GPT
AMA	CID	MSY	MSN	XNA
MDT	SHV	MKC	PBI	ABE
GSO	SAV	PHF	SJC	JAN
GRB	XNA	GSO	CAE	HPN
SHV	LEX	CAK	TPA	CID
SBN	OGG	GSP	SWF	COS
BTR	MDT	STX	TUS	PWM
ROC	ROC	RSW	LGA	HSV
TYS	GSO	HOU	ORF	GSP
HPN	SYR	BGR	SYR	CAE
SYR	MSN	BUF	GEG	GEG
MSN	GEG	TPA	BHM	MDT
CAE	CHS	GPT	SHV	MSN
DAY	CAE	LIT	HSV	SAV

Table 15. (continued)

CHS	TYS	TUL	CMH	LIT
GEG	HNL	CMH	CVG	HNL
BOI	BOI	JAX	BGR	BUR
JAN	DAY	LEX	CAK	TYS

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