Seoul Journal of Business
Volume 13, Number 1 (June 2007)

Scale-free Networks in the Presence of Constraints: An Empirical Investigation of the Airline Route Network

Jeho Lee*
Korea Advanced Institute of Science and Technology
Seoul, Korea

Namgyoo K. Park**
Seoul National University
Seoul, Korea

Abstract

Classifying the types of networks has been a focus of analysis in the recent, small-world research. A unifying theory has been introduced to provide an integrative perspective on the statistical properties of a variety of real-world networks. This theory postulates that the existence of constraints deters the emergence of a scale-free network. For example, the theory argues that the constraints of airport capacity limit the growth of air traffic, blocking the emergence of a scale-free network. We challenge this argument by reexamining the context of the airline industry. We empirically show that the U. S. airline route network is a scale-free network despite the presence of capacity constraints. We propose a new avenue for future research.

Keywords: small world, scale-free distribution, network, airline industry

---

* Main author, Associate Professor of management, Graduate School of business, Korea Advanced Institute of Science and Technology (jlee@kgsm.kaist.ac.kr).

** Coauthor, Associate Professor of Strategy and International Business, Graduate School of Business, Seoul National University (npark@snu.ac.kr).

The authors would like to thank the Institute of Management Research, Seoul National University for their financial support of this research.

INTRODUCTION

In 1938, passengers who flied with Delta Airlines from Fort Worth, Texas to Atlanta, Georgia had to stop at six intermediate points along the route (Lewis and Newton 1979). If any airline company maintains this type of route structure today, perhaps it will not stay in business. Passengers prefer to choose a carrier that minimizes possible stopovers between origins and destinations if other things are held constant. Due to this preference, carriers wish to design the route networks that connect origins and destinations with a minimum number of stopovers. This number is often called “degrees of separation,” which is one of the defining properties of the small-world phenomenon (Strogatz 2001).

Understanding the mechanisms that reduce the degrees of separation in a network has been a key issue in the burgeoning literature on the small-world phenomenon (e.g., Barabasi and Albert 1999; Barabasi, Albert and Jeong 1999; Milgram 1967; Watts and Strogatz 1998). Prior research has identified hubs as a mechanism to reduce the degrees of separation (Barabasi and Albert, 1999; Barabasi et al. 1999). A hub is a node linked to many other nodes — e.g., a hub airport is highly connected to other airports, playing a role of minimizing the number of stopovers. Empirical research has shown that many real-world networks with hubs are characterized by scale-free distributions, a kind of distribution that decays with a fat tail (see figure 1 for the shape of the curve; e.g., Albert, Jeong and Barabasi 1999; Faloutsos, Faloutsos and Faloutsos 1999; Liljeros et al. 2001). Identifying the conditions under which this sort of distribution emerges became of paramount importance in small-world studies. Prior research recognized three mechanisms for the emergence of scale-free networks: (1) networks continuously expand by adding new nodes; (2) new nodes preferentially attach to sites that are highly connected (Barabasi and Albert 1999; Barabasi et al. 1999); and (3) capacity constraints limit the growth of nodes (Amaral et al. 2000). In particular, Amaral et al. (2000) argued that the existence of constraints on node capacity restrains the emergence of scale-free networks. By analyzing the number of visitors at each airport, they found that its distribution is not scale-free but with a fast-decaying tail (see figure 1 for the shapes of the different curves).

It has been commonly understood that airports cannot accommodate increasing traffic without limits. The additions of both destinations and connecting flights to an airport are bounded by capacity constraints such as runways, landing slots, and/or terminal size (e.g., Bailey, Graham and Kaplan 1985; Holloway 1997; Levine 1987). Therefore, the capacity constraints in popular airports are roadblocks to building airline route networks. In this paper, however, we challenge Amaral et al.'s (2000) argument by reexamining the context of the airline industry. We show that the U. S. airline route network is a scale-free network.

We also show that the structure of this network is very stable over time after the enactment of the Airline Deregulation Act in 1978. It has been claimed that the airline deregulation changed the nature of competition significantly. Indeed, carriers subsequently competed on the basis of building more efficient

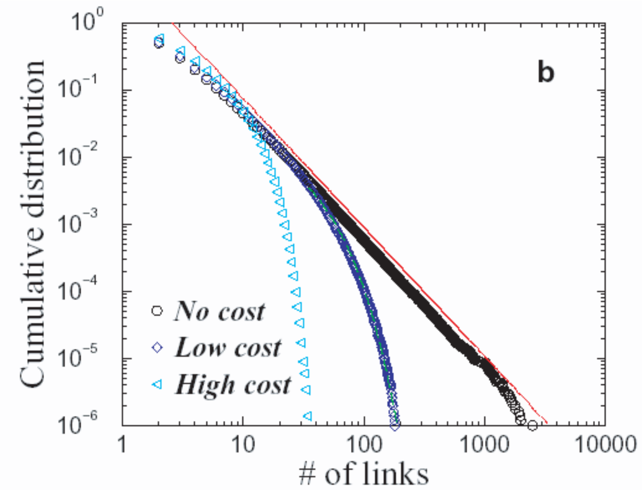

Figure 1. Truncation of Scale-Free Connectivity with Constraints*

* Source: Amaral, L.A.N., Scala, A., Barthelemy, M., & Stanley, H.E. 2000. Classes of small world networks. Proceedings of the National Academy of Science of America, 97(21): 11151

* The cumulative distribution curve with no cost is a scale-free network, the cumulative distribution curve with low cost is a broad-scale network, and the cumulative distribution curve with high cost is a single-scale network.

route networks such as hub-and-spoke systems (Levine 1987; Poole and Butler 1999). Intensified competition cornered airlines with less efficient route networks, resulting in a series of mergers and bankruptcies (Donohue and Ghemawat 1995). Therefore, it is rather natural to believe that such a sea change in the competitive landscape might have changed the properties of the scale-free network after 10 or 20 years. Yet, our analysis shows that the structure of the scale-free network has been surprisingly stable for about twenty years since the deregulation. The stability of the scale-free distribution indicates that the hubs of some carriers are connected with the unusually large numbers of destinations. Our research further shows that these carriers increased their market shares at the top twenty hub airports over time whereas weaker carriers were driven out of competition. This finding suggests that building highly connected hubs, which reduce the degrees of separation for air travelers, has been a source of competitive advantages. This is a functional implication of being a small-world.

LITERATURE REVIEW

A small-world phenomenon has attracted attention from various disciplines. The essence of this phenomenon is captured by the small-world hypothesis: Although there are so many people in the world, two randomly chosen individuals are separated by six degrees at most. Milgram (1967) provided the first systematic evidence for this hypothesis. Conducting an experiment to trace a chain of acquaintances in the U. S., he found that people are, indeed, separated by six degrees at most.

Recent studies have investigated how this phenomenon is possible, providing two explanations. The first explanation is related to the concept of shortcuts (Watts and Strogatz 1998), or what Granovetter (1973) called social bridges. The role of shortcuts could be illustrated by the study of homosexual networks in the early spread of AIDS (Klovdahl 1985). Homosexuals tend to interact with other homosexuals who live within geographically close areas. That is, geographical distance should limit the spread of the disease. But it quickly spread through homosexuals across the entire North America. The

Centers for Disease Control and Prevention found that one patient, who was a flight attendant for Air Canada, played a key role in the spread of the disease. He traveled worldwide and frequented bathhouses in San Francisco, Los Angeles, Vancouver, Toronto, and New York. Strogatz (2003, p. 252) noted: "At least 40 of the first 248 men diagnosed with AIDS had sex either with him or with one of his previous partners." The flight attendant is an exemplary case of shortcuts, whose function is to reduce the degrees of separation between two randomly chosen individuals.

The second explanation for the small-world phenomenon (Barabasi and Albert 1999; Barabasi et al. 1999) is associated with the concept of hub. Its role was illustrated in Albert et al.'s (1999) research on the Word-Wide Web (WWW). Although there are a vast number of documents in WWW, two randomly chosen documents on the Web are on average only 19 clicks away from each other. They found the presence of hubs — for example, some websites such as CNN and Yahoo are connected with thousands of newly created Web pages while the hundreds of billions of documents with no link at all. Like shortcuts, the presence of hubs dramatically reduces the degrees of separation in a large network.

Such a small-world phenomenon led many researchers to examine various large networks that consist of a vast number of nodes, such as WWW, cellular networks, metabolic networks, and neural networks (e.g., Bhalla and Iyengar 1999; Jeong et al. 2000; Kohn 1999; Achacoso and Yamamoto 1992). When a network has more than a couple of hundred nodes, it becomes difficult to visualize its patterns. A typical way to study such a large network has been to look into a connectivity distribution (a number of links for each node and its frequency). In particular, patterns of a tail in a distribution became the focus of analysis for large networks. Based on the tail patterns, networks are classified into three classes: (1) single-scale, (2) scale-free, and (3) broad-scale networks (Amaral et al., 2000; see figure 1 for the shapes of the distribution curves for the three networks). First, single-scale networks are characterized by a connectivity distribution with a fast decaying tail — such distribution has a characteristic scale like mean. For example, the power grid of the western U.S. and a social network of Mormons in Utah are single-scale networks. Second, scale-free networks are characterized by a fat tail, or a connectivity distribution curve that tails off toward zero much more slowly than that of a single scale network. More precisely, the tail behavior is characterized by a power-law curve — when one draws the power-law curve in a log-log plot, it will show a straight line. For example, the network of WWW is characterized by a scale-free (power-law) distribution. Albert et al. (1999, p. 130) noted: "The power-law tail indicates that the probability of finding documents with a large number of links is significant, as the network connectivity is dominated by highly connected web pages (hubs)." Third, broad-scale networks are characterized by a connectivity distribution that has a power-law regime followed by a sharp cut-off as shown in figure 1. They are sometimes called "truncated" scale-free networks. For example, the co-authorship network of scientists is shown as a broad-scale network (Newman 2001).

Prior research has examined how different classes of networks could emerge. Barabasi and Albert (1999) identified two mechanisms that generate scale-free networks: (1) networks continuously expand by adding new nodes; (2) new nodes preferentially attach to sites that are highly connected. Consider, for example, WWW. It grows over time by adding new Web pages. A newly created Web page will be more likely to include links to well-known popular documents with already-high connectivity. As the network evolves over time, popular documents (i.e., hubs) will attract more and more newly created Web pages. In a nutshell, the preferential attachment rule implies that the rich will get richer over time.

However, Amaral et al. (2000) argued that preferential attachment can be hindered by constraints. That is, when the cost of adding new links to an existing node increases over time or when a node has a capacity limit for adding links, "the rich-get-richer principle" will not generate a scale-free network. Through computer simulations, they found that constraints to preferential attachment lead to cut-offs on power-law curves. Whether a network grows into a single-scale network or a broad-scale network depends on the magnitude of constraints. When constraints are modest, a power-law region is possible but followed by a sharp cut-off (broad-scale network). For example, consider the co-authorship network of scientists. Once a researcher becomes famous in a certain area, many researchers may want to collaborate with her. Through this rich-get-richer principle, she will publish more papers by working with many collaborators. However, the limited life span does not allow her to publish forever through collaboration. This implies that the connectivity distribution of co-authorship networks will have a power-law regime followed by a modest cut-off. When constraints are strong enough, no power-law region is visible (single-scale network). For example, consider the acquaintance network of Mormons in Utah. Because of time constraints, each individual cannot make hundreds of or thousands of close friends. Such strong constraints put brake on the rich-get-richer principle, resulting in a single-scale network.

In short, Amaral et al. (2000) provided a unifying framework that generates three classes of networks by controlling the magnitude of constraints. Do these constraints always matter? Do they always put brake on the emergence of scale-free networks? In this paper, we offer an anomaly to the unifying framework by reexamining the context of the airline industry. Amaral et al. (2000, p. 11151) noted that the existence of capacity constraints in the airline industry limits the generation of scale-free networks as follows:

> This effect [cost of adding links to the nodes and the limited capacity of a node] is exemplified by the network of world airports: for reasons of efficiency, commercial airlines prefer to have a small number of hubs where all routes connect. In fact, this situation is, to a first approximation, indeed what happens for individual airlines; however, when we consider all airlines together, it becomes physically impossible for an airport to become a hub to all airlines. Because of space and time constraints, each airport will limit the number of landings/departures per hour and the number of passengers in transit. Hence, physical costs of adding links and limited capacity of a vertex [node] will limit the number of possible links attaching to a given vertex.

We agree that the capacity constraints in popular hubs do restrain the rich-get-richer principle. However, we empirically show that the route network in the U.S. airline industry follows a scale-free distribution.

EMPIRICAL CONTEXT AND DATA

This study examines the evolution of the route network of all the airline companies in the U. S. after the enactment of the Airline Deregulation Act in 1978. Prior to the deregulation, the industry competition including price, entry, and exit was pretty much controlled by the Civil Aeronautics Board. After 1978, airline companies were allowed to compete on all the three dimensions. Poole and Butler (1999: 44) noted: “American cities have been offered much greater air travel access, thanks to an aviation marketplace in which airlines are free to provide service when and where demand exists, without having to seek permission from central planners.” Deregulation led to a significant increase in air traffic, triggering the process of making air service a commodity.

In the era of the regulatory protection, airlines mostly ran a route network of often fragmented and semi-exclusive point-to-point segments that link major cities directly. During the first ten years of deregulation, the major airlines changed their route structures from point-to-point to hub-and-spoke route systems (Poole and Butler 1999). Prior to the 1978 deregulation, Delta pioneered the concept of hub-and-spoke route systems at Atlanta, Georgia. Intense competition after the 1978 deregulation encouraged airlines to consider the new type of network architecture for their routes. Emulating the Delta model, major trunk airlines began to establish hubs at what had been initially origin-and-destination airports (point-to-point route networks). Some of these airports include Charlotte, Dallas, Detroit, Minneapolis, Pittsburgh, and St. Louis. The hub-and-spoke route systems increased the number of route connections for air travelers. For example, Poole and Butler (1999, p. 45) noted:

> First, those living in the hub-airport city gained access to a many-fold increase in the number of destinations and the number of flights. Second, residents of small cities on the spokes of the hub, who may have lost some point-to-point service, gained access to potentially hundreds of destinations

via the hub.

By scheduling many feeder flights — the spokes of the network — into the hub airport, airlines were able to achieve substantial cost advantages. Well-designed hub and spoke architectures can improve operating efficiencies with fewer aircrafts, fewer crew members, and higher frequencies. Furthermore, the market power of an airline company at an airport is positively associated with the number of destinations from that airport. For example, Donohue and Ghemawat (1995, p. 8) noted: "Well-developed hub systems let incumbents underprice entrant point-to-point competition and still maintain satisfactory systemwide yield levels." As obtaining hubs with better locations became critical in competitive warfare during the mid-1980s, major carriers acquired many second-tier carriers to secure valuable hubs. For example, by acquiring Ozark, TWA was able to dominate the St. Louis hub.

In order to examine the evolution of the route network for all U.S. airlines, we collected data for all the U.S. domestic airline routes, annual operation capacity at route level, and annual frequency of flights at each route in 1979, 1981, 1986, 1991, 1996, 2000, and 2002. The data are obtained from a commercial database firm in the airline industry, the BACK Association. The number of destinations for an airline at an airport is the unit of analysis. This is more relevant and important for studying the strategic behavior of airline companies than the number of visitors at an airport, which was the focus of analysis in Amaral et al. (2000). We analyzed the connectivity distribution of all airline routes in the U. S. for the seven years. We also investigated changes in the market share of a dominant carrier at the top twenty airports between 1979 and 2000.

FINDINGS

Figure 2 presents the connectivity distribution of the U.S. airline route network in 1981, 1991, and 2001. It shows that the connectivity distribution decays with a power-law tail. More specifically, the probability that an airline has k destinations at an airport has a power-law tail for large k, following $P(k) \sim k^{\gamma}$,

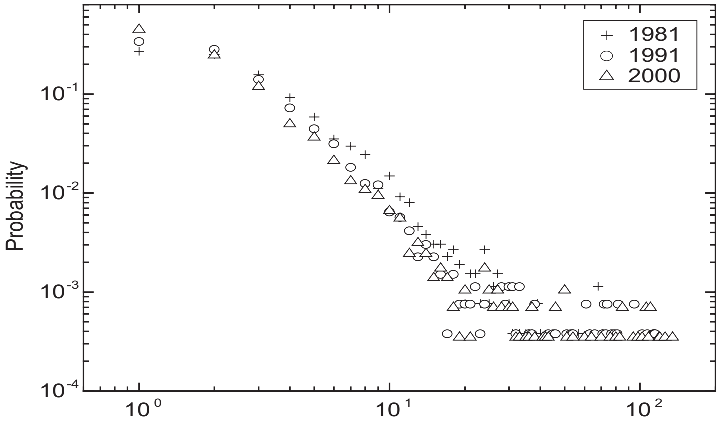

Figure 2. Connectivity Distribution of U.S. Airline Route Network

where $\gamma = 2.6 \pm 2$ (see table 1 for details). In contrast to the study of Amaral et al. (2000), our study shows that the fat-tail pattern is stable over the last two decades. In addition, figure 3 shows that the U.S. airline route network is resilient against the terrorist attack on September 11, 2001. This external shock decreased domestic airline passengers by 18% in the fourth quarter of 2001 compared to the same quarter of the previous year (Department of Transportation 2003). However, the fat-tail pattern remains unchanged although there are minor changes in the detail. Our finding is consistent with Albert et al. (2000), who numerically showed that scale-free networks are robust against a random shock.

It is well-known that airports cannot accommodate increasing traffic without a limit. Expanding both passenger capacity and connecting flights at an airport is bounded by constraints such as runways, landing slots, and/or terminal size. Why, then, does the connectivity distribution remain stable? To address this question, we investigated changes in major characteristics of the top twenty airports (by the rank of passenger traffic in 2001)

Table 1. Power-law Exponents Over Time

Year	1979	1981	1986	1991	1996	2000	2002
Power law exponent	2.5	2.4	2.7	2.7	2.8	2.7	2.7
Number of Observations	2982	2620	2815	2650	2980	2879	2608

Table 2. Dominant Carriers at the Top Twenty Airports

Top 20 Airports	1979				2000			
	Dominant Carrier	Market Share	No of Desti.	No of Departing Passengers	Dominant Carrier	Market Share	No of Desti.	No of Departing Passengers
Atlanta	DL	48.4	62	37,217,876	DL	76.9	135	53,852,805
Chicago	UA	35.4	63	44,354,517	UA	50.9	126	45,627,912
Dallas	AA	24.1	41	23,601,674	AA	66.9	120	39,532,727
Los Angeles	UA	25.2	37	30,726,366	UA	31.0	54	38,188,431
Phoenix	AA	21.3	18	7,966,658	HP	43.6	76	28,350,746
Denver	UA	29.6	45	21,618,374	UA	70.4	106	25,650,865
Las Vegas	WA	19.7	10	8,828,665	WN	31.4	41	23,102,793
Minneapolis	NW	42.3	26	10,716,235	NW	77.7	119	24,014,137
Houston	WN	15.7	7	14,663,678	CO	79.8	110	20,419,880
Detroit	NW	19.5	10	12,253,587	NW	77.0	110	23,786,631
San Fran.	UA	37.0	39	21,246,755	UA	52.6	50	23,142,816
NY (Newark)	EA	26.5	22	9,560,220	CO	51.8	60	20,339,402
St Louis	TW	38.4	41	12,402,787	TW	72.8	102	24,635,690
Seattle	UA	30.1	19	11,263,796	AS	43.7	46	19,081,922
Orlando	DL	38.2	12	7,749,707	DL	31.2	36	17,930,414
Miami	EA	34.7	35	14,863,798	AA	55.8	38	12,502,852
Philadelphia	US	25.4	31	10,640,650	US	66.2	85	19,058,658
NY (LG)	EA	24.0	20	14,532,516	US	31.9	51	19,747,322
Charlotte	EA	60.4	23	3,987,040	US	90.2	98	18,263,461
Boston	DL	23.9	17	12,258,732	US	26.5	36	20,169,666

between 1979 and 2000 (see table 2). Those characteristics include dominant carrier's market share (by the number of passenger per airlines), total number of departing passengers, and the number of destinations for a dominant carrier. The table shows that while there is a marginal increase in the total number of departing passengers over the last two decades, market shares and the number of destinations for a dominant carrier increased significantly. The evolution of the route networks shows a dramatic increase in concentration level by single dominant carriers. Windle and Dresner (1993) defined hub monopoly airports as those airports where one carrier had at least 60 percent market share of the departures. In 1979, there was only one monopoly hub out of the top twenty airports. In 2000, the number of monopoly hubs increases to nine. Furthermore, all of

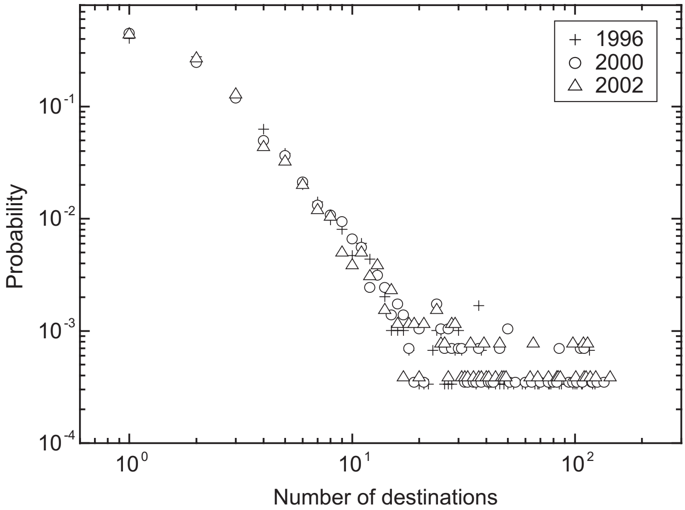

Figure 3 . Connectivity Distribution of U.S. Airline Route Network

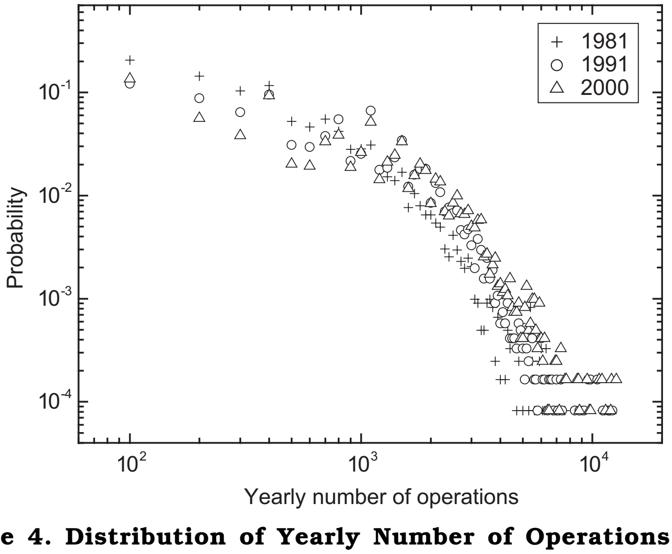

Figure 4. Distribution of Yearly Number of Operations for U.S. Airlines

the top twenty hubs except the Orlando International Airport show increases in market share by their dominant carriers. Table 2 also shows that the number of destinations for dominant

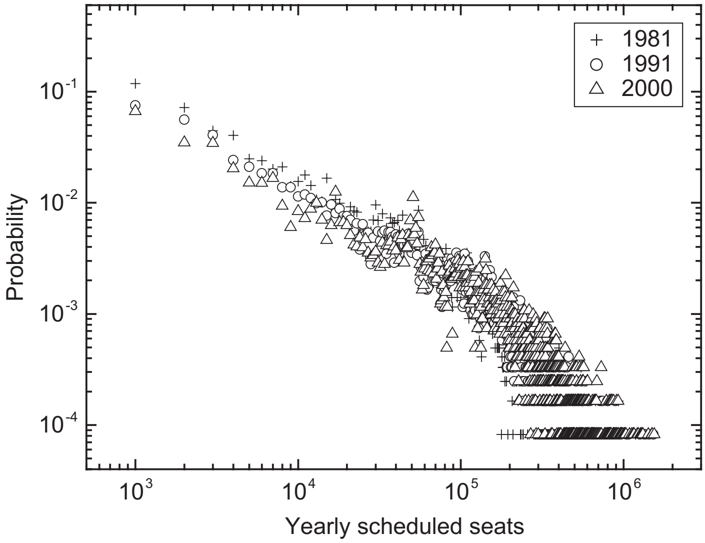

Figure 5 . Distribution of Yearly Scheduled Seats for U.S. Airlines

carriers increased substantially. For example, the number of destinations for the dominant carrier at the George Bush Intercontinental Airport in Houston was only seven in 1979 but increased to 110 in 2000. Delta had 62 destinations from the Hartsfield-Jackson Atlanta International Airport in 1979 but 135 in 2000. These facts suggest that the "rich-get-richer" principle may be in operation, letting the connectivity distribution remain stable.

On the other hand, some of our empirical findings support the theoretical prediction of Amaral et al. (2000). That is, capacity constraints do sometimes hinder the rich-get-richer principle in generating scale-free networks. Figures 4 and 5 show the distributions for the numbers of flights and annual scheduled seats respectively. Unlike the distributions curves in figures 2 and 3, those in figures 4 and 5 are characterized by power-law regions followed by cut-offs. This indicates that the distributions for the numbers of flights and scheduled seats are broad-scale networks or truncated scale-free networks. These results suggest that capacity constraints at airports do matter for flight frequency and scheduled seats. In addition, the distribution curve in figure 4 is more sharply curtailed at the right than that in figure 5. One possible explanation is that the number of yearly scheduled seats can be flexibly controlled by changing the size of fleets. That is, airline companies do have some strategic capabilities to cope with the capacity constraints.

DISCUSSION AND CONCLUSION

We reexamined the main argument of the unifying framework in the context of the U. S. airline route network. The unifying framework posits that the existence of constraints restrains the emergence of scale-free networks (Amaral et al. 2000). However, we found that the connectivity distributions of the U. S. airline route network decay with power-law tails (scale-free network). Surprisingly, the fat-tail pattern is stable over time despite the contention that the growth of airline companies has been bounded by capacity constraints at hub airports. This finding is in direct contrast to that of Amaral et al. (2000).

We do believe that capacity constraints exist at popular airports. Then, why could the unifying framework not explain the empirical regularity in the airline industry? The evolution of the U.S. airline industry shows that after the 1978 deregulation, weak carriers were driven out of competition and left rooms for surviving airlines. If there is intense competition in the industry, then who will be more likely to take over the space of exiting players? The rich-get-richer principle predicts that carriers with higher connectivity are more likely to overtake the space (Barabasi and Albert 1999). Indeed, our data demonstrate that carriers who built up highly connected networks with hubs enhanced their dominant status at the top twenty hub airports over the last two decades. This suggests that carriers with better route networks tended to grow at the expense of weak carriers. For example, after 1978, Braniff, Eastern, Frontier, Western, Republic, National, Ozark, and Piedmont were either liquidated or acquired by dominant carriers. An explanation for the rich-get-richer principle in this industry is that some airlines that bring more feeder traffic at hub airports generally perform better. For example, Delta initially built its hub at the Atlanta airport by connecting flights to several destinations even before the 1978 deregulation. The initial advantage with high connectivity appeared to allow Delta to add more destinations over time, leading its Atlanta hub to become the largest hub connecting 135 destinations. In short, the growth of “the rich” at the expense of “the poor” may have lifted the constraining bar on the emergence of scale-free networks.

A plethora of real-world networks are found to be small-world networks, which are characterized by small degrees of separation. Now, researchers begin to explore the question of whether small-world networks, such as scale-free networks, provide any functional advantages. The empirical context analyzed in this study offers insight into this question. One reason why airlines with hubs and high connectivity can do better over time is associated with customer preference. Customers prefer to choose an airline that provides service with the fewer stopovers when other things are held constant. An airline with higher connectivity will be more flexible in providing air service with fewer stopovers between an origin and a destination. Indeed, building an efficient hub and spoke system, which is designed to reduce the number of stopovers (or degrees of separation in a general term), became a source of competitive advantage in the industry. This is one functional implication of being a small-world in the airline industry.

Our study provides a new avenue for future theoretical research. The unifying framework thus far provided an integrative perspective on the role of network growth, preferential attachment, and constraints. What is missing in this framework is an explicit selection process — the rich gets richer, driving out the poor simultaneously. The context of the airline industry suggests a clue for the existence of natural selection pressures that weed out less fit airlines, leaving their space at the hub airports for the growth of dominant carriers. Future research can model this context by incorporating competition among agents, who grow by building networks and drive out others. More broadly, future studies can investigate mechanisms that allow the emergence of scale-free networks in the presence of constraints.

REFERENCES

Achacoso, Theodore B., and William S. Yamamoto (1992), *AY's Neuroanatomy of C. elegans for Computation*, Boca Roton, FL: CRC Press.

Albert, Ravi, Hawoong Jeong, and Albert -L. Barabasi (1999), "Diameter of the World-Wide Web," *Nature*, 401, 130-131.

_______ and Albert -L. Barabasi (2000), "Error and Attack Tolerance of Complex Networks," *Nature*, 406, 378-381.

Amaral, Luis A.N., Antonio Scala, Marc Barthelemy, and H. Eugene Stanley (2000), "Classes of Small World Networks," *Proceedings of the National Academy of Science of America*, 97(21), 11149-11152.

Bhalla, Upinder S., and Ravi Iyengar (1999), "Emergent Properties of Networks of Biological Signaling Pathways," *Science*, 283, 381-387.

Bailey, Elizabeth E., David R. Graham, and Daniel P. Kaplan (1985), *Deregulating the Airlines*, Cambridge, MA: MIT Press.

Barabasi, Albert -L., and Reka Albert (1999), "Emergence of Scaling in Random Networks," *Science*, 286, 509-512.

Collins, James J., and Carson C. Chow (1998), "It's a Small World," *Nature*, 393, 409-410.

Donohue, Nancy, and Pankaj Ghemawat (1995), "The U.S. Airline Industry, 1978-1988 (A)," The Harvard Business School Case: 9-390-025.

Faloutsos, Michalis, Petros Faloutsos, and Christos Faloutsos (1999), "On Power-law Relationships of the Internet Topology," *Computer Communication Review*, 29, 251-263.

Granovetter, Mark S. (1973), "The Strength of Weak Ties," *American Journal of Sociology*, 6, 1360-1380.

Holloway, Stephen (1997), *Straight and level: Practical airline economics*, Sydney, Australia: Ashgate.

Jeong, Hawoong, Balint Tombor, R?ka Albert, Zoltan N. Oltavi, and Albert -L. Barabasi (2000), "The Large-scale Organization of Metabolic Networks," *Nature*, 407, 651-654.

Klovdahl, Alden S. (1985), "Social Networks and the Spread of Infectious Diseases: The AIDS example," *Social Science Medicine*, 21(11), 1203-1216.

Kohn, Kurt W. (1999), "Molecular Interaction Map of the Mammalian Cell Cycle Control and DNA Repair Systems," *Molecular Biology of the Cell*, 10, 2703-2734.

Levine, Michael E. (1987), "Airline Competition in Deregulated Markets: Theory, Firm Strategy and Public Policy," *The Yale Journal of*

Regulation, 4, 393-494.

Lewis, W. David, and Wesley P. Newton (1979), *Delta: The History of an Airline*. Athens, Georgia: The University of Georgia Press.

Liljeros, Fredrik, Christofer Edling, Luis A. N. Amaral, H. Eugene Stanley, and Yvonne Aberg (2001), "The Web of Human Sexual Contacts," *Nature*, 411, 907-908.

Milgram, Stanley (1967), "The Small World Problem," *Physiology Today*, 2, 60-67.

Newman, Mark E. J. (2001), "The Structure of Scientific Collaboration Networks," *Proceedings of the National Academy of Science of America*, 98, 404-409.

Poole, Robert W., and Viggo Butler (1999), "Airline Deregulation: The Unfinished Revolution," *Regulation*, 22(1), 44-51.

Strogatz, Steven H. (2001), "Exploring Complex Networks," *Nature*, 410, 268-276.

_______ (2003), *Sync: The Emerging Science of Spontaneous Order*. New York, NY: Theia.

Watts, Duncan J., and Steven H. Strogatz (1998), "Collective Dynamics of Small-world Networks," *Nature*, 393, 440-442.

Windle, Robert J., and Martin E. Dresner (1993), "Competition at Duopoly Airline Hubs in the U.S.," *Transportation journal*, 33(2), 22-30.