ECO 2901
EMPIRICAL INDUSTRIAL ORGANIZATION

Lecture 10:
Dynamic Games with Networks

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Lecture 10: Dynamic Games with Networks

- An industry is a **network** when (local) markets are **endogeneously interconnected**.

- Markets can be interconnected through demand or/and costs.

- Firms' operations / decisions in one market may have implications on their own demand/costs in other markets. We expect firms to internalize these links.

- The industry is a **network** where markets are **endogeneously interconnected**.

- Questions:
  - How network structure affects costs & demand.
  - Propagation of shocks within a network.
  - (Dynamic) strategic interactions in the network.

Dynamic Games with Networks

In this lecture, we will study two papers on this topic.

1. Aguirregabiria & Ho (JoE, 2012):
"A Dynamic Oligopoly Game of the US Airline Industry: Estimation and Policy Experiments"

2. Brancaccio, Kalouptsidi, & Papageorgiou (ECMA, 2020):
"Geography, Transportation, and Endogenous Trade Costs"

1. Airline Industry as a Dynamic Network Game

Aguirregabiria & Ho (2012) - Outline

1. A Brief History of Airline Networks

2. Motivation & Questions

3. Model

4 Data & Descriptive Evidence

5. Estimation

6. Counterfactuals

Airlines Networks (Route Maps)

- An airline's network is the set of city-pairs that the airline connects via non-stop flights.
- The choice of network structure is one of the most important strategic decisions of an airline.
- Two network structures that have received particular attention are **hub-and-spoke (HS)** and **Point-to-Point (P2P)**.
- In HS an airline concentrates most of its operations in one airport called the hub. All other cities in the network (the spokes) are connected to the hub by non-stop flights.
- In P2P, cities are directly connected with each other through nonstop flights.

Airlines Networks – Hubbing Index

- Pure HS or P2P networks are rare. Airlines have different degree of hubbing, and they may have multiple hubs.

- We can measure this using Hubbing indexes.
  - M_i = Total number of nonstop routes for airline i
  - M_{ic} = Number of nonstop routes for airline i with city (airport) c as origin/destination
  - Let $M_{i1} \geq M_{i2} \geq M_{i3} \geq ...$

- Hubbing index 1: $CR_{i1} = \dfrac{M_{i1}}{M_i}$

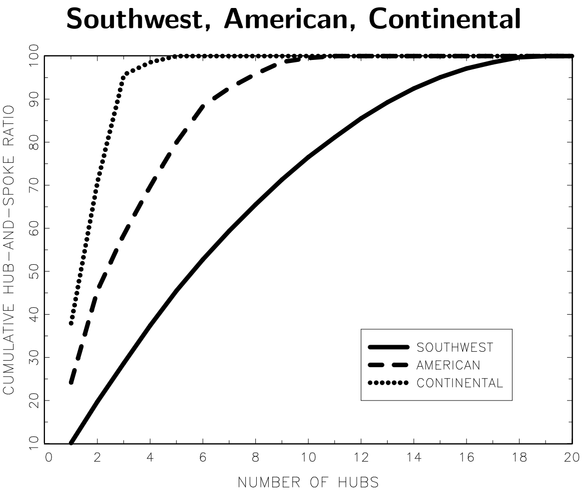
- Hubbing index 2: $CR_{i2} = \dfrac{M_{i1} + M_{i2}}{M_i}$

'Hubbing' in the US Airline Industry: Year 2004

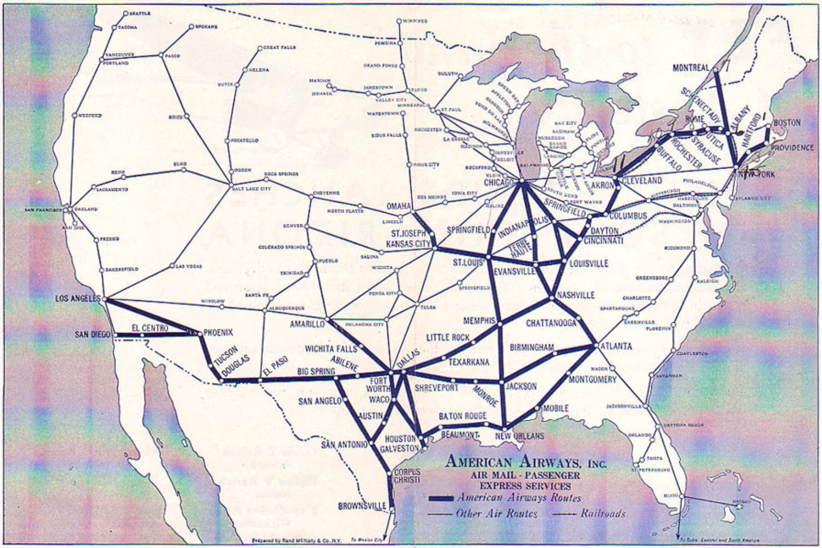
Airline (Code)	1st largest hub (# connections)	CR1	2nd largest hub (# connections)	CR2
Continental (CO)	Houston (52)	36.6	New York (45)	68.3
American (AA)	Dallas (52)	22.3	Chicago (46)	42.0
Southwest (WN)	Las Vegas (35)	9.3	Phoenix (33)	18.2

Source: DB1B Database form the US Bureau of Transportation. Year 2004.

Hub-and-Spoke Concentration Ratios (2004)

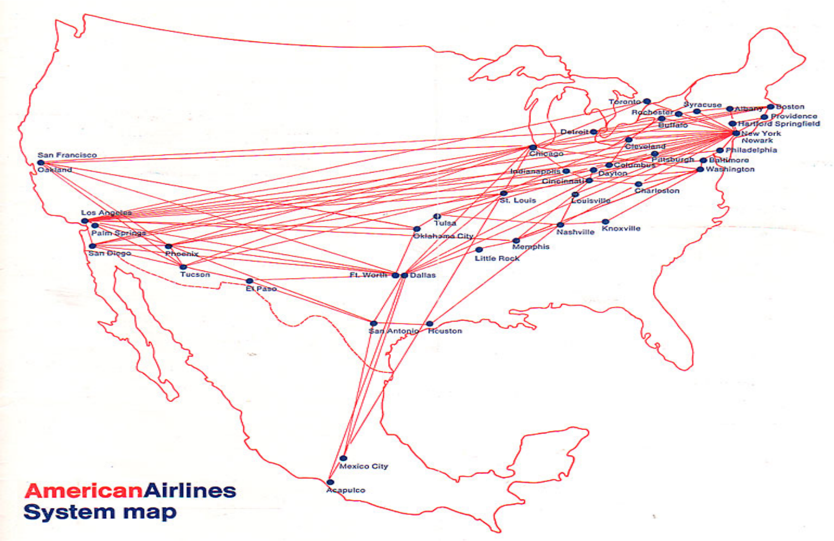


American Airlines Routes in 1934 ("railroad" network)

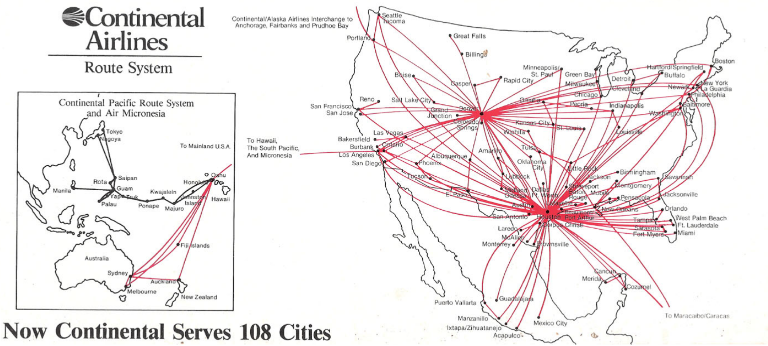


A Nation-Wide Network of Airlines

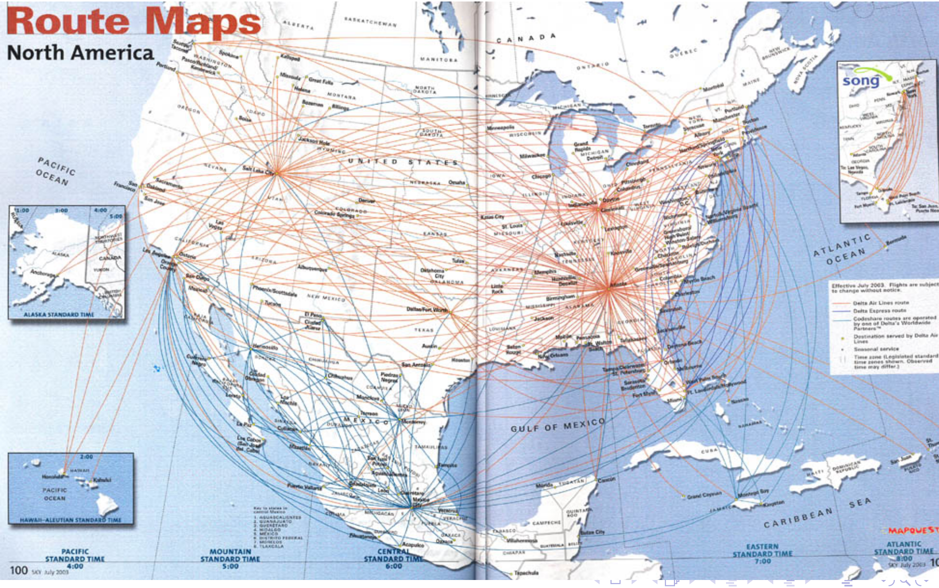
American Airlines Routes in 1968 (point to point)



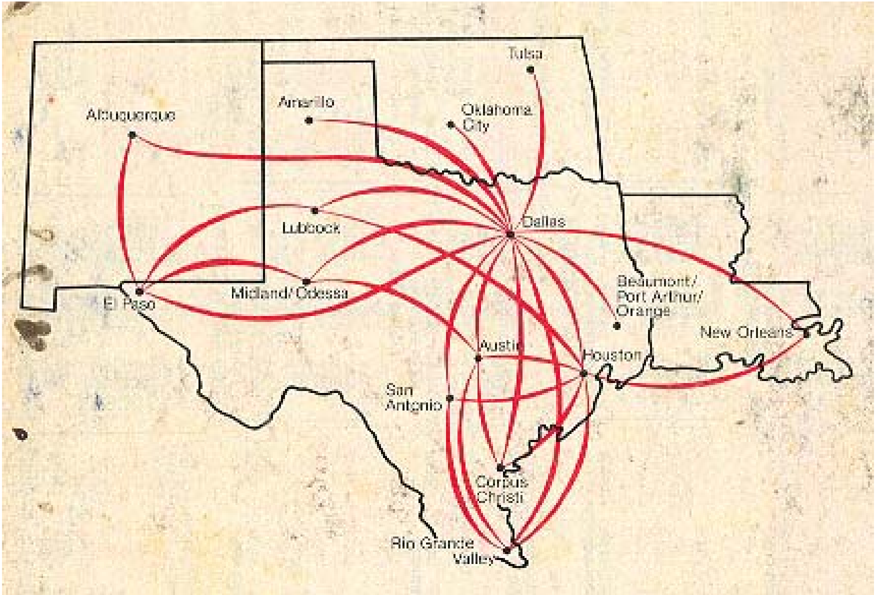
Continental Airlines. Routes Map in 1983 (Hub & Spoke)



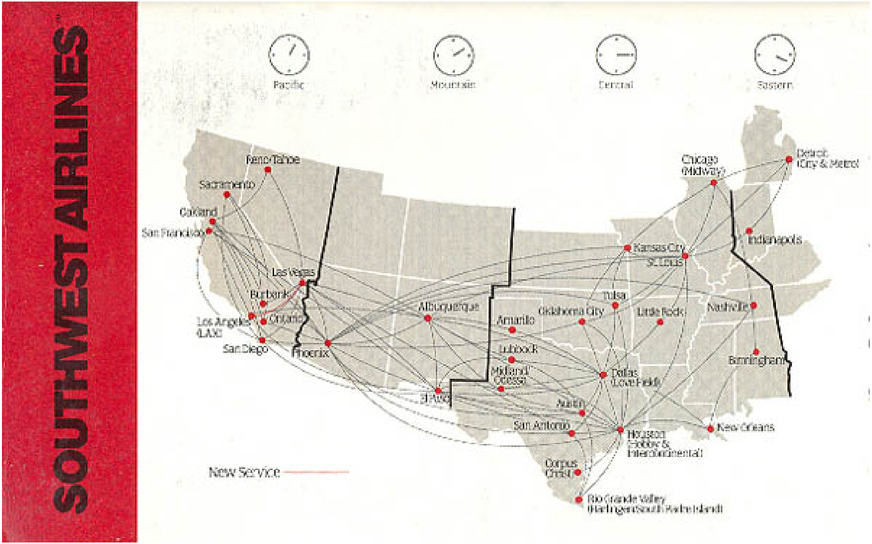
Delta Airlines. Routes Map in 2003



Southwest Airlines. Routes Map in 1980 (Hub & Spoke)



Southwest Airlines. Routes Map in 1990 (point to point)



Why does the structure of an airline network matter?

- Due to **economies of scope of an airline at the airport level**, it affects airline costs (variable, fixed, entry) and, therefore, competition.
  - Some operation costs increase less than proportionally with the number of routes / flights / passengers that an airline has in an airport.

- A hub-and-spoke network **facilitates entry deterrence strategies** such that it can affect competition and welfare even controlling for costs.

Contributions of this paper

- 1. Proposes a **dynamic game of network competition** in the airline industry.
- 2. Proposes methods to solve, estimate, and perform counterfactual experiments using the model.
- 3. It measures the **contribution of economies of scope** to different costs: variable, fixed, and entry costs..
- 4. Uses the model to study empirically the **role of strategic entry deterrence** as a factor to explain why many companies in the US airline industry operate using **hub-and-spoke networks**.

Contribution [1]: Endogenous network model

- Previous structural games of market entry in the airline industry (e.g., Berry, 1992) take into account the existence of **network effects**, but they treat them as **exogenous factors**.

  - Profit of entry airline i's in market m:

$$\Pi_{im} = X_m \beta - \delta \; n_{mt} + \gamma \; (\# \text{ routes served from airports in market } m)$$

- These models treat the "# routes served from airports in market m" as exogenous.

- For merger analysis, or to evaluate policy questions, we need **to endogenize airlines networks**.

Contribution [2]: Solution & Estimation methods

- The dimensionality of the decision space and state space in this problem is humongous.
- By combining simplifying assumptions (decentralizing the decision problem; inclusive-values) and Monte Carlo simulation, we develop a method to solve and to estimate this dynamic game.
- We also propose a method to implement counterfactual experiments using the estimated model and taking into account the existence of multiple equilibria in the model.

Contributions [3]: Economies of scope in entry costs

- One of our empirical findings is that the **main source of economies of scope is entry costs** (not so much in fixed costs or in variable costs).

- This introduces an interesting (and previously unstudied) benefit of hub-and-spoke networks: the **value of flexibility**.
  - Because the smaller entry costs, a HS network can easily adjust (entry & exit) to temporary shocks in demand or costs (e.g., seasonal shocks)

Contributions [4]: Measuring Entry Deterrence strategies

- We use the estimated the model and counterfactual experiments to measure the contribution of different factors (and in particular of **strategic entry deterrence**) to explain hub-and-spoke networks.
- We find that entry-deterrence motives varies very substantially across airlines. There are two airlines where this motive plays an important role.

H&S and Strategic Entry Deterrence

- **Hendricks et al. (ECMA, 1997)** show theoretically that a HS network can deter the entry of competitors.
- In HS an airline is willing to operate nonstop service in city-pair even if the direct profits from that route are negative because it can generate positive profits through its connection with other routes.
- Potential entrants are aware of this, and therefore, it may deter entry.

Model: Airlines, Cities, and Routes

- N airlines and C cities, exogenously given.
- Given the C cities, there are $M \equiv C(C-1)/2$ **non-directional city-pairs** (or markets).
- For each city-pair, an airline decides whether to operate non-stop flights.
- A **route** (or path) is a **directional round-trip between 2 cities**. A route may or may not have stops.
- A route-airline is a product, and there is a demand for each route-airline product.
- Airlines choose prices for each route they provide.

Model: Networks

- We index city-pairs by m, airlines by i, and time (quarters) by t.
- $x_{imt} \in \{0, 1\}$ is a binary indicator for the event "airline i operates non-stop flights in city-pair m"
- $\mathbf{x}_{it} \equiv \{x_{imt} : m = 1, 2, ..., M\}$ is the network of airline i at period t.
- The network $\mathbf{x}_{it}$ describes all the routes (products) that the airline provides, and whether they are non-stop or stop routes.
- Industry network: $\mathbf{x}_{t} \equiv \{\mathbf{x}_{it} : i = 1, 2, ..., N\}$

Model: Airlines' Decisions

- Every period, active airlines in a route compete in prices
- Price competition determines variable profits for each airline.
- Every period (quarter), each airline decides its network for next period. There is *time-to-build*.
- We represent this decision as $\mathbf{a}_{it} \equiv \{a_{imt} : m = 1, 2, ..., M\}$, though $a_{imt} \equiv x_{imt+1}$.

Model: Profit Function

- The airline's total profit function is:

$$\begin{aligned}\Pi_{it} &= \sum_{r \in L(\mathbf{x}_{it})} (p_{irt} - c_{irt}) q_{irt} \\ &- \sum_{m=1}^{M} a_{imt} \left(FC_{imt} + (1 - x_{imt})\ EC_{imt} \right)\end{aligned}$$

- $(p_{irt} - c_{irt}) q_{irt}$ = Variable profit in route r.

- FC_{imt} and EC_{imt} are fixed cost and entry cost

Model — Network effects in demand and costs

- An important feature of the model is that demand, variable costs, fixed costs, and entry costs depend on the scale of operation (number of connections) of the airline in the origin and destination airports of the city-pair: Variable HUB_{imt}.

- For instance,

$$
\begin{aligned}
FC_{imt} &= \gamma_1^{FC} + \gamma_2^{FC}\ HUB_{imt} + \gamma_3^{FC} DIST_m + \gamma_{4i}^{FC} + \gamma_{5c1}^{FC} + \gamma_{5c2}^{FC} \\
EC_{imt} &= \eta_1^{EC} + \eta_2^{EC}\ HUB_{imt} + \eta_3^{EC} DIST_m + \eta_{4i}^{EC} + \eta_{5c1}^{EC} + \eta_{5c2}^{EC}
\end{aligned}
$$

- This implies that markets are interconnected through these hub-size effects. Entry-exit in a market has implications of profits in other markets.

Dynamic Game / Strategy Functions

- Airlines maximize intertemporal profits, are forward-looking, and take into account the implications of their entry-exit decisions on future profits and on the expected future reaction of competitors.
- Airlines' strategies depend only on payoff-relevant state variables, i.e., Markov perfect equilibrium assumption.
- An airline's payoff-relevant information at quarter t is $\{\mathbf{x}_t, \mathbf{z}_t, \varepsilon_{it}\}$.
- Let $\sigma \equiv \{\sigma_i(\mathbf{x}_t, \mathbf{z}_t, \varepsilon_{it}) : i = 1, 2, ..., N\}$ be a set of strategy functions, one for each airline.
- A MPE is a set of strategy functions such that each airline's strategy maximizes the value of the airline for each possible state and taking as given other airlines' strategies.

Dynamic Game: Reducing the dimensionality

- Given the number of cities and airlines in our empirical analysis, the number of possible industry networks is $|X| = 2^{NM} \simeq 10^{10,000}$.
- We consider **two types of simplifying assumptions** that reduce the dimension of the dynamic game and make its solution and estimation manageable.
- 1. An **airline's choice of network is decentralized** in terms of the separate decisions of local managers.
- 2. The state variables of the model can be aggregated in a vector of **inclusive-values** that belongs to a space with a much smaller dimension than the original state space.

Decentralizing the Airline's Choice of Network

- Each airline has M regional managers, one for each city-pair.
- A regional manager decides whether to operate or not non-stop flights in her local-market: she chooses a_{imt}.
- Let R_{imt} be the sum of airline i's variable profits over all the routes that include city-pair m as a segment.
- **ASSUMPTION:** *Local managers maximize the expected and discounted value of*

$$\Pi_{imt} \equiv R_{imt} - a_{imt} \left(FC_{imt} + (1 - x_{imt}) EC_{imt} \right) .$$

- IMPORTANT: A local manager internalizes the effects of his own entry-exit decision in many other routes. Entry deterrence.

Inclusive-Values

- Decentralization of the decision simplifies the computation of players' best responses, but the state space of the decision problem of a local manager is still huge.

- Notice that the profit of a local manager depends only on the variables:

$$\mathbf{x}^*_{imt} \equiv \left(x_{imt},\ R_{imt},\ HUB_{imt}\right)$$

- **ASSUMPTION:** The *vector* $\mathbf{x}^*_{imt}$ *follows a controlled first-order Markov Process:*

$$\Pr\left(\mathbf{x}^*_{im,t+1} \mid \mathbf{x}^*_{imt}, a_{imt}, \mathbf{x}_t, \mathbf{z}_t\right) = \Pr\left(\mathbf{x}^*_{im,t+1} \mid \mathbf{x}^*_{imt}, a_{imt}\right)$$

Dynamic Game: Reducing the dimensionality

- A MPE of this game can be describe as a vector of probability functions, one for each local-manager:

$$P_{im}(\mathbf{x}^{*}_{imt}) : i = 1, 2, ..., N; \;\; m = 1, 2, ..., M$$

- $P_{im}(\mathbf{x}^{*}_{imt})$ is the probability that local-manager (i, m) decides to be active in city-pair m given the state $\mathbf{x}^{*}_{imt}$.
- An equilibrium exits.
- The model typically has multiple equilibria.

Data

- Airline Origin and Destination Survey (DB1B) collected by the Office of Airline Information of the BTS.
- Period 2004-Q1 to 2004-Q4.
- $C = 55$ largest metropolitan areas. $N = 22$ airlines.
- City Pairs: $M = (55 * 54)/2 = 1,485$.

Airlines: Passengers and Markets

	Airline (Code)	# Passengers (in thousands)	# Nonstop City-Pairs (max = 1,485)
1.	Southwest (WN)	25,026	373
2.	American (AA)(3)	20,064	233
3.	United (UA)(4)	15,851	199
4.	Delta (DL)(5)	14,402	198
5.	Continental (CO)(6)	10,084	142
6.	Northwest (NW)(7)	9,517	183
7.	US Airways (US)	7,515	150
8.	America West (HP)(8)	6,745	113
9.	Alaska (AS)	3,886	32
10.	ATA (TZ)	2,608	33
11.	JetBlue (B6)	2,458	22

Distribution of City-Pairs by # Airlines with non-stop flights	
Markets with 0 airlines	35.44%
Markets with 1 airline	29.06%
Markets with 2 airlines	17.44%
Markets with 3 airlines	9.84%
Markets with 4 or more airlines	8.22%

Number of "Monopoly" Non-stop Markets by Airline	
Southwest	157
Northwest	69
Delta	56
American	28
Continental	24
United	17

Entry and Exit	
	All Quarters
Distribution of Markets by Number of New Entrants	
Markets with 0 Entrants	84.66%
Markets with 1 Entrant	13.37%
Markets with 2 Entrants	1.69%
Markets with 3 Entrants	0.27%
Distribution of Markets by Number of Exits	
Markets with 0 Exits	86.51%
Markets with 1 Exit	11.82%
Markets with 2 Exits	1.35%
Markets with more 3 or 4 Exits	0.32%

Transition Matrix for Market Structure

	# Airlines in t+1						
# Airlines at t	0	1	2	3	4	>4	Total
0	93.8%	5.8%	0.4%	-	-	-	516 (100%)
1	9.1%	79.5%	11.2%	0.2%	-	-	430 (100%)
2	0.8%	19.9%	68.4%	10.1%	0.8%	-	247 (100%)
3	0.2%	3.8%	20.2%	52.3%	19.2%	4.3%	160 (100%)
4	-	1.6%	6.4%	31.7%	46.0%	14.3%	63 (100%)
>4	-	-	-	5.1%	33.9%	61.0%	59 (100%)
Total	525	425	259	140	73	53	1,475

Estimation of the Structural Model

- Our estimation approach proceeds in three stages.

1. **Estimation of demand system.** IV estimation (a la BLP) where the IV's are the competitors' hub-sizes.
2. **Estimation of marginal cost functions.**
3. **Estimation of dynamic game of entry-exit.** Nested Pseudo Likelihood (NPL) method.

Demand estimation

	OLS		IV	
Variable	Estimate	(S.E.)	Estimate	(S.E.)
FARE (in $100) [Parameter $-\alpha$]	-0.329	(0.085)	-1.366	(0.110)
ln(s*) [Parameter σ]	0.488	(0.093)	0.634	(0.115)
NON-STOP DUMMY	1.217	(0.058)	2.080	(0.084)
Hubsize-Origin (million people)	0.032	(0.005)	0.027	(0.006)
Hubsize-Destination (million people)	0.041	(0.005)	0.036	(0.006)
Distance (thousand miles)	0.098	(0.011)	0.228	(0.017)

Estimation of Marginal Cost

Variable	Estimate	(S.E.)
NON-STOP DUMMY	0.006	(0.010)
HUBSIZE-ORIGIN (in million people)	-0.023	(0.009)
HUBSIZE-DESTINATION (in million people)	-0.016	(0.009)
DISTANCE (in thousand miles)	5.355	(0.015)

Estimation of Dynamic Game of Entry-Exit		
Data: 1,485 markets × 22 airlines × 3 quarters = 98,010 observations		
	Estimate (in thousand $)	**(Std. Error)**
Fixed Costs (quarterly):		
Fixed cost (average)	119.15	(5.233)
Effect of hub-size on FC	-1.02	(0.185)
Effect of distance on FC	4.04	(0.317)
Entry Costs:		
Entry cost (average)	249.56	(6.504)
Effect of hub-size on EC	-9.26	(0.140)
Effect of distance on EC	0.08	(0.068)

Goodness of fit

		Actual (Avg. All Quarters)	Predicted (Avg. All Quarters)
	Herf. ind. (median)	5338	4955
Distribution	Markets with 0 air	35.4%	29.3%
of City-Pairs	" " 1 air	29.1%	32.2%
by # Airlines	" " 2 air	17.4%	24.2%
	" " 3 air	9.8%	8.0%
	" " $\geq$4 air	8.2%	6.2%

Goodness of fit [2]

		Actual (Avg. All Quarters)	Predicted (Avg. All Quarters)
Number (%) of	Southwest	151 (43.4%)	149 (38.8%)
'Monopoly'	Northwest	66 (18.9%)	81 (21.1%)
City-Pairs	Delta	57 (16.4%)	75 (19.5%)
for top 6 airlines	American	31 (8.9%)	28 (7.3%)
	Continental	27 (7.7%)	27 (7.0%)
	United	16 (4.6%)	24 (6.2%)

Goodness of fit [3]

		Actual (Avg. All Quarters)	Predicted (Avg. All Quarters)
Distributio–n	Markets with 0 ent	84.7%	81.9%
of City-Pairs	" " 1 ent	13.4%	16.3%
by # entrants	" " 2 ent	1.7%	1.6%
	" " $\geq$3 ent	0.3%	0.0%
Distribution	Markets with 0 ex	86.5%	82.9%
of City-Pairs	" " 1 ex	11.8%	14.6%
by # of exits	" " 2 ex	1.4%	1.4%
	" " $\geq$3 ex	0.3%	0.0%

Counterfactuals of empirical results

- Effects of Economies of Scope and Entry Deterrence motives on airlines propensity to hubbing.
- A first group of experiments consists in **shutting down economies of scope** by making zero the parameters associated with HUB_{imt} in: demand, marginal costs, fixed costs, and entry costs (one by one).
- In the experiment that measures the **entry deterrence motive for HS**, we consider that local managers maximize the value of profits where revenue comes only from the nonstop product in the city pair, and ignore revenue from connecting flights that have this city-pair as a segment. This eliminates the entry deterrence mechanism in Hendricks et al.

Counterfactual Experiments (CR2 Hub ratios)

Carrier	Obs.	Zero Hub-Size Effects in: var. profits	fixed costs	entry costs	No entry Deter
Southwest	18.2	17.3	15.6	8.9	16.0
American	42.0	39.1	36.5	17.6	29.8
United	45.7	42.5	39.3	17.8	32.0
Delta	48.0	43.7	34.0	18.7	25.0
Continental	68.3	62.1	58.0	27.3	43.0
Northwest	49.2	44.3	36.9	18.7	26.6
US Airways	45.3	41.7	39.0	18.1	34.4

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Summary of empirical results

1. Hub-size effects on **demand, variable costs and fixed operating costs** are significant but can **explain very little of the propensity to hub-spoke networks**.

2. **Hub-size effects on Sunk Entry Costs are large**. This is the most important factor to explain hub-spoke networks.

3. **Strategic factors: hub-spoke network as a strategy to deter entry** is the second most important factor for some of the largest carriers (Northwest and Delta).

4. **Sunk Entry Costs are positively with Entry Deterrence.** Airlines with larger entry costs tend to have higher propensity to use hub-and-spoke networks to deter entry of competitors.

Further Questions

- **Economic interpretation of the negative effect of hub-size on entry costs**: is it due to technological reasons, OR it has to do with contracts between airports and airlines?. Allocation of gates? Rent sharing between airports and airlines?

- **Explaining 'hubbing' and 'de-hubbing'.** Over a longer period of time, some airlines have experienced a 'hubbing-process' (increasing concentration in a few airports) and other have experienced a 'de-hubbing process'. Can this model explain this evolution? Or can be extended to explain this evolution?

- **Medium-run and Long-run effects of airline mergers**. Endogenous changes in network structure after a merger are important to evaluate the effect of mergers. This type of model can be used for this purpose.