Airline Consolidation and the Distribution of Traffic between Primary and Secondary Hubs[*]

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Abstract

Several airline consolidation events have recently been completed both in Europe and in the United States. The model we develop considers two airlines operating hub-and-spoke networks, using different hubs to connect the same spoke airports. We assume the airlines to be vertically differentiated, which allows us to distinguish between primary and secondary hubs. We conclude that this differentiation in air services becomes more accentuated after consolidation, with an increased number of flights being channeled through the primary hub. However, congestion can act as a brake on the concentration of flight frequency in the primary hub following consolidation. Our empirical application involves an analysis of Delta's network following its merger with Northwest. We find evidence consistent with an increase in the importance of Delta's primary hubs at the expense of its secondary airports. We also find some evidence suggesting that the carrier chooses to divert traffic away from

those hub airports that were more prone to delays prior to the merger, in particular New York's JFK airport.

1 Introduction

The global airline industry is currently undergoing a major process of consolidation. In particular, the US market is experiencing its second wave of consolidation since the deregulation of the US airline industry in 1977, while the European market is experiencing its first wave of mergers since the gradual liberalization of the EU airline market was completed in 1997. Globally, the industry is coming under the increasing domination of the three global alliances (Oneworld, Star Alliance, and SkyTeam). The most recent high-profile events on the European market include the Air France-KLM merger, Lufthansa's acquisition of Swiss International Airlines and Austrian Airlines, and British Airways' mergers with Iberia and BMI. On the other side of the Atlantic, Delta Air Lines purchased Northwest Airlines, and United Airlines merged with Continental Airlines.[1] In each of these cases, the partners to the merger operated hub-and-spoke networks, sometimes featuring multiple hubs. After consolidation, the airlines are expected to reorganize flight frequencies in their joint hub-and-spoke networks.

This paper focuses on the effects of airline consolidation on the distribution of traffic between primary and secondary hubs, taking into account the impact of congestion at the partners' airports. The question of the impact of airport congestion on an airline's network choice is important and complex. The complexity of the matter lies in the trade-off between the efficiency a hub-and-spoke operator gains by consolidating most of its traffic in a single hub, and the eventual increased congestion that may result in losses to the airline and its passengers alike.

Airline consolidation can involve different types of agreements across the companies depending on the extent of their integration. The literature on airline consolidation, which includes both alliances and mergers, is surprisingly not very extensive. Brueckner (2001) studies the effects of airline alliances on fares and Brueckner (2003) distinguishes the effects of codesharing and antitrust immunity,[2] whereas Flores-Fillol and Moner-Colonques (2007) focus on the profitability of airline alliances.[3] A recent paper by Brueckner and Proost (2010) studies *carve-outs* in the airline industry, which are occasionally imposed by regulators when granting antitrust immunity to alliances and joint ventures in response to concerns about their potential anti-competitive effects. In the case of mergers, the first wave of US mergers (in the 1980s) has been empirically examined by Borenstein (1990), Kim and Singal (1993), and Kwoka and Shumilkina (2010). These studies focus on the price and market power effects of mergers. The impact of the recent US airline merg-

ers (US Airways/America West, Delta/Northwest, and Continental/United) has yet to be evaluated comprehensively owing to problems of data availability. However, Bilotkach (2011) shows that the US Airways/America West merger did have an effect on the airlines' frequency of services because of the resulting change in the level of multimarket contact. Most recently, Luo (forthcoming) provides an analysis of price effects of Delta-Northwest merger. She finds that this consolidation event did not lead to significant fare increases on individual routes where the merger partners used to compete. European airline mergers remain largely unstudied, due to relatively poor data availability. Dobson and Piga (2013) analyze business model assimilation following mergers between European low-cost carriers. Finally, Fageda and Perdiguero (2014) identify asymmetric effects of a merger involving three Spanish airlines, reflecting airline type (i.e., low-cost or network carriers).

Our theoretical model assumes two airlines operating hub-and-spoke networks, using different hubs to connect the same spoke airports. We assume the airlines to be vertically differentiated,[4] which allows us to distinguish between primary and secondary hubs. Consumer heterogeneity arises from different valuations of flight frequency, which serves as a measure of service quality, as in Brueckner and Flores-Fillol (2007).[5] We consider a pre-consolidation scenario with each airline operating independently, as well as a post-consolidation case, where carriers make joint frequency decisions, leading to the reallocation of the spoke-to-spoke traffic on routes between the two hubs in the joint network. Generally, our modeling exercise suggests that even though the airline will tend to give increasing priority to its main hub airport following consolidation, the resulting build-up of congestion at the main hub may lead to some diversion of traffic to its secondary hub. This is indicative of a particular kind of self-internalization of the congestion externality, where the secondary hub is used to relieve congestion at the main hub airport.[6]

For our empirical application, we examine the network reorganization subsequent to the Delta-Northwest merger. We use frequency data at the route level obtained from RDC aviation, together with route- and airport-level control variables. For the purposes of our analysis, we have included data for all flights operated by Delta and Northwest in the three-year period preceding the merger (2007, 2008, and 2009), as well as for all the services operated by Delta in the two years following the merger (2010 and first quarter of 2011).

We then implement a simple difference-in-differences estimator to determine whether the merger led to significant changes in the frequency of services from and to the hubs in

the joint network. The hubs involved are Atlanta, Cincinnati, New York JFK, Salt Lake City, Detroit, Minneapolis, and Memphis. We used market-level and spoke-level fixed effects to account for the corresponding heterogeneity. The results obtained from the data analysis indicate that, following the merger, Delta Air Lines increased its reliance on the Atlanta and Salt Lake City hubs (Atlanta being the main hub in Delta's network, and Salt Lake City being Delta's regional hub in the western United States). We also found some evidence consistent with the declining importance of other hub airports (in particular, all of Northwest Airlines' former hubs) in the joint network.

The increased importance of Atlanta and Salt Lake City following the merger confirms the predictions of our modeling exercise. After consolidation, Delta became less dependent on what prior to the merger had been its least reliable hubs (most notably, New York JFK and Northwest Airlines' former hubs). Since our post-merger period coincides with a period of generally lower demand for air travel (and one that as a result is associated with more reliable air services), it is not easy to determine whether and to what extent any post-merger congestion build-up at the airports in Atlanta and Salt Lake City airports might have contributed to the diversion of some traffic to Delta's secondary hubs.

The rest of the paper is organized as follows. The theoretical model is presented in Section 2 and the empirical analysis is reported in Section 3. A brief conclusion closes the paper. The proofs of the theoretical model can be consulted in the Appendix.

2   The model

2.1   Pre-consolidation scenario

Before the merger, each airline operates a simple hub-and-spoke network, as shown in Fig. 1.

<center>—Insert Fig. 1 here—</center>

It is assumed that the only relevant demand is in the city-pair market AB, which is served by two vertically-differentiated airlines.[7] This theoretical model is derived from the literature on vertical product differentiation, initiated by Gabszewicz and Thisse (1979) and Shaked and Sutton (1982 and 1983) and summarized by Tirole (1988). Consumer utility is given by $\sigma f - p$, where f is product quality and p is price.[8] Consumer heterogeneity arises from different valuations of product quality (σ).

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Applying this setting to the airline industry, product quality is assumed to be flight frequency, and prices can be considered as airfares. Various studies (see, for example, Brueckner and Flores-Fillol, 2007) consider flight frequency to be the best proxy to service quality, as a higher frequency increases passengers' travel opportunities. Indeed, regional services (addressed primarily to business travelers) typically offer high frequencies at high fares, whereas low-cost connections (addressed primarily to leisure travelers) typically offer low frequencies at low fares.[9]

More specifically, we assume utilities to be $U_1 = \sigma f_1 - p_1$ and $U_2 = \sigma f_2 - p_2$, where $\sigma \sim U[1, z]$ and $z \geqslant 2$, with z being a measure of preference dispersion. At this juncture, we assume airline 1 to be characterized by a lower quality of service, which is offered at lower fares. Therefore, both $f_2 > f_1 > 0$ and $p_2 > p_1 > 0$ hold. Denoting $d = f_2 - f_1 > 0$ the service quality gap and assuming fully-served markets, the indifferent consumer's valuation of service quality is given by $\sigma_0 = \frac{p_2 - p_1}{d}$, as depicted in Fig. 2.

$$-\text{Insert Fig. 2 here}-$$

Travelers with a low valuation of service quality purchase the lower-quality product (i.e., product 1) and travelers with a high valuation of service quality purchase the higher-quality product (i.e., product 2). This framework corresponds to the situation prevailing between Delta and Northwest before the merger, with Delta offering a larger network and richer connectivity possibilities at its hubs (above all in Atlanta - the world's largest airport by passenger volume). Since markets are fully-served, then $U_1(\sigma = 1) \geqslant 0$ and $U_2(\sigma = \sigma_0) \geqslant 0$ require $f_1 \geqslant p_1$ and $\frac{p_2 - p_1}{d} f_2 \geqslant p_2$, respectively. Since market shares for airlines 1 and 2 are $\phi_1 = \frac{\sigma_0 - 1}{z - 1}$ and $\phi_2 = \frac{z - \sigma_0}{z - 1}$, demands are given by

$$q_1 = \underbrace{\frac{(p_2 - p_1) - d}{d(z - 1)}}_{\phi_1} H, \text{ and} \tag{1}$$

$$q_2 = \underbrace{\frac{dz - (p_2 - p_1)}{d(z - 1)}}_{\phi_2} H, \tag{2}$$

where $H \geqslant 0$ stands for market size. Note that $d \leqslant p_2 - p_1 \leqslant dz$ is assumed to ensure non-negative quantities. A consequence of having fully-served markets is that either a higher quality gap (d) or a lower fare gap (i.e., $p_2 - p_1$) imply a higher relative traffic volume (i.e., $q_2 - q_1$). It can be observed that q_1 decreases with d whereas q_2 increases with d.

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On the cost side, as in Flores-Fillol (2009), a flight's operating cost for carrier 1 in the absence of congestion is given by $\theta f_1 + \tau s_1$ where s_1 stands for carrier 1's aircraft size (i.e., the number of seats) on a given route (either AC or BC). Parameters θ and τ are the marginal cost per departure (or aircraft-operation cost) and the marginal cost per seat, respectively. Cost per departure (θf_1) increases with frequency, reflecting decreasing returns as in Brueckner (2009).[10] This cost consists of fuel for the duration of the flight, airport maintenance, renting the gate at which passengers board and disembark, and the landing and air-traffic control fees. As in Brueckner (2004) and Brueckner and Flores-Fillol (2007), it is assumed that all seats are filled, so that the load factor equals 100% and therefore $s_1 = q_1/f_1$, i.e., aircraft size can be determined residually by dividing the airline's total traffic on a given route by the number of planes.[11] Note that the cost per seat, which can be written $\theta q_1/s_1^2 + \tau$, visibly decreases with s_1 capturing the presence of economies of traffic density (i.e., economies from operating a larger aircraft) that are unequivocal in the airline industry.

Now let us consider airline congestion costs. Note that the level of congestion experienced by carrier 1 on a route (either AC or BC) is attributable to aircraft movements both at the hub airport $(2f_1)$, and at the spoke airport $(f_1 + f_2)$. As a consequence, airline 1's congestion costs on a route are given by $\eta (3f_1 + f_2)$ with $\eta \geqslant 0$ being the congestion damage. Thus, a *flight's operating costs on a route* is $\theta f_1 + \tau s_1 + \eta (3f_1 + f_2)$. Therefore, carrier 1's total cost from operating on a route is $f_1 [\theta f_1 + \tau s_1 + \eta (3f_1 + f_2)]$ or, equivalently,

$$c_1 = \theta f_1^2 + \tau q_1 + \eta f_1 (3f_1 + f_2). \tag{3}$$

Thus, airline 1's profit is $\pi_1 = p_1 q_1 - 2c_1$, and it can be rewritten as $\pi_1 = (p_1 - 2\tau) q_1 - 2f_1 [\theta f_1 + \eta (3f_1 + f_2)]$, indicating that variable costs are independent of the number of flights, and that the city-pair market AB is a connecting market that is served making use of two routes. The corresponding expressions for carrier 2 are derived simply by interchanging subscripts 1 and 2. This model is used to study the effect on fares, frequencies, and travel volumes of a consolidation process involving carriers 1 and 2.[12]

Since fares can be adjusted more readily than frequencies, the model is solved sequentially, with flight frequency being selected before fares.[13] In this way, fares are chosen in a second stage conditional on frequencies, while frequencies are chosen in a first stage taking into account their impact on fares in the second stage. The outcome is a Subgame Perfect Nash equilibrium.

Proceeding by backwards induction, we solve the second stage of the game in which the airlines choose p_1 and p_2 as functions of f_1 and f_2. After plugging Eqs. (1) and (2) into π_1 and π_2 and computing $\partial \pi_1 / \partial p_1 = 0$ and $\partial \pi_2 / \partial p_2 = 0$,[14] the airlines' reaction functions are

$$p_1 = \frac{p_2 + 2\tau - d}{2}, \text{ and} \tag{4}$$

$$p_2 = \frac{p_1 + 2\tau + dz}{2}, \tag{5}$$

which show that fares are strategic complements. Note that $p_2 + 2\tau \geqslant d$ needs to be assumed to ensure $p_1 \geqslant 0$. From Eqs. (4) and (5), we obtain the following second-stage equilibrium fares

$$p_1 = \frac{d(z-2)}{3} + 2\tau, \text{ and} \tag{6}$$

$$p_2 = \frac{d(2z-1)}{3} + 2\tau. \tag{7}$$

These equilibrium fares impose a mark-up over the marginal cost. The following lemma arises from the fare difference $p_2 - p_1 = \frac{d(z+1)}{3}$.

Lemma 1 *The airline that offers higher-quality services sets higher fares, and the fare difference $p_2 - p_1$ increases with the service quality gap (d). In addition, $p_2 - p_1$ rises with preference dispersion (z) since more heterogeneous consumers require more differentiated frequencies and therefore fares.*

By inspection of Eqs. (1) and (2) together with the fare difference $p_2 - p_1$, it can be seen that the direct effect of d on q_1 and q_2 is offset by its indirect effect through the fare difference. As a consequence, traffic volumes are independent of flight frequencies in equilibrium. Thus, after plugging Eqs. (6) and (7) into Eqs. (1) and (2), we obtain

$$q_1^n = \frac{z-2}{3(z-1)} H, \text{ and} \tag{8}$$

$$q_2^n = \frac{2z-1}{3(z-1)} H, \tag{9}$$

where superscript n denotes the pre-consolidation scenario. We can verify that $q_2^n - q_1^n > 0$, which is a direct consequence of $d > 0$ because a higher flight frequency typically results in a higher traffic volume.

Using Eqs. (6) and (7) and $d = f_2 - f_1$, we obtain the airlines' first-stage profit functions

$$\pi_1 = \underbrace{\frac{H(z-2)^2(f_2-f_1)}{9(z-1)}}_{(p_1-2\tau)q_1^n} - 2f_1[\theta f_1 + \eta(3f_1 + f_2)], \text{ and} \tag{10}$$

$$\pi_2 = \underbrace{\frac{H(2z-1)^2(f_2-f_1)}{9(z-1)}}_{(p_2-2\tau)q_2^n} - 2f_2[\theta f_2 + \eta(3f_2 + f_1)], \tag{11}$$

which become functions of just f_1 and f_2. The first term in the expressions is the margin, which is larger for airline 2, given that $p_2 > p_1$ and $q_2^n > q_1^n$. By inspection of Eq. (10), it can be verified that $\partial \pi_1 / \partial f_1 < 0$. Therefore, airline 1 will choose the minimum possible f_1 (corner solution). Given that markets are fully-served, this value of f_1 will be the one making $U_1(\sigma = 1) = 0$, as shown in Fig. 2. This implies that $f_1 = p_1$ and therefore airline 1's reaction function is

$$f_1 = \frac{(z-2)f_2 + 6\tau}{z+1}. \tag{12}$$

From $\partial \pi_2 / \partial f_2 = 0$,[15] we obtain the remaining reaction function,[16] which is given by

$$f_2 = \frac{H(2z-1)^2 - 18\eta f_1(z-1)}{36(z-1)(3\eta+\theta)}. \tag{13}$$

The reaction functions have different slopes and yield a stable equilibrium outcome,[17] which allows us to compute the equilibrium service quality gap, which is

$$d^n = \frac{H(2z-1)^2 - 36\tau(z-1)(7\eta+2\theta)}{6(z-1)[\eta(7z+4) + 2\theta(z+1)]}, \tag{14}$$

and $H > \underline{H}_1 \equiv \frac{36\tau(z-1)(7\eta+2\theta)}{(2z-1)^2}$ is required to ensure $d^n > 0$.[18] To illustrate the properties of the equilibrium, we undertake a comparative-static analysis, which is summarized in the lemma that follows.

Lemma 2 *Assuming $H > \underline{H}_1$, the quality gap (d) falls with an increase in the congestion damage (η), the fixed flight cost (θ), or the marginal seat cost (τ). The quality gap rises with an increase in preference dispersion (z) with $z > 2.4$ or market size (H).*

On the one hand, the above lemma suggests that an increase in costs (marginal seat cost, fixed cost, and congestion damage) has a more marked impact on the quality of carrier 2 and, as a consequence, the quality gap becomes narrower. On the other hand, larger

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and more disperse markets both have a positive impact on the service quality gap. These results seem to be driven by the fact that airline 2 operates more flights and has a higher traffic volume.

Substituting in the second-stage choice variables, we can compute p_1^n, p_2^n,[19] and

$$p_2^n - p_1^n = \frac{d^n (z+1)}{3} = \frac{(z+1) \left[H (2z-1)^2 - 36\tau (z-1)(7\eta + 2\theta) \right]}{18 (z-1) \left[\eta (7z+4) + 2\theta (z+1) \right]}, \qquad (15)$$

which is obviously positive as long as $H > \underline{H}_1$.

Finally, in line with Shaked and Sutton (1983), we can verify that in the case of minimum preference dispersion, intense fare competition drives the low service quality airline out of the market, i.e., when $z = 2$, the equilibrium fare for airline 1 is $p_1^n = 2\tau$ and thus $q_1^n = 0$ and $\pi_1^n < 0$. Therefore, z determines the number of airlines operating in the industry and, hence, the intensity of competition (regardless of demand size and fixed costs).[20]

2.2 Post-consolidation scenario

We model a consolidation process involving carriers 1 and 2 by assuming they are able to make joint decisions regarding flight frequencies, whereas their fares are determined independently. A setup permitting joint fare and frequency setting requires assuming partially-served markets, which complicates substantially the analysis. A numerical analysis of the full-cooperation merger with partially-served markets has been carried out and partially confirms our theoretical results.[21]

In addition, looking at recent consolidation processes in the airline industry, it is not unusual to observe individual airlines retaining their independence in fare setting decisions even under joint ownership (this has happened in Lufthansa's acquisition of Swiss International Airlines and Austrian Airlines). Further, an eventual full integration of carriers following the merger does take time. For instance, it has taken years to resolve all the labor related issues following each of the recent US airline mergers; and integration of the merger partners' booking and yield management systems is also far from immediate and smooth.[22] In any case, a full-cooperation merger can only be attained some years after the formal signature of the agreement. In conclusion, we think that our theoretical model fits well: i) in particular, for some specific consolidation processes, and ii) in general, for all consolidation processes at their early stage. At this point, we would like to stress that our

empirical application focuses on the first two years after the Delta-Northwest merger.

Thus, the second stage of the game remains as in the pre-consolidation scenario, i.e., $q_1^c = q_1^n$ and $q_2^c = q_2^n$, where superscript c denotes the consolidation scenario. In the first stage, firms jointly choose f_1 and f_2 to maximize

$$\pi_{12} = \underbrace{\frac{H(z-2)^2(f_2-f_1)}{9(z-1)}}_{(p_1-2\tau)q_1^n} + \underbrace{\frac{H(2z-1)^2(f_2-f_1)}{9(z-1)}}_{(p_2-2\tau)q_2^n} - 2f_1\left[\theta f_1 + \eta(3f_1+f_2)\right] - 2f_2\left[\theta f_2 + \eta(3f_2+f_1)\right],$$
(16)

and again it can be verified that $\partial\pi_{12}/\partial f_1 < 0$, meaning that the optimal f_1 is obtained as a corner solution (i.e., $f_1 = p_1$). Consequently, we obtain the same reaction function for airline 1 as in the pre-consolidation scenario (see Eq. (12)). From $\partial\pi_{12}/\partial f_2 = 0$,[23] we obtain the remaining reaction function, which is given by

$$f_2 = \frac{H[z(5z-8)+5] - 36(z-1)\eta f_1}{36(z-1)(3\eta+\theta)}.$$
(17)

The equilibrium frequencies are obtained from these reaction.[24] The equilibrium service quality gap is therefore

$$d^c = \frac{H[z(5z-8)+5] - 72\tau(z-1)(4\eta+\theta)}{12(z-1)[\eta(4z+1)+\theta(z+1)]},$$
(18)

and $H > \underline{H}_2 \equiv \frac{72\tau(z-1)(4\eta+\theta)}{z(5z-8)+5}$ is required to ensure $d^c > 0$.[25] The comparative-static analysis in the post-consolidation case shows the same effects as in the pre-consolidation scenario (i.e., see Lemma 2), except for the higher minimum z that is required to have a quality gap that increases with preference dispersion.

Lemma 3 *Assuming $H > \underline{H}_2$, the quality gap (d) falls with an increase in the congestion damage (η), the fixed flight cost (θ), or the marginal seat cost (τ). The quality gap rises with an increase in preference dispersion (z) with $z > 2.9$ or market size (H).*

Finally, substituting in the second-stage choice variables, we can compute p_1^c, p_2^c,[26] and

$$p_2^c - p_1^c = \frac{d^c(z+1)}{3} = \frac{(z+1)\{H[z(5z-8)+5] - 72\tau(z-1)(4\eta+\theta)\}}{36(z-1)[\eta(4z+1)+\theta(z+1)]},$$
(19)

which is obviously positive as long as $H > \underline{H}_2$.

As in the pre-consolidation scenario, the consolidated firm would stop providing low quality services in the case of minimum preference dispersion (i.e., $z = 2$).

In the light of these results, we can compare the pre- and post-consolidation scenarios and study the effect of the parameters of the model in such comparisons.

2.3 Comparison

In this subsection we first assess the effects of airline consolidation by comparing flight frequencies and fares in the two scenarios outlined above. We then analyze the impact of congestion damage on the results of these comparisons.

Let us denote $\Delta^{f_1} = \Delta^{p_1} = f_1^c - f_1^n$,[27] $\Delta^{f_2} = f_2^c - f_2^n$, and $\Delta^{p_2} = p_2^c - p_2^n$. By observing these differences, it can be seen that all of them are positive for $H > \underline{H}_3 \equiv \frac{216\eta\tau(z-1)(3\eta+\theta)}{(z-2)(z+1)[3\eta(z-3)+2\theta(z-2)]}$ and $z \geqslant 3$. Let us denote $\underline{H} = \max\{\underline{H}_1, \underline{H}_2, \underline{H}_3\}$ the required lower bound for market size ensuring comparable results between the two scenarios. Then the following lemma summarizes the results of these comparisons.

Lemma 4 *Assuming $H > \underline{H}$ and $z \geqslant 3$, both flight frequencies and fares increase after consolidation.*

This result indicates that, in a vertically-differentiated market, airline consolidation seems to produce an up-market movement, providing higher quality services at higher fares.

Equivalently, we define $\Delta^d = d^c - d^n$ and $\Delta^{p_2-p_1} = (p_2^c - p_1^c) - (p_2^n - p_1^n)$, where $\Delta^d = \Delta^{f_2} - \Delta^{f_1}$ and $\Delta^{p_2-p_1} = \Delta^{p_2} - \Delta^{p_1} = \Delta^{p_2} - \Delta^{f_1}$ because $\Delta^{f_1} = \Delta^{p_1}$.[28] The proposition below shows that the quality gap and the fare gap also increase after consolidation for $H > \underline{H}$ and $z \geqslant 3$.

Proposition 1 *Assuming $H > \underline{H}$ and $z \geqslant 3$, both the quality gap and the fare gap increase after consolidation, i.e., $\Delta^d > 0$ and $\Delta^{p_2-p_1} > 0$.*

This proposition suggests that the differentiation between high and low quality air services is accentuated after consolidation, and more flights are channeled via the higher service-quality routing.[29]

Having explained the effects of airline consolidation, we now shift our attention to the analysis of congestion in order to determine its impact on the reorganization of fares and flight frequencies after consolidation. Thus, we compute the derivative of the above differentials with respect to the congestion damage (η). It can be verified that $\partial\Delta^{f_1}/\partial\eta = \partial\Delta^{p_1}/\partial\eta < 0$, $\partial\Delta^{f_2}/\partial\eta < 0$, and $\partial\Delta^{p_2}/\partial\eta < 0$ for $z \geqslant 3$, as summarized in the following lemma.

Lemma 5 *Assuming $z \geqslant 3$, then Δ^{f_1} (and thus Δ^{p_1}), Δ^{f_2}, and Δ^{p_2} fall with an increase in congestion damage (η).*

We know from Lemma 4 that both flight frequencies and fares increase after consolidation. However, Lemma 5 suggests that this up-market movement is mitigated in presence of congestion. Finally, to determine the effect of congestion on consolidation processes, we need to know the effect of congestion damage on Δ^d and $\Delta^{p_2-p_1}$. The proposition below shows that $\partial \Delta^d / \partial \eta < 0$ and $\partial \Delta^{p_2-p_1} / \partial \eta < 0$ for $z \geqslant 3$.

Proposition 2 *Assuming $z \geqslant 3$, both Δ^d and $\Delta^{p_2-p_1}$ fall with an increase in congestion damage (η).*

Although congestion moderates the increase in fares and frequencies on both routings following consolidation, Proposition 2 shows that the impact is more marked on the higher service-quality routing. This being the case, an increase in congestion damage mitigates the increase of the quality gap and the fare gap after consolidation. Thus, congestion may serve to prevent the concentration of flight frequency on the higher service-quality routing after consolidation by creating incentives to use the poorer service-quality connection more intensively.

2.4   The social optimum

With the effects of airline consolidation understood, attention now shifts to welfare analysis where a social planner with the power to dictate airline and consumer choices decides flight frequency and traffic so as to maximize social surplus, that is computed as the sum of total utility and airline profit. The social optimum is independent of the interaction between carriers.

Consumer surplus (i.e., total utility) can be written

$$U = U_1 + U_2 = \left[\int_1^{\sigma_0} (\sigma f_1 - p_1) \frac{1}{z-1} d\sigma + \int_{\sigma_0}^z (\sigma f_2 - p_2) \frac{1}{z-1} d\sigma \right] H, \qquad (20)$$

and carriers' total profits are

$$\pi = \pi_1 + \pi_2 = \left[(p_1 - 2\tau) \int_1^{\sigma_0} \frac{1}{z-1} d\sigma \right] H - 2f_1 \left[\theta f_1 + \eta \left(3f_1 + f_2 \right) \right] +$$
$$\left[(p_2 - 2\tau) \int_{\sigma_0}^z \frac{1}{z-1} d\sigma \right] H - 2f_2 \left[\theta f_2 + \eta \left(3f_2 + f_1 \right) \right]. \qquad (21)$$

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Adding utilities and profits for both carriers and performing the integration in Eqs. (20) and (21) we obtain

$$
W = \left[\frac{f_1}{z-1} \left(\frac{\left(\sigma_0^*\right)^2 - 1}{2} \right) + \frac{f_2}{z-1} \left(\frac{z^2 - \left(\sigma_0^*\right)^2}{2} \right) - 2\tau \right] H -
$$
$$
2\theta f_1^2 - 2\theta f_2^2 - 6\eta f_1^2 - 6\eta f_2^2 - 4\eta f_1 f_2,
$$
(22)

where σ_0^* determines the optimal share of air traffic traveling with each of the carriers. Note that the first element gives the frequency benefits and the aggregate seat cost and the rest of the terms are the cost per departure and the congestion costs. The planner chooses σ_0^* along with flight frequencies to maximize Eq. (22). Observe that airfares do not appear in the expression because they are a transfer between airlines and air travelers. From the first-order condition for choice of σ_0^*, we obtain $\sigma_0^* = 0$, which means that the lower-quality service should not be provided. From $\sigma_0^* = 0$ and the first-order conditions for f_1 and f_2, we obtain

$$
f_1^* = 0, \; f_2^* = d^* = \frac{Hz^2}{8\left(z-1\right)\left(\theta + 3\eta\right)},
$$
(23)

where $f_1^* = 0$ is consistent with $\sigma_0^* = 0$ and f_2^* is strictly positive.

Using these results, the social optimum and the equilibrium are easily compared from Eqs. (14), (18), and (23).

Proposition 3 *There is an overprovision of flight frequency of the lower-quality service (the lower-quality service should not be provided) and the quality gap is suboptimal (i.e., $d^* > d^n, d^c$).*

The proposition shows that the provision of two vertically-differentiated services is inefficient and that the lower-quality service should be abandoned. The overprovision of flight frequency of the lower-quality service may be explained by an aggregated overprovision of frequencies. This is a result of airline competition in the presence of congestion, which is consistent with previous studies (see Flores-Fillol, 2010; and Fageda and Flores-Fillol, 2013).

The abandonment of the lower-quality service, despite the presence of congestion externality, constitutes an interesting aspect of the welfare analysis in our model. This brings us back to the discussion at the beginning of the paper, where we noted the efficiency-congestion trade-off that the airline operating a multi-hub network may face.[30] Interestingly, our analysis indicates that this trade-off is not important enough for the social

planner, but the airline does take congestion into account when deciding on the traffic allocation in the multi-hub network.

Looking at Proposition 1 along with Proposition 3, the following corollary arises.

Corollary 1 *Assuming $H > \underline{H}$ and $z \geqslant 3$, airline consolidation reduces the inefficiency associated to the quality gap.*

This efficiency gain is explained by the increased differentiation between high and low quality air services after consolidation and the suboptimality of the quality gap.

3   The empirical analysis

The empirical analysis uses the results of the theoretical model developed in this section to examine the reorganization of the joint network operated by Delta Air Lines and Northwest Airlines following the merger between the two carriers.

3.1   Delta-Northwest merger

The Delta-Northwest consolidation presents a very good case for the empirical application of our model because it is sensible to consider that Delta was offering a higher-quality service than Northwest in the period before the merger. Looking at data from the US Department of Transportation in the period before the merger (2007-2009), Delta was globally offering one third more flights than Northwest. Looking at our dataset in the same period, Delta's and Northwest's mean route frequencies are 414 and 318 quarterly flights, respectively.

In addition, there are other reasons that recommend the empirical analysis of this consolidation process. First, a sufficient amount of time has elapsed since the merger for the reorganization of the network to be fairly close to completion; and second, both carriers operated multi-hub networks prior to the merger. Specifically, Delta used Atlanta's Hartsfield-Jackson airport as its main hub, with Salt Lake City and Cincinnati airports serving as the carrier's regional hubs. New York's JFK airport was also used as a hub by Delta, largely to feed the carrier's domestic traffic to an extensive network of the airline's international flights out of that gateway. Northwest Airlines' main hub airports were Minneapolis-St. Paul and Detroit international airports. Memphis was a third, less important hub in the carrier's network.

In April 2008, Delta Air Lines and Northwest Airlines announced their intention to merge, with the expanded carrier to operate under the Delta trade name. The consolidation resulted in what was then the largest commercial airline in the world (only to be surpassed by United Airlines in 2011 following its merger with Continental). The merger was approved by the US Department of Justice in October of the same year. While strategic decision-making regarding the airline's operations has been moved to Atlanta (the location of Delta Air Lines headquarters),[31] it took some time for the two airlines to completely integrate. Specifically, Delta and Northwest's operating certificates were not merged until 31 December 2009, the date on which Northwest ceased to operate as a separate carrier.

3.2   Data

We examine network restructuring following a merger by evaluating the post-merger changes in the frequency of services to Delta and Northwest's hub airports. A hub operator makes service-frequency decisions on individual segments involving a hub airport (e.g., Los Angeles to Atlanta) based on expected traffic from the airport of origin to end-points beyond the hub (e.g., Los Angeles to points such as Charleston, SC via Atlanta). The frequency decisions are made by taking into account both the expected demand on these routes, and the importance of the hub airport in the airline's network. Then, ceteris paribus, if the carrier decides to stop channeling traffic via a hub, service frequencies on individual segments will fall, even if demand for traffic to the hub itself remains unchanged. In terms of the above example, Delta would fly fewer services to Atlanta from Los Angeles, even if it continued to carry as many Los Angeles-Atlanta passengers as before. We implement a straightforward difference-in-differences estimation strategy to evaluate whether after the merger the carrier changes service frequencies to individual hub airports in a manner that differs from predictions based on the time trend, individual hub airport effects, and changes in other demand shifters.

The regression equation we estimate seeks to explain the choice of the segment-level flight frequency by the partners to the merger both before and after consolidation. As explanatory variables we use route features, including distance, airline concentration, route-level demand shifters (population and wages at the Metropolitan Statistical Area level), and time dummies. Our sample includes all the services operated by Delta Air Lines, Northwest Airlines, and the corresponding regional feeder carriers,[32] aggregated at the quarterly level from the first quarter of 2007 through to (and including) the first quarter of

2011. Airline frequency data have been obtained from RDC aviation (Capstats statistics), and represent an aggregation of the T100 segment dataset, collected by the US Department of Transportation. Note that we only consider traffic in the US domestic market and so exclude international services from the analysis. The data are non-directional, meaning that we only include, for example, the Los Angeles - Atlanta flight frequency, but not that for Atlanta - Los Angeles flights. The reason for this being the generally symmetrical nature of the data: typically, the number of flights scheduled from A to B coincides with the number scheduled from B to A.

We also use the frequency data to compute segment-level Herfindahl-Hirschman Indices (HHI) - a conventional measure of market concentration, constructed as the sum of the squares of the market shares of all the firms on the market. Data for the control variables used in the regressions are drawn from the following sources: one-way segment distances are obtained from the Official Airline Guide and the WebFlyer site (http://www.webflyer.com) and population and wage data at the Metropolitan Statistical Area (MSA) level are obtained from the US Census Bureau. In the regressions, population is averaged across the MSAs of origin and destination, while average weekly wages are weighted by the populations in the MSAs of origin and destination. Our dataset contains a total of 8,351 quarterly airline-segment observations, encompassing the entire US domestic network operated by the partners to the merger. Of these observations, nearly 90 per cent correspond to services to or from the airlines' seven hub airports.

—Insert Table 1 here—

Table 1 presents the descriptive statistics for the aforementioned sample variables. It can be seen that all the variables present sufficient variability given that the standard deviation is high in relation to the mean values. As we can see, an average service in our sample features four daily flights, with about half of the services operated more frequently than that. It is also worth noting that the endpoints tend to be highly populous cities. Furthermore, the routes tend to be highly concentrated, as illustrated by a mean HHI close to 0.90.

—Insert Table 2 here—

Table 2 provides additional evidence on competition at the route level differentiating across hub airports. With the exception of routes from/to JFK, our sample presents a high proportion of monopoly routes and the concentration levels are close to 0.90 (confirming

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the value provided in Table 1). In addition, in all the considered hub airports, we find no significant differences in route-level concentration before and after the merger. Thus, our empirical set-up is framed in a context of limited competition, which is not unusual for the non-stop routes in the US airline industry (see Peteraf and Reed, 1994).[33] Although our analysis is not aimed at identifying the strategic interaction across competitors, there are no other US major carriers (outside of the new Delta Air Lines) having implemented any substantial change in their networks over the time period covered by our data.[34]

As we stated above, our analysis focuses on the following hub airports: Atlanta (ATL), Cincinnati (CVG), New York (JFK), and Salt Lake City (SLC) in the case of Delta; and Detroit (DTW), Memphis (MEM), and Minneapolis (MSP) in the case of Northwest. Some discussion of the differences across these hubs is therefore required, especially as we are interested in addressing the question of differences in congestion at these airports before the merger took place.

−Insert Table 3 here−

Table 3 provides the relevant numbers for these hub airports in the period just prior to the merger. All the hub airports (with the exception of JFK) are quite heavily concentrated as regards services in the US domestic market. The flight share operated by the dominant airline in six out of the seven hubs (the exception being JFK) is high and similar across the airports. However, at JFK, Delta is not even the carrier with the highest market share; moreover this airport is the only one with a concentration ratio (measured with the HHI) well much below 0.50.

Atlanta is clearly the largest airport of the seven, handling more than twice the total number of departures recorded at any of the other airports. Here, at its primary hub, the concentration of Delta's traffic is remarkable. Delta's other hub airports are much smaller than Atlanta and, as mentioned above, Delta does not dominate traffic at JFK. By contrast, the distribution of traffic between the Northwest Airlines' various hubs is much more balanced. Detroit and Minneapolis are similarly sized airports, and Northwest's share of traffic at the two gateways is almost identical. Memphis would appear to be the carrier's secondary hub, given its smaller size.[35]

To evaluate differences in levels of congestion across the seven hub airports, we use the percentage of on-time arrivals at those gateways, as reported by the Bureau of Transportation Statistics (BTS, US Department of Transportation).[36] Previous empirical studies on the determinants of delays (Mayer and Sinai, 2003; Rupp, 2009; Santos and Robin, 2010)

use data at the flight level and measure congestion either as the difference between the actual and the scheduled time or as the difference between the actual and the minimum feasible time of the flight (or both). These measures of congestion cannot be applied in our context because we use aggregated route data for quarterly periods. As a consequence, we deal with a conservative measure of congestion given that airlines may be adjusting their flight schedules to expected congestion levels.[37] The numbers reported in Table 3 are the mean annual percentage of on-time arrivals at each airport and include all the domestic services of airlines operating in that airport. From Table 3, it can be seen that JFK appears to be the most congested of the seven hubs, whereas Memphis and Salt Lake City are the least congested airports.

<center>−Insert Figs. 3 and 4 here−</center>

Figs. 3 and 4 show the evolution in traffic and delays at the seven hub airports between 2007 and 2010, based on data provided by the BTS. Given the prevailing economic crisis (above all in 2008 and 2009), we did not expect substantial increases in traffic at any of the hub airports. In fact, only Atlanta has been able to maintain its traffic levels stable over this period. JFK, Salt Lake City, and Memphis have each lost one million passengers, while Detroit has lost four million, and Minneapolis three million. Particularly important is the reduction of traffic in Cincinnati, which has lost almost half its air traffic over the time period considered.

Fig. 4 reveals that, before the merger, three groups of airports could be clearly defined in terms of their congestion levels. In 2007, SLC and MEM were the least congested hubs of the seven. MSP, DTW, and JFK were markedly more congested, while the congestion levels at ATL and CVG lay somewhere between these two groups. The substantial improvements in on-time performance post-2008 across the board are related to the general decline in air travel demand after the financial crisis and subsequent recession.

Empirically, measuring the welfare effect of consolidation processes would require estimating a structural model to incorporate fares and distribution of traffic across various one-stop markets. Unfortunately, we do not have available data on fares and airline costs. We can, however, assess the change in frequencies that consumers may gain (or lose) after consolidation.

<center>−Insert Table 4 here−</center>

Table 4 provides some preliminary evidence on the change of frequencies on routes from/to the different hub airports of the merged airlines. Although the analysis must

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take into account other variables that influence airline frequencies (which are considered in the following subsection), this exploratory examination of data shows that only passengers from/to Atlanta have clearly taken benefit from an increase of frequencies after the merger.

3.3 Estimation methodology

To evaluate Delta's network restructuring following its merger with Northwest, we have chosen to implement a simple difference-in-differences identification strategy. The general idea underpinning this strategy is to evaluate whether post-merger changes in service frequencies to particular hubs are greater than would otherwise be predicted by time-invariant hub airport effects and hub-airport-invariant time effects, while controlling also for possible changes in other demand shifters. Specifically, we operationalize the difference-in-differences estimator through the following specification

$$\log\left(Frequency_{it}\right) = \sum_i \alpha_i Hub_i + \sum_t \beta_t Year_t + \sum_i \gamma_i D^{Hub_i} * Year_{post-merger} + \delta X + error,$$
(24)

where Hub_i corresponds to the hub airport dummy variable (there are seven such variables in the spoke-airport fixed effects specifications, and the corresponding coefficients are all identified since our data include the two carriers' services between airports that are not their hubs, such as Delta Air Lines' flights from Los Angeles to Boston),[38] and $Year_t$ corresponds to the time controls.[39] The key variables then are the $D^{Hub_i} * Year_{post-merger}$ interaction terms, coefficients that should identify the effects we are seeking. Finally, X is the vector of control variables, which includes distance (for those specifications where it is identified), HHI, and two demographic measures (population and wages). We define the post-merger time period so as to include all observations from the first quarter of 2010 up to and including the first quarter of 2011 (end of our sample period).

The focus of our empirical exercise is, therefore, on these seven γ_i coefficients. We are interested in determining the significance of each individual coefficient (a positive sign indicating that a particular hub becomes more important after the merger, and a negative sign indicating a decline in the importance of the hub in the airline's network), and the differences across the coefficients for the various hubs.

As for our control variables, we expect a negative relationship between frequency and route length. On longer routes airlines may prefer to reduce flight frequency and use larger aircraft whose efficiency increases with distance. In addition, airlines may offer lower

frequencies on long-haul routes since intermodal competition with cars, trains, and ships is weak. A negative distance-frequency relationship has also been reported in previous studies (see Bilotkach *et al.*, 2010). We expect a negative relationship between flight frequencies and the market concentration index, since airlines will tend to offer fewer flights as competition on the route weakens. We expect a positive relationship between population and wages with respect to frequency. Demand should be higher in richer and more populated endpoints, and airlines should increase their flight frequencies when the demand at the endpoint rises.

We need, however, to overcome a number of econometric challenges. First, while the basic specification presented above controls for the time-specific effects, market-specific and airline-specific heterogeneities still need to be addressed. Second, our measure of market concentration is likely to be endogenous. Third, heteroscedasticity and autocorrelation are likely to be present in our data, necessitating an appropriate correction of the standard errors.

In order to control for market-specific and airline-specific heterogeneity, the panel nature of our dataset enables the use of a fixed effects model. We have used two approaches here. First, we estimate route fixed effects: a typical cross-section would be, for example, the route from Los Angeles (LAX) to Atlanta (ATL). Note that, in this model, individual hub airport indicator variables are absorbed by the fixed effects; however, the coefficients of the hub-post-merger interaction variables can be identified. Second, we have estimated a spoke-airport fixed effects model. In this setup, a typical cross-section would include all services from a spoke airport (e.g., Los Angeles). We have identified such cross-sections for every airport in the dataset, except for the seven hub airports. Here, we have a within-variation that allows us to identify individual hub airport effects.

To deal with the issue of the potential endogeneity of the market concentration variable, we have included one-year lagged HHI instead of the current period HHI in all specifications. It is difficult to make a case for the correlation between lagged concentration and current unobserved shocks. Likewise, in all the estimation results presented, we report standard errors that are robust to both heteroscedasticity across, and autocorrelation within, the respective cross-sections.

Finally, for each of the fixed effects specifications described above, we have estimated our models for the entire sample and for the sub-sample of routes originating at spoke airports served by both Delta and Northwest prior to the merger (in 2007). The reason

for excluding endpoints not served by both partners to the merger (as a robustness check) is that we might reasonably expect that, following the merger, Delta would retain services to Northwest hubs from cities not previously served by Delta. For example, International Falls, MN was not served by Delta prior to the merger, with Northwest operating flights to Minneapolis from this airport. It is not particularly reasonable to suggest that Delta would move this service to Salt Lake City or Cincinnati after acquiring Northwest Airlines, as both Delta hubs are located at some distance from International Falls. At the same time, were Delta to decide to decrease the importance of MSP as a hub in its network after the merger, we would expect a decrease in flight frequency from MSP to International Falls. Although this decrease in frequency would affect the magnitude of our estimates, it would not be a direct result of network restructuring, but more of a secondary effect. We can therefore conclude that, by focusing on endpoints served by both partners to the merger in 2007, we focus our attention more directly on network restructuring after the merger.

3.4   Results and discussion

Our estimation results are reported in Tables 5 and 6. Table 5 reports the results of the market fixed effects specification, whereas the outcomes of the spoke-airport fixed effects model are presented in Table 6. Within each table, we report results separately for the entire sample and for the sub-sample of endpoints served by both partners to the merger in 2007. Spoke airport specifications include more observations than are included in the market fixed effects, because some of the market-level cross-sections that are only observed once in the dataset have been included in the spoke-level fixed effects but not in the market-level sample.

$-$Insert Tables 5 and 6 here$-$

Most of the control variables exhibit the expected behavior: the airlines reduce frequencies on longer hauls, on more concentrated routes, and on routes between less populous MSAs. Indeed, the coefficients associated with distance and concentration are negative and highly statistically significant. The coefficient associated with the population variable is positive and statistically significant in the regressions with route fixed effects. However, the effect of population presents the unexpected sign and is not statistically significant in the spoke-airport fixed effects specifications. The coefficients for the wages variable are not statistically significant and thus do not confirm our expectations. This might reflect the

fact that the year dummies better capture the influence of travelers' income (which was in decline during most of the time period covered by our sample). The coefficients of all the year dummies confirm that the airlines have reduced their flight frequencies during the recession when compared to 2007 levels.

As expected, the coefficients associated with individual indicator variables for Delta and Northwest hub airports are positive and statistically significant in the spoke fixed effects regressions, where such coefficients are identified. The only exception is JFK, where the frequencies offered by the airlines involved in the merger are lower than elsewhere in their networks. Recall that JFK is the only hub airport in our sample where the hub airline, Delta, does not have a dominant position.

The coefficients of our key variables (hub-airport-post-merger interactions) do differ across specification; yet the overall picture is clear. We infer from our results that, after the merger, Delta has boosted somewhat the roles played by Atlanta and Salt Lake City as hubs in the new joint network. The coefficients associated with the interaction terms for these hub airports are positive in all the regressions, and statistically significant in specifications that include all routes (except Salt Lake City in the spoke-airport fixed effects regressions). Both airports were the main hubs of Delta Air Lines, which in the process of consolidation was very much in the role of the buyer. In general, the coefficients associated with the interaction terms for the other hub airports are negative and largely statistically significant. Our results clearly indicate that, following the merger, Delta decided to limit the role of Northwest Airlines' former hub airports in its network. This result is especially clear in the spoke-airport fixed effects specifications. The importance of the role played by CVG and JFK airports has also been diminished somewhat. According to Fig. 3, Delta effectively decided to shut down CVG as its hub (our data analysis clearly supports this observation). Thus, our results can be interpreted as evidence of an increase in the quality gap after the consolidation event as predicted in the theoretical model.[40]

Numerically, our estimation results suggest the following. The results reported in Table 5 indicate that, on average, following the merger Delta Air Lines changed its flight frequencies on routes not involving any of the seven hub airports by between 11-22 per cent more than it did on routes involving former Northwest Airlines hubs. The average difference in the change of frequencies on routes to Atlanta as compared to the background markets is about 5 per cent (or 3 per cent - and therefore not statistically significant - when considering just the sub-set of endpoints served by both carriers before the merger).

Frequencies are between 8 and 9 per cent higher in Salt Lake City than in non-hub airports (see Table 5). The diminishing role of Cincinnati airport in the joint network following the merger is self evident in both Tables 5 and 6. The results in Table 6 are qualitatively similar in part to those presented in Table 5; but, the following differences should be stressed. First, there is no evidence of traffic being diverted from DTW. Second, the changes in flight frequency to SLC are in line with Delta's general policy on non-hub routes after the merger. Third, and somewhat surprisingly, there is evidence of a decline in the importance of JFK as a hub (after 2005, Delta substantially expanded its international network at this gateway, leading us to assume that the carrier would have increased domestic flight frequency commensurately to feed traffic to its international services). Numerically, the effect of the merger on the frequency of flights on routes to MSP and MEM observed in Table 6 is about half that reported in Table 5. At the same time, Table 6 coefficients on the CVG post-merger interaction variable are about twice as high as they are in Table 5.

When attempting to link the results of our empirical analysis with our theoretical model and airport congestion figures, we first need to classify the airports by their respective levels of congestion and their status as either primary or secondary hubs in Delta Air Lines' network. Atlanta is clearly the airline's largest and most important hub airport. However, Salt Lake City can also be considered a key airport in the airline's network, being Delta's only real hub west of the Rocky Mountains. This means that were the carrier to abandon this airport, such a step would effectively weaken its position throughout the whole of western US and, above all, in the markets between the West Coast and the central states. At the same time, CVG, ATL, MEM, DTW, and to a certain degree MSP are largely substitutable as far as channeling traffic from West to East (and vice versa) is concerned. JFK, MSP, and DTW are airports of comparable size, while MEM and CVG are clearly secondary hubs. In terms of their pre-merger congestions levels, ATL, CVG, and MEM reported lower levels of flight delays in 2007 compared to those of MSP, DTW, and JFK.

With the above considerations in mind, our estimation results clearly demonstrate a post-merger redistribution of passenger traffic in favor of Delta Air Lines' main hubs. The smaller secondary hubs (CVG and MEM) become effectively shut down after the consolidation event. The decline in importance of JFK is both interesting, given that it was the most delay-prone airport before the merger, and surprising, given Delta Air Lines' expansion of its international services out of that gateway post-2005.

Our model also suggested that increased congestion at the main hub might mitigate

the concentration of traffic in the main hub. We are not able to provide a clear test of this prediction due to the specific characteristics of the underlying data generation process. Our post-merger period is characterized primarily by a fall in demand for air travel, associated with the 2008 financial crisis and the subsequent recession that hit the US economy. These events led to a reduction in air traffic delays, a trend that Fig. 4 clearly captures for the seven hubs included in our study. It is therefore quite possible that congestion at the main hubs was simply not great enough for Delta to channel traffic via the secondary gateways.

Overall, our empirical results are largely consistent with the predictions of the theoretical model. Indeed, our theoretical model predicts an increase in the quality gap after consolidation which could be mitigated by an increase in congestion. In a context in which congestion levels are modest, the empirical analysis confirms that the differentiation between higher and lower-quality air services is accentuated after consolidation: more flights are channeled via the primary hubs of the airline that offers higher-quality services. In terms of welfare, our empirical results suggest that the consolidation event may have contributed to reduce the overprovision of frequencies of the lower-quality services.

4   Concluding remarks

Processes of consolidation are reshaping the global airline industry. At the same time, the development of hub-and-spoke networks, coupled with an increase in global demand for air travel, have brought the issue of airport congestion to the forefront of the policy debate. While some researchers have suggested that airport congestion is less of a problem than it might initially seem, theoretical studies and their supporting empirical evidence on the self-internalization of airport congestion are more ambiguous in their findings.

Our study of network reorganization following a merger is jointly concerned with issues of airline consolidation and airport congestion. We provide both a theoretical framework for analyzing these concerns - paying specific attention to congestion at the hubs, and an empirical application to network reorganization - following one of the largest recent airline mergers (Delta-Northwest). Our theoretical framework suggests the possibility of an airline opting to use its secondary hub to relieve congestion at the primary hub, pointing to a particular kind of self-internalization.

In a situation without congestion, our model points to a scenario in which the airline would give additional priority to its primary hub after the merger. This concentration

of traffic in the main hub is mitigated in presence of congestion. The empirical analysis suggests that, after the merger, some Delta's hubs (especially Atlanta) are reinforced in the consolidated network while the traffic to former Northwest hubs and to New York's JFK (which was congested prior to the merger) is reduced.

The following caveats should be noted with respect to our theoretical model and the empirical application undertaken here. As regards the theory, we model a consolidation event that falls short of a full-scale merger – the latter requires the assumption of partially-served markets and presents an intractable modeling exercise under our setup. Furthermore, most of our data are taken from a period of declining demand for air travel where airport congestion problems have had a somewhat diluted influence in airline network choices.

Overall, we find that consolidation processes involving heterogeneous carriers in terms of service quality may have positive effects on welfare. However, a potential implication of our analysis is that airfares could increase in the primary hub of the consolidated airline. This increase in airfares could be due to an increase in service quality or/and to a market power effect given that consolidation processes could damage competition. Thus, even though our results suggest a simultaneous increase in fares and service quality, a complete assessment would also require the examination of collusive effects, any abuse of dominance, and the influence that indirect competition may exert on the consolidated airline.

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Notes

[1] At the time of this writing, a merger between American Airlines and US Airways is in progress. The companies expect to finalize the transaction, subject to regulatory approval, in the third quarter of 2013.

[2] Brueckner (2001) shows that airline alliances reduce fares in interline city-pair markets while the effect in interhub markets is the opposite. Brueckner (2003) finds that the presence of codesharing on an international interline itinerary reduces the fare by 8 to 17%, whereas the presence of antitrust immunity (which allows partners to cooperate in the realm of pricing) reduces the fare by 13 to 21%.

[3] Other studies on alliances include Park (1997), Brueckner and Whalen (2000), Hassin and Shy (2004), Bilotkach (2005), Zhang and Zhang (2006), and Heimer and Shy (2006). The last four references assume product differentiation, although only Brueckner and Whalen (2000) consider economies of traffic density.

[4] Our theoretical model is related to the literature on vertical product differentiation, pioneered by Gabszewicz and Thisse (1979), and Shaked and Sutton (1982), and summarized by Tirole (1988).

[5] Other studies of frequency choice and scheduling competition include works by Brueckner (2004) and Flores-Fillol (2010).

[6] The literature on congestion-pricing does not provide an unambiguous answer to the question of whether a hub operator will self-internalize the congestion externality (see Daniel, 1995; Brueckner, 2002; Mayer and Sinai, 2003; and Rupp, 2009).

[7] Barbot (2001) studies the triopoly case under partially-served markets using a much simpler model with no parameters, zero marginal cost, and no congestion (which is tantamount to a particular numerical analysis). This paper concludes that the partners' quality gap increases after merger. In fact, in the merger of the low and the intermediate quality firms, the lower-quality product is abandoned after merger. This degenerated outcome could be seen as an extreme version of our result (both theoretical and empirical) suggesting an accentuated differentiation in air services after consolidation (Proposition 1 in the theoretical model and Tables 5 and 6 in the empirical analysis).

[8] Introducing frequencies additively in the utility function simplifies the analysis with respect to the approach in Brueckner and Flores-Fillol (2007), where higher frequencies reduce the cost of schedule delay. A similar formulation to ours is suggested in Heimer and Shy (2006) and Flores-Fillol (2009).

[9] In a model studying air services on thin point-to point routes provided by network airlines, Fageda and Flores-Fillol (2012) conclude that an airline may find it profitable to serve these routes with regional jets when the distance between endpoints is sufficiently short and there is a high proportion of business travelers; and that the airline may be interested in serving them by means of a low-cost subsidiary when the distance between endpoints is longer and there is a high proportion of leisure travelers.

[10] A similar formulation is used in Heimer and Shy (2006) and Flores-Fillol (2009). While related papers including Brueckner (2004), Brueckner and Flores-Fillol (2007), and Flores-Fillol (2010) consider a constant cost per flight, the assumption of decreasing returns is needed to generate sensible results.

[11] Fageda and Flores-Fillol (2012) extend this approach by introducing a measure of load factor in the analysis.

[12] This setup could also be adapted to model other scheduled transportation modes, as well as freight transportation.

[13] Brueckner and Flores-FIllol (2007) also analyze the sequential case.

[14] Since $\frac{\partial \pi_1}{\partial p_1} = \frac{H}{d(z-1)}(p_2 - 2p_1 - d + 2\tau)$ and $\frac{\partial \pi_2}{\partial p_2} = \frac{H}{d(z-1)}(p_1 - 2p_2 + dz + 2\tau)$, the second-order conditions are satisfied by inspection.

[15] Since $\frac{\partial \pi_2}{\partial f_2} = \frac{H(2z-1)^2}{9(z-1)} - 2\eta(6f_2 + f_1) - 4\theta f_2$, the second-order conditions are satisfied by inspection.

[16] Thus, we do not obtain the typical maximal-differentiation result (see Tirole, 1988) because the equilibrium f_2 is obtained as an interior solution.

[17] The equilibrium flight frequencies are given by $f_1^n = \frac{H(2z-1)^2(z-2)+216\tau(z-1)(3\eta+\theta)}{18(z-1)[\eta(7z+4)+2\theta(z+1)]}$ and $f_2^n = \frac{H[z(4z^2-3)+1]-108\eta\tau(z-1)}{18(z-1)[\eta(7z+4)+2\theta(z+1)]}$. Although these expressions have a complex intuitive explanation (because f_1^n arises from a corner solution), we observe that both of them increase with market size (H). In fact, $H > \frac{108\eta\tau(z-1)}{z(4z^2-3)+1}$ is required to ensure $f_2^n > 0$.

[18] Note that, since $f_1^n > 0$ (see footnote 17), then $d^n > 0$ implies $f_2^n > 0$.

[19] The equilibrium fares are given by $p_1^n = f_1^n$ (corner solution) and $p_2^n = \frac{d^n(2z-1)}{3} + 2\tau = (2z-1)\frac{H(2z-1)^2-36\tau(z-1)(7\eta+2\theta)}{18(z-1)[\eta(7z+4)+2\theta(z+1)]} + 2\tau$.

[20] More generally, Shaked and Sutton (1983) report the "finiteness result": there can be at most a finite number of firms with a positive market share in the industry.

[21] The numerical analysis of the full-cooperation merger with partially-served markets is extremely complex and it is unsolvable for $\tau > 0$; therefore, we have done the analysis for $\tau = 0$. The model leads to the elimination of the lower-quality service after merger, i.e., the good quality expels the bad quality (independently of the congestion level). The explanation is that the merger prefers to produce only the best quality and captures some of the lower-quality ancient consumers. A similar result is obtained in Barbot (2001) using a much simpler model with no parameters, zero marginal cost, and no congestion (which is tantamount to a particular numerical analysis). This degenerated outcome could be seen as an extreme version of our result suggesting an accentuated differentiation in air services after consolidation (Proposition 1 of the theoretical model and Tables 5 and 6 on the empirical analysis).

[22] For instance, in the merger between US Airways and America West, once their reservation systems were integrated a year and a half after the merger between the two airlines, a computer glitch caused the united system to crash on the first day of joint operations, leading to significant travel disruptions in the now joint network.

[23] Since $\frac{\partial \pi_{12}}{\partial f_2} = \frac{H[(2z-1)^2+(z-2)^2]}{9(z-1)} - 4\eta(3f_2 + f_1) - 4\theta f_2$, the second-order conditions are satisfied by inspection.

[24] The equilibrium flight frequencies are given by $f_1^c = \frac{H(z-2)[z(5z-8)+5]+216\eta\tau(z-1)}{36(z-1)[\eta(4z+1)+\theta(z+1)]}$ and $f_2^c = \frac{H(z+1)[z(5z-8)+5]-216\eta\tau(z-1)}{36(z-1)[\eta(4z+1)+\theta(z+1)]}$. Although these expressions have a complex intuitive explanation (because f_1^c arises from a corner solution), we observe that both of them increase with market size (H). In fact, $H > \frac{216\eta\tau(z-1)}{(z+1)[z(5z-8)+5]}$ is required to ensure $f_2^c > 0$.

[25] Note that, since $f_1^c > 0$ (see footnote 24), then $d^c > 0$ implies $f_2^c > 0$.

[26] The equilibrium fares are given by $p_1^c = f_1^c$ (corner solution) and $p_2^c = \frac{d^c(2z-1)}{3} + 2\tau = (2z-1)\frac{H[z(5z-8)+5]-72\tau(z-1)(4\eta+\theta)}{36(z-1)[\eta(4z+1)+\theta(z+1)]} + 2\tau$.

[27] Recall that in both scenarios we have a corner solution for p_1, so that $f_1 = p_1$.

[28] Note that $\Delta^d = d^c - d^n = (f_2^c - f_1^c) - (f_2^n - f_1^n) = (f_2^c - f_2^n) - (f_1^c - f_1^n) = \Delta^{f_2} - \Delta^{f_1}$. Equivalently, $\Delta^{p_2-p_1} = \Delta^{p_2} - \Delta^{p_1}$.

[29]Since the high-quality service becomes relatively more expensive, we cannot think of a consolidated entity favoring the high-quality service to the detriment of the low-quality service.

[30]Note that the abandonment of the lower-quality service implies savings in terms of lower costs per departure and congestion costs and a better exploitation of economies of traffic density.

[31]Shortly after the merger, employees working at Northwest headquarters in the Minneapolis area were moved to other area offices. A year after the merger's approval, Delta put the building that used to house Northwest's headquarters up for sale.

[32]Regional carriers operate as Delta and Northwest contractors, typically on thinner routes. Flight scheduling and ticket sales are handled by the corresponding major carrier, allowing us to treat regional airlines as agents that do not make any strategically relevant decisions. Hence, all services by regional airlines have been re-coded as operated by the corresponding major carriers (Delta or Northwest, depending on the hub airport involved).

[33]Hub-and-spoke networks operated by the US major carriers imply that, outside of the large markets (such as New York - Los Angeles), competition on non-stop routes focuses on hub-to-hub markets.

[34]The Delta-Northwest consolidation event did not coincide with any other merger on the US side of the market. Note that the United-Continental merger was completed in October 2010 - two quarters before our post-merger period ends. We believe that insufficient time passed since that merger was approved for the new United Airlines to substantially change its network.

[35]As a side note, MEM has been and remains the main hub airport for FedEx - a leading freight carrier in the US and global markets.

[36]According to the methodology used by the BTS, a flight is considered to be on-time if it has arrived no later than 15 minutes after its scheduled arrival time.

[37]This phenomenon is known as *schedule padding*. However, note that setting up schedule buffers increases airlines' costs as the carrier has to pay the crew for the highest of the actual and scheduled flight time (clear evidence for this is provided in Zou and Hansen, 2012). Also, having analyzed the schedule data for millions of flights, Mayer and Sinai (2003) conclude that expected congestion does not appear to play a role in the carriers' scheduling decisions - rather, the airlines' scheduled travel time is close to the minimum allowed by federal regulations.

[38]These services correspond to about ten percent of all our observations.

[39]Note that although we report results of specifications with year dummies, the use of both year and quarter, and year-quarter indicator variables, produces qualitatively similar outputs.

[40]The diminished importance of Northwest former hubs in the joint network could be interpreted as an evidence of favoritism towards Delta's hubs (considering that Delta played the lead role in this transaction). We however believe that declining importance of Cincinnati and JFK airports strongly speaks against such a claim.
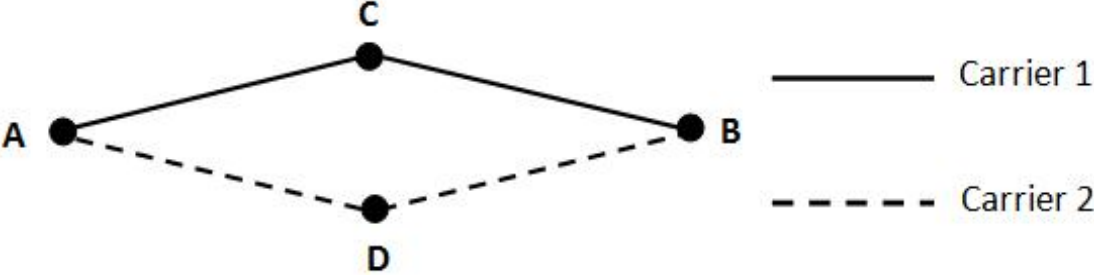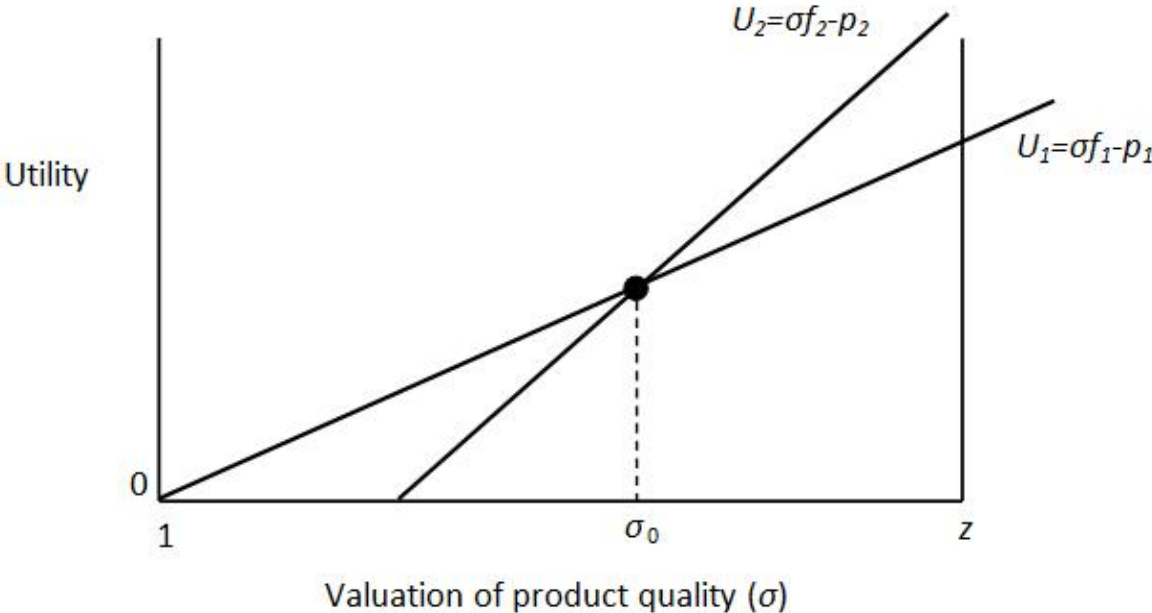
Figures and Tables
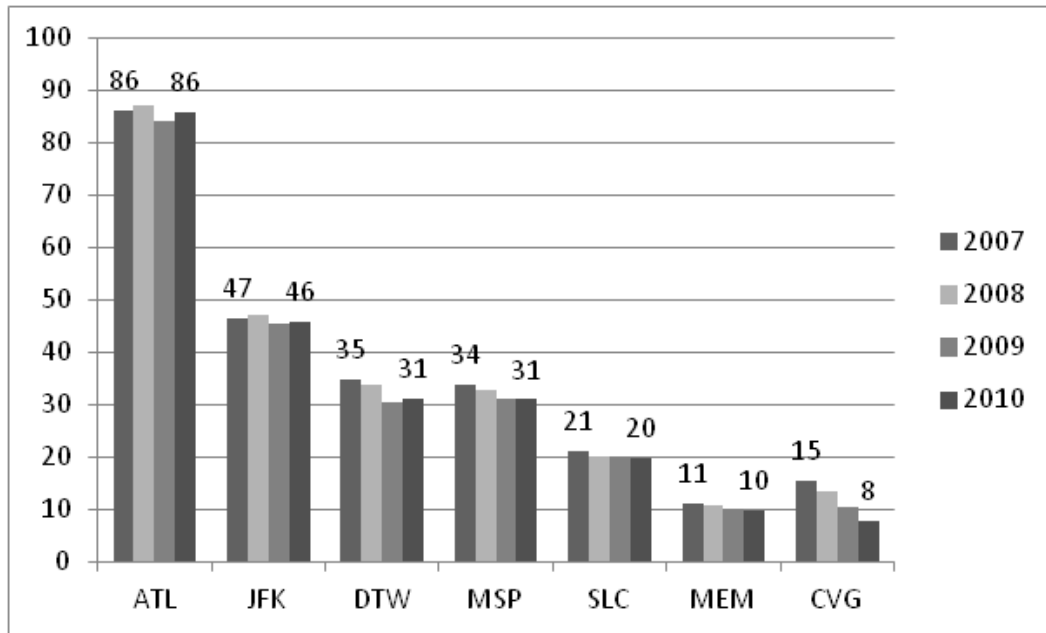

Fig. 1: Network

Fig. 2: Utilities

Fig. 3: Total traffic (million passengers)
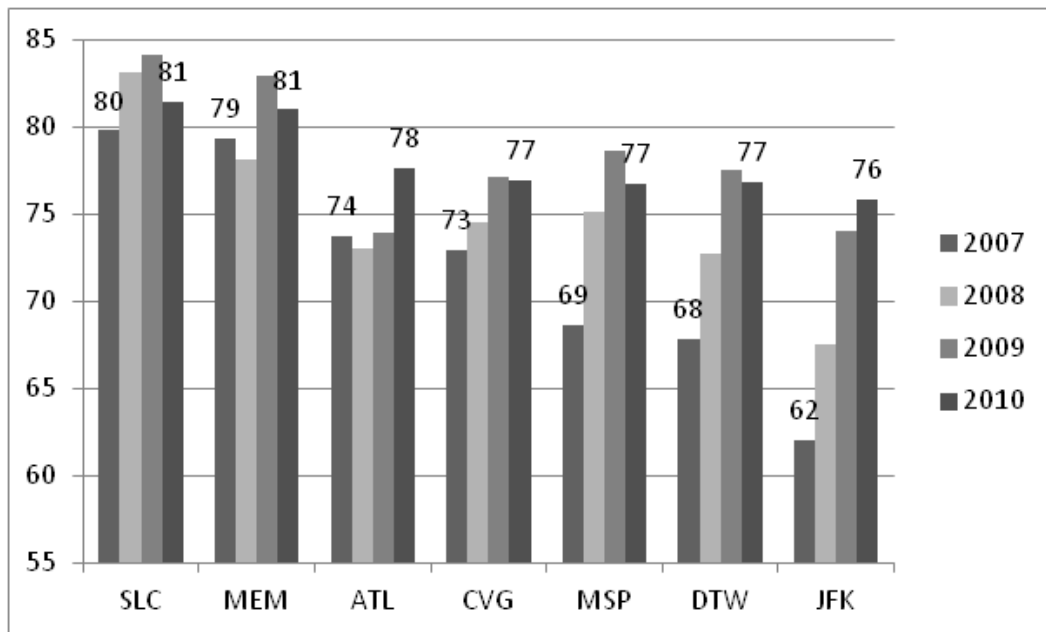
Fig. 4: Percentage of ontime arrivals

Table 1: Descriptive statistics

	Mean	Median	Standard deviation
Frequency	376.24	323.00	229.31
HHI	0.84	1.00	0.24
One-way distance (miles)	631.04	500.20	229.31
Population (MSA)	4,923,765	3,958,981	4,324,522
Wage (weekly)	935.98	918.51	116.13

Table 2: Competition at the route level by hub airport

Airport	% Monopoly routes	Mean HHI (in terms of route departures) before the merger	Mean HHI (in terms of route departures) after the merger
Atlanta (ATL)	63	0.82	0.83
Cincinnati (CVG)	80	0.90	0.91
Detroit (DTW)	74	0.89	0.83
New York (JFK)	22	0.60	0.57
Memphis (MEM)	83	0.94	0.87
Minneapolis (MSP)	77	0.91	0.84
Salt Lake City (SLC)	71	0.86	0.87

Note: Routes are typically considered a monopoly when HHI>0.90.

Table 3: Hub airports data (mean values for 2007-2009)

Airport	Total departures	HHI (in terms of departures)	Share dominant airline (in terms of airport departures)	% On-time arrivals
Atlanta (ATL)	448,895	0.53	Delta (70%)	73.60
Cincinnati (CVG)	129,376	0.71	Delta (84%)	74.88
Detroit (DTW)	222,101	0.54	Northwest (73%)	72.70
New York (JFK)	145,652	0.26	JetBlue (36%), Delta (35%)	67.85
Memphis (MEM)	102,246	0.58	Northwest (76%)	80.14
Minneapolis (MSP)	212,932	0.55	Northwest (74%)	74.14
Salt Lake City (SLC)	156,058	0.49	Delta (67%)	82.36

Note: All data refer to annual values for the US domestic traffic.

Table 4: Change in route frequencies in the post-merger period

Airport	Mean route frequency in the pre-merger period (1)	Mean route frequency in the post-merger period (2)	Mean T-test diff=mean(1)-mean(2)
Atlanta (ATL)	543.87	569.72	-1.98**
Cincinnati (CVG)	337.50	221.79	13.40***
Detroit (DTW)	340.18	339.65	0.06
New York (JFK)	325.56	292.74	2.16**
Memphis (MEM)	243.09	218.10	5.93***
Minneapolis (MSP)	350.45	317.84	2.80**
Salt Lake City (SLC)	371.35	359.43	1.02

Note: Statistical significance at 1% (***), 5% (**), 10% (*).

Table 5: Estimation results (route fixed effects)

	All routes (1)	Spoke routes where DL and NW were present before the merger (2)
$Population$	0.54 (0.16)***	0.53 (0.19)***
$Wage$	-0.56 (0.36)	-0.56 (0.42)
$Lagged\ HHI$	-0.06 (0.02)***	-0.05 (0.02)***
$D^{ATL}*Year_{post-merger}$	0.05 (0.03)*	0.03 (0.03)
$D^{CVG}*Year_{post-merger}$	-0.17 (0.03)***	-0.21 (0.03)***
$D^{JFK}*Year_{post-merger}$	0.01 (0.04)	-0.02 (0.04)
$D^{SLC}*Year_{post-merger}$	0.08 (0.03)**	0.09 (0.04)**
$D^{DTW}*Year_{post-merger}$	-0.12 (0.03)***	-0.11 (0.03)***
$D^{MSP}*Year_{post-merger}$	-0.20 (0.03)***	-0.18 (0.03)***
$D^{MEM}*Year_{post-merger}$	-0.22 (0.04)***	-0.20 (0.04)***
D^{2008}	-0.02 (0.009)**	-0.03 (0.01)***
D^{2009}	-0.04 (0.01)***	-0.04 (0.01)***
D^{2010}	-0.11 (0.03)***	-0.10 (0.03)***
D^{2011}	-0.14 (0.03)***	-0.13 (0.03)***
$Intercept$	1.42 (0.10)***	1.54 (0.11)***
R^2	0.06	0.07
$Test\ F\ (joint\ sig.)$	68.67***	50.61***
$Modified\ Bhargava\ et\ al.\ Durbin\text{-}Watson$	0.91	0.94
$Number\ observations$	7,827	5,683

Note 1: Dependent variable is natural logarithm of quarterly flight frequency.

Note 2: Model used: market level fixed effects.

Note 3: All continuous variables are in logs.

Note 4: Standard errors are in parentheses (robust to heteroscedasticity across and autocorrelation within cross-sections).

Note 5: Statistical significance at 1% (***), 5% (**), 10% (*).

Table 6: Estimation results (spoke-airport fixed effects)

	All routes (1)	Spoke routes where DL and NW were present before the merger (2)
$Population$	-0.02 (0.02)	-0.04 (0.02)
$Wage$	0.12 (0.12)	0.04 (0.16)
$Distance$	-0.67 (0.01)***	-0.66 (0.01)***
$Lagged\ HHI$	-0.36 (0.02)***	-0.41 (0.02)***
D^{ATL}	1.02 (0.02)***	1.09 (0.03)***
D^{CVG}	0.20 (0.03)***	0.26 (0.04)***
D^{JFK}	-0.20 (0.03)***	-0.15 (0.04)***
D^{SLC}	0.37 (0.04)***	0.34 (0.05)***
D^{DTW}	0.44 (0.03)***	0.50 (0.03)***
D^{MSP}	0.44 (0.03)***	0.50 (0.03)***
D^{MEM}	0.13 (0.03)***	0.16 (0.04)***
$D^{ATL}*Year_{post-merger}$	0.06 (0.03)*	0.01 (0.04)
$D^{CVG}*Year_{post-merger}$	-0.34 (0.04)***	-0.39 (0.05)***
$D^{JFK}*Year_{post-merger}$	-0.14 (0.07)**	-0.23 (0.09)**
$D^{SLC}*Year_{post-merger}$	0.05 (0.04)	0.08 (0.06)
$D^{DTW}*Year_{post-merger}$	0.02 (0.04)	-0.01 (0.05)
$D^{MSP}*Year_{post-merger}$	-0.07 (0.04)	-0.10 (0.05)**
$D^{MEM}*Year_{post-merger}$	-0.08 (0.04)*	-0.12 (0.05)**
D^{2008}	-0.03 (0.009)***	-0.03 (0.01)***
D^{2009}	-0.06 (0.009)***	-0.06 (0.01)***
D^{2010}	-0.07 (0.03)**	-0.03 (0.04)
D^{2011}	-0.16 (0.04)***	-0.15 (0.04)***
$Intercept$	8.90 (0.69)***	9.63 (0.89)***
R^2	0.74	0.73
$Test\ F\ (joint\ sig.)$	102.65***	108.70***
$Durbin\text{-}Watson$	0.44	0.46
$Number\ observations$	8,320	6,650

Note 1: Dependent variable is natural logarithm of quarterly flight frequency.

Note 2: Model used: spoke airports fixed effects (see text for details).

Note 3: All continuous variables are in logs.

Note 4: Standard errors are in parentheses (robust to heteroscedasticity across and autocorrelation within cross-sections).

Note 5: Statistical significance at 1% (***), 5% (**), 10% (*).

A   Appendix: proofs

Proof of Lemma 1.

Straightforward. ∎

Proof of Lemma 2.

- $\frac{\partial d^n}{\partial \eta} = -\frac{42\tau}{\eta(7z+4)+2\theta(1+z)} - \frac{(7z+4)\left[H(2z-1)^2-36\tau(z-1)(7\eta+2\theta)\right]}{6(z-1)[\eta(7z+4)+2\theta(z+1)]^2}$ and thus a sufficient condition for $\frac{\partial d^n}{\partial \eta} < 0$ is $H(2z-1)^2-36\tau(z-1)(7\eta+2\theta) > 0$. This is tantamount to $H > \underline{H}_1$, which is assumed to hold.

- $\frac{\partial d^n}{\partial \theta} = -\frac{12\tau}{\eta(7z+4)+2\theta(1+z)} - \frac{(7z+4)\left[H(2z-1)^2-36\tau(z-1)(7\eta+2\theta)\right]}{6(z-1)[\eta(7z+4)+2\theta(z+1)]^2}$ and thus a sufficient condition for $\frac{\partial d^n}{\partial \theta} < 0$ is $H(2z-1)^2-36\tau(z-1)(7\eta+2\theta) > 0$. This is tantamount to $H > \underline{H}_1$, which is assumed to hold.

- $\frac{\partial d^n}{\partial \tau} = -\frac{6(7\eta+2\theta)}{\eta(7z+4)+2\theta(1+z)}$, which is always negative.

- $\frac{\partial d^n}{\partial z} = -\frac{H(2z-1)[\eta(8z-19)+4\theta(z-2)]+36\tau(z-1)^2(7\eta+2\theta)^2}{6(z-1)^2[\eta(7z+4)+2\theta(z+1)]^2}$ and thus a sufficient condition for $\frac{\partial d^n}{\partial z} < 0$ is $8z > 19$, i.e., $z > 2.4$.

- $\frac{\partial d^n}{\partial H} = \frac{(2z-1)^2}{6(z-1)[\eta(7z+4)+2\theta(z+1)]}$, which is always positive. ∎

Proof of Lemma 3.

- $\frac{\partial d^n}{\partial \eta} = -\frac{24\tau}{\eta(4z+1)+\theta(1+z)} - \frac{(4z+1)[H(z(5z-8)+5)-72\tau(z-1)(4\eta+\theta)]}{12(z-1)[\eta(4z+1)+\theta(z+1)]^2}$ and thus a sufficient condition for $\frac{\partial d^c}{\partial \eta} < 0$ is $H(z(5z-8)+5) - 72\tau(z-1)(4\eta+\theta) > 0$. This is tantamount to $H > \underline{H}_2$, which is assumed to hold.

- $\frac{\partial d^n}{\partial \theta} = -\frac{6\tau}{\eta(4z+1)+\theta(1+z)} - \frac{(z+1)[H(z(5z-8)+5)-72\tau(z-1)(4\eta+\theta)]}{12(z-1)[\eta(4z+1)+\theta(z+1)]^2}$ and thus a sufficient condition for $\frac{\partial d^c}{\partial \theta} < 0$ is $H(z(5z-8)+5) - 72\tau(z-1)(4\eta+\theta) > 0$. This is tantamount to $H > \underline{H}_2$, which is assumed to hold.

- $\frac{\partial d^n}{\partial \tau} = -\frac{6(4\eta+\theta)}{\eta(4z+1)+2\theta(1+z)}$, which is always negative.

- $\frac{\partial d^n}{\partial z} = -\frac{H\{\eta[z(17z-50)+23]+4\theta(z-2)(2z-1)\}+72\tau(z-1)^2(4\eta+\theta)^2}{12(z-1)^2[\eta(4z+1)+\theta(z+1)]^2}$ and thus a sufficient condition for $\frac{\partial d^c}{\partial z} < 0$ is $17z > 50$, i.e., $z > 2.9$.

- $\frac{\partial d^n}{\partial H} = \frac{z(5z-8)+5}{12(z-1)[\eta(4z+1)+\theta(z+1)]^2}$, which is always positive. ∎

Proof of Lemma 4.

- $\Delta^{f_1} = \Delta^{p_1} = (z-2)\,\Omega$, where $\Omega \equiv \frac{H(z-2)(z+1)[3\eta(z-3)+2\theta(z-2)]-216\eta\tau(z-1)(3\eta+\theta)}{36(z-1)[\eta(4z+1)+\theta(z+1)][\eta(7z+4)+2\theta(z+1)]}$. The denominator of Ω is always positive and the numerator is also positive for $H > \underline{H}_3 \equiv \frac{216\eta\tau(z-1)(3\eta+\theta)}{(z-2)(z+1)[3\eta(z-3)+2\theta(z-2)]}$ for $z \geqslant 3$. Thus, $\Delta^{f_1} = \Delta^{p_1} > 0$ for $H > \underline{H}_3$ and $z \geqslant 3$.

- $\Delta^{f_2} = (z+1)\,\Omega$. Thus, $\Delta^{f_2} > 0$ for $H > \underline{H}_3$ and $z \geqslant 3$.

- $\Delta^{p_2} = (2z-1)\,\Omega$. Thus, $\Delta^{p_2} > 0$ for $H > \underline{H}_3$ and $z \geqslant 3$. ∎

Proof of Proposition 1.

- $\Delta^d = \Delta^{f_2} - \Delta^{f_1}$ (see footnote 25). Therefore, $\Delta^d = (z+1)\,\Omega - (z-2)\,\Omega = 3\Omega$. Thus, $\Delta^d > 0$ for $H > \underline{H}_3$ and $z \geqslant 3$.

- $\Delta^{p_2-p_1} = \Delta^{p_2} - \Delta^{p_1} = \Delta^{p_2} - \Delta^{f_1}$ because $\Delta^{f_1} = \Delta^{p_1}$. Then $\Delta^{p_2-p_1} = (2z-1)\,\Omega - (z-2)\,\Omega = (z+1)\,\Omega = \Delta^{f_2}$. Thus, $\Delta^{p_2-p_1} = \Delta^{f_2} > 0$ for $H > \underline{H}_3$ and $z \geqslant 3$. ∎

Proof of Lemma 5.

- $\frac{\partial \Delta^{f_1}}{\partial \eta} = \frac{\partial \Delta^{p_1}}{\partial \eta} = -(z-2)\,\Psi$, where
$$\Psi \equiv \frac{H\left\{(z-2)(z+1)\left[3\eta^2(z-3)(4z+1)(7z+4)+4\eta\theta(z-2)(4z+1)(7z+4)+6\theta^2(z+1)\left(4z^2-6z-1\right)\right]\right\}}{36(z-1)[\eta(4z+1)+\theta(z+1)]^2[\eta(7z+4)+2\theta(z+1)]^2} +$$
$$\frac{216\theta\tau(z-1)\left\{\eta^2[z(17z+40)+14]+12\eta\theta(z+1)^2+2\theta^2(z+1)^2\right\}}{36(z-1)[\eta(4z+1)+\theta(z+1)]^2[\eta(7z+4)+2\theta(z+1)]^2}.$$
The denominator of Ψ is always positive and the numerator is also positive as long as $z \geqslant 3$. Therefore, $\Psi > 0$ for $z \geqslant 3$ and thus $\frac{\partial \Delta^{f_1}}{\partial \eta} = \frac{\partial \Delta^{p_1}}{\partial \eta} < 0$.

- $\frac{\partial \Delta^{f_2}}{\partial \eta} = -(z+1)\,\Psi$. Therefore, $\frac{\partial \Delta^{f_2}}{\partial \eta} < 0$ for $z \geqslant 3$.

- $\frac{\partial \Delta^{p_2}}{\partial \eta} = -(2z-1)\,\Psi$. Therefore, $\frac{\partial \Delta^{p_2}}{\partial \eta} < 0$ for $z \geqslant 3$. ∎

Proof of Proposition 2.

- $\frac{\partial \Delta^d}{\partial \eta} = -\Psi$. Therefore, $\frac{\partial \Delta^d}{\partial \eta} < 0$ for $z \geqslant 3$.

- Since $\Delta^{p_2 - p_1} = \Delta^{f_2}$ (shown in proof of Proposition 1), then $\frac{\partial \Delta^{p_2 - p_1}}{\partial \eta} = \frac{\partial \Delta^{f_2}}{\partial \eta} = -(z+1)\Psi$, which is negative for $z \geqslant 3$. ■

Proof of Proposition 3.

- From Eqs. (14) and (23), a sufficient condition for $d^* > d^n$ is $\frac{Hz^2}{8(z-1)(\theta+3\eta)} > \frac{H(2z-1)^2}{6(z-1)[\eta(7z+4)+2\theta(z+1)]}$, which is equivalent to $2\theta(3z^3 - 5z^2 + 8z - 2) + 3\eta(7z^3 - 12z^2 + 16z - 4) > 0$. This inequality is always observed for $z \geqslant 2$, which is assumed to hold.

- From Eqs. (18) and (23), a sufficient condition for $d^* > d^c$ is $\frac{Hz^2}{8(z-1)(\theta+3\eta)} > \frac{H[z(5z-8)+5]}{12(z-1)[\eta(4z+1)+\theta(z+1)]}$, which is equivalent to $\theta(3z^3 - 7z^2 + 16z - 10) + \eta(12z^3 - 27z^2 + 48z - 30) > 0$. This inequality is always observed for $z \geqslant 2$, which is assumed to hold. ■

Proof of Corollary 1.

Straightforward. ■