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Airport capacity and inefficiency in slot allocation[☆]

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This paper studies the time slot allocation of flight departures when travelers have a preference for departing on peak times and the number of available peak-time slots is constrained by airport capacities. We show that, compared to public airports, private airports may restrain their supply of peak slots strictly below their capacity levels when they serve airlines that compete to the same destinations. Such an inefficiency takes place in airports that have low per-passenger charges and are not too busy. It does not occur in the absence of competition in destination markets.

1. Introduction

Over the past decades, airline traffic growth has outpaced capacities at many of the world's major airports.[1] Limited airport capacities are expected to become a more acute

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[1] For instance, over half of Europe's 50 largest airports have already reached or are close to their saturation points in terms of declared ground capacity (Madas and Zografos, 2008).

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and widespread issue in the coming decades because of the expanding travel demand from emerging and developing countries.[2]

The literature on airport capacity presents "congestion pricing" as the appropriate regulatory tool to deal with congestion.[3] Accordingly, carriers pay a toll according to their contribution to congestion. However, despite its theoretical attractiveness, congestion pricing has seldom been adopted in the real world. By contrast, slot allocation is the usual approach to management of airport capacity. According to IATA World Scheduling Guidelines, a slot is "the permission given by a managing body for a planned operation to use airport infrastructure that is necessary to arrive or depart at a airport on a specific date and time".[4] Under a slot allocation system, the airport authority distributes the slots according to some allocation rule.[5] Because of the prevalence of this system, it is important to investigate the factors underlying slot allocation under airport capacity constraints.

A recent issue in airport management is related to unused or misused slots. Even at congested airports, where capacity cannot satisfy the demand for slots, over 10% of the allocated slots are not eventually utilized (Zografos et al., 2013). ACI Europe (2009) provides some quantitative evidence of this problem by estimating that unused slots account for approximately euro 20 million fewer revenues per season for large, congested European airports. Katsaros and Psaraki (2012) provide evidence of slot allocation misuse in the Greek airport system.

Moreover, there is evidence that the observed slot misuse is magnified by inefficiencies in the slot allocation mechanism per se (Zografos et al., 2012). Irrespective of the reasons, unused or misused slots indicate a poor efficiency of the allocation process itself, and they impact economically on airports, airlines, passengers and the society at large (Zografos et al., 2013). To the best of our knowledge, this recent issue has not been analyzed in the economic literature on airport policies.

The objective of this paper is to understand the airports' choices of slot allocations, private or public management incentives and airline competition in the presence of limited airport capacity.[6] We examine a setting where an airport sorts the time slots according to different departure flights while airlines compete in each market to a destination city. As in Brueckner (2002), we distinguish between peak and offpeak time periods

[2] The European Commission estimated that half of the world's new traffic will come from the Asia Pacific region in the next 20 years. They expect that air traffic in Europe will roughly double by 2030, and that 19 key airports will be at saturation. See MEMO/11/857.

[3] For an early contribution on congestion pricing, see Levine (1969). Recent representative studies include Brueckner (2002); 2005) and Basso and Zhang (2008). Under congestion pricing, carriers could place as many flights as they wish provided they pay the toll; thus the overall level of congestion is determined by airline decisions.

[4] See IATA Worldwide Slot Guidelines (http://www.iata.org).

[5] For example, FAA (Federal Aviation Administration) capped peak hour flight movements at New York La Guardia, J.F. Kennedy, and Neward airports. As for Chicago's O'Hare airport, FAA persuaded two major airlines, United and American Airlines, to reduce peak flight activities while prohibiting smaller airlines from increasing flights to fill the gap.

[6] Though in practice congestion is not exclusively confined to runway congestion, and might embody other capacity dimensions such as environmental concerns, we nevertheless focus on runway congestion.

according to the travelers' preferences for their departure time.[7] Because travelers have preferences over the same departure time window, the airport is likely to face a capacity shortage at that time. However, a formal slot allocation that respects the peak time capacity constraint eliminates any peak time congestion. In this sense, congestion does not emerge in the model. We analyze both a private and a public airport: the private airport maximizes its profit from passenger traffic, while the public airport maximizes social welfare.[8] We assume that the airport obtains exogenous and uniform revenues from each passenger. Per-passenger revenues are key features of airport revenues, stemming from passenger flows like various travel fees,[9] parking tickets, shop revenues and so forth. We consider separately the cases when destination markets are served by competing airlines and when they are not.

Our first finding is that private airports have incentives to allocate different types of slots (peak vs. offpeak) to airlines that compete in same destination markets. Because peak slots occur in the passengers' preferred time windows, the airport is able to create a quality differential by assigning competing flights to different peak and offpeak slots. As airlines choose their travel offers conditional on this quality differential, the resulting prices, passenger volumes and airport revenues depend on slot assignments. In fact, such quality differentiation induces airlines to target different types of travelers and raises the total number of passengers in the airport while it also helps airlines to soften competition. We show that the first effect dominates so that slot differentiation increases airport revenues.

Our second finding is that private airports have incentives to keep peak slots unused when they are served by competing airlines. Airports therefore do not use their full peak slot capacity. The intuition is as follows. As said above, private airports have incentives to create quality differentiation. They are therefore willing to allocate competing airlines distinct peak and offpeak slots for a maximal number of destinations. When the number of peak time flights to such destinations is smaller than the number of available peak slots, airports fill only a share of the available peak slots. As a result, private airport revenues are higher if they withhold some peak slots and do not fully exploit their capacity. In this

[7] Our approach differs from Brueckner (2002) as follows. In Brueckner's (2002)) framework, a monopoly airport chooses the critical points on the continuum that respectively define whether to fly or not and whether to fly in peak or offpeak slots. Focusing on finding the optimal congestion pricing, that framework implicitly assumes that airport capacity is sufficient to meet peak hour demands. Unlike Brueckner (2002), our interest stems from the scarcity of peak hour slots. Thus we focus on the allocation instead of the pricing tool.

[8] Although airports have long been owned by governments, there has been a worldwide privatization wave since the middle of the 1980s. Following the United Kingdom, many major airports in Europe, Australia and Asia have undergone privatization or are in the process of being privatized. As a result, it is important to understand the impact of airport ownership.

[9] For instance, in the real world airports are allowed to levy a uniform per-passenger fee for flight activities, this being pre-determined by administrative or regulatory bodies. The regulation of per-passenger fees is common in many countries. In EU, the Commission Regulation (EC) No. 1794/2006 as well as Council Directive 96/67/EC sets out common charging scheme for air navigation and ground handling services. In the UK, the Civil Aviation Authority regulates the charges of Heathrow and Gatwick airports to airlines since 1986. In Germany, airport charges are laid down by the main national legislative instrument German Air Traffic Act (LuftVG) (Abeyratne, 2009).

paper, we highlight the conditions under which this strategy takes place and show that it is not used by public airports. In this sense, private ownership leads to an allocative inefficiency. Such allocative inefficiency may correspond to airport managements' practice to declare fewer slots than under their full capacities (Mac Donald, 2007). As De Wit and Burghouwt (2008, p. 153), point out, "an efficient use of the slots at least requires a neutral and transparent determination of the declared capacity". This result also explains some recent empirical evidence on allocative inefficiency (Zografos et al., 2013; 2012; ACI Europe, 2009).

Things, however, differ if each destination is served by an airline monopoly. Monopoly airlines have incentives to operate one flight to each destination. We show that they have no incentives to split their demand into different time slots and gather into the same airplane all the passengers departing to a given destination. With one flight to each destination, the airport is unable to apply the above quality differentiation strategy. As a result, private ownership does not lead to allocative inefficiency: private and public airports choose the same slot allocation.

So far, slot allocation has drawn relatively little interest in the economic literature, with few but noteworthy contributions. As in this paper, Barbot (2004) assumes that slots for airline activities are vertically differentiated products with high or low quality, but, unlike this paper, she assumes that carriers choose the number of flights they operate. Verhoef (2008) and Brueckner (2009) compare the pricing and slot policy regimes. They show that the first best congestion pricing and slot trading/auctioning generate the same amount of passenger volume and total surplus. They investigate a single congested period. Their contributions do not distinguish between peak and offpeak hours, or allow the airport to allocate slots without charges. Although this seems a plausible description of some public airports, non-profit behavior is relevant for many other airports. In this respect, Basso and Zhang (2010) generalize Verhoef (2008) and Brueckner's (2009)) analyses by taking into account airport profits. By contrast, they find that congestion pricing and slot allocation mechanisms lead to different outcomes. Departing from those authors, we consider that passengers have preferences for peak times and each airline operates a single flight, and we discuss the possible inefficiency.

The remainder of the paper is organized as follows. Section 2 introduces the model. Section 3 analyzes the equilibrium in airline markets, where duopoly airlines determine their seat supplies. Section 4 examines the slot allocation equilibrium, the case with monopoly airlines, and shows some stylized facts of airline markets that support our theoretical analysis. Section 5 investigates the case of slot markets. Section 6 concludes.

2. The model

We consider an airport offering a mass N of airport pair connections with heterogenous market sizes z, distributed according to the cumulative distribution function $G : [\underline{z}, \overline{z}] \to [0, 1]$, $0 \leq \underline{z} < \overline{z}$. Each airport pair is indexed by its market size z, the parameter z being the only parameter that differentiates airport pairs.

The departing time is the only quality dimension perceived by passengers.[10] There are two travel periods i: offpeak ($i = 0$) and peak ($i = 1$). A peak period is a time window that includes the most desirable travel times in a day, for instance early morning and late afternoon: for example, 7:00–9:00 a.m. for a morning peak and 5:00–7:00 p.m. for an afternoon peak. Offpeak periods are all other time intervals that are not desired as much. Each airport-pair market z hosts a mass z of vertically differentiated passengers (Gabszewicz and Thisse, 1979). Each passenger differs by her idiosyncratic taste parameter $v \in [0, 1]$, v being uniformly distributed. Passengers perceive the convenience of time period to have values vs_0 and vs_1 where s_0 and s_1 are the intrinsic value parameters of offpeak and peak departure times ($0 < s_0 < s_1$). For simplicity we assume that each passenger flies at most once in an airport pair and has zero reservation utility. Passengers are endowed with the utility function: $U_i(v, p_i) = vs_i - p_i$ where $i = 0$ or 1 if they respectively take the offpeak or peak flight with fare p_i. Under vertical differentiation, all passengers prefer the peak hour at a given price. For simplicity, destinations are assumed to be independent in the sense that they are neither substitutes nor complements; therefore the demand for one destination is irrelevant to demands for other destinations.[11]

In this paper we consider that passengers flows bring a per-passenger revenue ϕ to the airport. Those revenues stem from airport charges to airlines and passengers and from the revenues from passengers' non-travel activities in the airport. Because each air travel is an indivisible good for each passenger, those charges have the same effects whenever they are paid by airlines or passengers. So, in this model, we shall suppose that ϕ is paid by the airline. Furthermore, we consider that such per-passenger revenues are exogenous and time invariant. In the US, airports charge airlines with passenger facility charges (PFCs) that are capped to 4.5 USD per passenger, which is far below the average fare. Also, IATA recommends aeronautical "direct passenger based charges" that are proportional to passenger flows (see IATA policy website).[12] Per-passenger revenues also stem from the part of landing fees that vary according to the aircraft weight, and therefore to the number of passengers. Passengers also pay fees directly to airports, as is the case in Canada and China (e.g. "explicit improvement fees"). Finally, airports obtain significant revenues from the charges levied on shopping and parking lots. To the extent that those activities are broadly proportional to passenger flows, the associate profit per passenger can be considered as constant. Based on these considerations, our assumption of exogenous, time invariant airport revenue seems natural.

We assume that each airport-pair market z is served by a set $\mathcal{A}(z)$ of two airlines that each operate a single flight (for example, $\mathcal{A}(z) = \{$Delta, United Airlines$\}$). Airlines

[10] Although the quality of an airline depends on many other factors, this approach allows us to concentrate on the peak capacity issue.

[11] We also assume that the origin airport's allocation decisions do not affect the flight scheduling at the destination airports. Furthermore, we focus on the case of outbound flights. Return trip flights can be dealt with by either an identical analysis with two runways, or simply by adding a scale factor if there is a single runway.

[12] See Wendell H. Ford Aviation Investment and Reform Act for 21st Century, AIR-21. See https://www.iata.org/policy/Documents/passenger-based-airport-charges.pdf.

compete with each other and engage in seat (quantity) competition in each destination market.[13] In such an airport-pair market, airline $a \in \mathcal{A}(z)$ sets its aircraft seat capacity $q^a(z)$, taking the other airline b's seat capacity $q^b(z)$, $b \in \mathcal{A}(z)$, as a given. Airline a's profit in airport pair z is given by $\pi^a(z) = [p^a(z) - \phi]q^a(z)$ where $p^a(z)$ is its fare, ϕ is a per-passenger charge paid to the airport and other variable operating costs are normalized to zero without loss of generality.[14]

A slot allocation is the allocation of the rights for airlines to depart either in a peak or an off-peak period. More formally, it is a mapping n such that $n^a(z) = 1$ if the airline a in airport pair z gets the right to depart at peak time and $n^a(z) = 0$ otherwise. The slot allocation is meant to solve the issue of airport capacity. In the reality, the number of departures is constrained by some upward bounds on peak and offpeak times, say M and L. To make relevant our discussion, we consider the case where the airport is constrained only at peak time but never during the offpeak period. That is, we assume that $M < 2N < M + L$.[15] Accordingly, the peak time slot allocation must satisfy

$$\int_{\underline{z}}^{\overline{z}} \left[n^a(z) + n^b(z)\right] N \mathrm{d}G(z) \ \leq M.$$

This assumption captures the traffic patterns of most busy airports. The allocative problem with peak time capacity constraint entails that congestion does not emerge in the present setting. Indeed, since peak flights are allocated in a number no greater than M, no congestion occurs.

To focus on this capacity problem, we set airport operating costs to zero. The airport gets a revenue ϕ per passenger, so that its total revenue in the airport pair z is equal to $\sum_{a\in\mathcal{A}(z)} \phi q^a(z)$. A private airport proposes a slot allocation that maximizes its revenues

$$\Pi = \int_{\underline{z}}^{\overline{z}} \phi\left[q^a(z) + q^b(z)\right] N \mathrm{d}G(z),$$

while a public airport implements the slot allocation that maximizes the social welfare

$$W = \int_{\underline{z}}^{\overline{z}} \left[w^a(z) + w^b(z)\right] N \mathrm{d}G(z),$$

where $w^a(z)$ (resp. $w^b(z)$) is the welfare generated by the airline a (resp. b) and the airport in the airport-pair market z. Welfare is equal to the consumer and producer surpluses generated the travel activities. Observe that most public airports are operated under a

[13] Quantity competition is common in the airline economics literature. Brueckner (2009) discusses competition in “flight volume”, Pels and Verhoef (2004) competition in “passengers”. Brander and Zhang (1990) find empirical evidence that the rivalry between duopoly airlines is consistent with Cournot behavior.

[14] Variable costs are actually equivalent to parallel shifts in demand functions. Pels and Verhoef (2004), Brueckner and Van Dender (2008), and Basso (2008) discuss non zero variable costs.

[15] In most airports, offpeak time periods last longer than peak time periods ($L > M$), so that the condition $M + L > 2N$ is very likely to hold. We thank the Editor for this point.

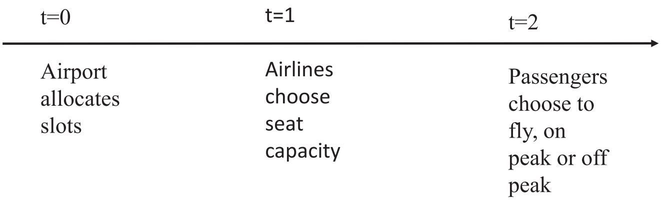

Fig. 1. Timing.

budget constraint. Many have mixed shareholder participation where private investors require dividends. In this case, the airport management maximizes a combination of airport revenue and welfare objectives, with a higher weight on the former when budget constraints are tighter or private participation higher. An airport's decisions will lie between the ones of the private and public airports that are defined above. For the sake of exposition, we exclusively focus on private and public airports endowed with airport revenue and welfare objectives. Choices under mixed objectives are easy to extrapolate.

Fig. 1 shows the timing of the game. In the first stage the airport allocates slots for peak and offpeak travel periods, for a given per-passenger revenue and a given set of airport pairs. In the second stage, the airlines operating in airport pairs non-cooperatively choose their seat supplies based on the slot allocation. In the third stage passengers in each destination decide whether to depart during offpeak or during the peak time, or not to fly at all. The equilibrium concept is the sub-game perfect Nash equilibrium. The timing follows the commitment strength of each type of decision. Airports' slot allocations are usually made for a significantly long time horizon with rather strong commitment because of the long run relationships between airports, airlines and civil aviation authorities. By contrast, the passengers' travel choices are very short run decisions while the airlines' choices of aircraft capacity involve some fleet restructuring and an intermediate time horizon. The two last stages constitute what we now study as the airlines' market equilibrium.

3. Airlines' market equilibrium

In this section, we characterize the equilibrium supply of seats by the airlines (second and third stage). Toward this aim we characterize the equilibrium prices for given aircraft seat supplies and then determine those supplies in a Cournot Nash equilibrium. In this case, each airline chooses the aircraft seat capacity that maximizes its profit, taking as given the competitor's seat capacity and the airport's per-passenger revenue. In the main part of this text, we consider two airlines a and $b \in \mathcal{A}(z)$ that fly to the same destination z. Because destinations are independent for both travelers and airlines, travel demand and airline decisions can be studied separately for each airport pair market. As a result, we temporarily dispense with the reference to airport-pair market z. Let airline a and b's seat supply be denoted by q^a and q^b. We distinguish between the cases where the two airlines serve the market in the same or different time periods.

3.1. Supplies in the same time period

Consider first that airlines a and b supply q^a and q^b seats in two flights departing in the same time period $i \in \{0, 1\}$. Those seats are seen as homogeneous goods by passengers. In the last stage, passengers choose to travel only if $s_i v - p$ is larger than their zero reservation utility. Given the uniform distribution of v, a passenger v is willing to fly if

$$v > v_i = \frac{p}{s_i}. \tag{1}$$

The travel demand is thus given by $x = z(1 - p/s_i)$. At the equilibrium, the market price p balances the demand and supply so that $x = q^a + q^b$, which gives the inverse demand function

$$p = s_i\left(1 - \frac{q^a + q^b}{z}\right). \tag{2}$$

As a result, airline a's profits are given by

$$\pi^a = \left[s_i\left(1 - \frac{q^a + q^b}{z}\right) - \phi\right]q^a, \tag{3}$$

and a symmetric expression holds for airline b. Profits are concave functions in seat capacities.

In the second stage, each airline chooses the number of seats that maximizes its profit, taking as given the competitor's seat capacity and the airport's passenger revenue. The equilibrium seat capacities solve the first order conditions so that $q^a = q^b = zq_i$ where

$$q_i \equiv \frac{s_i - \phi}{3s_i}. \tag{4}$$

Seat capacities are symmetric across airlines and proportional to the market size z. To ensure non zero seat supply, we assume a low enough per-passenger revenue

$$\phi < s_0, \tag{A0}$$

in the sequel. By (2) the equilibrium prices are equal to $p^a = p^b = p_i$ where

$$p_i \equiv \frac{s_i + 2\phi}{3}. \tag{5}$$

Since the airport's revenue is a cost for airlines, prices are naturally increasing functions of ϕ.

3.2. Supplies in different time periods

Consider now that airlines a and b supply q^a and q^b seats in two flights departing respectively in the offpeak and peak period. Because of their preference for peak time departure, passengers do not see those seats as homogeneous goods. In the equilibrium of the last stage, there exist two offpeak and peak flight ticket prices p^a and p^b such that passengers with taste parameter v decide to fly off the peak time if $vs_0 - p^a > vs_1 - p^b > 0$ and travel at peak time if $vs_1 - p^b > vs_0 - p^a > 0$. Otherwise, they do not travel. The offpeak travel price must be smaller than the peak one since offpeak departure is less attractive to passengers: $p^a < p^b$. The passenger indifferent between the peak and offpeak flights has taste

$$v^b = \frac{p^b - p^a}{s_1 - s_0}. \tag{6}$$

Likewise, a passenger is indifferent between flying or not and has taste valuation

$$v^a = \frac{p^a}{s_0}. \tag{7}$$

Given the uniform distribution of v, the mass of passengers flying at peak time is then given by $x^b = z(1 - v^b)$ while the demand for departing off peak is $x^a = z(v^b - v^a)$. In equilibrium, market prices balance demands and supplies such that $x^a = q^a$ and $x^b = q^b$. Solving for those two equations, we get the following inverse demand functions:

$$\begin{aligned} p^a &= s_0\left[1 - \frac{1}{z}\left(q^a + q^b\right)\right], \\ p^b &= s_1\left[1 - \frac{1}{z}\left(\frac{s_0}{s_1}q^a + q^b\right)\right]. \end{aligned} \tag{8}$$

In the aggregate, offpeak and peak travels are imperfect substitutes because the coefficients of q^a and q^b in those expressions are both negative. According to (8), airlines' profits are expressed by

$$\pi^a = \left[s_0 - \frac{1}{z}s_0\left(q^a + q^b\right) - \phi\right]q^a, \tag{9}$$

$$\pi^b = \left[s_1 - \frac{1}{z}\left(s_0 q^a + s_1 q^b\right) - \phi\right]q^b. \tag{10}$$

Finally, it can readily be checked that profits are concave functions of seat capacities.

In the second stage, each airline chooses the aircraft seat capacity that maximizes its profit, taking as given by competitor's seat capacity and airport's per-passenger revenue. The following first order conditions yield the Nash equilibrium conditions:

$$\begin{aligned} \frac{\partial \pi^a}{\partial q^a} &= -\phi + s_0 - \frac{2}{z}s_0 q^a - \frac{1}{z}s_0 q^b = 0, \\ \frac{\partial \pi^b}{\partial q^b} &= -\phi + s_1 - \frac{2}{z}s_1 q^b - \frac{1}{z}s_0 q^a = 0. \end{aligned}$$

Given profits' concavity, these conditions express a unique maximum for each firm. Solving those equations yields the equilibrium seat capacities $q^a(z) = z\ q_{01}$ and $q^b(z) = z\ q_{10}$ where

$$q_{01} \equiv \frac{s_0 s_1 - \phi(2s_1 - s_0)}{(4s_1 - s_0)s_0} \quad \text{and} \quad q_{10} \equiv \frac{2s_1 - s_0 - \phi}{4s_1 - s_0}. \tag{11}$$

Seat capacities linearly increase in market size z. To ensure interior solutions, we assume the condition

$$0 < \phi < \overline{\phi} \equiv \frac{s_0 s_1}{2s_1 - s_0}. \tag{A1}$$

Equilibrium prices can then be computed as

$$p^a = p_{01} \equiv \frac{s_1(s_0 + 2\phi)}{4s_1 - s_0},$$
$$p^b = p_{10} \equiv \frac{(2s_1 - s_0)s_1 + (3s_1 - s_0)\phi}{4s_1 - s_0},$$

which are positive under the above assumption. Similarly, one readily checks that $p_{01} < p_{10}$ and $q_{01} < q_{10}$ so that $p^a < p^b$ and $q^a < q^b$. Therefore, in this model, offpeak flights supply fewer and cheaper seats than peak ones. As result, offpeak flights have lower price-cost margins and are therefore less profitable. As in the previous configuration, prices are increasing functions of the per-passenger revenue ϕ.

Finally, we compare the two above configurations.

3.3. Comparison

The allocation of flights within identical or different time periods yields different aircraft sizes. First, we get

$$q_{10} > q_1 > q_0 > q_{01} \tag{12}$$

(see computation in Appendix A). This means that peak flights carry larger numbers of passengers than offpeak ones and that this difference is more acute when airlines are allocated to different travel periods. Second, we have

$$q_{01} + q_{10} > 2q_0. \tag{13}$$

Accordingly, an allocation of flights to both peak and offpeak time periods generates a larger flow of passengers than an allocation of the flights to the offpeak period. Finally, we have

$$q_{01} + q_{10} > 2q_1 \iff \phi < \widehat{\phi} \equiv \frac{s_0 s_1}{6s_1 - 2s_0}, \tag{14}$$

where $\widehat{\phi} < \overline{\phi}$. At low airport per-passenger revenue $\phi < \widehat{\phi}$, the flow of passengers is larger when the flights are differentiated in term of their departure times. The opposite holds for revenues higher than $\widehat{\phi}$.

There are three forces operating in this setting. First, airlines have low market power when they compete for the same high valuation passengers in a peak/peak configuration. This tends to decrease prices and attract more passengers. Second, the peak/offpeak configuration allows airlines to segment passengers in two groups and offers each one the price and departure time that it prefers. This should also increase the travel demand in the peak/offpeak configuration. Finally, because of the differentiation in departure times, each airline gets stronger market power, which should raise prices and reduce travel demand. Given (13), the second force dominates: the introduction of a peak time departure flight permits better service to high valuation passengers and attracts more of them. Given (14), the second force dominates only for low airport revenues. Indeed, when $\phi < \widehat{\phi}$, travel prices are low and offering an offpeak flight at a low price permits better service to low valuation passengers, which increases the total passengers. To the contrary, when $\phi > \widehat{\phi}$, prices must be high to cover the airport's revenue and are unattractive to low valuation passengers. The introduction of an offpeak flight will not attract a high number of them.

We now turn to the analysis of the airport's choice of allocation of flights to offpeak and peak travel periods.

4. Slot allocation

In this section we examine the slot allocation equilibrium, which requires determining the airport behavior in the first stage of the game. In particular, we consider the slot allocation choice of private and public airports facing a limited capacity of peak slots.

4.1. Private airport

When the airport is privately owned, it maximizes its profit by allocating peak slots subject to its limited capacity. In the airport-pair market z, the number of passengers is given by the airlines' total supply $\sum_{a\in\mathcal{A}(z)} q^a(z)$ and their use of peak slots by $\sum_{a\in\mathcal{A}(z)} n^a(z)$. Let us denote by $n_0(z)$, $n_{01}(z)$ and $n_1(z) \in \{0, 1\}$ the airport's decision variables to allocate respectively an offpeak/offpeak, peak/offpeak and peak/peak configuration in the airport-pair market z. Those decisions are exclusive in the sense that only one variable takes a value equal to 1 (i.e. $n_k(z) = 1$ and $n_{k'} = n_{k''} = 0$ for $k \neq k' \neq k'' \in \{0, 1, 01\}$). We can then simplify the airport allocation problem to the following linear program:

$$\max_{n_0(\cdot), n_{01}(\cdot), n_1(\cdot)} \phi \int_{\underline{z}}^{\overline{z}} z[2q_0 n_0(z) + (q_{01} + q_{10}) n_{01}(z) + 2q_1 n_1(z)] N \mathrm{d}G(z),$$

subject to

$$\int_{\underline{z}}^{\overline{z}} [n_{01}(z) + 2n_1(z)] N \mathrm{d}G(z) \leq M .$$

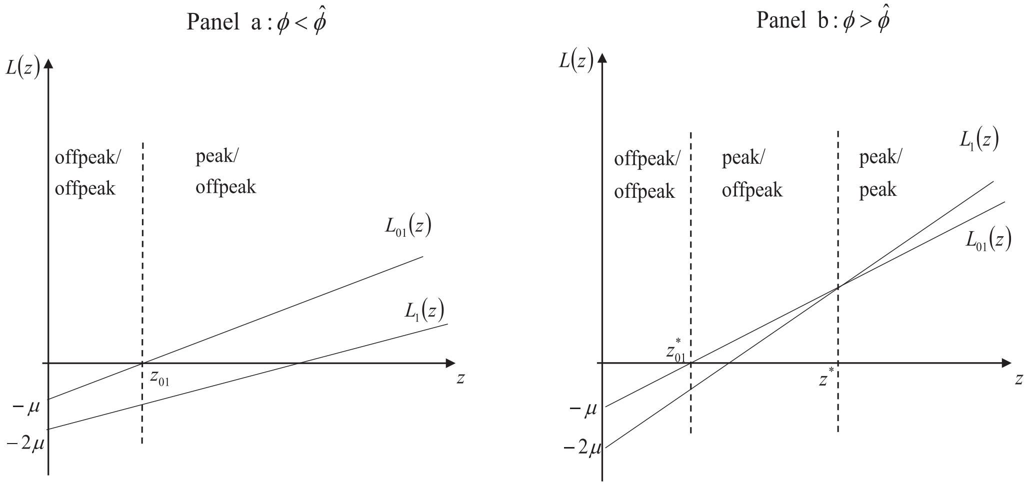

Fig. 2. Marginal profits of shifting one or two flights to the peak period.

Using $n_0 = 1 - n_{01} - n_1$, we write the Lagrangian function

$$\mathcal{L} = \int_{\underline{z}}^{\overline{z}} z \begin{bmatrix} 2q_0(1 - n_{01} - n_1) + (q_{01} + q_{10})n_{01} + 2q_1 n_1 \\ -\mu\left(n_{01} + 2n_1 - \frac{M}{N}\right) \end{bmatrix} N\mathrm{d}G(z),$$

where $\mu > 0$ is the Kuhn–Tucker multiplier associated with the capacity constraint and where we suppress the z argument of decision variables. We treat the variables n_k as continuous functions on [0, 1] and select only the solutions at the corner values 0 and 1. Pointwise differentiation with respect to n_{01} and n_1 yields

$$\mathcal{L}_{01}(z) = z(q_{01} + q_{10} - 2q_0) - \mu, \tag{15}$$

$$\mathcal{L}_1(z) = 2z(q_1 - q_0) - 2\mu. \tag{16}$$

The first expression reflects the marginal profit of shifting one flight to the peak slot in an airport pair that initially hosts two airlines with offpeak flights. By (13), the marginal profit rises with the market size z and falls with a more stringent capacity constraint (higher μ). Similarly, the second expression gives the marginal profit of shifting two flights from offpeak to peak slots in the airport pair. By (12), it also rises with larger market size. It falls with the stringency of the capacity constraint twice as fast as in the previous case because two flights are moved to the capacity constrained peak period.

The panel (a) of Fig. 2 describes the airport's marginal profit according to airport-pair market sizes when the airport's revenue per passenger is small ($\phi < \widehat{\phi}$). By (14), the flow of passengers is larger in the peak/offpeak configuration than in the peak/peak configuration ($q_{01} + q_{10} > 2q_1$). As a result, the marginal profit of shifting one flight to the peak slot $\mathcal{L}_{01}(z)$ is always larger than the marginal profit of shifting two flights

$\mathcal{L}_1(z)$. The airport has therefore no incentive to set-up peak/peak slots. As shown in the figure, the airport allocates peak/offpeak configurations in the large markets such that $\mathcal{L}_{01}(z) > 0$, or equivalently $z > z_{01}$, where

$$z_{01} = \frac{\mu}{q_{01} + q_{10} - 2q_0},$$

is the root of $\mathcal{L}_{01}(z) = 0$. It allocates offpeak/offpeak configurations in the small market when $\mathcal{L}_{01}(z) \leq 0$, or $z \leq z_{01}$. When the number of destinations is large enough ($N > M$), the peak period is filled by a single flight to each destination market with $z > z_{01}$, so that $M = N(1 - G(z_{01}))$, which yields the values of z_{01} and thus μ. By contrast, when the number of destinations is not too large ($N < M$), $z_{01} = 0$ holds and the airport allocates peak/offpeak configurations to all markets (the curve $\mathcal{L}_{01}(z)$ then lies above zero for all z in panel a of Fig. 2). But some peak slots are unused even though consumers would benefit from traveling at the peak time. In this case, $\mu = 0$ and $M > N(1 - G(z_{01})) = N$.

This defines our first type of allocation schedule:

Definition 1. A discriminatory slot allocation schedule grants at most one peak flight per destination market. It allocates a peak/offpeak configuration to high demand destinations with $z > z_{01}$ and an offpeak/offpeak configuration to low demand ones with $z \leq z_{01}$, where z_{01} solves $G(z_{01}) = 1 - M/N$ for $M \leq N$. When $M > N$, then all destination markets are granted a peak/offpeak configuration. Some peak slots are unused.

In this allocation schedule, the airport does not use all its peak slots when $M > N$. In this case, all destinations are given exactly one peak slot although $M - N$ peak slots are unused.

Panel (b) of Fig. 2 displays the marginal profits when the airport revenue per passenger is large ($\phi > \widehat{\phi}$). By (14), the flow of passengers is now larger in the peak/peak configuration ($2q_1 > q_{01} + q_{10}$). For large market sizes z, the marginal profit of shifting two flights on peak $\mathcal{L}_1(z)$ is larger than that of shifting only one flight $\mathcal{L}_{01}(z)$. Hence, the airport has an incentive to allocate peak/peak configurations to any large destination market that yields a positive marginal profit $\mathcal{L}_1(z)$; that is, for airport pairs $z > z^*$, where

$$z^* \equiv \frac{\mu^*}{2q_1 - (q_{01} + q_{10})} \tag{17}$$

is the root of $\mathcal{L}_{01}(z) = \mathcal{L}_1(z)$ and where we put a star superscript * to distinguish this case from the previous one. It can be shown that $z^* \geq z^*_{01}$ where z^*_{01} solves $\mathcal{L}_{01}(z) = 0$.

By contrast, for destination market sizes $z^*_{01} < z \leq z^*$, $\mathcal{L}_1(z)$ is smaller than $\mathcal{L}_{01}(z)$ so that the airport prefers the peak/offpeak configuration. Finally, for market sizes $z \leq z^*_{01}$, the marginal profits of shifting one or two flights to the peak period are always negative so that the airport puts all flights in the offpeak period. To sum up, the airport grants two peak slots to large market destinations and none to the small ones. Destinations with intermediate market sizes receive only one peak slot. The airport peak capacity is then filled by the two flights of each large airport-pair market destination and a flight of each intermediate market size destination. The binding capacity constraint is given by the identity: $M = 2N(1 - G(z^*)) + NG(z_{01}^*)$, from which the value of z_{01}^*, z^* and μ can be computed. Note that this slot allocation schedule uses all available peak slots.[16]

It is convenient to refer to this slot allocation by the ratio between the lowest and highest market sizes of peak/offpeak configurations:

$$\omega^* \equiv \frac{z_{01}^*}{z^*} = \frac{2q_1 - (q_{01} + q_{10})}{q_{01} + q_{10} - 2q_0} < 1.$$

This ratio relates the range of market sizes of peak/offpeak configurations (LHS of the equality sign) to the airport's economic incentives (RHS). The RHS indeed compares the airport's gains from shifting a flight from offpeak to peak time. The ratio is lower than one because the airport gains less from shifting that flight from a peak/offpeak configuration (numerator) than from an offpeak/offpeak one (denominator). The more the difference between those gains, the more the airport has incentives to grow the set of airport-pair markets with peak/offpeak configurations (smaller z_{01}^*/z^*).

Using $z_{01}^* = \omega^* z^*$, this defines our second type of allocation schedule:

Definition 2. A balanced slot allocation schedule with parameter ω^* grants a peak/peak configuration to high demand destinations $z \geq z^*$, a peak/offpeak configuration to intermediate demand ones $z \in [\omega^* z^*, z^*)$ and an offpeak/offpeak to low demand ones $z \leq \omega^* z^*$ where z^* solves $G(\omega^* z^*) + G(z^*) = 2 - M/N$.

The following proposition summarizes the results.

Proposition 1. *If $\phi < \widehat{\phi}$, the private airport implements a discriminatory slot allocation schedule. Otherwise, it implements a balanced slot allocation with parameter $\omega = \omega^*$.*

For small per-passenger revenues ($\phi < \widehat{\phi}$), the airport adopts the rule to *allocate one peak flight per destination market* and does not use the full airport peak capacity when $M > N$. This reflects the above incentive to set peak/offpeak slot configurations. In this case, some peak slots are not used although they have a value to all passengers. As mentioned above, by segmenting the departure time, the airport increases the number of passengers. As shown below this is not the choice of a public airport.

4.2. Public airport

We here consider a public airport that maximizes social welfare, given by the sum of passenger surplus, airlines' and airport's profits.

[16] The peak capacity constraint always binds under our assumption $M < 2N$. Indeed, if it were not binding, we would have $\mu = z^* = 0 \geq z_{01}$ so that the capacity constraint would be given by $M > 2N(1 - G(z^*)) + NG(z_{01}) = 2N$, which is not acceptable.

Because ticket purchases and airport revenues are transfers between those agents, they cancel out in the evaluation of social welfare. Also, because we assumed zero marginal costs for airlines and airport operations, the total welfare in an airport pair z, $\sum_{a\in\mathcal{A}(z)} w^a(z)$, is equal to the gross consumer surplus obtained under the equilibrium seat supplies $q^a(z)$, $a \in \mathcal{A}(z)$. As a result, when the airport allocates the airlines to the same type of time period $i\in\{0, 1\}$, each flight generates a welfare level equal to $\frac{1}{2}\int_{1-2q_i}^{1} vs_i z\mathrm{d}v$. By contrast, when it allocates them to different time periods, the offpeak flight generates a welfare level equal to $\int_{1-q_{01}-q_{10}}^{1-q_{10}} vs_0 z\mathrm{d}v$ while the peak flight yields $\int_{1-q_{10}}^{1} vs_1 z\mathrm{d}v$. One can check that welfare levels are equal to zw_{ij}, where

$$w_i = \frac{(s_i+\phi)(2s_i-\phi)}{9s_i}, \tag{18}$$

for two flights in the same time period $i\in\{0, 1\}$, and

$$w_{01} = \frac{[s_1(s_0-2\phi)+s_0\phi][3s_1s_0+\phi(2s_1+s_0)]}{2s_0(4s_1-s_0)^2}, \tag{19}$$

$$w_{10} = \frac{s_1(2s_1-s_0-\phi)(6s_1-s_0+\phi)}{2(4s_1-s_0)^2}, \tag{20}$$

for two flights in different time periods. By comparing the welfare level obtained in each configuration, we show in Appendix B that

$$2w_1 > w_{01} + w_{10} > 2w_0. \tag{21}$$

The peak/peak configuration always yields higher welfare. Market segmentation does not bring a welfare benefit as it moves departure times away from passengers' preferences and increases prices because of weaker competition.

The airport's allocation problem then simplifies to the following linear program:

$$\max_{n_0(\cdot),n_{01}(\cdot),n_1(\cdot)} \phi\int_{\underline{z}}^{\overline{z}} z[2w_0n_0(z)+(w_{01}+w_{10})n_{01}(z)+2w_1n_1(z)]N\mathrm{d}G(z),$$

subject to

$$\int_{\underline{z}}^{\overline{z}} [n_{01}(z)+2n_1(z)]N\mathrm{d}G(z) \le M.$$

where $n_0(z)$, $n_{01}(z)$ and $n_1(z)\in\{0, 1\}$ are the airport's decision variables as defined in the previous section. The problem is solved in the same way. Pointwise differentiation of the Lagrangian function yields

$$\mathcal{L}_{01}(z) = z(w_{01}+w_{10}-2w_0)-\mu,$$
$$\mathcal{L}_1(z) = z(2w_1-2w_0)-2\mu,$$

where $\mu \ge 0$ is the Kuhn–Tucker multiplier associated with the capacity constraint.

As in the previous section, those expressions reflect the marginal increase in welfare obtained from shifting respectively one or two flights from the offpeak to the peak period. They all increase in market size z but, in contrast to the previous section, by (21), the second expression always increases faster than the first. As a result, the airport has an incentive to set up peak/peak configurations in sufficiently large destination markets. Also, because those expressions are negative for low enough z, it has no incentive to choose a configuration with a peak period for a small enough destination market. For intermediate destination markets, the airport chooses a peak/offpeak configuration. More formally, the airport implements a balanced slot allocation schedule with a peak/peak configuration to high demand destinations $z \geq z^o$, a peak/offpeak configuration to intermediate demand ones $z \in [\omega^o z^o, z^o)$ and an offpeak/offpeak to low demand ones $z \leq \omega^o z^o$. Here, z^o solves $G(\omega^o z^o) + G(z^o) = 2 - M/N$ and the parameter

$$\omega^o = \frac{2w_1 - (w_{01} + w_{10})}{(w_{01} + w_{10}) - 2w_0} < 1,$$

reflects the welfare gain from allocating a second flight to the peak period compared to the loss of moving a second flight to offpeak time. The ratio indicates decreasing welfare gains in allocating additional peak slots to a same destination.

We summarize those results in the following proposition.

Proposition 2. *The public airport implements a balanced slot allocation schedule with parameter ω^o. It offers all available peak slots.*

Proof. See Appendix C. □

The public airport always operates at its maximum peak capacity. The reason is that it internalizes passengers' loss when departure times are away from their preferences. This contrasts with the private airport that keeps some unused peak slots. This is particularly true when per-passenger airport revenues are small, $\phi < \widehat{\phi}$. Indeed, when $M > N$, the private airport implements a peak/offpeak configuration to all airport pairs whereas the public airport allocates such a configuration only to destination with market sizes $z^o\omega^o \leq z \leq z^o$. Similarly, when $M < N$, only the destination market sizes such that $\max\{z^o\omega^o,\ z_{01}\} \leq z \leq z^o$ get an peak/offpeak slot allocation in both public and private airports. Those with $z \leq \min\{z^o\omega^o,\ z_{01}\}$ are allocated to the offpeak period in both types of airports. The rest of airport pairs are misallocated from a welfare point of view.

When $\phi \geq \widehat{\phi}$, both public and private airports adopt a similar structure for slot allocations, reserving two peak slots for large destination markets, one peak slot for medium sized markets, and none for small markets. The main difference lies in the values of the thresholds $(z^*,\ z^*\omega^*)$ and $(z^o,\ z^o\omega^o)$. From the identity $G(z\omega) + G(z) = 2 - M/N$

defining the balanced slot allocation schedule, one can deduce that[17]

$$\frac{\mathrm{d}z}{\mathrm{d}\omega} < 0 < \frac{\mathrm{d}(z\omega)}{\mathrm{d}\omega}.$$

Hence, z falls and $z\omega$ rises with larger $\omega \in (0, 1)$ while z and $z\omega$ reach the same value at $\omega = 1$. The interval $[z\omega, z)$ therefore shrinks with larger $\omega \in (0, 1)$ so that the interval $[z^*\omega^*, z^*)$ includes $[z^o\omega^o, z^o)$ if $\omega^* < \omega^o$. Under the last condition, private airports allocate too many peak/offpeak configurations compared to public airports.

Proposition 3. *For $\phi < \widehat{\phi}$, the private airport implements too many peak/offpeak slot airport pairs from a welfare viewpoint. For $\phi \geq \widehat{\phi}$ the same conclusion applies if and only if $\omega^* < \omega^o$.*

The private airport keeps some peak slots unused because, by doing so, it expands the airport-pair markets by attracting more numerous low valuation passengers. Yet those passengers lose from travelling at an offpeak time. By contrast, the public airport internalizes this loss and uses all peak slots. In practice, airports may misallocate peak slots by misreporting their true handling capacity (De Wit and Burghouwt 2008). The results of allocative inefficiency concerning private airports are consistent with the recent empirical evidence of unused or misused slots (Zografos *et al.*, 2013, Zografos *et al.*, 2012, Katsaros and Psaraki, 2012; ACI Europe, 2009).

4.3. Monopoly

Having examined competition between duopolists in each destination market, we shall now investigate the case in which each destination market is served by a single airline that acts as a monopolist and may operate two flights. As with the baseline model, we analyze the second stage in each possible configuration separately, while the analysis of the third stage remains unchanged.

Consider the case where a monopoly airline m operates all its flights at time period $i \in \{0, 1\}$ in the airport pair with market size z ($\mathcal{A}(z) = \{m\}$).[18] Passengers perceive the same utility for the flights and have the same demands in this time period. The monopoly airline profit is given by:

$$\pi^m(z) = \left[\left(1 - \frac{q^m(z)}{z}\right)s_i - \phi\right]q^m(z),$$

where the number of seats offered in time period i is $q^m(z)$, and s_i is the passenger's intrinsic value parameter of departure times. Under the above concave profit function

[17] One computes $\mathrm{d}z/\mathrm{d}\omega = -zg(z\omega)/[g(z) + \omega g(z\omega)] < 0$ and $\mathrm{d}(z\omega)/\mathrm{d}\omega = \omega^{-1}g(z)/[g(z) + \omega g(z\omega)] > 0$.

[18] This configuration is mainly made for the sake of comparison. It is certainly the case in configurations where there are two (morning and evening) peak slots per day. The case where the airline merges the two flights is left for future research.

and (A0), the equilibrium travel price and number of seats are given by $p^m(z) = p_i^m$ and $q^m(z) = zq_i^m$ where

$$p_i^m \equiv \frac{s_i + \phi}{2} \quad \text{and} \quad q_i^m \equiv \frac{s_i - \phi}{2s_i}.$$

The equilibrium number of passengers is larger at peak time since $q_1^m > q_0^m$. The airline is indifferent to allocating passengers to aircraft of different sizes.

Consider then the case where the monopoly airline is granted an offpeak and peak slot. It turns out that it will not use the offpeak slot. This result is well-known in the theory of 'menu pricing' that studies firms' incentives to offer the same good with a menu of quality levels and prices (see Salant, 1989 and Belleflamme and Peitz, 2010, Ch. 9.2.2.). A menu allows the firm to accommodate high- and low-willingness-to-pay consumers with high and low quality goods. However, it faces a cannibalization effect as the introduction of the low quality good reduces the demand for the high quality one. Salant (1989) shows that the cannibalization effect dominates when the monopoly has the same costs for two quality versions of its good. This applies for our framework with a monopoly airline with two departing offpeak and peak flights: it prefers to put all seats in the peak flight. In practice, it assigns a bigger airplane flying at the peak time.

The airport choice is formulated in a similar way as in the previous section. However, given the peak capacity constraint, both private and public airports choose to offer a single peak slot so that the monopoly airline operates a single flight. A private airport allocates the slots according to the passenger flows $q^m(z)$. Its allocation problem is

$$\max_{m(\cdot)} \phi \int_{\underline{z}}^{\overline{z}} z[q_0^m(1 - m(z)) + q_1^m m(z)] N \mathrm{d}G(z),$$

subject to peak capacity constraint $\int_{\underline{z}}^{\overline{z}} m(z) N \mathrm{d}G(z) \leq M$ where $m(\cdot) \in \{0, 1\}$ is the airport's decision variable to allocate a peak slot in the airport-pair market z. The same allocation problem applies for the public airport, replacing the passenger flows q_0^m and q_1^m by welfare levels $w_0^m = \int_{v_0}^1 v s_0 \mathrm{d}v$ and $w_1^m = \int_{v_1}^1 v s_1 \mathrm{d}v$ with $w_0^m < w_1^m$. The slot allocation is simpler than in the duopoly structures and summarized in the following proposition:

Proposition 4. *Suppose all destination markets are served by monopoly airlines. Then, airlines operate one flight per destination and the (public or private) airport fills the peak slots starting from the largest airline destination markets, until capacity is reached.*

Proof. See Appendix D. □

Very intuitively, the airport gives a peak slot to large destination flights because the latter yield larger passenger flows. The important point is that airport pairs served by monopoly airlines are given the same type of slots. By contrast, those served by duopolies receive different slot configurations. This result is consistent with our empirical fact in the next section, which shows that monopoly airlines more often operate flights in the same time periods.

4.4. Some supporting evidence

To illustrate the empirical relevance of our discussion, we briefly investigate the slot allocation in the airport-pair markets of U.S. airports using the database "Airline On-Time Performance Data", collected by the Office of Airline Information, Bureau of Transportation Statistics, U.S. Department of Transportation. We consider the flight departures during the morning (6:00 a.m. - 11:00 a.m.).[19] We adopt the definition for peak load according to the website of O'Hare International Airport (ORD).[20]

In the American airport system, only four airports have adopted, over the past decades, a slot control system (Hawks, 2015): New York's La Guardia Airport (LGA), New York's John Fitzgerald Kennedy airport (JFK), Newark Liberty National Airport (EWR) and Washington Reagan International Airport (DCA). We find that those airports have about 47%, 36%, and 17% of all flight departures in airport-pair markets with monopoly, duopoly or more airline markets, respectively. Peak time departure flights account for 47%, 38%, and 15% on average.

We focus on the relationship between airline competition and the peak/offpeak slot allocation within each airport pair in the above four slot-controlled airports. We pick up a random week day and month for the period 1988–2016 (Fridays, January). This allows us to exploit a sample with 44,811 flight departures and 19,191 airport pair connections. We want to show thatairport pairs served by a monopoly airline are more often given the same peak or offpeak slot for its flights than those served by multiple airlines. To do this, we build an index expressing the airport average divergence in slot allocation between airport pairs served by a single or two airlines. For the sake of simplicity, we consider all airport pairs with a competition structure involving either one or two airlines (i.e. monopoly or duopoly airlines). To control for any bias related to the number of flights, we restrict the data to the airport pairs served by two flights only. Then, we attribute a zero value to an airport pair if all its flights depart at either the peak or offpeak time period (no divergence), while we attribute a unit value otherwise (full divergence). We build our average divergence index by averaging those values for each airport, morning and competition structure. A low index suggests that many flights to the same destinations depart on the same time period while a high index gives evidence that they are put on different time periods. Fig. 3 shows the histograms of this index for each competition structure. The frequency distribution of monopoly airport pairs is concentrated on low values of the index, suggesting small divergence in the slot allocation. Monopoly airlines are more often flying on the same time period for their flights. By contrast, the frequency distribution of airport pairs served by duopoly airlines is concentrated on intermediate

[19] We focus morning flight departures because their distribution in each airport is rather well centered about the official peak time period of 8:00–9:00. Flight departure time distributions in mid-time and evening are less well centered on their respective official peak time periods, which introduces unnecessary variations in the data.

[20] ORD defines 8–9 am, 15–16 pm, 17–18 pm, and 19–22 pm as peak hours. See Chicago O'Hare Airport Communications Guide.

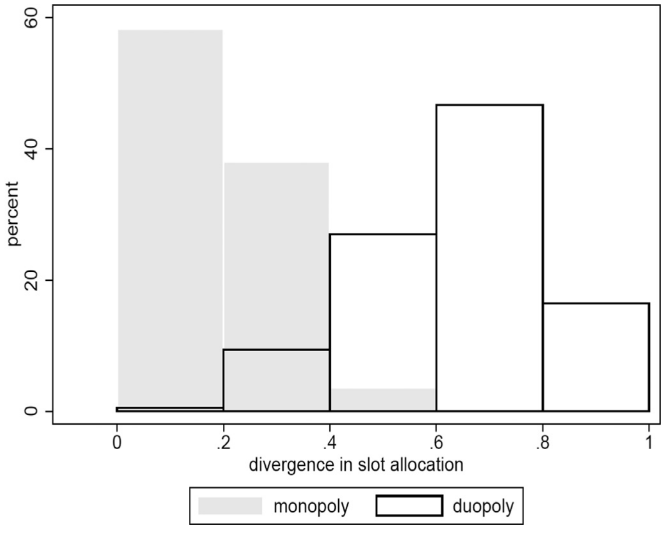

Fig. 3. Histograms of divergence in slot allocation between airport pairs (two flights operated by monopoly or duopoly airlines). Note: The histograms reports the airport average divergence in the slot allocation of airport pairs that are served by two flights operated by one or two airlines. LGA, JFK, NEW and DCA airports. All Fridays in January months for 1988–2016.

value of the index. Airport pairs served by duopolies are thus less often granted the same peak slots, as predicted by our theoretical results.

5. Slot markets

The economic literature advocates for the implementation of slot allocation with auctions (Brueckner, 2009).[21] In practice, slot auctioning is a difficult task in hub airports since it requires allocating complementary flights to various slots, which requires the adoption of combinatorial auctions (Rassenti et al., 1982) In addition, up to now, few airports have set up such auction mechanisms because of airlines' resistance to a transfer of their rents and the complexity of such auctions. Slot auctioning has been fully or partly implemented in a few international airports like Hong Kong, Guangzhou Baiyun and others. Those experiences have had mixed success because of incumbents' market power and market manipulations. Given its prevalence in economic analysis and recommendations, we nevertheless investigate the properties of the slot allocation through the analysis of a simple slot market mechanism.

We focus on a market for peak slots.[22] We assume that a slot market authority[23] sets the peak slot price t and collects the demand by airlines. At the slot market equilibrium, the slot price should give airlines no incentives to change departure periods, so that

[21] Earlier, Grether et al. (1979) proposed to use the competitive sealed-bid auctions for primary markets.
[22] Because we assumed no capacity constraint on off-peak slots, the off-peak slot price should be zero. The implementation of a market for this type of slot is not necessary.
[23] For example, the market can be implemented by an agent or algorithm of the Aviation Authority.

Table 1
Duopoly airlines' profits in an airport pair with market size.

$(\pi^a,\ \pi^b)$	$y^b = 0$	$y^b = 1$
$y^a = 0$	$(z\pi_0,\quad z\pi_0)$	$(z\pi_{01},\quad z\pi_{10} - t)$
$y^a = 1$	$(z\pi_{10} - t,\ z\pi_{01})$	$(z\pi_1 - t,\ z\pi_1 - t)$

they operate their flights in the demanded slots. The authority has the objective to assign slots up to peak capacity fulfillment. Therefore, by construction, there are no inefficiencies resulting from unused peak slots but, as will be seen, the slot market does not necessarily lead to the public airport's choice. As before, we assume that once slots are allocated, airlines competitively set their seat capacities and passengers choose their preferred flights.

Consider again the two airlines that supply each one aircraft in the destination market $z \in \mathcal{A}(z)$. The two airlines in airport-pair market $z \in \mathcal{A}(z)$ obtain the same profit $z\pi_0$ or $z\pi_1$ when they depart together at peak or offpeak time. When they depart in different time periods, the airline departing during the offpeak time period gets $z\pi_{01}$ while the other flying at peak time gets $z\pi_{10}$. It can be shown that $\pi_{10} > \pi_1 > \pi_0 > \pi_{01}$ (see Appendix E).[24] So, an airline increases its profit when its flight shifts to peak time but gets a lower profit when the other flight also shifts to peak time.

Airlines uncooperatively decide about their slot demand. In a Nash equilibrium, they do not deviate from their slot demand decisions. Let us denote by $y^a \in \{0, 1\}$ the slot demanded by airline $a \in \mathcal{A}(z)$: when $y^a = 1$ the airline demands to use a peak slot at a price t, while it flies off the peak when $y^a = 0$. The game between airlines a and $b \in \mathcal{A}(z)$ has the following normal form (See Table 1):

The airlines' equilibrium demands $(y^a,\ y^b)$ depend on how destination market sizes z compare to the peak slot price. For large z, both airlines demand peak slots while they both demand offpeak slots for low z. For intermediate z, their demand are slightly more complicated because the above game yields different types of equilibria. Let us define the threshold

$$\omega^e \equiv \frac{\pi_{10} - \pi_0}{\pi_1 - \pi_{01}},$$

which compares the *airline*'s gains from shifting a flight from offpeak to peak time. Suppose that $\omega^e > 1$. In this case, it is shown that only one airline in each intermediate-sized market demands a peak slot. The other airline avoids head-to-head competition and flies in the offpeak period (see Appendix E). The slot market authority is then able to find a slot price t that is attractive only for all flights in large markets and for one flight in each intermediate-sized markets. As a result, flights follow a balanced slot allocation with parameter ω^e. The equilibrium slot market price is equal to $t = z^*(\pi_{10} - \pi_0)$ where z^* is given in the definition of the balanced slot allocation.

[24] Note also that, as in Brueckner (2009), we avoid entry issues by assuming that no airline exits in any airport pair (z is sufficiently large).

Suppose now that $\omega^e < 1$. Then, airlines operating in intermediate-sized markets (uncooperatively) make the same decision. They both fly either on or off the peak. Airlines find it more profitable to match the time slot of their competitors. Indeed, an airline can save on the slot price t when it matches the offpeak slot of its competitor (i.e. $\pi_{00} > \pi_{10} - t$). It raises its operational profit when it matches the peak slot of its competitor (i.e. $\pi_{11} - t > \pi_{01}$). The absence of airlines' coordination leads a large number of equilibria so that some equilibrium refinements are needed. Toward this aim, we assume that airlines can exchange their peak slot rights with side payments or re-allocate their peak slots to the most profitable flights across their fleets. This refinement ensures the selection of unique and efficient slot allocation equilibrium where peak time slots are assigned to the largest markets. The slot market equilibrium then leads to the following allocation schedule:

Definition 3. A pooled slot allocation schedule assigns the same type of slot to the flights to the same destination: a peak/peak configuration for $z > z^*$ and an offpeak/offpeak for $z \leq z^*$ where $G(z^*) = 1 - M/(2N)$.

Comparing those results to the ones for private and public airport we can state the following proposition:

Proposition 5. Suppose $\omega^e > 1$. *Then, in equilibrium, the slot market results in a balanced slot allocation schedule with parameter* ω^e. *Otherwise, if* $\omega^e < 1$, it yields a pooled slot allocation schedule.

Proof. See Appendix E. □

The important conclusion from Proposition 5 is that the slot allocation in a slot market equilibrium can be different from the one chosen by a public and private airport. The first reason is that the willingness to pay for peak slots is driven by each individual airline's profit in a city pair market. By contrast, the slot allocation by the public and private airports is driven by the welfare and passenger flows generated within each market. Indeed, ω^e reflects the airline individual profits rather than airport pair profit, welfare or passenger flow. The second reason lies in the peak slot competition between airlines and the equilibrium in each airport pair. In a slot market with a same price for each type of slot, airlines may end up with the same decision on their slot purchases. This is why the slot market equilibrium is biased toward the same slot structure when $\omega^e < 1$.

Finally, it must be noted that the above slot markets has a rather simple structure and appears more equitable from the airlines' point of view than a full fledged auction mechanism. The slot markets apply the same slot price to all airlines and also imply lower rent extraction. However, the above discussion does not explain how the slot market authority determines equilibrium slot prices. This question is left for further research.

6. Concluding remarks

This paper studies the allocation of departing slots in airports with limited capacity. Because slot management is the standard tool to manage airport capacity, it is important to investigate the impact of capacity constraints on one of the main factors underlying the use of time slots, namely the preference for peak time travel.

We found that private airports have incentives to grant their departure slots so that airlines competing in the same destination market fly in different time periods. Depending on the revenues that the airport extracts from passengers, private airports may also keep some peak slots unused in the destination markets with competing airlines. This implies that airports may not exploit their full peak slot capacity, leading to allocative inefficiency. By contrast, monopoly airlines operating alone in a airport-pair market prefer to operate one flight to each destination. Airports have no incentives in using different time slots to segment those markets. This entails one flight to each destination, so that the airport cannot differentiate quality as with airport pairs served by duopolies. Finally, in each airport, authorities may design and implement a market for peak slots so that no peak slot becomes unused. However the outcome of such a market does not achieve the welfare optimal slot allocation. Our results help to explain some empirical regularities in the U.S. airline markets. These results also provide a theoretical explanation to the recent phenomenon of allocative inefficiency in several airport systems.

Appendix A. Equilibrium seat capacities and profits

To compare individual seat capacities, we compute

$$q_{10} - q_1 = \frac{(s_1 - s_0)(2s_1 + \phi)}{3s_1(4s_1 - s_0)} > 0 \quad \text{and} \quad q_0 - q_{01} = \frac{(s_1 - s_0)(s_0 + 2\phi)}{3s_0(4s_1 - s_0)} > 0,$$
$$q_1 - q_0 = \frac{(s_1 - s_0)\phi}{3s_1 s_0} > 0 \quad \text{and} \quad q_{01} + q_{10} - 2q_0 = \frac{(s_1 - s_0)(s_0 + 2\phi)}{3s_0(4s_1 - s_0)} > 0.$$

where the inequalities obtain because $s_1 > s_0$. Also, we have

$$q_{01} + q_{10} - 2q_1 = \frac{(s_1 - s_0)[s_0(s_1 + 2\phi) - 6s_1\phi]}{3s_1 s_0(4s_1 - s_0)} > 0 \iff \phi < \widehat{\phi} \equiv \frac{s_0 s_1}{6s_1 - 2s_0}.$$

The equilibrium profits can be computed as

$$\pi_i = \frac{1}{9}\frac{(\phi - s_i)^2}{s_i}, \quad \pi_{10} = s_1\left(\frac{2s_1 - \phi - s_0}{4s_1 - s_0}\right)^2 \text{ and } \pi_{01} = \frac{1}{s_0}\left[\frac{s_0 s_1 - \phi(2s_1 - s_0)}{4s_1 - s_0}\right]^2.$$

To compare individual airline profits, we compute

$$\pi_{10} - \pi_1 = \frac{(s_1 - s_0)[(7s_1 - s_0)\phi - 2s_1(5s_1 - 2s_0)]}{9s_1(4s_1 - s_0)^2} > 0,$$

$$\pi_1 - \pi_0 = \frac{(s_1 - s_0)\left(s_1 s_0 - \phi^2\right)}{9 s_1 s_0} > 0,$$
$$\pi_0 - \pi_{01} = \frac{z(s_1 - s_0)(s_0 + 2\phi)[(s_0(7s_1 - s_0) - 2(5s_1 - 2s_0)\phi)]}{9s_0(4s_1 - s_0)^2} > 0,$$

where the inequalities obtain by (A1). Also, we compute

$$\pi_{10} - \pi_0 = -\frac{(s_1 - s_0)\left[\phi^2(16s_1 - s_0) + \phi\left(2s_0^2 + 4s_0 s_1\right) + s_0\left(-36s_1^2 + 16s_0 s_1 - s_0^2\right)\right]}{9s_0(4s_1 - s_0)^2} > 0,$$

The inequality obtains because the convex quadratic function of ϕ in the square brackets is negative for $\phi \in [0, \overline{\phi}]$. Indeed, the latter has one positive root, is increasing for $\phi > 0$ and is negative at both $\phi = 0$ and $\phi = \overline{\phi}$. Hence the profit ranking is given by

$$\pi_{10} > \pi_1 > \pi_0 > \pi_{01}.$$

Appendix B. Public airport

Note first that interior solutions obtain for $0 < 1 - 2q_i < 1$ and $0 < 1 - q_{01} - q_{10} < 1 - q_{10} < 1$. This implies that $0 < w_i < \frac{1}{2} s_i \int_0^1 v\mathrm{d}v = \frac{1}{4} s_i$, $0 < w_{01} + w_{10} = \int_{1-q_{01}-q_{10}}^1 v s_0 \mathrm{d}v < \frac{1}{4} s_0$, $0 < w_{10} = \int_{1-q_{10}}^1 v s_1 \mathrm{d}v < \frac{1}{4} s_1$ and finally $0 < w_{01} = \int_{1-q_{01}-q_{10}}^{1-q_{10}} v s_0 z \mathrm{d}v$. It can be shown from (18)–(20) that the last inequality is satisfied for $\phi < \overline{\phi}$ and the rest for $\phi < s_0/2$.

We further need to show that $2w_1 > w_{01} + w_{10} > 2w_0$. We compute

$$w_1 - w_0 = \frac{(s_1 - s_0)\left(\phi^2 + 2s_1 s_0\right)}{9 s_1 s_0} > 0,$$
$$2w_1 - w_{10} - w_{01} = K\left[s_1^2 s_0(20s_1 + s_0) + 4s_1 s_0 \phi(2s_1 + s_0) + \phi^2\left(36s_1^2 - 19s_1 s_0 + 4s_0^2\right)\right] > 0,$$
$$w_{10} + w_{01} - 2w_0 = K\left[108s_1^2 s_0 + s_0\left(8s_0^2 - 4s_0\phi - 13\phi^2\right) + s_1\left(28\phi^2 - 65s_0^2 - 8s_0\phi\right)\right] > 0,$$

where $K = (s_1 - s_0)/\left[18s_0(4s_1 - s_0)^2\right] > 0$. The positive sign in the second and third expressions results from $\phi < \overline{\phi}$ and $\phi < s_0/2$.

Appendix C. Proof of Proposition 2

We prove that the airport allocates a peak/peak configuration to the destination markets $z \in [z^o, \overline{z}]$ where z^o solves $G(z^o\omega^o) + G(z^o) = 2 - \frac{M}{N}$. It gives a peak/offpeak configuration to the destination markets $z \in [z^o\omega^o, z^o)$ and an offpeak/offpeak configuration to those with $z \in [\underline{z}, z^o\omega^o)$. In any case, the airport uses all available peak slots.

Pointwise differentiation yields

$$\mathcal{L}_{01} = z(w_{01} + w_{10} - 2w_0) - \mu^o,$$

$$\mathcal{L}_1 = z(2w_1 - 2w_0) - 2\mu^o,$$

where $\mu^o \geq 0$ is the Kuhn–Tucker multiplier associated with the capacity constraint. By (21), the second expression rises faster with z than the first one. Also, we have $\mathcal{L}_{01} \geq 0$ if and only if $z \geq z_{01}^o$, $\mathcal{L}_1 \geq 0$ if and only if $z \geq z_1$ and $\mathcal{L}_1 \geq \mathcal{L}_{01}$ if and only if $z \geq z^o$ where

$$z_{01}^o \equiv \frac{\mu^o}{(w_{01} + w_{10}) - w_0}, \quad z_1^o \equiv \frac{2\mu^o}{2(w_1 - w_0)} \quad \text{and} \quad z^o \equiv \frac{\mu^o}{w_1 - (w_{01} + w_{10})}.$$

By (21), we have $0 < z_{01}^o < z_1^o < z^o$ when the constraint is binding, $\mu^o > 0$. As a result, when the constraint is binding, we get that $\mathcal{L}_1 > \max\{\mathcal{L}_{01}, 0\}$ so that the optimal allocation is equal to $(n_0, n_{01}, n_1) = (0, 0, 1)$ for any $z > z^o$. Similarly, we have that $\mathcal{L}_{01} > \max\{\mathcal{L}_1, 0\}$ and the optimal allocation is equal to (0, 1, 0) for any $z_{01}^o < z < z^o$. Finally, we get that $0 > \max\{\mathcal{L}_{01}, \mathcal{L}_1\}$ and the optimal allocation is given by (1, 0, 0) for $z < z_{01}^o$. The binding constraint implies that $\int_{\underline{z}}^{\overline{z}} (n_{01} + 2n_1) N \mathrm{d}G(z) = N \int_{z_{01}^o}^{\overline{z}} \mathrm{d}G(z) + N \int_{z^o}^{\overline{z}} \mathrm{d}G(z) = N[2 - G(z_{01}^o) - G(z^o)] = M$. One finally can check that $z_{01}^o = z^o \omega^o$ where

$$\omega^o = \frac{2w_1 - (w_{01} + w_{10})}{(w_{01} + w_{10}) - 2w_0} < 1.$$

This yields z^o as the solution of the following equation: $G(z^o \omega^o) + G(z^o) = 2 - M/N$.

Finally, suppose that the constraint is not binding ($\mu = 0$). Then, by (21) $\mathcal{L}_1 > \mathcal{L}_{01}$ for any z. Therefore, the optimal allocation is $(n_0, n_{01}, n_1) = (0, 0, 1)$. This case occurs if $\int_{\underline{z}}^{\overline{z}} (n_{01} + 2n_1) N \mathrm{d}G(z) = 2N < M$, which we have assumed away in this paper.

Appendix D. Monopoly

The Lagrangian is written as

$$\mathcal{L}(z) = \int_{\underline{z}}^{\overline{z}} \left\{ \phi z [q_0^m (1 - m(z)) + q_1^m m(z)] + \mu \left[\frac{M}{N} - m(z) \right] \right\} N \mathrm{d}G(z),$$

Taking $m(z)$ as a continuous function, pointwise differentiation w.r.t. $m(z)$ yields

$$\mathcal{L}_1(z) = \phi z (q_1^m - q_0^m) - \mu.$$

Hence, $m(z) = 1$ if $\mathcal{L}_1(z) > 0 \iff z > \mu / [\phi(q_1^m - q_0^m)]$. Otherwise, $m(z) = 0$. The binding constraint yields $\mu = [\phi(q_1^m - q_0^m)] G^{-1}(1 - M/N)$. Hence, the solution is $m(z) = 1$ if $G(z) > 1 - M/N$ and $m(z) = 0$ otherwise.

Appendix E. Slot market equilibrium

Consider two airlines a and $b \in \mathcal{A}(z)$ that supply each an aircraft respectively with q^a and q^b seats in the destination market z. If they share the same travel period $i \in \{0, 1\}$, we know that they will set a seat capacity equal to $q^a = q^b = q_i$, where we dispense with the reference to z when it does not bring confusion. They will make a total profit equal to $2\pi_i = 2[(1-2q_i)s_i - \phi]zq_i$. Similarly, when they operate in different time periods, we have that, say, $q^a = zq_{01}$ and $q^b = zq_{10}$, which yields the total profit $\pi_{01} + \pi_{10} = \{s_0[1-(q_{01}+q_{10})] - \phi\}zq_{01} + \{s_1[1-(q_{01}s_0/s_1 + q_{10})] - \phi\}zq_{10}$. Comparison of individual profits (see Appendix A) yields

$$\pi_{10} > \pi_1 > \pi_0 > \pi_{01}. \tag{22}$$

Hence, airlines prefer to be the unique recipient of a peak period. By contrast, they make their worst profit realization when they operate the unique offpeak flight, and therefore prefer to demand a peak slot. As a result, there is competition for peak slots, which pushes the airport to its peak capacity constraint.

We first determine the Nash equilibrium in the game between the two airlines in each destination market z for a given slot price t and then determine the slot price t that is compatible with an equilibrium. Let us define $z_0 = t/(\pi_{10} - \pi_0)$ and $z_1 = t/(\pi_1 - \pi_{01})$, which are positive by (22). We get the threshold

$$\omega^e \equiv \frac{z_1}{z_0} = \frac{\pi_{10} - \pi_0}{\pi_1 - \pi_{01}}.$$

Suppose first that $z_0 < z_1$ so that $\omega^e > 1$. Then, it can readily be checked that, the slot game of Table 1 yields a Nash equilibrium in which both airlines demand a peak slot for large destination markets $z \geq z_1$ and demand no peak slots for small ones $z \leq z_0$. For market sizes $z \in (z_0, z_1)$, only one airline demands a peak slot while the other does not (there are actually two equilibria). In a slot market equilibrium, the slot market authority fills slots up to capacity. To achieve this it should be that $M = 2N(1 - G(z_1)) + N(G(z_1) - G(z_0))$ and $t = z_0(\pi_{10} - \pi_0)$. The former condition yields

$$G(z_0) + G(z_0\omega^e) = 2 - M/N.$$

This corresponds to the condition for a balanced slot allocation schedule with parameter threshold ω^e. However, since ω^e is generically different from ω^* and ω^o, it implies a different slot allocation. The above identity solves for z_0.

Suppose then that $z_0 \geq z_1$ so that $\omega^e \leq 1$. Then, for a given slot price t, the Nash equilibrium of the above game implies that, as above, both airlines demand a peak slot for large destination markets $z \geq z_0$ and demand none for small markets $z \leq z_1$. For market sizes $z \in (z_1, z_0)$, two Nash equilibria arise: one where both airlines jointly demand two peak slots $((y^a, y^b) = (1,1))$ and another one where none express a demand for peak slots $((y^a, y^b) = (0,0))$. Thus, there exist an infinity of equilibrium profile $(y(z), y(z))$, $y(z) \in \{0, 1\}$, $z \in (z_1, z_0)$. The slot market clears for infinite combination of $(y(z), y(z))$, $z \in (z_1, z_0)$, that satisfies the capacity constraint: $M = 2N(1 - G(z_1)) + \int_{z_0}^{z_1} 2y(z)N\mathrm{d}G(z)$. The slot market is not able to determine a unique combination of $y(z)$, $z \in (z_1, z_0)$.

To select amongst Nash equilibria for $z \in (z_1, z_0)$, we assume possible side payments and flight re-allocation within multiple-destination airlines. An airline operating in a larger destination market has incentives to make side payments to obtain the peak slot of another airline operating in a smaller destination market. Multiple-destination airlines have incentives to re-allocate their peak slots to their destinations with largest market sizes z. As a result, the destinations with largest market sizes will demand and purchase peak slots. Formally, there exists a destination market size $\widehat{z} \in (z_1, z_0)$ such that airlines with $z \geq \widehat{z}$ demand a peak slot while others do not. More explicitly, airlines jointly demand $(y^a, y^b) = (1, 1)$ for $z > z_0$, $(y^a, y^b) = (1, 1)$ for $z_0 > z > \widehat{z}$, $(y^a, y^b) = (0, 0)$ for $\widehat{z} > z > z_1$ and also for $z \leq z_1$.

The slot market mechanism assures the equalization of peak slot demand to peak capacity. That is, $M = 2N(1 - G(\widehat{z}))$. As a result, the slot market yields to a pooled slot allocation schedule that assigns the same type of slot to the flights on the same destination: a peak/peak configuration for $z \geq \widehat{z}$ and an offpeak/offpeak for $z < \widehat{z}$ where $G(\widehat{z}) = 1 - M/(2N)$.

Although the market mechanism result here in a unique slot allocation, it results in a multiplicity of market prices. The market price must indeed map to an interior solution for $\widehat{z} \in (z_1, z_0)$ where $z_0 = z_1/\omega^e = t/(\pi_{10} - \pi_0)$. This implies that the equilibrium price t must lie within the interval $[\widehat{t}, \widehat{t}/\omega^e]$ where $\widehat{t}$ solves $G(\widehat{t}/(\pi_{10} - \pi_0)) = 1 - M/(2N)$.

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