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Congestion pricing vs. slot constraints to airport networks

Achim I. Czerny*

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Abstract

Congestion has become a problem for many airports throughout the world. Two different policy options to control congestion are analyzed in this paper: slot constraints and congestion pricing. In particular, our model takes into account that the airline industry is characterized by significant demand uncertainty. Furthermore, due to the network character of the airline industry, the demand for airport capacities normally is complementary. We show that this favors the use of slot constraints compared to congestion pricing from a social point of view. In contrast, for monopolistic airports, prices as instruments constitute a dominant choice.

JEL Classification: D42, L93.

Keywords: Slots, uncertainty, monopolistic airports, regulation.

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1 Introduction

Compared to other transport modes, air transport has realized the most impressive growth in the last decades. However, this went not along with a respective growth in airport capacity. As a consequence, congestion of airports has become a relevant problem because of delays which are costly for airlines, passengers, and the environment. Since air traffic forecasts show that growth will continue to be high during the next years, congestion problems are expected to increase in the future.

In order to control airport congestion the most overloaded airports outside the U.S. are slot constrained. An airline that wishes to incorporate a slot constrained airport into its networks needs to have a respective permission (slot) to use that airport at a specified time. Because the number of slots is constrained, airline operations at the airport are limited and, consequently, demand and congestion can effectively be controlled and optimized. There is, however, another possibility to reduce congestion. An increase of take off and landing fees can reduce slot demand until the optimal level of congestion is reached. Under certain conditions, these two different ways to deal with congestion can always generate the optimal result from a social point of view. However, this requires that airport slots are allocated efficiently among airlines and that the regulator has perfect information about the benefits and costs of take off and landing operations. Both of these premises are normally not fulfilled in reality.

At present airport slots are basically allocated by grandfather rights or, in other words, by history. This guarantees continuity of airline operations because airlines are allowed to constantly regain slots which they have used in the past. On the other hand, allocation based on grandfather rights does not account for the willingness to pay of airlines and, therefore, hampers al-

locative efficiency. Additionally, regulators are not perfectly informed about the social benefits and costs of airport operations [4]. The airline industry, in particular, is characterized by a fluctuating demand that is difficult to foresee. Thus, the benefits of airport operations in terms of the airlines' willingness to pay for slots are difficult to predict. The same holds for the social costs of airport operations. Although the airports' cost for operation and maintenance as well as the airlines' congestion costs can be estimated fairly well, the measurement of the passengers' and the environmental costs of congestion is problematic. For these reasons a regulator has to deal with considerable uncertainty regarding the social benefits and costs of airport operations.

Resource management under uncertainty was extensively analyzed in the field of environmental economics. For instance, Weitzman [8], referring to pollution management (amongst others), showed that under uncertainty about benefits and costs of pollution the expected welfare depends on the choice between prices (e.g., pollution taxes) or quantities (e.g., emission standards) as instruments. His analysis is based on the assumption that the amount of uncertainty is sufficiently small to justify a second order approximation of benefit and cost functions in the relevant range. In contrast, Adar and Griffin [1] directly focus on linear marginal benefit and marginal cost functions where uncertainty is modelled as producing parallel shifts of these functions. They demonstrate that optimal choice of instruments depends on the relative slopes of the marginal benefit and the marginal cost function, which is equivalent to the result indicated by Weitzman [7]. Prices as instruments generate a higher expected social welfare than quantities as instruments if the slope of the marginal benefit function is higher than that of the marginal cost function in absolute values et vice versa. The result

will reappear as a special case of our own model. Note that the result also holds for uncertain social costs as long as the benefit and cost functions are not stochastically correlated [6], [7], [8]. Stavins [7] additionally finds that positive correlation of benefits and costs favors quantities as instruments. In a general equilibrium setting Kelly [5] also provides theoretical support for a quantity based regulation.

However, these results are of limited use for the management of airport facilities like runway capacities. The reason is that the demand for the runway capacities of different airports is interdependent, i.e. slot usage at one airport affects slot demand at other airports. In principle, two types of interdependencies exist: substitutability due to airport competition or complementarity. Airports might compete for passengers or air cargo if they are closely located to each other. Another source for airport competition is the hub-and-spoke networks of airlines, because hub-airports can compete for transfer passengers. With competition an increase of runway usage at one airport decreases the demand for runway usage at other airports. However, due to the network character of the industry, airports normally provide complementary services because flights connect different airports. Thus, an increase of slot usage at one airport raises slot demand at other airports. In this paper we focus on the second effect which we shall call *demand complementarity* in the following.

The contribution of this paper is to model and analyze the welfare effects of slot constraints and congestion pricing under uncertainty and demand complementarity. We show that this changes the standard results provided by Weitzman [8] and Adar and Griffin [1]. The difference in expected social welfare generated by congestion pricing or, respectively, slot constraints still depends on the relative slopes of the marginal benefit and marginal social cost function. However, the level of demand complementarity also plays an im-

portant role. We show that slot constraints become more favorable compared to congestion pricing if demand complementarities are taken into account. Under congestion pricing the price for take off and landing operations is fixed but not the number of operations, as under slot constraints. Therefore, due to the demand uncertainty, under congestion pricing the amount of take off and landing operations is also uncertain. Moreover, the demand complementarity for airport facilities reinforces the effect of demand uncertainty on runway usage. If demand at one airport is higher than expected it also increases the demand for other airports, due to the demand complementarity, which in turn increases demand for the former airport and so forth. For this reason, if demand complementarity plays an important role, the expected social welfare under congestion pricing decreases compared to slot constraints.

The analysis of socially optimal regulation is complemented by an investigation of monopolistic airport behavior. Profit maximizing monopolistic airports can be expected to raise take off and landing fees above the efficient level. However, at overloaded airports, price increases constitute an adequate measure to reduce congestion and improve efficiency. Therefore, one might ask whether monopolistic airport pricing can compensate for the negative effects arising from external congestion costs. In order to analyze the need to regulate congested airports we will therefore analyze the behavior of monopolistic airports under uncertainty and demand complementarity. We show that in a non-cooperative game airports always choose prices as instruments. Hence, they fail to choose quantities as instruments when this is socially optimal. Moreover, given that they correctly choose prices as instruments from a social planners point of view, monopoly prices turn out to be too high and, therefore, produce a deadweight loss.

In the next section we present the model. Section three compares the effects of slot constraints and congestion pricing on expected social welfare. Section four analyzes monopolistic airport behavior. Finally, in section five we conclude.

2 The model

We consider two monopolistic airports in a regulated area and some outside airports. Each regulated airport serves perfectly separated catchment areas. Figure 1 illustrates this case. Passengers are assumed to make only direct flights (no transfers). Airports 1 and 2 are under the control of a regulator or, respectively, a social planner. The other airports are not. For instance, suppose that they belong to a different jurisdiction. Airports 1 and 2 are assumed to be symmetric with regard to cost and demand conditions.

Airport usage at each airport is denoted by $q_i \geq 0$ with $i \in \{1, 2\}$. Airlines connecting airports 1 and 2 need to use airport facilities at both airports and will serve customers at both airports. We capture this demand complementarity by introducing a parameter α in the airlines' inverse demand for runway capacity at airport i :

$$P_i(q_1, q_2) = \alpha q_j + a - b q_i + e_i \quad (1)$$

with $i \neq j$, $a, b > 0$, and $b > \alpha \geq 0$. By equation (1) the demand for runway facilities depends on runway usage at the other airport. An increase of the runway usage at one airport induces a parallel shift of the inverse demand curve of the other airport. As a consequence, for given prices an increase of slots demanded at airport j raises the demand for slots of airport i . The intensity of this effect depends on α . Since, by assumption, airports 1 and 2 do not compete, α is non-negative. Furthermore, airport demand is

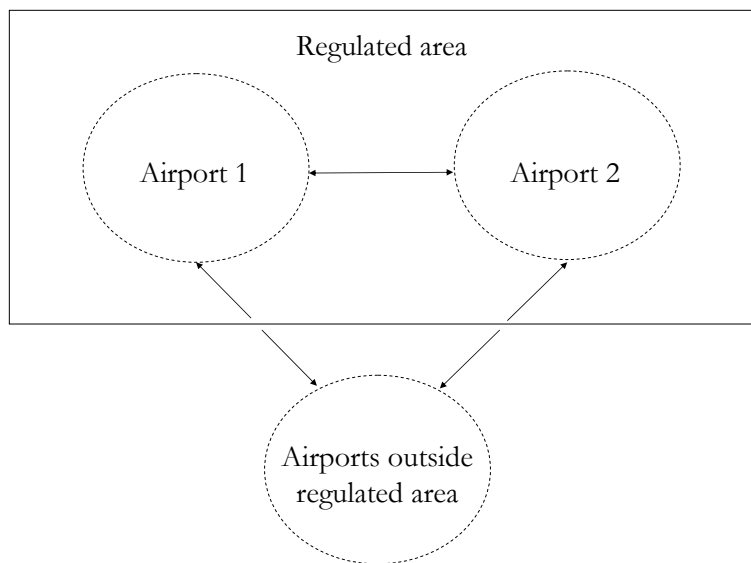


Figure 1: Two airports in a regulated area with perfectly separated catchments.

determined by a stochastic term e_i for $i \in 1, 2$ that also generates parallel shifts of the demand curve. Demand shocks e_1 and e_2 are supposed to be independent, with expectation value zero and variance $\sigma_p^2 > 0$.

Solving simultaneously the two equations given by (1) generates the demand function for slots at airport i :

$$q_i(p_1, p_2) := \frac{a b + a \alpha - b p_i - \alpha p_j + b e_i + \alpha e_j}{b^2 - \alpha^2}. \quad (2)$$

Assuming that airlines are in perfect competition, the inverse demand function depicts the marginal benefits of passengers from slot usage minus the marginal costs of airlines. The former accounts for the private congestion costs of passengers and the latter for the private congestion costs of airlines. The passenger benefits B from using airports 1 and 2 can be expressed by the line integral

$$B(q_1, q_2) = \oint_{(0,0)}^{(q_1, q_2)} \left(\sum_{i=1}^2 P_i(x_1, x_2) dx_i \right).$$

The integrability condition is satisfied since, in a partial economic context, there are no income effects [3]. This implies that the solution of the line integral is independent of the particular path along which integration is taken. Therefore, one way to calculate benefits is

$$\begin{aligned} B(q_1, q_2) &= \int_0^{q_1} P_1(x_1, 0) dx_1 + \int_0^{q_2} P_2(q_1, x_2) dx_2 \\ &= \alpha q_1 q_2 + a (q_1 + q_2) - \frac{b}{2} (q_1^2 + q_2^2) + e_1 q_1 + e_2 q_2. \end{aligned}$$

The variable airport costs of runway usage by airlines are supposed to be zero. External congestion costs are assumed to be quadratic in runway usage

$$C_i(q_i) = \frac{c e_c q_i^2}{2}$$

with $c > 0$ and a stochastic term e_c with expectation value one and a variance $\sigma_c^2 > 0$ which determine the slope of the marginal external congestion costs curve. Demand shocks and external congestion costs shocks are supposed to be independent. In contrast, costs shocks are perfectly correlated for airports 1 and 2. Brueckner [2] found that external social cost depends on the airlines' market share at airports. However, since airlines are assumed to be in perfect competition, each airline's market share is negligible. Therefore, external social costs are independent of the identity of airlines. Welfare W generated by airport usage in the regulated area is determined by

$$\begin{aligned} W(q_1, q_2) &= B(q_1, q_2) - \sum_{i=1}^2 C_i(q_i) \\ &= \alpha q_1 q_2 + a(q_1 + q_2) - \frac{b + c e_c}{2} (q_1^2 + q_2^2) + e_1 q_1 + e_2 q_2. \end{aligned}$$

3 Welfare optimal congestion control

To control congestion, two different policy measures are usually under discussion: slot constraints and congestion pricing. With slot constraints airlines need to have take-off or landing permissions (slots) to incorporate the regulated airport into their networks. Currently the allocation of slots is based on grandfather rights which do not guarantee an efficient allocation because they do not account for the willingness to pay for slots. However, in the following we assume that slots are efficiently allocated (say, by an auction). The other instrument, congestion pricing, internalizes external congestion costs by a price premium and, thus, effectively reduces slot demand and congestion.

To compare the effects of slot constraints and congestion pricing on expected social welfare we calculate the optimal slot constraints $(\hat{q}_1, \hat{q}_2) := \arg \max_{q_1, q_2} E[W(q_1, q_2)]$ where $E[\cdot]$ is the expected value operator. Due to

the symmetry of airports we can denote the optimal slot constraint for each airport by \hat{q} . Straightforward calculations show that:

$$\hat{q} = \frac{a}{b + c - \alpha}.$$

Observe that \hat{q} is increasing in α . Therefore, with demand complementarity the optimal slot constraint is higher compared to the case without complementarity. This is due to the fact that an increased runway usage at one airport increases the benefits of using the runway of the other airport. The resulting expected social welfare is

$$E[W(\hat{q}, \hat{q})] = \frac{a^2}{b + c - \alpha}. \quad (3)$$

Note that $E[W(\hat{q}, \hat{q})] > 0$ always holds. Hence, the expected welfare under slot constraints is always positive in optimum.

On the other hand, for optimal congestion prices it holds $(\hat{p}_1, \hat{p}_2) := \arg \max_{p_1, p_2} E[W(q_1, q_2)]$ s.t. $q_i = D_i(p_1, p_2)$ for $i \in \{1, 2\}$. Due to the symmetry of airports, we can denote the optimal congestion price for each airport by \hat{p} . Straightforward calculations give

$$\hat{p} = \frac{a c}{b + c - \alpha}. \quad (4)$$

The optimal expected slot price is also increasing in α . The reason is that passenger benefits increase if α increases and, hence, prices also have to increase to bring congestion to the optimal level. The expected social welfare with congestion pricing is

$$E[W(\hat{p}_1, \hat{p}_2)] = \frac{a^2}{b + c - \alpha} + \frac{(b^3 - b^2 c - b \alpha^2 - c \alpha^2) \sigma_p^2}{(b - \alpha)^2 (b + \alpha)^2}. \quad (5)$$

Observe that $E[W(\hat{p}_1, \hat{p}_2)]$ can become negative if c is high enough.

Proposition 1 *Congestion pricing leads to higher expected welfare compared to slot constraints if and only if*

$$\alpha \leq \sqrt{\frac{b^2 \max\{b - c, 0\}}{b + c}}. \quad (6)$$

Proof Comparison of equations (5) and (3) gives

$$E[W(\hat{p}_1, \hat{p}_2)] - E[W(\hat{q}_1, \hat{q}_2)] = \frac{(b^3 - b^2 c - b \alpha^2 - c \alpha^2) \sigma_p^2}{(b - \alpha)^2 (b + \alpha)^2}. \quad (7)$$

It directly follows that $E[W(\hat{p}_1, \hat{p}_2)] - E[W(\hat{q}_1, \hat{q}_2)] \geq 0$ if and only if condition (6) holds. ■

Condition (7) shows that uncertainty about external congestion costs is not relevant for instrument choice which is in line with the findings from Weitzman [8]. The reason is that uncertainty about costs does not affect the airports' behavior.

To explain the intuition behind condition (6) we begin with assuming that $\alpha = 0$ holds, i.e. we assume that demand complementarity does not exist. Then this condition is equivalent to $c \leq b$. Hence, without demand complementarity expected welfare with congestion pricing is higher compared to the expected welfare with slot constraints if and only if $c \leq b$ is satisfied. This is equivalent to the standard result shown by Weitzman [8] and Adar and Griffin [1]. Figure 2 illustrates two cases where $c > b$ or, respectively, $c < b$ holds. Suppose that demand is higher than expected, i.e. $e_i > 0$ realizes. Because demand was underestimated with congestion pricing prices are too low and airport usage is too high compared to the welfare optimum. The resulting welfare loss is of size B . On the other hand, with slot constraints the number of slots is too low, prices are too high, and the resulting welfare loss is of size A . Figure 2a demonstrates that $A < B$ if $c > b$ holds. On the other hand, 2b shows that $A > B$ holds if $c < b$ is satisfied. Clearly, for $c = b$

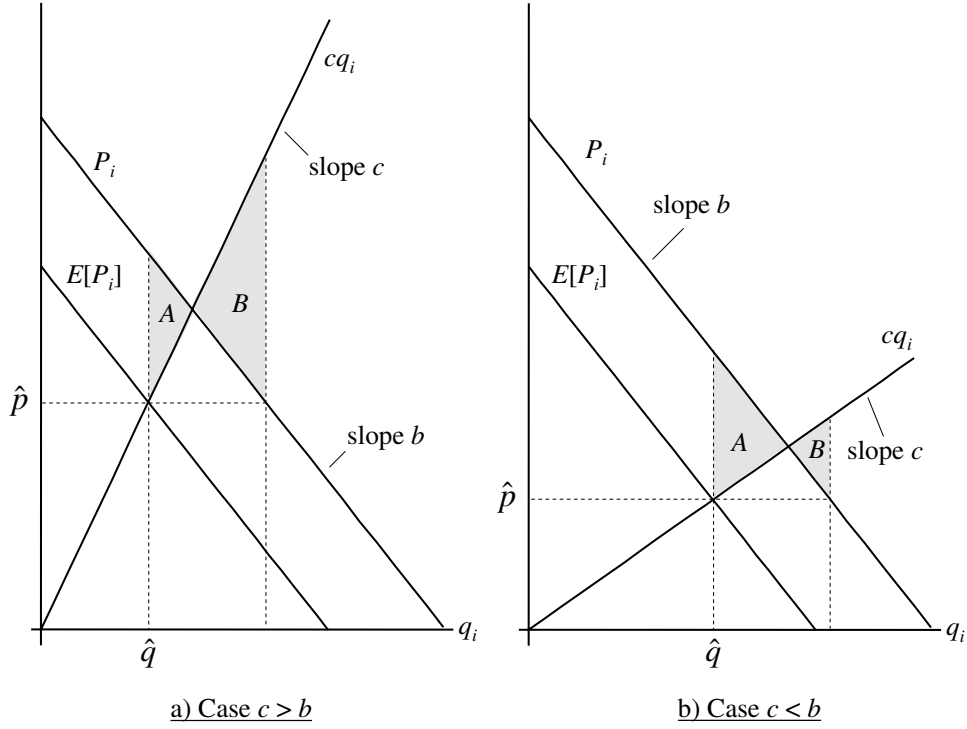


Figure 2: Slot constraints vs. congestion pricing without demand complementarity.

the two areas denoted by A and B are of the same size so that instruments perform equally well. These relations also hold for the case that demand is lower than expected.

Now assume that complementarities exist, i.e. $\alpha > 0$ holds. Condition (6) shows that congestion pricing only reaches a higher expected welfare compared to slot constraints if demand complementarity stays below a critical level. In other words, the difference between b and c must be strictly positive. Therefore, in contrast to the standard result, with $b = c$ slot constraints generate a higher expected welfare than congestion pricing. The reason is

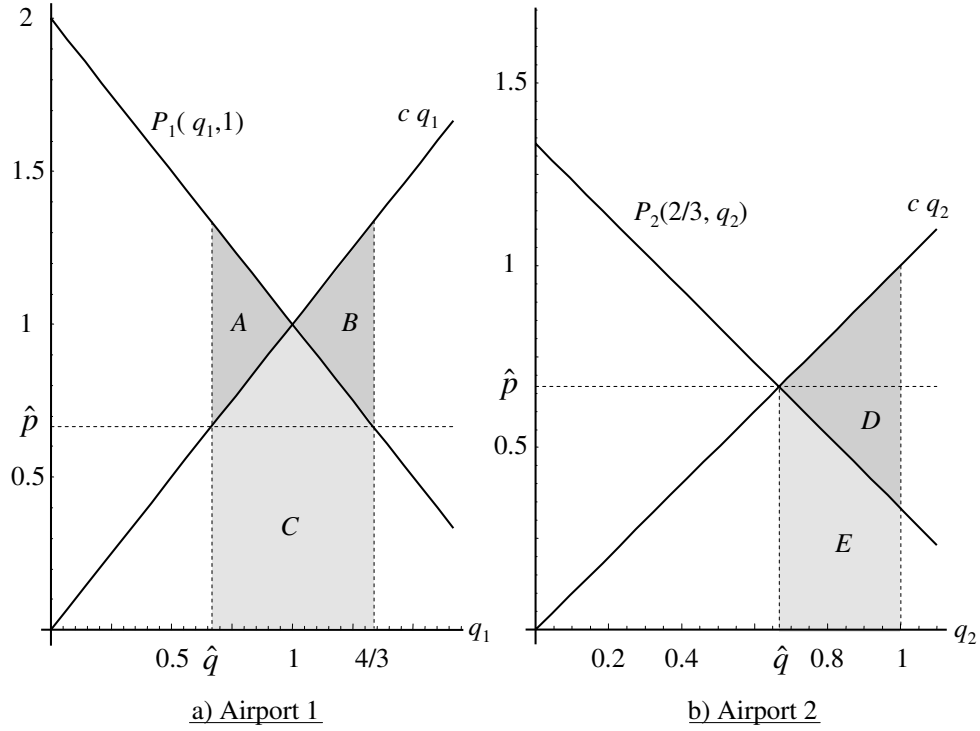


Figure 3: Slot constraints vs. congestion pricing with demand complementarity. Parameters: $a = b = c = 1$, $e_1 = 0.5$, $e_2 = 0$, $e_c = 1$, and $\alpha = 0.5$.

that under congestion pricing airport usage is uncertain and demand complementarity propagates demand uncertainty of one airport to the other. As a consequence, under demand complementarity slot constraints gradually become more favorable compared to congestion pricing from a social planners point of view.

The following example with $a = b = c = 1$ and $\alpha = 0.5$ demonstrates. For congestion pricing and slot constraints $\hat{p} = \hat{q} = 2/3$ holds. Suppose prices are chosen as instruments and demand shocks $e_1 = 0.5$ and $e_2 = 0$ and costs

shock $e_c = 1$ realize. The resulting equilibrium quantities are $q_1 = 4/3$ and $q_2 = 1$. Figure 3a shows the corresponding inverse demand curve $P_1(q_1, 1)$ and the quantity $q_1 = 4/3$ implied by \hat{p} of airport 1 and 2. The inverse demand of airport 2 when airport 1 chooses slot constraints as instruments with $q_1 = \hat{q} = 2/3$ is given by $P_2(2/3, q_2)$ in figure 3b. This figure also shows $q_2 = 1$ at airport 2. Now the change in benefits arising from a shift of the regulatory regime from congestion pricing to slot constraints can be calculated in the following way:

$$\begin{aligned}
B(\hat{q}, \hat{q}) - B(q_1(\hat{p}, \hat{p}), q_2(\hat{p}, \hat{p})) &= \int_{(4/3, 1)}^{(2/3, 2/3)} \left(\sum_i P_i(q_1, q_2) dq_i \right) \\
&= \int_{4/3}^{2/3} P_1(q_1, 1) dq_1 + \int_1^{2/3} P_2(2/3, q_2) dq_2 \\
&= -(A + C) - E.
\end{aligned}$$

On the other hand, the change in external congestion cost is equal to

$$\begin{aligned}
C(\hat{q}, \hat{q}) - C(q_1(\hat{p}, \hat{p}), q_2(\hat{p}, \hat{p})) &= \sum_{i=1}^2 (C_i(\hat{q}) - C_i(q_i(\hat{p}, \hat{p}))) \\
&= -(B + C) - (D + E).
\end{aligned}$$

Hence, the change in welfare generated by the shift of the regulatory regime is

$$W(\hat{q}, \hat{q}) - W(q_1(\hat{p}, \hat{p}), q_2(\hat{p}, \hat{p})) = -A + B + D = D = 1/9 > 0.$$

The shift of the regulatory regime from congestion pricing to slot constraints increases welfare by $-A + B + D$ (see figure 3a and 3b). However, from $b = c$ it follows that $A = B$ holds. Therefore, the overall welfare increase is given by $D = 1/9$. Note that the size of D , at airport 2, depends on the shift of the inverse demand due to the change of runway usage at airport 1. This in turn depends on α . Hence, this is where complementarity comes into play.

Note that this does not imply that, due to the regime shift, welfare at airport 2 increases while welfare at airport 1 remains unaffected. Changing the particular path along which integration is taken would change the picture. Therefore, with complementarities it is not possible to split the overall increase in welfare from a regime shift between the two airports.

4 Monopolistic behavior

Due to the demand complementarity decisions on prices or slot constraints of one airport affect the performance of the other airport although airports are considered to be monopolies. In order to analyze the effect of demand complementarity on profit maximizing airports we model the interaction between airport one and two as a two-stage game. In the first stage the airports simultaneously decide between slot constraints or pricing as instruments to allocate runway capacity. In this stage, it is possible that airports choose the same or different instruments. In the second stage airports individually and simultaneously decide on their own, specific slot constraint respectively pricing level. Finally, the costs shock and the demand shocks realize. We solve this game by backward induction.

Assume that both airports choose slot constraints as instruments (regime Q). Airport profit in quantities is $\Pi_i(q_1, q_2) := q_i P_i(q_1, q_2)$. The corresponding reaction function $q_i^r(q_j) := \arg \max_{q_i} E[\Pi_i(q_1, q_2)]$ is given by

$$q_i^r(q_j) = \frac{a + \alpha q_j}{2b} \quad (8)$$

for $i \in \{1, 2\}$. Solving simultaneously the two equations given by (8) generates the symmetric equilibrium solution

$$q_i^Q = \frac{a}{2b - \alpha}.$$

One shows that the expected profit is given by

$$E[\Pi_i(q_1^Q, q_2^Q)] = \frac{a^2 b}{(\alpha - 2b)^2} \quad (9)$$

in equilibrium.

Now assume that both airports choose prices as instruments (regime P). Then, the reaction function $p_i^r(p_j) := \arg \max_{p_i} E[\Pi_i(p_1, p_2)]$ with $\Pi_i(p_1, p_2) := p_i q_i(p_1, p_2)$ is given by

$$p_i^r(p_j) = \frac{ab + a\alpha - \alpha p_j}{2b} \quad (10)$$

for both airports. The symmetric equilibrium solution implied by (10) is

$$p_i^P = \frac{a(b + \alpha)}{2b + \alpha}. \quad (11)$$

and the expected equilibrium profit is given by

$$E[\Pi_i(p_1^P, p_2^P)] = \frac{a^2 b (b + \alpha)}{(b - \alpha) (2b + \alpha)^2}. \quad (12)$$

Finally, assume that airport i chooses prices and airport j slot constraints with $i \neq j$ (regime PQ). Then i maximizes $E[\Pi_i(p_i, q_j)]$ by choice of p_i , where

$$E[\Pi_i(p_i, q_j)] := E[p_i q_i(p_i, q_j)] = p_i \frac{a + q_j \alpha - p_i}{b}.$$

The expression for $q_i(p_i, q_j)$ follows directly from (1). Denote the reaction function of airport i by $p_i^r(q_j) := \arg \max_{p_i} E[\Pi_i(p_i, q_j)]$. Straightforward calculations show that

$$p_i^r(q_j) = \frac{a + q_j \alpha}{2}. \quad (13)$$

On the other hand, airport j maximizes $E[\Pi_j(p_i, q_j)]$ by choice of q_j , where

$$E[\Pi_j(p_i, q_j)] := E[q_j P_j(p_i, q_j)] = q_j \frac{(b + \alpha) (a + (\alpha - b) q_j) - \alpha p_i}{b}.$$

Rearrangement of equation (2) gives $P_j(p_i, q_j)$. The reaction function of j , $q_j^r(p_i) := \arg \max_{q_j} E[\Pi_j(p_i, q_j)]$, is given by

$$q_j^r(p_i) = \frac{a b + a \alpha - \alpha p_i}{2 b^2 - 2 \alpha^2}. \quad (14)$$

Using the reaction functions given by equations (13) and (14) one shows that

$$(p_i^{PQ}, q_j^{PQ}) = \left(\frac{1}{2} \left(a + \frac{a \alpha (2b + \alpha)}{4b^2 - 3\alpha^2} \right), \frac{a(2b + \alpha)}{4b^2 - 3\alpha^2} \right)$$

holds in equilibrium. In this case equilibrium profits are given by

$$(\Pi_i(p_i^{PQ}, q_j^{PQ}), \Pi_j(p_i^{PQ}, q_j^{PQ})) = \left(\frac{a^2(2b^2 + b\alpha - \alpha^2)^2}{b(4b^2 - 3\alpha^2)^2}, \frac{a^2(2b + \alpha)^2(b^2 - \alpha^2)}{b(4b^2 - 3\alpha^2)^2} \right). \quad (15)$$

Lemma 1 *For each monopolistic airport, prices as instruments is a strictly dominant strategy in stage 1 of the game if $\alpha > 0$. In particular, in the subgame perfect Nash equilibrium airports choose prices as instruments.*

Proof From equations (15) and (9) it follows that $\Pi_i(p_i^{PQ}, q_j^{PQ}) > \Pi_i(q_i^Q, q_j^Q)$ if and only if $\alpha > 0$. Furthermore, from (15) and (12) it follows that $\Pi_i(p_i^P, p_j^P) > \Pi_i(q_i^{PQ}, p_j^{PQ})$ if and only if $\alpha > 0$. Hence, no matter what the other airport does, it is always better to use prices as instruments. This shows that the choice of prices as instruments is a strictly dominant strategy in stage one of the game. It directly follows that in the subgame perfect Nash equilibrium airports choose prices as instruments. ■

Lemma 2 *Airports set $p_i^P > \hat{p}$ if condition (6) holds.*

Proof One shows that $p_i^P > \hat{p}$ if and only if $\alpha < \sqrt{b(b-c)}$. Furthermore, since

$$\sqrt{\frac{b^2(b-c)}{b+c}} < \sqrt{b(b-c)} \quad (16)$$

it follows that condition (6) implies $p_i^P > \hat{p}$. ■

Proposition 2 *Monopolistic airports produce a suboptimally low expected social welfare if $\alpha > 0$ is satisfied.*

Proof Necessary conditions for monopolistic airports to optimize expected social welfare are, first, to choose the optimal instruments in stage 1, and, second, to choose the optimal price or slot constraint, respectively. Due to lemma 1 in the subgame perfect equilibrium airports always choose prices as instruments if $\alpha > 0$ is satisfied. By proposition 1, prices as instruments optimize expected social welfare if and only if condition (6) is fulfilled. However, due to lemma 2 prices of monopolistic airports do not maximize expected social welfare because they are too high in equilibrium. ■

Proposition 2 indicates that airports should be regulated for any $\alpha > 0$. The reason is, first, that monopolistic airports do not switch to slot constraints when they should. Second, even if they correctly choose prices as instruments, equilibrium prices are too high from a social point of view.

Only in one specific case would monopolists take their instruments right. Note, from (9), (12), and (15) it follows that for $\alpha = 0$:

$$\Pi_i(q_i^Q, q_j^Q) = \Pi_i(p_i^P, p_j^P) = \Pi_i(p_i^{PQ}, q_j^{PQ}) = \Pi_j(p_i^{PQ}, q_j^{PQ}) = \frac{a^2}{4b}. \quad (17)$$

Now:

Proposition 3 *Monopolistic airports maximize expected social welfare if and only if $\alpha = 0$ and $b = c$.*

Proof If and only if $\alpha = 0$ the expected profits of monopolistic airports are identical for both instruments (see (17)). It follows from inequality (6) that in optimum the expected social welfare is identical no matter which instruments are chosen if $\alpha = 0$ and $b = c$ holds. Furthermore, $p_i^P = p_i^{PQ} = \hat{p}$ and $q_i^Q = q_i^{PQ} = \hat{q}$ holds for $\alpha = 0$ and $b = c$. ■

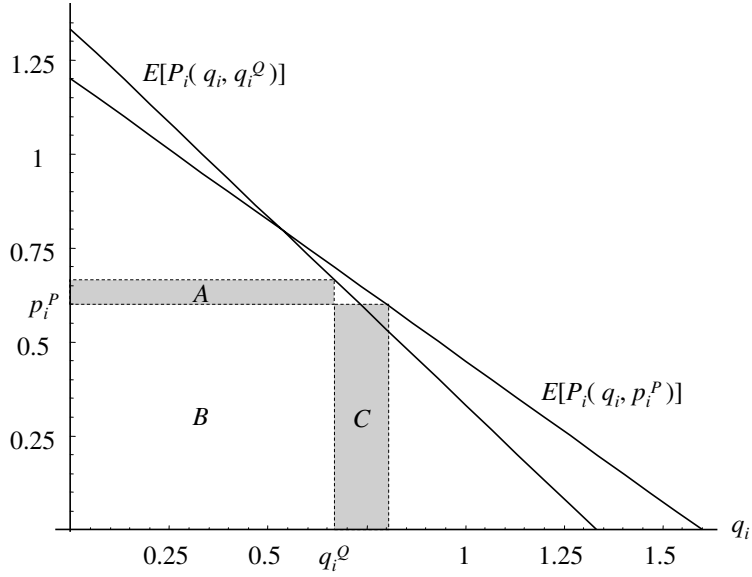


Figure 4: Expected monopoly profits under prices as instruments and slot constraints with $a = b = 1$ and $\alpha = 0.5$.

For the general case, $\alpha > 0$, figure 4 illustrates why airports are in favor of prices as instruments compared to slot constraints. Suppose that $a = b = 1$ and $\alpha = 0.5$. Additionally, assume that both airports choose slot constraints as instruments. The equilibrium number of slots is given by $q_i^Q = 2/3$ for both airports, and the expected profit of each airport under slot constraints is equal to the sum of A and B . Now assume that both airports choose prices as instruments. In equilibrium $p_i^P = 3/5$ for both airports. In this case the expected profit of each airport is equal to the sum of B and C . Comparison of A and C shows that expected profits are higher under congestion pricing than under slot constraints. The reason is that under congestion pricing demand is more elastic because airport usage is not fixed and changes of demand are reinforced by demand complementarity. Moreover, the reason why the choice of the instruments can be diverse from the airports' and a

social planner's point of view is that airports do not take external congestion costs into account.

5 Conclusions

To control airport congestion two different policy options are normally under discussion: slot constraints and congestion pricing. The former requires airlines to buy slots for the operation of flights at congested airports. The latter reduces the demand for take off and landing operations of airlines by rising airport fees. Under perfect information about the social benefits and costs of slot usage both instruments can reach optimal welfare results. In contrast, under uncertainty about the social benefits of slot usage the choice of instrument normally affects the expected level of social welfare.

Due to the network character of the airline industry, the demand for slots of monopolistic airports is complementary. As a consequence, the advantageousness of congestion pricing and slot constraints depends on the slope of the inverse demand and marginal congestion cost function *and* on the level of demand complementarity between airport services. In particular, we show that demand complementarity increases the expected social welfare under slot constraints compared to congestion pricing. The reason is that under congestion pricing demand uncertainty translates into uncertainty with regard to airport usage. Furthermore, demand complementarity for airport services reinforces the effect of demand uncertainty on airport usage and, as a consequence, reduces expected social welfare under congestion pricing.

Turning to the behavior of monopolistic airports we also showed that they fail to optimize expected social welfare. The interaction between airports is modelled as a two-stage game in which, first, the airports choose

prices or slot constraints as instruments, and, second, they choose prices or slot constraints, respectively. In stage one of the game prices as instruments is a dominant airport strategy. Therefore, in the subgame perfect equilibrium airports always choose prices as instruments. Since prices only have the potential to optimize expected social welfare if the level of demand complementarity is low enough, this is a first source of market failure. A second source of market failure is that monopolistic airport prices are too high, if prices are the correct instruments from a social point of view. These results indicate a need for the regulation of monopolistic airports which is not only based on the effects of monopolistic market power and external congestion costs, but also arises from the network character of the air transport industry, namely demand complementarity.

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