DECENTRALIZED CONGESTION POLICIES: PRICING VERSUS (GRANDFATHERED) SLOTS IN AIRPORT NETWORKS

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Decentralized Congestion Policies: Pricing Versus (grandfathered) Slots in Airport Networks

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CERTIFICATE OF ORIGINALITY

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____(Signed)

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ABSTRACT

This dissertation consists of four related studies on the assessment of decentralized welfare-maximizing airport congestion policies involving (grandfathered) slot policy and pricing policy. Different demand structures and airport networks are considered in the presence of origin-destination passengers. These studies capture that local and non-local origin-destination passengers may have one or two destinations to choose from, in which the two destinations may or may not be considered as substitutes. This dissertation shows that even a small variation can fundamentally change the analysis and the assessment of the congestion policies.

The first study considers networks with two or three airports. The results show that equilibrium policies involve slots when airport profits do not matter and pricing policies when airport profits matter. The main results show that in the presence of congestion effects, equilibrium slot policies will lead to too high and equilibrium pricing policies to too low passenger quantities relative to the first best outcome that maximizes the welfare of all airport regions.

The second study considers a stylized airport network with two airports designed to clearly identify the role of local and non-local passengers. The analysis shows that the local welfare-maximizing slot quantity can coincide with the first-best outcome whereas this is impossible in the case of pricing policy. Whether the outcomes coincide in the case of slot policy depends on the shares of inframarginal and marginal local and non-local passengers. The results provide clear insights on the reasons why slot quantities are found to be excessive in the three-airport network considered in the first study.

The third study is an extension of the analysis of the three-airport network considered in the first study. This extension involves a variation of the demand structure in the sense that the air services offered at the congested airports are

considered as imperfect substitutes whereas they are not considered as substitutes in the first study. The analysis shows that the presence of substitute air services is a necessary condition for equilibrium slot quantities to reach the first-best outcome. The results derived from the second study help understand the reasons why equilibrium slot quantities can lead to first-best outcome. Whereas equilibrium pricing levels will always be too high relative to the first-best prices independent of the presence or absence of substitute air services.

By contrast with the third study, the fourth study proceeds with the consideration of substitute air services for non-local passengers in a three-airport network to concentrate on the role of airport competition. The results show that airport competition will lead to too low equilibrium slot quantities in the case of slot policies, or too low equilibrium prices in the case of pricing policies, to maximize the total welfare of the two congested airports. The results further show that slot policies can lead to first-best outcome that maximizes the total welfare of three airport regions. Whereas pricing policies are too strict with too high equilibrium prices relative to the first-best outcome.

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CHAPTER 1

INTRODUCTION

In 2018, there were around 4.38 billion aviation passengers carried worldwide. Among the heavy air transport traffic, close to 4 billion trips were origin-destination trips. The domestic market in China provided the largest incremental increase globally, adding just under 50 million trips. Whereas the domestic market in the US continued to be the world’s largest single origin-destination market with almost 590 million trips undertaken (IATA, 2019b). One reason for the fast growth in origin-destination trips is the overall development of air transport market that brings in sufficient demand to justify point-to-point flying instead of relying on hub-and-spoke flying. Another reason is the development of aircraft technology. The introduction of new aircraft, such as Boeing787 and A350, leads to a reduction in maintenance costs and an increase in fuel efficiency, allowing more point-to-point flying.

Origin-destination passengers, along with transfer passengers, will continue growing fast in number and will probably outpace the capacity growth in the long term. Therefore, increasing airport delays are expected in the future. This highlights that airport congestion is a relevant problem in practice, despite of the devastating effects of the Coronavirus outbreak and the corresponding international lockdowns in 2020, which will slow down the growth of the aviation industry for years (for example, Pearce, 2020, and Czerny et al., 2020).

Cirium (2020)'s record of global departure performance in 2019 indicates that the average delay time for the top 20 global airports was 50.7 minutes for around 364,000 delayed flights. The Federal Aviation Administration (2020b) estimated that the airline cost for an hour of delay ranges from about $1,400 to $4,500 and that passenger time valuations range from $35 to $63 per hour. These numbers indicate that air transport delays are costly,[1] which highlights the importance for airport congestion policies.

Many airports are utilizing "slots" to mitigate delays by imposing an upper limit on the number of flight movements per period (for example, 30 minutes). An airport slot (or simply "slot") is "a permission given by a coordinator for a planned operation to use the full range of airport infrastructure necessary to arrive or depart at a Level 3 airport on a specific date and time" (IATA, 2019c). Airports can control delays and congestion effects by ensuring that the scheduled air traffic does not exceed the "declared airport capacity".[2] There are around 204 airports using slots worldwide serving around 43 percent of the passengers (IATA, 2019b). Interestingly, only three airports in the US---John F. Kennedy International Airport (JFK), LaGuardia Airport (LGA), and Ronald Reagan Washington National Airport (DCA)---currently make use of slots (Federal Aviation Administration, 2020b). Most airports in the US allocate their capacity on a first-come-first-serve basis. This includes Hartsfield-Jackson Atlanta International Airport (ATL), which was the biggest airport in the world in terms of passenger numbers prior to the Coronavirus outbreak.

Alternatively, airports may increase airport charges to suppress demand and reach desirable levels of delay (Daniel, 1995; Brueckner, 2002; Pels and Verhoef, 2004; Zhang and Zhang, 2006; Basso, 2008; Czerny and Zhang, 2011, 2014a and 2014b). In contrast to quantity-based policies such as slots, the proposed pricing policies can hardly be found in practice (Zhang and Czerny, 2012). This could be a consequence of the distributional effects of airport congestion policies. Whereas

[1] Ball et al. (2010) estimated the cost of air transportation delay in the US to be $31.2 billion in 2007.

[2] A few factors including the number and layout of runways, meteorological conditions, traffic mix characteristics, and the regulatory environment (Gillen, Jacquillat and Odoni, 2016) decide the declared airport capacity per time unit.

<table>
<tr><th rowspan="3">Substitute air services</th><th rowspan="3">Type of passengers</th><th colspan="3">Number of airports</th></tr>
<tr><td colspan="2">two</td><td>three</td></tr>
<tr><td>one congested, one uncongested</td><td>two uncongested</td><td>two congested, one uncongested</td></tr>
<tr><td rowspan="2">no</td><td>locals</td><td rowspan="2">Chapter 3</td><td colspan="2" rowspan="2">Chapter 2</td></tr>
<tr><td>non-locals</td></tr>
<tr><td rowspan="2">yes</td><td>locals</td><td colspan="2"></td><td>Chapter 4</td></tr>
<tr><td>non-locals</td><td colspan="2"></td><td>Chapter 5</td></tr>
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Table 1: A summary of different demand structures and airport networks considered in each chapter that arises from the four studies.

pricing policies will lead to higher payments from the airlines to airports, slot policies can avoid such distributional effects by using grandfather rights (for example, Czerny and Lang, 2019).

Another defining feature of air transport industry, besides the importance of airport slots and grandfathering, is that airports are operating in a network and typically owned and controlled by local governments.[3] This suggests that airports presumably distinguish between local and non-local passengers, leading to the maximization of the local airport's welfare as opposed to the first-best outcome that maximizes the total welfare across all airport regions. Therefore, the local welfare-maximizing policy exhibits a feature of decentralized decision making and has an impact not only on the non-local passengers who use the local airport but also on other airports that may or may not necessarily have direct flights to the local airport. One example for the latter case is to consider substitute destinations for non-local passengers. A tightening of slots at the local airport will drive non-local passengers to fly to other airports, adding to the congestion of other airports. Destination choices are usually highly dependent on the prices, that is, passengers may choose to fly to one destination if the trip is cheap and convenient relative to trips to other destinations.

All the features in the air transport market mentioned above motivate the

[3] In North America, only one percent of airports involve private sector participation, whereas this share reaches between 11 and 75 percent outside North America (Airport Council International, 2017).

researches on the assessment of decentralized welfare-maximizing airport congestion policies involving (grandfathered) slot policy and pricing policy in the presence of origin-destination passengers. Different demand structures and airport networks are considered in this dissertation in the sense that local and non-local origin-destination passengers may have one or two destinations to choose from, in which the two destinations may or may not be considered as substitutes. This dissertation shows that even a small variation in these demand structures and airport networks can fundamentally change the analysis and the assessment of the congestion policies. Table 1 summarizes the different demand structures and airport networks considered in each chapter that arises from the four studies, which will be discussed in detail as follows.

Chapter 2 arises from Czerny and Lang (2019) and considers networks with two or three complementary airports. In each case, two congested airports are present and independently choose between slot and pricing policies. The results show that equilibrium policies involve slots when airport profits do not matter and pricing policies when airport profits matter. This justifies the consideration of slots and pricing policies in the whole dissertation. The results further show that the equilibrium slot policies reach the first-best passenger quantities when congestion effects are absent. Otherwise, equilibrium slot policies will lead to excessive and equilibrium pricing policies to too low passenger quantities relative to the first best outcome that maximizes the welfare of all airport regions. The analysis formally distinguishes the sources for the different outcomes under slot and pricing policies by distinguishing between a variable effect and a distribution effect. The variable effect captures that decision variables are quantities in the case of slot policies and prices in the case of pricing policies. The distribution effect captures that airport slot allocation is based on grandfather rules.

Chapter 3 arises from Lang and Czerny (2020a) and considers a stylized airport network with two airports designed to clearly identify the role of local and non-local passengers. The analysis shows that the local welfare-maximizing slot quantity can coincide with the first-best outcome that maximizes the welfare of all airport regions whereas this is impossible in the case of pricing policy. Whether the outcomes coincide in the case of slot policy depends on the shares of inframarginal and marginal local and non-local passengers. The intuition is developed based on cost-benefit ratio as measured by the marginal external congestion cost divided by the (slot) price. The results provide clear insights on the reasons why slot quantities are found to be excessive in the three-airport network considered in Chapter 2.

Chapter 4 arises from Lang and Czerny (2020b). It develops and analyzes an extended framework of the three-airport network considered in Chapter 2. This extended framework involves a variation of the demand structure in the sense that the air services offered at the congested airports are considered as imperfect substitutes whereas they are not considered as substitutes in Chapter 2. The analysis shows that the presence of substitute air services is a necessary condition for equilibrium slot quantities to reach the first-best outcome. The results derived from Chapter 3 help understand the reasons why equilibrium slot quantities can lead to first-best outcome. Whereas equilibrium pricing levels will always be too high relative to the first-best prices independent of the presence or absence of substitute air services.

By contrast with Chapter 4, Chapter 5 arises from Lang and Czerny (2020c) and proceeds with the consideration of substitute air services for non-local passengers in a three-airport network to concentrate on the role of airport competition. The results show that airport competition will lead to too low equilibrium slot quantities in the case of slot policies, or too low equilibrium prices in the case of pricing policies, to maximize the total welfare of the two congested airports. The non-local passengers benefit from the airport competition compared with the case in which airport competition is absent. The results further show that slot policies can lead to first-best outcome. Whereas pricing policies are too strict with too high equilibrium prices relative to the first-best outcome.

These studies contribute to various strands of the literature. They contribute to the literature on slots versus pricing policies. Brenck and Czerny (2002), Czerny (2008, 2010) and De Palma and Lindsey (2018) considered an environment with uncertain demand and congestion costs. Based on Weitzman's (1974) seminal study, Czerny (2010) found that pricing is beneficial relative to slot policies from the social viewpoint when demands take linear forms because (i) demand functions will be steeper than marginal external congestion cost functions under these conditions and (ii) uncertainty in the congestion costs can lead to a negative correlation between demands and marginal external congestion costs. Slots, however, can be beneficial in the case of quadratic marginal external congestion costs. Czerny (2010) also considered a three-airport network and found that the existence of airport networks can improve the benefits of pricing policies relative to slots. He considered a centralized airport system in the sense that airports were assumed to fully coordinate their congestion policies. De Palma and Lindsey (2018) extended this analysis by also capturing scenarios where the slot constraint may not be binding amongst other things. Brueckner (2009) considered an environment with small and large airlines and showed that slot trading or auctions can lead to an efficient outcome that would only be achievable with pricing if prices would be differentiated across carriers. Daniel (2014) highlighted the challenges of combinatorial auctions if the slots of multiple airports would be auctioned simultaneously. Basso and Zhang (2010) found that slot auctions are preferred by the airports and lead to higher total traffic relative to pricing when the social weight attached to airport profits exceeds the unit weight. Czerny (2007) and Basso, Figueroa, and Vásquez (2017) considered price versus quantity controls in the case of monopoly regulation. The main contribution of these studies is to cover the possibility of decentralized decisions upon slot and pricing policies.

These studies further contribute to the strands of the literature on local objectives and the tolling of passengers or customers from other legislations. De Borger, Proost, and Van Dender (2005) considered tax competition in the presence of congestion and rival networks. They showed that transit tolls can lead to large welfare gains from the viewpoint of the local economy. De Borger, Dunkerley, and Proost (2007) concentrated on complementary transport networks and showed that welfare can be increased in the absence of tolling. Mantin (2012) considered endogenous, local public and private ownership structures in a complementary airport network. He found that countries may be caught in a prisoner's dilemma situation with private airports and too high prices from the viewpoint of the aggregate economy because privatization is used to exploit non-local passengers. Czerny, Höffler and Mun (2014) considered endogenous, local ownership structures in a network with rival seaports. They found that countries may be caught in a prisoner's dilemma situation because they keep seaports under public ownership in order to protect local customers from excessive port prices, while private seaports and higher port prices would be helpful to exploit non-local users and increase local welfares. Wan and Zhang (2013) considered port competition as part of the rivalry between alternative intermodal transportation chains. They focused on quantity-competition model and found that an increase in road capacity by an intermodal chain will likely benefit its port while negatively influence the rival port. Wan, Basso and Zhang (2016) investigated the strategic investment decisions of local governments on regional landside accessibility in the context of seaport competition. They found that when ports are public, an increase in accessibility investment reduces port regions' welfare but improves inland regions' welfare. When ports are private and captive shipper's utility is high enough, an increase in accessibility benefits the rival port region while it harms the inland. Studies typically concentrate on local welfare maximization as the only objective of policy makers, while these studies extend this view and also capture the possibility that some policy makers may attach a unit weight to consumer surplus and a zero weight to infrastructure profits.

These studies finally contribute to the growing literature on congestion management in airport networks. Pels and Verhoef (2004) concentrated on a network of two complementary airports and used numerical examples to illustrate that equilibrium pricing strategies differ from the first-best solution. Benoot, Brueckner and Proost (2012) analyzed the pricing of congested rival airports that serve both domestic and intercontinental passengers. They found that the presence of intercontinental passengers can distort prices in a way that leads to a welfare loss. Silva, Verhoef, and van den Berg (2014) considered congested airports and endogenous airline networks. They found that airport pricing policies cannot ensure socially efficient airline network formations. Lin (2017) investigated an airport network with one congested hub airport, and several spoke airports that belong to different countries. He found that discriminatory prices for non-stop and transfer passengers can be used to maximize global welfare. Lin and Zhang (2017) considered a hub-and-spoke network and found that per-flight prices and discriminatory passenger prices are required to achieve the welfare-maximizing quantities of local and transfer passengers.

The remainder of this dissertation is organized as follows. Chapter 2 considers congestion policy games in airport networks with two or three complementary airports. Chapter 3 considers a stylized airport network with two airports designed to clearly identify the role of local and non-local passengers. Chapter 4 extends the framework of three-airport network in Chapter 2 by incorporating substitute air services for local passengers into the analysis of equilibrium airport congestion policies. Chapter 5 proceeds with the consideration of substitute air services for non-local passengers in a three-airport network to concentrate on airport competition. Chapter 6 concludes the dissertation and discusses avenues for future research.

CHAPTER 2

A PRICING VERSUS SLOTS GAME IN AIRPORT NETWORKS

In this chapter, a basic model and various model extensions are developed to analyze pricing versus slots games in different airport networks. The basic model involves a network of two complementary and uncongested airports, where each airport independently and simultaneously chooses between slot and pricing policies and their respective slot quantity and pricing levels. Two different sets of airport objectives are considered to capture that airports are owned by the (local) governments and that local governments may wish to limit payments from airlines or passengers to airports and, thus, have limited interest in airport profits. First, governments can pursue the objective of local consumer surplus maximization, which is equivalent to a situation where airport profits do not matter. Second, airports may pursue the objective of local welfare maximization, which is equivalent to a situation where airport profits matter.

The basic model and the model extensions are used to show that slots and pricing policies can be weakly dominant strategies depending on whether governments attach a zero or a unit weight to airport profits, respectively. Policy makers prefer slot policies if airport profits do not matter to them, whereas they prefer pricing policies if airport profits matter. This illustrates that equilibrium policy choices in the form of slot or pricing policies can be explained by the corresponding distribution effects.

It is well-known that price and quantity controls are equally effective in managing negative externalities in a deterministic environment (for example, Weitzman, 1974). The present analysis shows that this result on the equivalence between price and quantity controls also depends on the presence of a centralized regulator. For instance, the analysis of the two-airport network shows that the unique equilibrium in terms of pricing policies does not achieve the set of first-best passenger quantities that maximize the total welfare of both airport regions. It further shows that a set of equilibrium constellations exist in the case of slot policies. Furthermore, this set of equilibrium constellations contains an equilibrium constellation where first-best passenger quantities are reached.

To concentrate on scenarios where unique equilibria in slot and pricing strategies exist, a model extension consisting of three uncongested, complementary and asymmetric airports is considered. The three-airport network involves two active airports with local populations and one inactive dummy airport without local population. This follows a common approach in the literature where the presence of such a dummy airport is implicitly assumed (while the present study applies a more transparent approach where the presence of a dummy airport is an explicit part of the set of modeling assumptions). The presence of the dummy airport allows for the consideration of a more realistic airport network where only a subset of the airports may be slot controlled, the consideration of unique best responses in slot quantities, and the description of a unique equilibrium in slot quantities.

Two effects that are involved in a move from pricing to slot policies are distinguished to transparently identify the causes and intuitions for the differences in local welfares implied by equilibrium policies. First, a so-called variable effect, which captures that such a policy change leads to a change in variables in the sense that quantities, not prices, are the decision variables. Second, a so-called distribution effect, which captures that such a policy change involves a change in airport revenues. The distribution effect is used to analyze the role of grandfather rules, which make it difficult for airports to internalize slot values. The goal is to find out how variable and distribution effects affect equilibrium policies relative to the first-best policies that maximize the total welfare of all airport regions.

To separate variable and distribution effects, the concept of the slot price is developed. In this context, the slot price represents the airport charge that would have to be (but is not) implemented to ensure that airport passenger demand equals the desired slot quantity. This slot price can also have the interpretation of a shadow price. This allows for the consideration of three scenarios. First, a scenario where airports choose slot quantities directly. This represents a scenario where quantities are the decision variables and airport revenues are zero. Second, a scenario where airports choose slot prices. This represents a scenario where prices are the decision variables and airport revenues are still zero. Third, a scenario where airports choose airport charges. This represents a scenario where prices are the decision variables and airport revenues can be strictly positive. Scenarios one and two are used to identify the variable effect of a move from pricing to slot policies. Scenarios two and three are used to identify the distribution effect of a move from pricing to slot policies.

The analysis of the three-airport network in Subchapter 2.4 abstracts away from congestion effects and reveals a variable effect of zero and a strictly positive distribution effect. The variable effect is zero because the equilibrium airport behaviors are independent of whether slot quantities or slot prices are the decision variables. The distribution effect is positive because airport charges are used to exploit non-local passengers. This exploitation leads to excessive airport charges and possibly a prisoner's dilemma situation. The incentives to exploit non-local passengers are eliminated by slot policies because slots are provided for free by construction to capture the notion of grandfather rules for airport slots. As a result, equilibrium slot policies lead to the first-best result that maximizes the total welfare of all airport regions. This result is conditional on the absence of congestion, however.

Subchapter 2.5 concentrates on symmetric (active) airports, where symmetry is assumed for tractability, and extends the three-airport network scenario by adding congestion effects. The presence of congestion does not change the result that equilibrium policies involve slot policies when airport profits do not matter and pricing policies when airport profits matter. We show that the equilibrium prices in the case of pricing policies can be written as the sum of the equilibrium slot price plus a weighted markup depending on the price elasticities of passenger demands, where this markup is higher when equilibrium prices are compared with slot quantities as decision variables than with slot price as decision variables. In this extended model version, neither slot nor pricing policies will ever reach the first-best solution in equilibrium. Airport charges will still be excessive in the case of pricing policies because of the distortions caused by the distribution effects. Such distribution effects are absent in the case of slots; but, slot quantity choices are distorted in a different way because local policy makers do not take into account how their slot choices will affect non-local passengers, which leads to too loose slot quantities relative to the first-best passenger quantities.

Numerical instances are used to derive an understanding of how time valuations affect the relative performance of slot and pricing policies. These instances show that there is a critical time valuation where local welfares are independent of whether slot or pricing policies are used. They further show that local welfares are higher under equilibrium slot policies than under equilibrium pricing policies if time valuations are low relative to this critical value, while local welfares are higher under equilibrium pricing policies than under equilibrium slot policies if time valuations are high relative to this critical value. The numerical instances are further used to illustrate that the distribution effect is positive for low and negative for high time valuations, while the variable effect is always negative.

Other extensions are considered in Subchapter 2.6 2.6 These extensions show that the consideration of a vertically integrated airport is under certain conditions equivalent to a situation with atomistic airlines. More specifically, these conditions involve two assumptions. The first is that local airlines exclusively serve local passengers. The second is that airports attach a unit weight to both local consumer surplus and the profits of their local airlines. The extensions are further used to show that equilibrium policy choices are robust with respect to changes in the timing of airport decisions.

2.1 Basic Model

Passengers travel between two airports, A and B. Airport i's passenger quantities are denoted as q_{ij} for those who originate from i with $i = A, B$ and $j \neq i$ (if i and j appear together, $j \neq i$ is assumed to hold true).[4] Passenger quantities are strictly positive on both routes, that is, $q_{ij} > 0$. The benefits of passengers with origin airport i are denoted as $B_i(q_{ij})$. Benefits are strictly concave in the sense that $B_i''(q_{ij}) < 0$ by assumption.

Airports A and B can choose between two policy measures, which are slots, denoted as S, and pricing, denoted as P. Let Q_i with $Q_i = q_{AB} + q_{BA}$ denote the total traffic at airport i, where the complementarity between airports implies $Q_A = Q_B$. There is an upper limit on the number of passengers at each airport, which is denoted as $\bar{Q}_i$. Together with perfect airport complementarity, this implies $Q_i \leq \left\{\bar{Q}_A, \bar{Q}_B\right\}$. Let ϕ_i with $\phi_i = S, P$ denote the policy variable. The upper limit $\bar{Q}_i$ is a function of the policy strategy, that is, $\bar{Q}_i = \bar{Q}_i(\phi_i)$. The upper limit $\bar{Q}_i(\phi_i)$ is finite in the case of slots, $\phi_i = S$, whereas it is infinite in the case of pricing,. $\phi_i = P$.

An integrated airport that offers both infrastructure and flight services is considered in this basic model to concentrate on *airport networks* by avoiding the

[4] Passengers only travel between i and j. The notation could therefore be economized by choosing q_i instead of q_{ij}. The more complex notation is, however, maintained because it will be useful in the extended scenarios considered in Subchapter 2.4 where a third airport C will be involved.

presence of airline profits, the need to distinguish between local and non-local airline profits, and the need to distinguish the potentially differing weights policy makers attach to airline and airport profits.[5] The airport charges a non-negative ticket price R_i to its passengers. Despite the assumption that air services are carried out by airports, we capture the distributional effects of slot policies based on grandfather rules by assuming that $R_i = 0$ in the case of slot policies. Thus, airports cannot earn from selling slots (as is the case under the IATA's Worldwide Scheduling Guidelines) and, thus, have zero airport revenues in the case of slot policies.[6] The airports' costs are all normalized to zero, which together with the assumption of non-negative ticket prices ensures that we can abstract away from problems of airport cost recovery under slot and pricing policies.[7]

Slots impose an upper limit on an airport's total traffic and non-negative (shadow) prices, denoted as $r_i(\phi_i)$, are used to indicate slot prices in the case of slot policies. Using the shadow prices $r_i(\phi_i)$, the airport charges can be written as $R_i = R_i\left(r_i\left(\phi_i\right), \phi_i\right)$. For $\phi_i = S$, $r_i(S) \geq 0$ is the shadow price of slots, simply called *slot price* hereafter, under efficient rationing where slots are allocated to the passengers with the highest willingness to pay. To capture that airport revenues from slot supply are zero under grandfather rules, $R_i\left(r_i\left(S\right), S\right) = 0$ is considered. For $\phi_i = P$,

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[5] We will highlight in the extensions that the present scenario resembles a scenario where airline markets are atomistic, local passengers use their local airlines only, slots are efficiently allocated to airlines by auctions, and policy makers attach a unit weight to airline profits.

[6] That airport charges can be far from market clearing levels is indicated by the high market prices for airport slots. For instance, one pair of take-off and landing slots at London Heathrow was sold for USD 75 million in 2016.

[7] The consideration of integrated airport services also helps to concentrate on airport cost recovery because airport subsidies may be required to implement the first-best outcome when airline markets are oligopolistic (for example, Pels and Verhoef, 2004).

$r_i(P) = R_i\left(r_i\left(P\right), P\right) \geq 0$, which means that airport usage can involve strictly positive airport revenues in the case of pricing policies.

Efficient rationing where passengers with the highest willingness to pay are served first can be guaranteed under pricing policies and is assumed to be present also in the case of slot policies. However, efficient rationing cannot be guaranteed under slots and the IATA rules based on grandfathering. Altogether, this provides a conservative assessment of pricing policies relative to slot policies.

We consider a one-shot game, where airports simultaneously choose between slot and pricing policies as well as slot quantities and prices, respectively. Two sets of objectives are considered: first, local consumer surplus maximization, where local airports attach a zero weight to their airport profits (airport profits do not matter); second, local welfare maximization where local airports attach a unit weight to airport profits (airport profits matter). The airport objectives are considered as given and equal for the two airports, thus, no asymmetries regarding airport objectives are considered.

2.2 Equilibrium Policies

It is well known that policy makers are indifferent between price and quantity controls if demand and cost functions are deterministic, firms are considered in isolation and the objective is welfare maximization (for example, Weitzman, 1974; Stavins, 1996; Czerny, 2010; De Palma and Lindsey, 2018). In this subchapter we analyze the role of airport networks and airport objectives for the choices of pricing and slot policies.

Since ticket prices are equal to airport charges, local consumer surplus, denoted as CS_i, can be written as

$$CS_i\left(q_{ij}, r_A\left(\phi_A\right), r_B\left(\phi_B\right), \phi_A, \phi_B\right) = B_i(q_{ij}) - q_{ij} \cdot \left(R_A\left(r_A\left(\phi_A\right), \phi_A\right) + R_B\left(r_B\left(\phi_B\right), \phi_B\right)\right). \quad (1)$$

The first term on the right-hand side is the benefit of passengers originating at airport i depending on the passenger quantities q_{ij}. The second term is the total payment of passengers with origin i who travel between A and B to both airports.

If airport profits do not matter, then the airports' objectives are to maximize local consumer surplus. We first show that airport i's local consumer surplus under slots is higher than under pricing for any given passenger quantities and prices where $r_i(S) = r_i(P)$ and any given instances of ϕ_j and $r_j(\phi_j)$. If $r_i(S) = r_i(P)$ and given $R_i\left(r_i\left(S\right), S\right) = 0$ and $R_i\left(r_i\left(P\right), P\right) = r_i\left(P\right)$, local consumer surplus under slots can be written as

$$CS_i\left(q_{ij}, r_i\left(S\right), r_j\left(\phi_j\right), S, \phi_j\right) = CS_i\left(q_{ij}, r_i\left(P\right), r_j\left(\phi_j\right), P, \phi_j\right) + q_{ij} \cdot r_i(P). \tag{2}$$

The right-hand side is the consumer surplus under pricing plus the airport profit under pricing for any $r_i(P) \geq 0$. This shows that local consumer surplus can be increased by the use of slots relative to pricing because local passengers save payments $q_{ij} \cdot r_i(P)$ under slots when $r_i(S) = r_i(P)$, where the equality of prices $r_i(S)$ and $r_i(P)$ implies that passenger quantities would remain the same despite the policy change. Consider the case where $r_i(P)$ is chosen to maximize local consumer surplus. Since slots are preferred for any $r_i(P) \geq 0$, slots are also preferred if $r_i(P)$ is chosen to maximize local consumer surplus. Slots are weakly preferred if $r_i(P) = 0$, while slots are strictly preferred if $r_i(P) > 0$.

Local airport profit, denoted as π_i, can be written as

$$\pi_i\left(Q_i, r_i\left(\phi_i\right), \phi_i\right) = Q_i \cdot R_i\left(r_i\left(\phi_i\right), \phi_i\right), \tag{3}$$

and local welfare, denoted as W_i, can be written as the sum of local consumer surplus and local airport profit:

$$W_i\left(q_{AB}, q_{BA}, r_A\left(\phi_A\right), r_B\left(\phi_B\right), \phi_A, \phi_B\right) = CS_i\left(q_{ij}, r_i\left(S\right), r_j\left(\phi_j\right), S, \phi_j\right) + \pi_i\left(Q_i, r_i\left(\phi_i\right), \phi_i\right). \tag{4}$$

If airport profits matter, the airports' objectives are to maximize local welfare.

We first show that airport i 's local welfare under pricing is higher than under slots for any given passenger quantities and prices where $r_i(P) = r_i(S)$ and any given instances of ϕ_j and $r_j(\phi_j)$. If $r_i(P) = r_i(S)$ and given $R_i\left(r_i\left(S\right), S\right) = 0$ and $R_i\left(r_i\left(P\right), P\right) = r_i\left(P\right)$, local welfare under pricing can be written as

$$W_i\left(q_{AB}, q_{BA}, r_i\left(P\right), r_j\left(\phi_j\right), P, \phi_j\right) = W_i\left(q_{AB}, q_{BA}, r_i\left(S\right), r_j\left(\phi_j\right), S, \phi_j\right) + q_{ji} \cdot r_i(P) \tag{5}$$

where the right-hand side is the welfare under slots plus the airport profit under pricing. This shows that local welfare can be increased by the use of pricing relative to slots because airport profits are increased by the revenues earned from non-local passengers, $q_{ji} \cdot r_i(P)$, under pricing. Consider the case where $r_i(S)$ is chosen to maximize local welfare. Since pricing is preferred for any $r_i(S) \geq 0$, pricing is also preferred if $r_i(S)$ is chosen to maximize local welfare. Pricing is weakly preferred if $r_i(P) = 0$, while pricing is strictly preferred if $r_i(P) > 0$.

Equilibrium policies in terms of policy variables ϕ_i can be summarized as:

Proposition 1 *If airport profits do not matter, slot policies $\phi_A = \phi_B = S$ form an equilibrium in (weakly) dominant strategies, while pricing policies $\phi_A = \phi_B = P$ form an equilibrium in (weakly) dominant strategies if airport profits matter. Whether the equilibrium policy choices are determined by dominant or weakly dominant strategies depends on whether $r_i(P) > 0$ or $r_i(P) = 0$ respectively.*

This proposition highlights that equilibrium policies depend on whether airport profits matter or do not matter and it can also be used to highlight the role of airport networks for equilibrium policies. If airport profits do not matter, slot policies are the airports' preferred choices. Relevant to this study, which concentrates on the role of airport networks on policy choices, is that this is independent of whether airports are in a network or isolated. This is because the consumer surplus of own passengers is independent of the number of passengers originating from airport j, q_{ji}, in the basic model as demonstrated by the consumer surplus expression in (2). Thus, airport networks have no effect on policy choices in terms of ϕ_i when airport profits do not matter. The picture changes if airport profits matter. In this case, pricing policies *are* the airports' preferred choices when they are in a network, while airports are *indifferent* between slot and pricing policies when airports are isolated. This is because the local welfares depend on the number of passengers originating from airport j, q_{ji}, through the revenue they generate at the own airport as shown by the welfare expression in (5) when airports operate in a network. Thus, airport networks are relevant to policy choices in terms of ϕ_i when airport profits matter. Airport networks therefore eliminate the equivalence between quantity- and pricing-based policies that prevails in the case of isolated airports and perfect information.

Proposition 1 demonstrates that slots and pricing schemes can both occur as equilibrium solutions in airport networks. This justifies the investigation of both policies in the following subchapter.

2.3 Equilibrium Slot Quantities Versus Equilibrium Prices

Given efficient rationing under both pricing and slot policies, the passenger demands for flights between A and B, denoted as $D_{ij}\left(r_A, r_B\right)$, are determined by the equilibrium conditions

$$B_i'(q_{ij}) - (r_A + r_B) = 0 \tag{6}$$

for $\phi_i = S, P$, where we concentrate on those cases where passenger demands, $D_{ij}\left(r_A, r_B\right)$, are strictly positive. In equilibrium, the passengers' marginal benefit of flying between A and B is equal to the sum of r_A and r_B because every passenger flies between A and B, and therefore will be charged twice. The strict concavity of the benefit function, $B_i(q_{ij})$, ensures the existence of a unique set of demands $D_{AB}\left(r_A, r_B\right)$ and $D_{BA}\left(r_A, r_B\right)$ with $\partial D_{ij} / \partial r_A = \partial D_{ij} / \partial r_B = 1 / B_i''(q_{ij})$, where the first equality appears because it is the sum of the prices that matters to passengers.[8]

Denote the equilibrium local welfares under pricing by $W_i(P)$ and the equilibrium local welfares under slots by $W_i(S)$. A policy change from pricing to slots has two effects which we call *distribution effect* and the decision variable effect, simply called *variable effect*. Recall equation (4) which shows that, for given passenger quantities, local welfares under slots are lower because the revenues from non-local passengers are zero. Thus, a change from pricing to slots can affect equilibrium passenger quantities because it involves zero revenues from non-local passengers by construction. Furthermore, a change from pricing to slots means that airports choose quantities rather than prices as decision variables. Whether quantities or prices are the decision variables makes a difference. This is because a change of the own slot quantity may keep the total passenger quantity at the other airport unchanged if the own slot quantity is at least as high as the other airport's slot quantity, while a change in the own price will always change the own and the other airport's passenger quantity when both airports adopt pricing policies.

To formally separate variable and distribution effects, a third policy regime indicated by $\phi_i = SP$ is introduced. This regime involves the choice of slot prices when airport revenues are zero by assumption. The total welfare effect of a move from pricing to slot policies is given by the difference $W_i(S) - W_i(P)$. Adding and deducting welfares when airports use slot prices as the decision variables given by $W_i(SP)$ leads to

[8] Here and hereafter it is assumed that passenger demands are smooth functions of airport charges.

$$W_i(S) - W_i(P) = \underbrace{W_i(S) - W_i(SP)}_{=\text{ variable effect}} + \underbrace{W_i(SP) - W_i(P)}_{=\text{ distribution effect}}, \tag{7}$$

which shows that the total change in equilibrium welfare can be written as the sum of the variable and distribution effects. Variable and distribution effects are defined in terms of local welfares, while slots can be equilibrium policies only if the airport profits do not matter. This is a consistent approach because local welfares are equal to local consumer surpluses in the case of slot policies.

Since airport costs are normalized to zero, the sum of welfares, $W_A + W_B$, is given by the sum of benefit functions $B_A(q_{AB}) + B_B(q_{BA})$. The first-best passenger quantities are determined by the first-order conditions $B_i'(q_{ij}) = 0$ for $i = A, B$ and are denoted as q_{ij}^*, while the first-best total passenger quantity is denoted as Q_i^* with $Q_i^* = q_{AB}^* + q_{BA}^*$. The equilibrium conditions in (6) imply the first-best prices $r_A = r_B = 0$, which reflects the zero airport costs. Congestion effects are absent in the present scenario. Thus, it is intuitive that zero prices maximize local welfares, as well as the total welfare. The following derives equilibrium passenger quantities under slots, slot prices, and prices as decision variables relative to the first-best passenger quantities implied by zero prices.

2.3.1 Equilibrium slot quantities

To analyze equilibrium slot quantities, it is useful to understand how changes in total passenger quantities, Q_i, translate into changes in local passenger quantities, q_{ij} (all the proofs are relegated to the appendix):

Lemma 1 *The effect of an increase in the total passenger quantities Q_A or Q_B on local passenger quantities q_{ij} can be written as:*

$$\frac{dq_{ij}}{dQ_i} = \frac{dq_{ij}}{dQ_j} = \frac{B_j''}{B_A'' + B_B''} > 0. \tag{8}$$

The first equality appears because, regardless of airports' slot strategies, Q_i is always equal to Q_j. The inequality shows that an increase in the total passenger quantities will always be associated with both an increase in q_{AB} and an increase in q_{BA}.

To derive the best responses in terms of slot quantities, it is useful to write the local passenger quantities as a function of the total passenger quantities, that is, $q_{ij} = q_{ij}(Q_i)$. The objective function can then be rewritten as $W_i\left(q_{ij}\left(Q_i\right)\right)$. Consider the cases (i) $Q_i = \bar{Q}_i$, (ii) $Q_i = \bar{Q}_j$ and (iii) $Q_i < \bar{Q}_A,\ \bar{Q}_B$.

Part (i) implies that the total passenger quantity is equal to the own slot quantity. Local welfare can then be written as $W_i\left(q_{ij}\left(\bar{Q}_i\right)\right)$ and best responses are given by the first-order condition $W_i'(q_{ij}) \cdot q_{ij}'(\bar{Q}_i) = B_i'(q_{ij}) \cdot q_{ij}'(\bar{Q}_i) = 0$, which means that slots are optimal if the slot price is equal to zero. Part (ii) implies that the total passenger quantity is equal to the other airport's slot quantity. Local welfare can then be written as $W_i\left(q_{ij}\left(\bar{Q}_j\right)\right)$, which means that an increase in the own slot quantity keeps local welfare unchanged. Part (iii) implies that the total passenger quantity is lower than the own and the other airport's slot quantity. Local welfare can then be written as $W_i\left(q_{ij}\left(Q_i\right)\right)$, which means that an increase in the own as well as the other airport's slot quantity keeps local welfare unchanged. Altogether, this implies:

Proposition 2 *If there are two airports and airport profits do not matter, the full set of equilibrium slot quantities is given by*

$$\left(\bar{Q}_A, \bar{Q}_B\right) \in \left\{\bar{Q}_A, \bar{Q}_B : \bar{Q}_A = \bar{Q}_B < Q^*, \bar{Q}_A, \bar{Q}_B \geq Q^*\right\}. \tag{9}$$

The full set of equilibrium slot quantities given by Proposition 2 implies that there are infinitely many sets of equilibrium slot quantities. Therefore, the set of equilibrium slot quantities is not uniquely defined. However, the set of equilibrium slot quantities where $\bar{Q}_A = \bar{Q}_B = Q^*$ might be considered as a focal point. This equilibrium set implies a scenario where both airports happen to choose slot quantities that are also the first-best passenger quantities as their best responses in equilibrium.

2.3.2 Equilibrium slot prices

In the previous sub subchapter, slot quantity $\bar{Q}_i$ was the decision variable and airport profits were considered to be zero. In this sub subchapter, the price is used as the decision variable and, consistently, airport profits are considered to be zero, which altogether constitutes the policy regime $\phi_i = SP$. Both regimes capture the grandfather rights but involve different variables. And this enables the comparison of the outcomes under two regimes by identifying the variable effect.

Zero airport profits mean that local consumer surplus is identical to local welfare. Local welfare can be written as

$$W_i\left(D_{ij}\left(r_A, r_B\right)\right) = CS_i\left(D_{ij}\left(r_A, r_B\right)\right) = B_i\left(D_{ij}\left(r_A, r_B\right)\right). \tag{10}$$

This equation implies that local welfare is identical to the local passengers' benefit from travelling. Assume that the best responses in terms of slot prices are determined by the first-order conditions, $\partial W_i / \partial r_i = 0$ and that the map of best responses in terms of the slot price is a contraction, which are maintained assumptions here and hereafter.[9] Using equilibrium demand conditions in (6), the first-order conditions for the best responses in terms of the slot prices can be written as

$$(r_A + r_B) \cdot \frac{\partial D_{ij}(r_A, r_B)}{\partial r_i} = 0. \tag{11}$$

The left-hand side shows how an increase in own and the other airport's slot price and

[9] Best responses are not uniquely defined if the other airport charges such an extremely high price that local passenger quantity is zero. However, we concentrate on strictly positive passenger quantities and rule out this case accordingly.

the corresponding reduction in slot quantities affects own passengers' benefits from travelling. Because the demand of local passengers is strictly decreasing in the own airport charge (that is, $\partial D_{ij}(r_A, r_B) / \partial r_i < 0$), the optimality of best response requires that the sum of slot prices, $r_A + r_B$, is equal to zero. Since slot prices are non-negative, given any r_j, the best response for the own airport is to always choose $r_i = 0$. In other words, any positive slot price r_i will decrease local welfare relative to the zero price. This is because local welfare is increasing in local passenger quantity q_{ij}, and the local passenger quantity is decreasing in the sum of slot prices, which is decreasing in the own slot price. Together with Proposition 2, this implies that:[10]

Proposition 3 *If there are two airports and airport profits do not matter, zero slot prices establish a unique equilibrium in dominant strategies.*

Since zero slot prices yield the first-best passenger quantities, this further implies:

Proposition 4 *If there are two airports and airport profits do not matter, the unique pair of equilibrium slot prices yields the first-best passenger quantities.*

Since the set of equilibrium slot quantities is not uniquely defined, this further implies:

Corollary 1 *If there are two airports and airport profits do not matter, the variable effect is not uniquely defined.*

Consider the focal point where $\bar{Q}_A = \bar{Q}_B = Q^*$. In this special case, both airports' equilibrium slot quantities are exactly equal to the first-best passenger quantities, which implies a variable effect equal to zero by Proposition 4.

[10] See Vives (1999) for an excellent discussion of the role of the contraction condition for uniqueness of equilibrium solutions.

2.3.3 Equilibrium prices

By Proposition 1, pricing policies are relevant strategies if airport profits matter. In this case, local welfare can be written as

$$W_i(r_A, r_B) = B_i(r_A, r_B) - r_j \cdot D_{ij}(r_A, r_B) + r_i \cdot D_{ji}(r_A, r_B). \tag{12}$$

Best responses in terms of prices are assumed to be determined by the first-order conditions $\partial W_i / \partial r_i = 0$. Using the equilibrium demand conditions (6), these first-order conditions can be written as

$$r_i \cdot \frac{\partial D_i}{\partial r_i} + D_{ji} = 0. \tag{13}$$

Consider zero prices $r_i = 0$. This instance violates the first-order condition (13) because the first term on the left-hand side becomes zero, while the second term, D_{ji}, is strictly positive by assumption. The second-order conditions for best responses, $\partial W_i'' / \partial r_i^2 < 0$, imply that best responses in terms of prices are strictly positive. Rearranging the first-order conditions in (13) yields

$$r_i = \frac{D_{ji}}{D_i} \cdot \left| \frac{D_i}{\partial D_i / \partial r_i} \right|. \tag{14}$$

The right-hand side is the inverse semi-price elasticity of own total demand with respect to the own price weighted by the share of non-local passengers. It shows that equilibrium prices tend to be higher if the share of non-local passengers is relatively high and if the own total demand is relatively inelastic. If airport profits matter, the equilibrium airport charge is strictly positive because it balances the local welfares of isolated airports with the profits from non-local passengers that exist in airport networks.

Given that the contraction condition for best responses in terms of prices is satisfied, this altogether leads to:

Proposition 5 *If there are two airports and airport profits matter, the unique pricing equilibrium implies that airport charges strictly exceed first-best prices.*

By Corollary 1, aggregate welfare may or may not be maximized in equilibrium when airport profits do not matter although the equilibrium scenario where aggregate welfare is maximized could be considered as a focal point. Yet, if airport profits matter and they directly pursue local welfare maximization, it is clear that they end up with excessive airport charges, fewer total passengers and a reduction in aggregate welfare relative to the first-best solution by Proposition 5.

Airports can even be caught in a prisoner's dilemma situation in the case of pricing. For instance, if airport profits matter and airports are symmetric, they choose prices to exploit non-local passengers. But, in equilibrium, both airports choose strictly positive prices and therefore the local welfare gain from charging positive prices on non-local passengers is exactly equal to the local welfare loss that arises because the other airport charges the same on own passengers. In this situation, the gains and losses from positive airport prices cancel each other out, while aggregate welfare is reduced and, because of symmetry, also local welfares are reduced relative to the case where airport profits do not matter and both airports choose slot policies.

A prisoner's dilemma situation may or may not occur under the circumstances determined by the basic model. For instance, consider the extreme asymmetric case where the number of passengers originating from the own airport approaches zero, while the number of non-local passengers is relatively large. In this scenario, the own airport charges a strictly positive price when airport profits matter, while the other airport will charge a price that approaches zero. A prisoners' dilemma situation will not occur because the own airport mostly gains from charging a strictly positive price and derives revenue from other passengers. Nevertheless, aggregate welfare is not maximized in this scenario either.

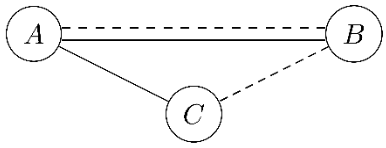

Figure 1: An illustration of the three-airport network. Solid lines: two airport connections for airport A 's origin-destination passengers; Dashed lines: two airport connections for airport B 's origin-destination passengers.

Strictly positive airport charges mean that there are too few passengers relative to the first-best solution, which further implies:

Corollary 2 *If there are two airports and airport profits matter, the distribution effect is strictly positive, that is,* $W_i(SP) - W_i(P) > 0$.

Altogether, Corollary 1 and Corollary 2 show that the choice of policy variables matters to the outcomes not only because it matters whether quantities or prices are the decision variables but also because of the grandfather rules associated with slot policies and the resulting positive distribution effect. The latter is positive because slots and grandfather rules can help to avoid the incentives to exploit non-local passengers.

2.4 Three-airport Network

The variable effect is not uniquely defined in the above case of a two-airport network. To derive more conclusive insights about the variable effect, this subchapter extends the airport network by adding a third airport, airport C, to the network. Airport C is different from airports A and B because local passengers are absent at this airport and the airport charge and slot price are normalized to zero, where the latter implies that binding slot constraints are absent at airport C. The present study further concentrates on origin-destination passengers by assuming that the number of passengers traveling between airports A and B via C, or between A and C via B is zero. Figure 1 illustrates the three-airport network. The solid lines depict the two airport connections for airport A's origin-destination passengers whereas the dashed lines depict the two airport connections for airport B's origin-destination passengers.

This three-airport network unifies two common airport network structures considered in the literature. First, if the number of passengers from A and B traveling to airport C approaches zero, this framework reduces to the two-airport network considered above and, for example, by Pels and Verhoef (2004) and Mantin (2012). Second, if the number of passengers traveling between airports A and B approaches zero, the two-airport network further reduces to the single-airport (or isolated-airport) framework (to be more precise, two single-airport cases are considered in this situation because airports A and B each represent a single-airport scenario) which is considered in the vast majority of airport studies (for example, Brueckner, 2002; Czerny, 2006; Zhang and Zhang, 2006; Basso and Zhang, 2010). These single-airport studies implicitly assume the presence of an airport C or, perhaps, multiple airports of the C- type as travelling destinations, without explicitly mentioning it. In this study, the presence of an airport of type C is made explicit and its important role is analyzed in full detail.

Let $q_{iC} > 0$ denote the quantity of passengers who travel between airports i and C. The total passenger quantity at airports A and B is given by $Q_i = q_{AB} + q_{BA} + q_{iC}$. The benefits of passengers with origin airport i are denoted as $B_i(q_{ij}, q_{iC})$. Benefits are strictly concave in the sense that $\partial^2 B_i / \partial q_{ij}^2$, $\partial^2 B_i / \partial q_{iC}^2 < 0$ and $\partial^2 B_i / \partial q_{ij} \partial q_{iC} = 0$ by assumption. The latter, $\partial^2 B_i / \partial q_{ij} \partial q_{iC} = 0$, implies that air services are neither substitutes nor complements. The case of substitute air services will be discussed and analyzed in Chapter 4.

The characterization of equilibrium policies in Proposition 1 is independent of the presence of the third airport. This is because local consumer surplus and local welfare under slots or pricing follow the same structures as the ones given by (2) and

(5), respectively. There are two differences between a two-airport and three-airport network in terms of local consumer surplus. The first difference is that the benefit of travelling in the presence of three airports is given by $B_i(q_{ij}, q_{iC})$, which is determined not only by the own passengers travelling to the other airport but also by the own passengers travelling to the third airport. The second difference involves the extra payments $q_{iC} \cdot r_i(P)$ of own passengers to the own airport in the case of pricing policies. There is only one difference between a two-airport and three-airport network in terms of local welfare, which is that the benefit of travelling in the presence of three airports is given by $B_i(q_{ij}, q_{iC})$ (payments $q_{iC} \cdot r_i(P)$) are cancelled out in the calculation of welfare). Observe that when the other airport's strategy and local passenger quantity are given, local consumer surplus is always decreased if the own airport moves from slots to pricing because local passengers will have to pay under pricing, while local welfare is always increased if the own airport moves from slots to pricing because there is an extra revenue from charging non-local passengers. The proof of Proposition 1 and the corresponding results can therefore be extended to the case with a three-airport network, which leads to:

Proposition 6 *Equilibrium choices of policy variables ϕ_i are unaffected by the presence of airport C.*

Thus, slots and pricing policies can both be equilibrium solutions depending on whether airport profits do not matter or matter, respectively, independent of whether a third airport is absent or present. This justifies the consideration of both slot and pricing policies in the presence of a three-airport network.

2.4.1 Demand functions

The passenger demands for trips between i and j, denoted as $D_{ij}(r_A, r_B)$, and, i and C, denoted as $D_{iC}(r_i)$ are determined by the equilibrium conditions

$$\frac{\partial B_i(q_{ij}, q_{iC})}{\partial q_{ij}} - (r_A, r_B) = 0 \text{ and } \frac{\partial B_i(q_{ij}, q_{iC})}{\partial q_{iC}} - r_i = 0 \tag{15}$$

for $\phi_i = S, P$ because efficient rationing is ensured under both slots and pricing policies by assumption. In equilibrium, the passengers' marginal benefit of travelling between A and B is equal to the sum of r_A and r_B, while it is equal to r_i for passengers travelling between i and C. The strict concavity of the benefit function, $B_i(q_{ij}, q_{iC})$, ensures the existence of a unique set of demands. Cramer's rule can be applied to derive the relationship between demands and prices:

Lemma 2 *If there are three airports, demands are decreasing in airport prices r_i in the sense that*

$$(i)\ \frac{\partial D_{ij}(r_A, r_B)}{\partial r_i} = \frac{\partial D_{ij}(r_A, r_B)}{\partial r_j} < 0 \ \textit{and}\ (ii)\ \frac{\partial D_{iC}(r_i)}{\partial r_i} < \frac{\partial D_{jC}(r_j)}{\partial r_i} = 0. \tag{16}$$

Part (i) shows that passengers who travel between airports A and B are indifferent between an increase in r_A or r_B by the same amount in the sense that passengers only care about the sum of the prices $r_A + r_B$. Part (ii) shows that passengers who travel between airports j and C are not affected by price changes at airport i. The total demand of airport i is denoted as

$$D_i(r_A, r_B) = D_{AB}(r_A, r_B) + D_{BA}(r_A, r_B) + D_{iC}(r_i) \tag{17}$$

and it is decreasing in r_i by Lemma 2.

2.4.2 Equilibrium slot quantities, equilibrium slot prices and equilibrium prices

A feature of the two-airport network is that the other airport's slot quantity imposes an upper limit on the own number of passengers. This is a strong assumption, which hardly reflects reality. Around 10,000 civil airports exist in the world (IATA, 2018) and 204 airports are slot coordinated (2019a). Moreover, not all the 204 slot coordinated airports operate at full capacity during all days and operating hours.

Altogether, this illustrates that it is useful to capture a scenario where the airports' passenger demands are determined by the airports themselves and not by their complementary counterparts. More specifically, with the third airport, a scenario where Q_i can exceed $\bar{Q}_j$ can be considered because the number of passengers traveling between airports i and C is independent of airport j's slot restriction.

In the three-airport network, the slot price $r_i(S)$ is implicitly determined by

$$\bar{Q}_i - D_i\left(r_A\left(S\right), r_B\left(S\right)\right) = 0.\text{[11]} \tag{18}$$

Applying Cramer's rule to the system of equations in (18) yields:

Lemma 3 *If there are three airports, (i) there is a unique pair of slot prices matched with each pair of slot quantities, and (ii) slot prices are decreasing in own slot quantities $\bar{Q}_i$ and increasing in the other airport's slot quantities, that is,*

$$\frac{\partial r_i(S)}{\partial \bar{Q}_i} = \frac{\partial D_j / \partial r_j}{\Phi(r_A, r_B)} < 0 < \frac{\partial r_j(S)}{\partial \bar{Q}_i} = -\frac{\partial D_j / \partial r_i}{\Phi(r_A, r_B)} < \left| \frac{\partial r_i(S)}{\partial \bar{Q}_i} \right| \tag{19}$$

$$\textit{with } \Phi(r_A, r_B) = \frac{\partial D_A}{\partial r_A}\frac{\partial D_B}{\partial r_B} - \frac{\partial D_B}{\partial r_A}\frac{\partial D_A}{\partial r_B} > 0. \tag{20}$$

An increase in the own slot quantity means that the passenger demand, D_i, at the own airport is increased, which is only possible if this increase in the own slot quantity is associated with a reduction of the own slot price. An increase in the own slot quantity increases the passenger throughput at the own airport, to avoid that this passenger increase increases the passenger throughput at the other airport, the other airport's slot price must be increased. This increase in the other airport's slot price is smaller in absolute value than the reduction of the own airport's slot price. This means

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[11] In the case of congested airports, it is assumed that slot constraints are always binding. Gillen et al. (2016) pointed out that meteorological and other stochastic factors may imply that airports may still not always operate at full capacity despite the presence of slot controls.

that the sum of ticket prices for flights between airports A and B is reduced by an increase in the own slot quantity.

By Proposition 6, slots are the relevant strategies if airport profits do not matter. Thus, local consumer surplus maximization is the relevant objective in this case, where local consumer surplus can be written as $CS_i(\bar{Q}_A, \bar{Q}_B) = W_i(\bar{Q}_A, \bar{Q}_B) = B_i(\bar{Q}_A, \bar{Q}_B)$. Assume that best responses in terms of slot quantities are determined by the first-order conditions, $\partial CS_i / \partial \bar{Q}_i = 0$ (given the presence of non-negativity constraints for slot prices, this may or may not be guaranteed in general) and that the map of best responses in terms of slot quantities is a contraction, which are maintained assumptions here and hereafter. Using equilibrium demand conditions in (15), the first-order conditions in terms of slot quantities can be written as

$$\frac{\partial CS_i}{\partial r_i}\frac{\partial r_i}{\partial \bar{Q}_i} = \left(r_j \cdot \frac{\partial D_{ij}}{\partial r_i} + r_i \cdot \frac{\partial \left(D_{ij} + D_{iC} \right)}{\partial r_i} \right) \cdot \frac{\partial r_i}{\partial \bar{Q}_i} = 0. \tag{21}$$

The left-hand side shows the product of two terms where the second term, $\partial r_i / \partial \bar{Q}_i$, is strictly negative by Lemma 3. The other term is shown in the middle of the equation in more detail in parentheses. If $r_A(S) = r_B(S) = 0$, this term is zero for both airports (non-negativity is just ensured in this case), which shows that there is a unique equilibrium where slot prices are zero when slot quantities are the decision variables.

Best responses in terms of slot prices are determined by the first-order conditions, $\partial CS_i / \partial r_i = 0$, which is also true in the case of slot quantities. Since demand functions are independent of whether $r_i(S)$ or $r_i(SP)$ is considered, which implies that $D_{ij}\left(\bar{Q}_A, \bar{Q}_B\right) = D_{ij}\left(r_A\left(SP\right), r_B\left(SP\right)\right)$ for $r_i(S) = r_i(SP)$, equilibrium results are independent of whether slot quantities or slot prices are the decision variables. Given that the contraction condition is satisfied for both best responses in terms of slot quantities and best responses in terms of slot prices, this altogether leads to:

Proposition 7 *If there are three airports, equilibrium slot prices are equal to the first-best prices independent of whether slot quantities or slot prices are considered as decision variables.*

By Proposition 6, pricing policies are the relevant strategies if airport profits matter. Assume that best responses in terms of prices are determined by the first-order conditions $\partial W_i / \partial r_i = 0$. Using the equilibrium demand conditions in (15), these first-order conditions lead to a characterization of equilibrium prices that is equal to the one obtained by using the two-airport network in (14). This implies that in the presence of both two- and three-airport networks, equilibrium prices strictly exceed first-best prices.

Altogether, this implies:

Corollary 3 *If there are three airports and airport profits do not matter, the variable effect is zero, that is,* $W_i(S) - W_i(SP) = 0$ *, while the distribution effect is strictly positive when profits matter, that is,* $W_i(SP) - W_i(P) > 0$.

This corollary shows that the variable effect is clearly identified and equal to zero in the presence of a three-airport network. The difference to a two-airport network is that the presence of a third airport allows for an interior solution for the best responses in terms of slot quantities, which ultimately and usefully leads to a unique equilibrium in slot quantities.

The discussion in this subchapter firstly shows that a third airport has a significant effect on the slot strategy in the sense that (i) the own equilibrium demand is determined by the own slot quantity and independent of the other airport's slot quantity in equilibrium, and (ii) the variable effect is uniquely defined and equal to zero. These results show that slots in combination with grandfather rules can serve as a tool to overcome excessive airport charges caused by the incentives to exploit non-local passengers, which exist in the case of pricing policies.

2.5 Congestion Effects

This subchapter extends the basic model with a three-airport network in order to capture congestion effects. A major factor for the cause of congestion is the ratio of traffic quantity to capacity (for example, Zhang and Czerny, 2012; Gillen et al., 2016). Traffic may be measured by passenger or flight numbers. Capacity can refer to runway capacity, air space capacity, and terminal capacity, where congestion will be positively related to flight numbers in the case of runway and air space capacity, and positively related to passenger quantities in the case of terminal capacity. Assuming given aircraft sizes and fixed load factors, as is common in the literature, the framework can represent both capacity limitations related to flights and passenger quantities because, in this case, an increase in passenger quantities translates into a fixed increase in flight numbers.[12] For tractability reasons, we concentrate on symmetric airports in the following subchapter.

Let $T_i(Q_i)$ with $T_i'(Q_i) > 0$ and $T_i''(Q_i) \geq 0$ denote the average delays at airport i and v denote the passengers' time valuations. The total congestion costs of local passengers, denoted as $TT_i(q_{ij}, q_{iC}, Q_A, Q_B)$, can be written as $TT_i(q_{ij}, q_{iC}, Q_A, Q_B) = v\left(q_{ij} \cdot \left(T_A\left(Q_A\right) + T_B\left(Q_B\right)\right) + q_{iC} \cdot T_i\left(Q_i\right)\right)$. Local consumer surplus can be rewritten as

$$\begin{aligned} & CS_i\left(q_{ij}, q_{iC}, r_A\left(\phi_A\right), r_B\left(\phi_B\right), \phi_A, \phi_B\right) \\ & = B_i\left(q_{ij}, q_{iC}\right) - q_{ij} \cdot \left(R_A\left(r_A\left(\phi_A\right), \phi_A\right) + R_B\left(r_B\left(\phi_B\right), \phi_B\right)\right) - q_{iC} \cdot R_i\left(r_i\left(\phi_i\right), \phi_i\right) - TT_i \end{aligned} \tag{22}$$

[12] See Czerny et al. (2016b) for a modelling framework with endogenous aircraft sizes and load factors.

and local welfare can be rewritten as

$$W_i\left(q_{AB},q_{BA},q_{iC},r_A\left(\phi_A\right),r_B\left(\phi_B\right),\phi_A,\phi_B\right)$$
$$=B_i\left(q_{ij},q_{iC}\right)+q_{ji}\cdot R_i\left(r_i\left(\phi_i\right),\phi_i\right)-q_{ij}\cdot R_j\left(r_j\left(\phi_j\right),\phi_j\right)-TT_i. \tag{23}$$

The only difference between local consumer surpluses in (1) and (22), and welfares in (4) and (23), are the last terms on the right-hand sides of (22) and (23), which represent the total congestion costs of local passengers. Observe that congestion costs are independent of the policy variables when passenger quantities are given. The proof of Proposition 1 and the corresponding results can therefore directly be extended to the case with congestion, which leads to:

Proposition 8 *Equilibrium policies in terms of policy variables ϕ_i are unaffected by the presence of airport congestion.*

Thus, slots and pricing policies can both be equilibrium solutions depending on whether airport profits do not matter or matter, respectively, independent of whether congestion effects are absent or present.

Passengers consider delays T_i as given. With congestion, demands $D_{ij}(r_A,r_B)$ and $D_{iC}(r_A,r_B)$ are determined by the equilibrium conditions

$$\frac{\partial B_i\left(q_{ij},q_{iC}\right)}{\partial q_{ij}}-\left(r_A+r_B+v\left(T_A+T_B\right)\right)=0 \text{ and } \frac{\partial B_i\left(q_{ij},q_{iC}\right)}{\partial q_{iC}}-\left(r_i+vT_i\right)=0. \tag{24}$$

Passengers will travel as long as their marginal benefit from travelling is at least as high as the sum of the corresponding prices and average congestion costs. Applying Cramer's rule to the system of equations in (24) and using symmetry yields:

Lemma 4 *In the presence of congestion and under symmetry, a marginal increase in price r_i changes demands as follows:*

$$\frac{\partial D_{ji}\left(r_A,r_B\right)}{\partial r_i}=\frac{\partial D_{ij}\left(r_A,r_B\right)}{\partial r_i}<0 \tag{25}$$

and

$$\frac{\partial D_{iC}\left(r_A,r_B\right)}{\partial r_i}<0<\frac{\partial D_{jC}\left(r_A,r_B\right)}{\partial r_i}<\left|\frac{\partial D_{iC}\left(r_A,r_B\right)}{\partial r_i}\right|. \tag{26}$$

The result described in (25) is similar to the one described in the first part in Lemma 2 and shows that an increase in one airport's price changes the demands for trips between airports A and B by the same amount independent of whether local or non-local passengers are considered. This is because generalized prices are composed of the sum of airport charges and congestion costs at airports A and B, and this sum is independent of the airport of origin. The results in (26) show how the interdependencies caused by congestion affect demand properties. Because an increase in airport i's charge reduces passenger demands for flights between airports A and B, and thus, congestion at airport j, this increases the passenger demand for flights between airports j and C. However, the increase in D_{jC} is smaller than the reduction in D_{iC} in absolute values, which means that an increase in the own price r_i reduces the passenger demand at the own airport, D_i, *and* the passenger demand at airports A and B, D_A+D_B.

The sum of local welfares, W_A+W_B, is given by the difference between the sum of local benefits, $B_A(q_{AB},q_{AC})+B_B(q_{BA},q_{BC})$, and the sum of local congestion costs, TT_A+TT_B. The first-best passenger quantities are determined by the first-order conditions $\partial B_i/\partial q_{ij}-\partial(TT_A+TT_B)/\partial q_{ij}=\partial B_i/\partial q_{iC}-\partial(TT_A+TT_B)/\partial q_{iC}=0$ for $i=A,\ B$. This together with the equilibrium conditions in (24) implies the first-best prices $r_A=D_A vT_A'$, $r_B=D_B vT_B'$. The first-best prices $D_i vT_i'$ represent the marginal external congestion costs of passengers traveling from i to C. The sum of the first-best prices, $D_A vT_A'+D_B vT_B'$, represents the marginal external congestion costs of passengers traveling between airports A and B.

2.5.1 Equilibrium slot quantities

The relationships between slot quantities and slot prices described in Lemma 3 is extended to the case of networks of congested airports. To see this, note that the results in parts (i) and (ii) of Lemma 3 depend on how $\partial D_i / \partial r_i$ relates to $\partial D_j / \partial r_i$. Furthermore, Lemma 2 and Lemma 4 imply that $\left|\partial D_i / \partial r_i\right| > \left|\partial D_j / \partial r_i\right|$ independent of whether networks of uncongested or congested and symmetric airports are considered. This implies:

Lemma 5 *The existence of a unique pair of slot prices matched with each pair of slot quantities, and the effect of changes in slot quantities $\bar{Q}_i$ on slot prices are unaffected by the presence of airport congestion in the sense that Lemma 3 extends to the present case of a three-airport network with two symmetric congested airports.*

By Proposition 8, it is still true that slots are relevant strategies if airport profits do not matter even though networks of congested airports are considered. Thus, local consumer surplus maximization is the relevant objective in this case, where local consumer surplus is the difference between the local passengers' benefits and the local passengers' congestion costs, which can be written as

$$CS_i\left(\bar{Q}_A, \bar{Q}_B\right) = B_i\left(\bar{Q}_A, \bar{Q}_B\right) - TT_i\left(\bar{Q}_A, \bar{Q}_B\right). \tag{27}$$

Best responses in terms of slot quantities are determined by the first-order conditions $\partial CS_i / \partial \bar{Q}_i = 0$. Using equilibrium demand conditions in (24), these first-order conditions can be written as

$$r_i(S) \cdot \left(\frac{\partial D_i}{\partial r_i} \frac{\partial r_i}{\partial \bar{Q}_i} + \frac{\partial D_i}{\partial r_j} \frac{\partial r_j}{\partial \bar{Q}_i} \right) - \left(D_{ij} + D_{iC} \right) v T_i' = 0. \tag{28}$$

The first term on the left-hand side is the product of the equilibrium slot price and a term in parentheses for which, by Lemma 3, the following is true:

Lemma 6 *An increase in the own slot quantity* $\bar{Q}_i$ *increases the own airport's passenger throughput* D_i *by the same amount, that is,*

$$\frac{\partial D_i}{\partial r_i}\frac{\partial r_i}{\partial \bar{Q}_i}+\frac{\partial D_i}{\partial r_j}\frac{\partial r_j}{\partial \bar{Q}_i}=1. \tag{29}$$

Using this lemma, the equilibrium slot price can be written as

$$r_i(S)=\left(D_{ij}+D_{iC}\right)vT_i', \tag{30}$$

where the right-hand side can be described as the marginal external congestion costs of local passengers. However, to reach the first-best solution that maximizes the welfare of the aggregate economy, a price equals to $D_i vT_i'$ with $D_i vT_i' > \left(D_{ij}+D_{iC}\right)vT_i'$ would be required at each airport, that is, not only local but also non-local passengers should be taken into account. More specifically, from the first-best viewpoint, equilibrium slot quantities in (30) are too high, which means that the sum of local consumer surplus and welfare could be increased by reducing slot quantities relative to the equilibrium solution.

Given that the contraction condition for best responses in terms of slot quantities is satisfied, this leads to:

Proposition 9 *If airport profits do not matter and in the case of a three-airport network with two symmetric congested airports, the unique equilibrium in slot quantities implies that airports imperfectly internalize the marginal external congestion costs,* $D_i vT_i'$ *, relative to the first-best prices.*

This shows that equilibrium slot quantities are too loose to maximize the total welfare of all airport regions when airport profits do not matter, and airports only care about local passengers.

2.5.2 Equilibrium slot prices

Consider $\phi_i = SP$ and assume that best responses in terms of slot prices are determined by the first-order conditions $\partial CS_i / \partial r_i = 0$ for $i = A, B$. Using equilibrium demand conditions in (24), these first-order conditions can be written as

$$r_i(SP) \cdot \frac{\partial\left(D_{ij} + D_{iC}\right)}{\partial r_i} + r_j(SP) \cdot \frac{\partial D_{ij}}{\partial r_i} - \left(D_{ij} + D_{iC}\right) vT_i' \frac{\partial D_i}{\partial r_i} - D_{ji} vT_j' \frac{\partial D_j}{\partial r_i} = 0. \tag{31}$$

The first term and the second term on the left-hand side shows how an increase in slot prices and the corresponding reduction in slot quantities affects own passengers' benefits from travelling. The third term shows the reduction in congestion cost for own passengers at the own airport, while the fourth term on the left-hand side shows the reduction in congestion costs for own passengers at the other airport.

Using symmetry and solving the first-order conditions in (31) yield the equilibrium slot prices, which are strictly positive and can be written as

$$r_i(SP) = \left(\frac{\partial\left(D_A + D_B\right) / \partial r_i}{\partial D_i / \partial r_i} D_{ij} + D_{iC} \right) vT_i'. \tag{32}$$

The right-hand side of (32) shows that the congestion externalities imposed on non-local passengers are only partly taken into account because Lemma 4 implies $\left(\partial\left(D_A + D_B\right) / \partial r_i\right) / \left(\partial D_i / \partial r_i\right) < 2$. In this sense, equilibrium slot prices are too low relative to the first-best prices for both $\phi_i = S$ and $\phi_i = SP$.

Given that the contraction condition is satisfied for both best responses in terms of slot quantities and best responses in terms of slot prices, this altogether leads to:

Proposition 10 *If airport profits do not matter and in the case of a three-airport network with two symmetric congested airports, the unique equilibrium in slot prices implies that airports imperfectly internalize the marginal external congestion costs,* $D_i vT_i'$*, relative to first-best prices although internalization is stronger than in the case where slot quantities are considered as decision variables.*

The intuition is that an increase in the own airport charge does not only improve the situation of local passengers by reducing passenger demand at the own airport but also by reducing passenger demand at the other airport because $\partial D_j / \partial r_i < 0$. This, therefore, provides stronger incentives to increase slot prices relative to the case where slot quantities are considered as decision variables and the other airport's total demand is independent of the own slot quantity.

The equilibrium slot prices in (32) show that airports charge a markup on slot prices in (30) where slot quantities are considered as decision variables so that it brings the equilibrium slot prices closer to the first-best prices when slot prices are considered as decision variables. This indicates that the variable effect, $W_i(S) - W_i(SP)$, is negative in sign. Considering that slot prices can be strategic substitutes, an increase in one airport's slot price could be associated with a reduction of the other airport's slot price. The total effect of a change in regimes from slots to slot prices as decision variables is therefore difficult to predict because there can be forces at play that work into opposite directions. Example 1 below will present a numerical example based on quadratic passenger benefit functions where the variable effect is indeed clear-cut and negative in sign.

2.5.3 Equilibrium prices

The local welfare function with congestion is given by (23). Using the equilibrium demand conditions in (24), the first-order conditions for the best responses in terms of the local welfare-maximizing prices, $\partial W_i / \partial r_i = 0$, can be written as

$$\begin{aligned}&r_i(P)\cdot\frac{\partial\left(D_{ij}+D_{iC}\right)}{\partial r_i}+r_j(\phi_j)\cdot\frac{\partial D_{ij}}{\partial r_i}-\left(D_{ij}+D_{iC}\right)vT_i'\frac{\partial D_i}{\partial r_i}-D_{ji}vT_j'\frac{\partial D_j}{\partial r_i}\\&-R_j\left(r_j\left(\phi_j\right),\phi_j\right)\cdot\frac{\partial D_{ij}}{\partial r_i}+r_i(P)\cdot\frac{\partial D_{ji}}{\partial r_i}+D_{ji}=0.\end{aligned} \tag{33}$$

Using symmetry, which implies $R_j(r_j(\phi_j),\phi_j) = r_i(P)$, as well as Lemma 4, the last three terms on the left-hand side reduce to D_{ji}. By the second-order conditions, this implies that best price responses, $r_i(P)$, exceed best responses in terms of slot prices, $r_i(SP)$. Solving the first-order condition (33) yields the equilibrium prices, $r_i(P)$, which can be written as the sum of the equilibrium slot prices plus a weighted markup depending on the price elasticities of passenger demands:

$$r_i(P) = r_i(SP) + \frac{D_{ji}}{D_i} \cdot \left| \frac{D_i}{\partial D_i / \partial r_i} \right|. \tag{34}$$

Thus, the markup is the product of the semi-price elasticity of demand, D_i, with respect to the own price and the share of other passengers at the own airport. The semi-price elasticity, $|D_i / \partial D_i / \partial r_i|$, represents the optimal price in the case of airport profit maximization. The notion of profit maximization only applies to other passengers when the airport maximizes local welfare, which is why the elasticity measure is weighted by the share of other passengers at the own airport. The markup also implies that regardless of whether it is a two-airport or three-airport network, or whether there are congestion effects or not, airports always have the incentives to charge strictly positive prices to exploit non-local passengers if airport profits matter, which again highlights the importance of considering the airport network effect.

While equilibrium slot prices are too low relative to the first-best prices, the opposite is true for equilibrium prices in the case of local welfare maximization:

Proposition 11 *If airport profits matter and in the case of a three-airport network with two symmetric congested airports, the unique equilibrium in prices overinternalizes the marginal external congestion costs, $D_i v T_i'$, relative to first-best prices.*

This shows that equilibrium prices are used to exploit non-local passengers when airport profits matter and this leads to excessive prices in equilibrium also in the case of congested airport networks.

The following example illustrates how time valuations affect the relative

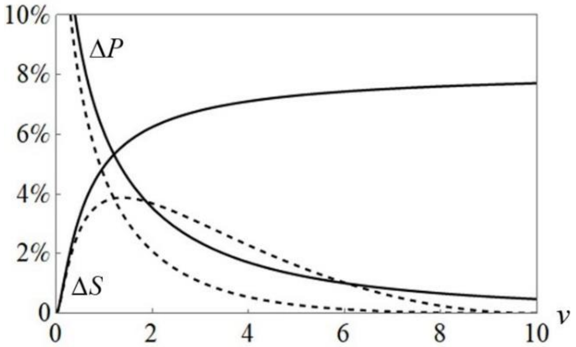

Figure 2: Welfare losses under slots, $\Delta(S)$, and pricing, $\Delta(P)$, relative to first-best in percent depending on time valuations. Parameters: $\alpha_2 = 3/5$, $\beta_1 = 2$, $\beta_2 = 4$, and $\alpha_{1i} = 6/5$ (solid lines) as well as $\alpha_{1i} = 1$ (dashed lines).

performance of slot and pricing policies relative to the first-best solution and the role of variable and distribution effects in the presence of congestion.

Example 1 The benefit of travelling is given by

$$B_i\left(q_{ij}, q_{iC}\right) = \alpha_{1i} \cdot q_{ij} + \alpha_2 \cdot q_{iC} - \frac{1}{2}\left(\beta_1 \cdot q_{ij}^2 + \beta_2 \cdot q_{iC}^2\right) \tag{35}$$

for airports A and B. To illustrate the relative performance of slot and pricing policies, the following notations are used. Using symmetry, the aggregate welfare is denoted as W with $W = W(\phi_i) = 2W_i(\phi_i)$. Let W^* denote the aggregate welfare under first-best prices $r_i = D_i v T_i'$. The relative welfare loss of slot policies, denoted as $\Delta(S)$, is given by $\Delta(S) = \left(W^* - W(S)\right)/W^*$, while the corresponding value for pricing policies, denoted as $\Delta(P)$, is given by $\Delta(P) = \left(W^* - W(P)\right)/W^*$.

Figure 2 illustrates the welfare losses of slot and pricing policies depending on time valuations in percent for parameters $\alpha_{1A} = \alpha_{1B} = 6/5$ (solid lines), 1 (dashed lines), $\alpha_2 = 3/5$, $\beta_1 = 2$, $\beta_2 = 4$, where $\alpha_{1i} = 6/5$ represents a scenario with large network effects, while $\alpha_{1i} = 1$ represents a scenario where network effects are relatively less important. The solid lines ($\alpha_{1i} = 6/5$) and dashed lines ($\alpha_{1i} = 1$) represent the welfare losses when airport profits matter, $\Delta(P)$, and do not matter,

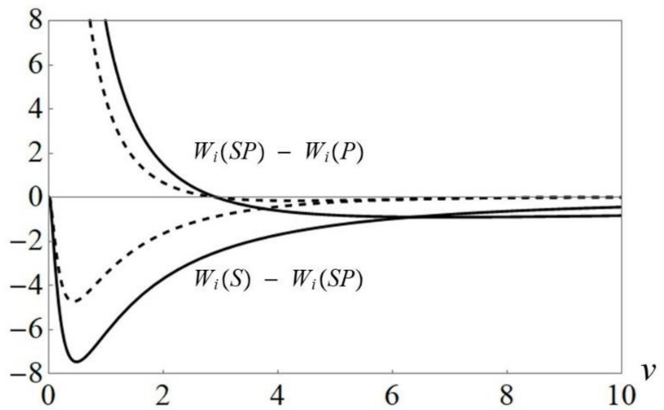

Figure 3: The variable effect, $W_i(S)-W_i(SP)$, and distribution effect, $W_i(SP)-W_i(P)$, depending on time valuations (values are multiplied by 1,000 for scaling reasons). Parameters: $\alpha_2 = 3/5$, $\beta_1 = 2$, $\beta_2 = 4$, and $\alpha_{1i} = 6/5$ (solid lines) as well as $\alpha_{1i} = 1$ (dashed lines).

$\Delta(S)$.

The figure illustrates that pricing performs particularly badly relative to slots when time valuations are low and, thus, congestion effects are of low importance to passengers. This is because in this case the distributional distortions and prisoner's dilemma situations occur under pricing. However, as time valuations increase, the too loose equilibrium slot policies with excessive levels of congestion become more problematic and, eventually, for sufficiently high time valuations, slots perform worse than pricing. This indicates that time valuations are crucial for the social evaluation of airport systems that rely on slots or pricing policies.

Figure 3 illustrates how time valuations affect the variable effect, $W_i(S)-W_i(SP)$, and the distribution effect, $W_i(SP)-W_i(P)$, in the presence of congestion for parameters $\alpha_{1i} = 6/5$ (solid lines) and $\alpha_{1i} = 1$ (dashed lines). When time valuations are zero, the variable effect is strictly equal to zero, while the distribution effect is strictly positive as shown in Corollary 3. The variable effect is always negative as anticipated, while the distribution effect is positive for sufficiently low time valuations and negative for sufficiently high time valuations. This shows that for large enough time valuations both the variable and the distribution effects are negative and explains the superiority of pricing policies relative to slot policies from the welfare viewpoint. ■

2.6 Other Extensions

This subchapter considers two extensions of the three-airport network model. The first extension captures the presence of atomistic airlines, while the second extension involves a two-stage game, where airports decide whether to apply slot or pricing policies in the first stage and where they choose the specific slot quantities or airport charges, respectively, in the second stage.

2.6.1 (Atomistic) Airlines

In the previous subchapters, we considered integrated airports which provide both infrastructure and air services. In this sense, we abstracted away from airline companies and especially airline profits to avoid complications caused by the consideration and especially the evaluation of airline profits. To illustrate the potential complications induced by the presence of airline profits, this extension considers the presence of atomistic airlines when the airlines' costs other than the airport charges are normalized to zero.

Consider the case of uncongested airports. Airline ticket prices are equal to the sum $r_A + r_B$, where r_i can represent airport charges or slot prices, for passengers flying between airports A and B. This is true independent of whether passengers use local or non-local airlines. Thus, passengers who only care about ticket prices are indifferent between the use of local or non-local airlines when they fly between airports A and B. Airline ticket prices are equal to r_i for passengers flying between airports i and C. Demands D_{ij} and D_{iC} are implicitly determined by the equilibrium conditions in (15). But, while demands D_{ij} are informative with respect to the local passenger demands for flights between airports A and B, they do not define the total passenger demands for local airlines, where the latter have a lower limit of zero and an upper limit of $D_{AB} + D_{BA}$. Let D_i^{AB} denote the total passenger demand for local airlines with $D_i^{AB} \le D_{AB} + D_{BA}$. In this case, the local airlines' total profits, denoted as Π_i, depending on whether slot or pricing policies are used, can be written as

$$\Pi_i = D_i^{AB} \cdot \left(r_A\left(\phi_A\right) + r_B\left(\phi_B\right) - R_A\left(\phi_A\right) - R_B\left(\phi_B\right)\right) + D_{iC} \cdot \left(r_i\left(\phi_i\right) - R_i\left(\phi_i\right)\right). \quad (36)$$

The first term on the right-hand side is the profit from local passengers travelling between airports A and B (independent of the share of local or non-local passengers served). The second term is the profit from local passengers travelling between airports i and C.

If airport profits matter, $\phi_A = \phi_B = P$ and $r_i(P) = R_i(P)$ in equilibrium; thus, airlines have zero profits (that is, $\Pi_i = 0$). This implies that the presence of atomistic airlines leaves the local welfare function unchanged, which leads to:

Proposition 12 *If airport profits matter, equilibrium airport behaviors are independent of whether atomistic airlines or a vertically integrated airport is considered.*

Consider a scenario where airports auction slots to atomistic airlines so that r_i reflects the auction prices for slots and where auction revenues accrue to airports. This reflects a scenario where $r_i = R_i$, which shows that Proposition 12 extends to such scenarios.

If airport profits do not matter, $\phi_A = \phi_B = S$ and airport charges are equal to $R_i\left(S\right) = 0$, while the slot prices can be positive, that is, $r_i\left(S\right) \ge 0$. This implies that airlines have positive profits if the slot quantities are small enough to ensure positive slot prices with $r_i\left(S\right) > 0$. Local consumer surplus can be written as

$$CS_i = B_i - D_{ij} \cdot \left(r_A + r_B\right) - D_{iC} \cdot r_i, \quad (37)$$

where the presence of atomistic airlines implies that passenger payments for flights are positive even when slot policies are considered. More specifically, equation (37) implies that regardless of the airports' slot or pricing strategies, local consumer surplus will always be equal to the difference between the benefits and the ticket payments of local passengers. Previously, with integrated airports, ticket prices were zero under slot strategies and, therefore, local welfare, local consumer surplus were both equal to the local passengers' benefits. The difference between vertically integrated airports and airports with atomistic airlines is that airports' slot strategies now enable atomistic airlines to gain positive profits, while the consumer surplus of local passengers is reduced.

Assume that the airport attaches a weight $\theta \in [0,1]$ to airline profits so that the local welfare function under slots takes the form

$$W_i = CS_i + \theta\Pi_i.^{13} \tag{38}$$

If the airport attaches a unit weight to the local airline's profits and the local airlines exclusively serve local passengers, the right-hand side is equal to the benefits of local passengers, B_i, as it is in the case of a vertically integrated airport when airport profits do not matter. This implies:

Proposition 13 *If airport profits do not matter, airports attach a unit weight to airline profits, and airlines exclusively serve local passengers, equilibrium slot strategies are independent of whether atomistic airlines or a vertically integrated airport is considered.*

This means that the scenario with a vertically integrated airport is equivalent to a scenario with atomistic airline markets when the airports attach unit weights to consumer surplus and airline profits and, additionally, airlines exclusively serve local

[13] Czerny and Forsyth (2008) considered a scenario with airport slots where a unit weight is attached to consumer surplus and a weight lower than the unit weight is attached to airport and airline profits.

passengers. But it further means that deviations from these conditions could potentially change the results derived for the case of a vertically integrated airport, which illustrates the complications induced by the presence of atomistic airlines relative to the presence of vertically integrated airports. The following discussion and examples illustrate how these complications can affect the results derived based on the consideration of a vertically integrated airport.

Consider the first partial derivative of the local welfare functions with respect to the local slot quantities, which can be written as

$$\frac{\partial W_i}{\partial r_i}\frac{\partial r_i}{\partial \bar{Q}_i} = \frac{\partial CS_i}{\partial r_i}\frac{\partial r_i}{\partial \bar{Q}_i} + \theta \frac{\partial \Pi_i}{\partial r_i}\frac{\partial r_i}{\partial \bar{Q}_i}. \tag{39}$$

The first term on the right-hand side is strictly positive because $\partial CS_i / \partial r_i < 0$, while the second term is strictly negative when slot prices are equal to zero. If airports attach a unit weight to their local airlines' profits and the local airlines exclusively serve local passengers, the right-hand side is exactly equal to zero when evaluated at zero slot prices by Proposition 7. If, however, the second term on the right-hand side is smaller in absolute values because $\theta < 1$ or $D_i^{AB} \leq D_{ij}$, the non-negativity constraints for airport charges become strictly binding, and do not change the equilibrium results derived for the case with a vertically integrated airport in the sense that equilibrium slot policies still imply zero slot prices.[14] However, also positive equilibrium slot prices can occur when, for example, $D_i^{AB} > D_{ij}$.

Consider the interesting alternative scenario where airport profits do not

[14] If airport subsidy payments from airports to airlines would be allowed, the first-order conditions $\partial W_i / \partial \bar{Q}_i = 0$ would imply negative slot prices under these conditions. The role of airline subsidies at airports with oligopolistic airlines has been highlighted by Pels and Verhoef's (2004). The present study highlights the role of airport subsidies arising from the social weights attached to airline profits and the distribution of local and non-local passengers to local and non-local airlines.

matter, airports attach a unit weight to their local airlines' profits, the local airlines exclusively serve local passengers, and a fraction of slots are auctioned by airports to airlines as proposed by Daniel (2014). In this scenario, airline profits are reduced relative to a scenario where all slots are freely allocated to them based on the grandfather rule. To emulate such a scenario (which cannot be an equilibrium policy scenario when the auctioned fraction of slots is strictly positive and airport profits do not matter), let θ represent the discount on airline profits rather than the weight attached to airline profits where an increase in the fraction of auctioned slots is associated with a reduced value of θ. This interpretation illustrates that the above scenario is rich enough to also cover such cases and that the results derived for a vertically integrated airport extend to such cases as well.

Consider the case of congested airports. Pricing policies lead to zero profits of atomistic airlines, which is independent of whether networks of uncongested or congested airports are considered. If airline markets are atomistic, the equilibrium pricing strategies derived for the case of vertically integrated airports are therefore unaffected by the presence of both atomistic airlines and congestion.

The picture changes again in the case of slot policies. Airline profits are positive in this case and the relative weight attached to local consumer surpluses increases when the weight, θ, attached to airline profits decreases (or local airlines serve few passengers relative to the local passengers' total demand). Since local consumer surpluses are decreasing functions of ticket prices, this tends to increase equilibrium slot quantities and reduce equilibrium slot prices, thus, equilibrium ticket prices. The following example numerically illustrates that the presence of atomistic airlines in combination with a less than unit weight attached to their profits loosens equilibrium slot strategies relative to the case of vertically integrated airports when congestion is involved.

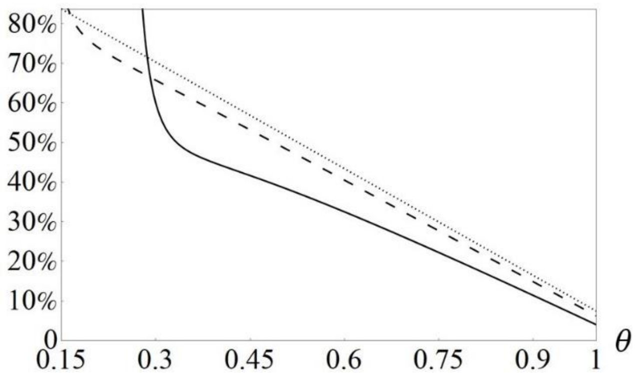

Figure 4: Relative local welfare losses under equilibrium slot policies relative to first-best policies depending on the weight attached to airline profits when time valuations are $v = 1/3$ (solid line), $v = 1$ (dashed line) and $v = 3$ (dotted line).

Example 2 The benefits of local passengers are given by (35) with parameters $\alpha_{1A} = \alpha_{1B} = 6/5$, $\alpha_2 = 3/5$, $\beta_1 = 2$ and $\beta_2 = 4$. Figure 4 displays the relative local welfare losses under slots relative to first-best policies depending on the weight θ attached to airline profits when airlines exclusively serve local passengers, where time valuations $v = 1/3$ (solid line), $v = 1$ (dashed line) and $v = 3$ (dotted line) are considered. The weight θ starts at $3/20$ to ensure that passenger quantities are non-negative in all markets. The figure indicates that the difference between local welfares in the case of first-best policies and local welfares in the case of equilibrium slot strategies are decreasing in the weight θ. The intuition is that if airports attach lower than unit weights to airline profits, then they loosen slot quantities in equilibrium to let more local passengers travel, which increases welfare loss. ■

2.6.2 Two-stage Game

Until now, the analyses assumed one-shot games where airports simultaneously choose policy variables and prices or quantities. This seems a strong assumption because it seems plausible that airports can easily change slot quantities or prices, while it may be more difficult for them to switch between slot and pricing policies. To better capture the timing of airport decisions and test the robustness of the above-derived results, this sub subchapter considers airports that choose the policy variable,

ϕ_i, in the first stage and slot quantities or prices in the second stage.

The sequential structure adds the following complication to the analysis. The simultaneous game structure involves symmetric policy choices in the sense that both airports will either choose slot policies or pricing policies depending on whether airport profits do not matter or matter, respectively. The derivation of the subgame-perfect equilibrium in policy choices requires consideration of policy constellations where one airport chooses the pricing policy, while the other chooses the slot policy, which is a scenario that could be omitted in the case of a one-shot game.

Consider uncongested airports. Furthermore, consider the case where airport profits do not matter. In this case, all airport prices (that is, prices r_i and R_i) implied by best responses are zero independent of whether slot or pricing policies are considered. A switch between policies has no impact on passenger quantities in this case. This implies that if there are three airports, airports are uncongested and airport profits do not matter, the equilibrium results derived for the one-shot game carry over to the two-stage game structure.

Consider the case where airport profits matter. In this case, all airport prices implied by the best responses are zero for the airport that uses slot policies. However, equilibrium airport charges are strictly positive for airports that make use of pricing policies. Since airports A and B are complements, one would expect that airport prices are strategic substitutes. Thus, the equilibrium price of the airport that chooses pricing policies should be higher if the other airport chooses slot policies relative to a scenario where both airports choose slot policies. Furthermore, the sum of equilibrium prices should be lower if airports choose different policies relative to the scenario where both choose pricing policies. The overall effect of a unilateral move from pricing to slot policies on local welfares in the two-stage game can therefore be positive or negative. The following example illustrates the likely negative effect of a

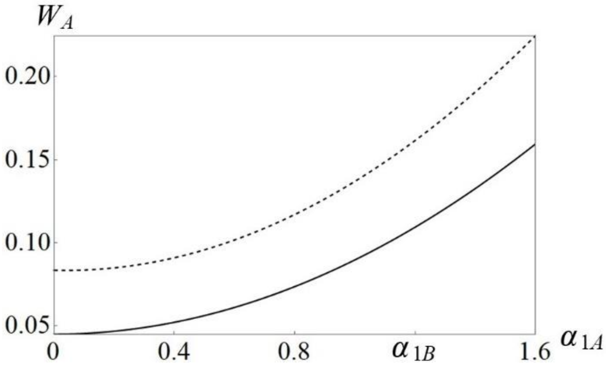

Figure 5: Equilibrium welfare of airport A under slot policies (solid line) and pricing policies (dashed line) depending on the maximum reservation price α_{1A} when airport B chooses pricing policies and airport profits matter. Parameters: $\alpha_{1B} = 6/5$, $\alpha_2 = 3/5$, $\beta_1 = 5$ and $\beta_2 = 4$.

unilateral move from pricing to slot policies on local welfares when airport profits matter.

Example 3 The benefit of travelling is given by (35) with parameters $\alpha_{1B} = 6/5$, $\alpha_2 = 3/5$, $\beta_1 = 5$ and $\beta_2 = 4$. Parameter α_{1A} remains undetermined to analyze asymmetric market sizes. Airport profits are assumed to matter for airports.

Figure 5 displays the equilibrium welfare of airport A under slot policies (solid line) and pricing policies (dashed line) depending on the market size measured by the maximum reservation price α_{1A} and given that airport B is engaged in pricing policies when airport profits matter. Parameter α_{1A} ends at $8/5$ to ensure that passenger quantities are non-negative. The figure illustrates that airport A has no reason to deviate from pricing policies in a sequential game structure under these conditions. This is true independent of whether it is smaller or larger than airport B.

Figure 6 displays the local welfare of airport A under slot policies (solid line) and pricing policies (dashed line) depending on the market size measured by the maximum reservation price α_{1A} and given that airport B chooses slot policies. Parameter α_{1A} starts at $2/5$ to ensure that passenger quantities are non-negative. The figure illustrates that airport A has no reason to deviate from pricing policies in a sequential game structure also under these conditions. This is true independent of

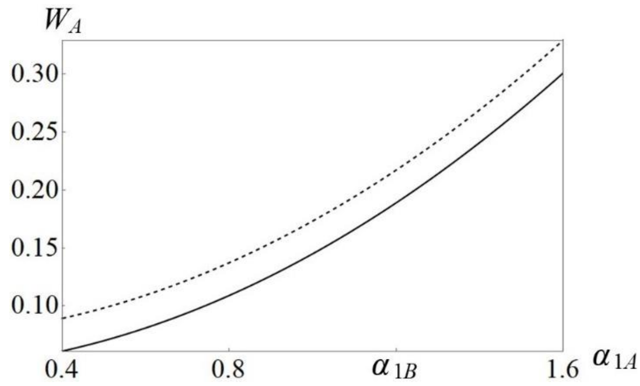

Figure 6: Equilibrium welfare of airport A under slot policies (solid line) and pricing policies (dashed line) depending on the maximum reservation price α_{1A} when airport B chooses slot policies and airport profits matter. Parameters: $\alpha_{1B} = 6/5$, $\alpha_2 = 3/5$, $\beta_1 = 5$ and $\beta_2 = 4$.

whether it is smaller or larger than airport B. ■

Altogether, this indicates that the equilibrium airport policies derived above for the cases of one-shot games are robust against changes in the timing of airport decisions. While congestion effects have been abstracted away in this sub subchapter, numerical simulations indicated that this robustness is also given in the presence of congested airports.

2.7 Summary

The present chapter started with a consideration of a two-airport network. The analysis showed that the equivalence between price- and quantity-based airport policies that exists in the case of a single airport (and deterministic demands) breaks down when airports individually maximize their local objective functions. The latter involves scenarios where airport profits do not matter or where airport profits matter. One way to see this, is to observe the existence of a unique equilibrium in the case of pricing policies (which does not achieve the set of first-best passenger quantities), and the absence of a unique equilibrium in slot quantities (where the set of equilibrium constellations includes the set of first-best passenger quantities).

To concentrate on scenarios where unique equilibria in slot and pricing strategies exist, a three-airport network with two active airports and one inactive dummy airport was considered. This follows a common approach in the literature where the presence of such a dummy airport is often implicitly assumed (while the present study applied a more transparent approach where the presence of a dummy airport is an explicit part of the set of modeling assumptions). The presence of the dummy airport allowed for the consideration of a more realistic airport network where only a subset of the airports may be slot controlled and the consideration of unique best responses in slot quantities and the description of a unique equilibrium in slot quantities.

Networks of uncongested and congested airports were considered. The comparison between passenger quantities implied by equilibrium pricing policies lead to too low passenger quantities relative to the first-best passenger quantities independent of whether uncongested or congested airports are considered. This is because airports raise airport charges to exploit non-local passengers when airport profits matter. By contrast, equilibrium slot quantities reproduce the first-best passenger quantities in the case of uncongested airports, while they lead to excessive passenger quantities in the case of congested airports. This is because airports ignore the delay reductions for non-local passengers in their choices of slot quantities. Numerical examples were used to show that slot policies can be beneficial relative to pricing policies when time valuations are low enough, while pricing policies can be beneficial relative to slots when time valuations are high enough.

The analysis formally captures that a move from pricing to slot policies can involve two effects: first, a so called variable effect that arises from the change in variables in the sense that quantities not prices are the decision variables; second, a so called distribution effect that arises from the change in airport revenues, which captures the notion of grandfather rules that make it difficult for the airports to internalize the slot values as measured by their slot prices (shadow prices). To formally separate variable and distribution effects, a third policy regime was introduced that involves prices as decision variables and given airport profits of zero. Numerical examples were used to illustrate how time valuations affect the variable and distribution effects and how an increase in time valuations increases the total welfare achieved under equilibrium pricing policies relative to the total welfare achieved under equilibrium slot policies.

Model extensions captured the presence of atomistic airline markets and a sequential game structure where airports decide upon slot and pricing policies in the first stage and upon the specific slot quantities and prices in the second stage. The analysis of these extensions showed that appropriate assumptions can ensure that the main results are independent of whether vertically integrated or vertically separated airport and (atomistic) airline markets are considered. But they also show that vertical separation adds complexity to the analysis.

CHAPTER 3

THE ROLE OF LOCAL AND NON-LOCAL PASSENGERS

This chapter develops a stylized but rich enough model to analyze the role of the shares of local and non-local passengers (simply called locals and non-locals) for the assessment of local welfare-maximizing airport congestion policies by comparing the local welfare-maximizing solutions with the first-best outcome. To capture the presence of non-locals, it is sufficient to consider a network with only two airports. Furthermore, to analyze the role of non-locals for congestion policies, it is sufficient to assume that only one of the two airports is congested.

The congested airport can use slot or pricing policies to mitigate the congestion problem for locals by choosing the slot quantity or the airport charge, respectively. In the case of slot policy, the airport does not earn from selling slots. This captures the notion of grandfather rules established by the Worldwide Scheduling Guidelines of the IATA. Efficient rationing is assumed to hold in the sense that slots are allocated to passengers with the highest willingness to pay. This implies a conservative assessment of pricing policies because the efficient allocation of slots among airlines cannot be guaranteed in reality (Czerny and Lang, 2019). In the case of pricing policy, the airport generates a positive profit from locals and non-locals. However, whereas the positive profit derived from non-locals matters to the local welfare-maximizing airport, the consumer surplus from non-locals is ignored by the local welfare-maximizing airport.

The main part of the analysis is based on the consideration of general functional forms. The analysis shows that the local welfare-maximizing slot quantity can coincide with the first-best outcome whereas this is impossible in the case of pricing policy. The main result is to show that whether the outcomes coincide in the case of slot policy depends on the relationship between two types of shares of locals and non-locals. The first type represents the shares of locals and non-locals relative to the total number of passengers, which we call the shares of inframarginal locals and non-locals, respectively. The second type is related to the effect of a marginal increase in the slot quantity on the quantities of locals and non-locals, which we call the shares of marginal locals and non-locals, respectively. More specifically, the second type of shares is equal to the increase in locals and non-locals relative to the increase in the total passenger quantity, or equivalently, the increase in the slot quantity.

Using these concepts, the analysis shows that the first-best outcome coincides with the local welfare-maximizing slot policy if the implied shares of inframarginal locals and non-locals are equal to the implied shares of marginal locals and non-locals, respectively. The intuition is developed with the help of cost-benefit ratios associated with a marginal increase in the slot quantity. The cost-benefit ratios are measured by the marginal external congestion cost divided by the (slot) price. If the shares of inframarginal and marginal locals and non-locals implied by the local welfare maximum are equal, then the cost-benefit ratios associated with a marginal increase in the slot quantity are equal from the local and the first-best viewpoints. It is shown that the intuition based on cost-benefit ratios carries over to the more complicated case with multiple congested airports. Linear functional forms are used to further illustrate the role of locals and non-locals for the policy comparison and derive analytical solutions.

The chapter is organized as follows. The model will be presented in Subchapter 3.1. Subchapter 3.2 analyzes airport policies based on general functional forms. More specifically, the role of locals and non-locals and the concepts of the shares of inframarginal and marginal locals and non-locals will be discussed in detail in this sub chapter. The difference between the exclusive and inclusive airline services is discussed in Subchapter 3.3 to shed lights on how the share of passengers served by the local airlines affects the assessment of local welfare-maximizing policies. In Subchapter 3.4, linear functional forms are used to illustrate the relationship between the cost-benefit ratios of a marginal increase in the slot quantity from the local and the first-best viewpoints. Subchapter 3.5 concludes this chapter.

3.1 The Model

There are two airports. One airport is congested in the sense that the physical capacity is low relative to the passenger or flight volume so that airline delays occur. The other airport is uncongested in the sense that the physical airport capacity is large enough to serve flights and passengers without any delay. This uncongested airport could represent an arbitrary number of uncongested airports (Brueckner, 2002). Locals from both airports fly between the two airports and take return flights. The following concentrates on policy decisions of the congested airport by referring to this airport as "the airport." The uncongested airport is a passive airport in the sense that it is uncongested, and the user costs of this airport are normalized to zero. This uncongested airport will be referred to as "the other airport."

The passenger quantity of locals is denoted as q_l and the quantity of non-locals is denoted as q_{nl}. Passenger quantities are non-negative, that is, $q_i \geq 0$ for $i = l, nl$. The strictly concave travelling benefits of airport i's passengers are denoted as $B_i(q_i)$ with $B_i''(q_i) < 0$. The total passenger quantity at the airport is denoted as Q with $Q = q_l + q_{nl}$.

This study assumes that local and non-local airlines exist, that airline markets are perfectly competitive, and that besides airport charges all other airline costs are normalized to zero. This basic model version further assumes that airlines offer exclusive services in the sense that locals only fly with their local airlines (a relaxed model with inclusive air services will be considered in Section 3.4). Airline load factors are assumed to be given by 100 percent, and aircraft sizes are fixed and normalized to one unit of passenger.[15] The latter implies that the number of flights is equal to the number passengers. Let the total passenger quantity Q determine the convex average passenger delay denoted as $T(Q)$ with $T'(Q) > 0$ and $T''(Q) \geq 0$. Because flight and passenger quantities are equal, the average delay function can represent delays caused by flights due to limited runway capacity and delays caused by passengers due to limited terminal capacity. The passengers' time valuations are denoted as v.

The airport can choose between two policy measures, which are slot policy, denoted as S, and pricing policy, denoted as P. Let ϕ with $\phi = S, P$ denote the policy variable. In the case of slot policy $\phi = S$, the airport sets an upper limit on the number of flights, which is equal to the number of passengers, at the airport. For convenience, this study considers the upper limit on the number of passengers denoted as $\bar{Q}$ and called the slot quantity. In the case of pricing policy $\phi = P$, the airport charges the local and non-local airlines a non-discriminatory per-passenger airport charge denoted as R with $R = R(\phi) \geq 0$.[16] In the case of slot policy and to capture the notion of grandfather rights, the airport charge is assumed to be zero, that is, $R(S) = 0$. This means the airport cannot earn from selling slots leading to zero airport revenue in the case of slot policy. This is an important feature of the present model because it captures the IATA's Worldwide Scheduling Guidelines imposing that airport slot allocation is based on historic precedence. The airports' costs are all normalized to zero. Together with the assumption of a non-negative airport charge, this means that airport cost recovery is always ensured.

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[15] Endogenous load factors and aircraft sizes have recently been considered Czerny, van den Berg and Verhoef (2016).

[16] Price discrimination violates the rules of the world trade organization (WTO) for free transit. Detailed regulations can be found in Article 5 of GATT 1994.

The ticket price is denoted as r with $r = r(\phi) \geq 0$. In the case of slot policy, airlines can generate positive profits because slots are provided for free whereas the ticket price is positive, that is, $r(S) \geq 0 = R(S)$. In the case of pricing policy, airlines generate zero profits because they have to pay the airport charge, which is exactly equal to the ticket price because of perfect competition, that is, $r(P) = R(P) \geq 0$. In this scenario, all the producer surplus is internalized by the airport.

Efficient rationing ensures that passengers with the highest willingness to pay are served first. This can be guaranteed under pricing policy and is assumed to be guaranteed in this study also in the case of slot policy. However, the current slot allocation practice based on grandfather rights cannot guarantee efficient rationing under slots.[17] Therefore, this study provides a conservative assessment of pricing policy relative to slot policy.

The model compares the local welfare-maximizing outcomes where airports are assumed to attach a unit weight to both local consumer surplus and the profits of their local airlines under slot and pricing policies with the first-best outcome. Czerny and Lang (2019) demonstrated that the consideration of slot and pricing policies can be justified in the sense that slot policy is relevant when airport profits do not matter for local governments whereas pricing policy is relevant when airport profits matter.

3.2 Policy assessment based on general functional forms

This subchapter starts with a discussion of passenger demands and how they relate to the slot quantity and the ticket price. This step provides crucial insights that will be used for the assessment of slot and pricing policies. The section continues with a discussion of the optimal slot and pricing policies from the local airport's viewpoint

[17] Efficient rationing under slots can be achieved by allowing carriers to trade their slots (Brueckner, 2009).

and compares them with the first-best outcome. Special attention will be given to the role of locals and non-locals for the results.

3.2.1 Demand relationships

The generalized price of traveling, denoted as η, is given by

$$\eta = r + vT(Q). \tag{40}$$

The right-hand is the sum of the ticket price r and the average congestion costs $vT(Q)$. Passengers consider the generalized price as given. Demands for locals and non-locals depending on r are denoted as $D_l(r)$ and $D_{nl}(r)$ respectively. They are determined by the conditions

$$B_l'(q_l) = B_{nl}'(q_{nl}) = \eta. \tag{41}$$

Passengers will travel if their marginal benefit from travelling is at least as high as the generalized price. Applying Cramer's rule to the system of equations in (41) yields:

Lemma 7 *The effect of a marginal increase in r on demands can be characterized as*

$$D_l'(r), D_{nl}'(r) < 0. \tag{42}$$

This lemma shows that both locals and non-locals' demands are decreasing in the price. This implies that the total demand is also decreasing in the ticket price.

The welfare assessment of slot policy requires an understanding of the relationship between the slot quantity $\bar{Q}$ and the demands D_l and D_{nl}. Here and hereafter, it is assumed that the slot constraint is always binding.[18] Let $D(r)$ denote the sum of the locals' and non-locals' demands depending on r with $D(r) = D_l(r) + D_{nl}(r)$. By Lemma 7, $D'(r) < 0$. The ticket price $r(S)$ in the case of slot policy is implicitly determined by

[18] Airports may not always operate at full capacity. Gillen, Jacquillat and Odoni (2016) pointed out that meteorological and other stochastic factors may contradict the current assumption.

$$\bar{Q} - D(r) = 0. \tag{43}$$

Let $r(\bar{Q})$ denote the ticket price depending on the slot quantity. Totally differentiating (43) yields:

Lemma 8 *The ticket price is decreasing in the slot quantity, that is,*

$$r'(\bar{Q}) < 0 \tag{44}$$

By Lemma 7, an increase in the slot quantity is associated with a reduction in the ticket price to ensure that the passenger demand is equal to the slot quantity. Substituting $r(\bar{Q})$ for r in demands $D_l(r)$ and $D_{nl}(r)$ yields the demands depending on the slot quantity, that is, $D_l(r(\bar{Q})) = D_l(\bar{Q})$ and $D_{nl}(r(\bar{Q})) = D_{nl}(\bar{Q})$, leading to $D(r(\bar{Q})) = D(\bar{Q}) = \bar{Q}$. Using Lemma 7 and Lemma 8, the relationships between the slot quantity and demands can be described in the following way:

Lemma 9 *The effect of a marginal increase in slot quantity $\bar{Q}$ on demands can be characterized as*

$$0 < D_l'(\bar{Q}), D_{nl}'(\bar{Q}) < D'(\bar{Q}) = 1. \tag{45}$$

This lemma first shows that the demands of locals and non-locals, and thus the total demand, are increasing in the slot quantity. It second shows that an increase in the slot quantity increases the total demand by an equal amount (a natural result).

For the comparison of the local welfare-maximizing price with the first-best price, it is useful to characterize the relationship between the ticket price r and the generalize price η. Using (40) and substituting Q by $D(r)$, the generalized price depending on r can be written as $\eta(r) = r + vT(D(r))$. Taking the derivative of the right-hand side with respect to r and rearranging yield:

Lemma 10 *The effect of a marginal increase in the ticket price r on the generalized price η can be characterized as*

$$0 < \eta'(r) < 1. \tag{46}$$

This lemma shows that an increase in r leads to an increase in the generalized price that is smaller than the increase in r. This is related to the structure of the generalized price. Equation (40) shows that the generalized price is the sum of the price r and the congestion cost $vT(Q)$. An increase in the price directly increases the generalized price because it is part of the generalized price. However, by Lemma 7, it also leads to a reduction in the total passenger quantity, thus reducing the generalized price because it reduces congestion and average congestion cost. This explains the inequality $\eta'(r) < 1$.

3.2.2 Slots vs pricing policy

The consumer surpluses of locals and non-locals, denoted as CS_i for $i = l, nl$, are equal to the differences between the benefits and the sum of ticket price payments and delays costs, which can be written as

$$CS_i(q_i) = B_i(q_i) - q_i \cdot \eta. \tag{47}$$

The first term on the right-hand side is the benefit of passengers. The second term is the passengers' total costs for travelling, including the total payment to their local airlines and the total delay costs.

The welfares of the airport and the other airport are denoted as W_i for $i = l, nl$. The airport's welfare W_l is equal to the sum of the locals' consumer surplus and the joint profit of the local airlines and the airport (that is, $q_l \cdot r(\phi) + q_{nl} \cdot R(\phi)$), which can be simplified and written as

$$W_l(q_l, q_{nl}) = B_l(q_l) + q_{nl} \cdot R(\phi) - q_l \cdot vT(Q). \tag{48}$$

The first term on the right-hand side is the benefit of locals. The second term is the airport profit derived from non-locals. The third term represents the total delays costs of locals. Comparing the airport's welfare in (48) with the consumer surplus of locals in (47), the difference is the second term. It captures that in the case of pricing policy $\phi = P$, there will be extra profit from charging non-locals. The extra profit, however, would be absent in the case of slot policy $\phi = S$ because $R(S) = 0$ by assumption.

The other airport's welfare can be written as

$$W_{nl}(q_l, q_{nl}) = B_{nl}(q_{nl}) - q_{nl} \cdot R(\phi) - q_{nl} \cdot vT(Q). \tag{49}$$

The first term on the right-hand side is the benefit of non-locals. The second term is the total payment to the airport, which is zero in the case of slot policy because $R(S) = 0$ by assumption. The third term represents the total delay costs of non-locals.

3.2.2.1 First-best outcome as a benchmark

The assessment of the congestion policies is based on a comparison of the local welfare-maximizing solutions under slot and pricing policies with the first-best outcome. The total welfare generated by the two airports, denoted as W with $W = W_l + W_{nl}$, is given by the difference between the sum of benefits and the sum of delays costs, which can be written as

$$W(q_l, q_{nl}) = B_l(q_l) + B_{nl}(q_{nl}) - QvT(Q). \tag{50}$$

Let the first-best solution be indicated by a double asterisk "**". The first-best passenger quantities are determined by the first-order condition, $\partial W / \partial q_i^{**} = 0$, which can be written as

$$B_i'(q_i^{**}) - \left(vT(Q^{**}) + Q^{**} \cdot vT'(Q^{**})\right) = 0.\text{[19]} \tag{51}$$

The first term on the left-hand side is the marginal benefit of either locals or non-locals. The sum of the two terms inside the parentheses is equal to the marginal congestion cost. The first-best outcome is achieved when the marginal benefits are equal to the

[19] The concavity of the benefit functions together with the convexity of the delay function imply that the Hessian of $W(q_l, q_{nl})$ in (50) is negative definite. Therefore, there exists a unique solution for the welfare-maximizing quantities of locals and non-locals.

marginal congestion costs.

Consider a laissez faire situation in which there are no slot controls and the airport charge is equal to zero. In this scenario, the generalized price is equal to the average congestion cost $vT(Q^{**})$, which is equal to first part of the marginal congestion costs in the parentheses. The second term, $Q^{**} \cdot vT'(Q^{**})$, describes the congestion cost that passengers impose on others when they travel. This part is not included in the generalized price in this scenario and, therefore, external. Passengers will make excessive use of the congested airport because of the existence of the marginal external congestion costs. Both slot and pricing policies can be used to implement the first-best outcome by adjusting the generalized price via the ticket price that is associated with the slot quantity or the airport charge.

In the case of slot policy, $\phi = S$, the first-best outcome can be achieved by setting the slot quantity $\bar{Q}$ equal to the first-best passenger quantity $\bar{Q}^{**}$. This leads to a first-best ticket price, $r^{**}(S)$, that equals the marginal external congestion costs, that is,

$$r^{**}(S) = \bar{Q}^{**} \cdot vT'(\bar{Q}^{**}). \tag{52}$$

In the case of pricing policy, $\phi = P$, the first-best outcome can be achieved by directly setting a first-best airport charge, $r^{**}(P)$, equal to the marginal external congestion costs, that is,

$$r^{**}(P) = D(r^{**}) \cdot vT'(D(r^{**})). \tag{53}$$

Together with equations (40) and (41), the first-best ticket price in (52) and the first-best airport charge in (53) imply that the first-best outcome is achieved by these policies because they ensure that the marginal benefits of locals and non-locals are equal to the marginal congestion costs in these situations. This shows that both policies will indeed achieve the first-best outcome. The following analyzes the decentralized decision making of the congested airport and compares the local welfare-maximizing solutions with the first-best outcome.

3.2.2.2 Local welfare-maximizing slot policy

Consider $\phi = S$. Plugging the demands of locals and non-locals depending on the slot quantity into the welfare function in (48) yields the local welfare depending on the slot quantity, that is, $W_l(\bar{Q}) = W_l(D_l(\bar{Q}), D_{nl}(\bar{Q}))$. Let the local welfare-maximizing solution be indicated by a single asterisk "*". Assume that the local welfare-maximizing slot quantity, is determined by the first-order condition, $W_l'(\bar{Q}^*) = 0$, which can be written as

$$\left(B_l'(D_l(\bar{Q}^*)) - vT(\bar{Q}^*)\right) \cdot D_l'(\bar{Q}^*) - D_l(\bar{Q}^*) \cdot vT'(\bar{Q}^*) = 0. \tag{54}$$

The first term on the left-hand side is the product of, $B_l'(D_l(\bar{Q}^*)) - vT(\bar{Q}^*)$, which is equal to the local welfare-maximizing ticket price, $r^*(S)$, by equations (40) and (41), and the derivative, $D_l'(\bar{Q}^*)$. By Lemma 9, $D_l'(\bar{Q}^*)$ takes a value between 0 and 1 and describes a share of locals, in which the share captures the increase in the quantity of locals associated with a marginal increase in the slot quantity. The second term captures the marginal external congestion cost of locals. Altogether, the local welfare-maximizing slot quantity ensures that the marginal increase in the benefit of locals as measured by the weighted ticket price, $r^*(S) \cdot D_l'(\bar{Q}^*)$, is equal to the locals' marginal external congestion cost.

Using the conditions in (41) and $D_l'(\bar{Q}^*) + D_{nl}'(\bar{Q}^*) = D'(\bar{Q}^*) = 1$, the left-hand side of (54) can be rewritten as

$$r^*(S) \cdot D_l'(\bar{Q}^*) - D_l(\bar{Q}^*) \cdot vT'(\bar{Q}^*) \cdot \left(D_l'(\bar{Q}^*) + D_{nl}'(\bar{Q}^*)\right) = 0. \tag{55}$$

Solving the first-order condition for the local welfare-maximizing slot quantity by dividing $D_l'(\bar{Q}^*)$ and rearranging (55) yields the local welfare-maximizing ticket price in the case of slot policy, which can be written as

$$r^*(S) = D_l(\bar{Q}^*) \cdot vT'(\bar{Q}^*) + \frac{D'_{nl}(\bar{Q}^*)}{D'_l(\bar{Q}^*)} \cdot D_l(\bar{Q}^*) \cdot vT'(\bar{Q}^*). \tag{56}$$

The first term on the right-hand side is the marginal external congestion cost of locals. The second term is a weighted marginal external congestion cost of locals. Lemma 9 mentions that $D'_l(\bar{Q}^*),\ D'_{nl}(\bar{Q}^*) > 0$, which implies that the weight in the second term, $D'_{nl}(\bar{Q}^*) / D'_l(\bar{Q}^*)$, is positive. Therefore, the local welfare-maximizing slot quantity leads to an over internalization of the locals' part of the marginal external congestion cost because $r^*(S) > D_l(\bar{Q}^*) \cdot vT'(\bar{Q}^*)$. The intuition can be described as follows.

In the presence of non-locals, they are taking up the airport's limited slot resources and, thus, benefit from the slot expansion. But they are not contributing to the congested airport's welfare. This reduces the local welfare-maximizing slot quantity relative to the case in which non-locals would be absent.

From the first-best viewpoint both locals and non-locals make excessive use of the congested airport capacity in the case of laissez faire. The local airport's incentives to reduce the slot quantity in the presence of non-locals may, therefore, be desirable from the first-best viewpoint. The following proposition highlights the main result of the paper. It describes the condition under which the local welfare-maximizing slot quantity implements the first-best outcome:

Proposition 14 *The consideration of general functional forms implies:*

(i) If in the local welfare-maximum the demand of locals and the total demand satisfies the equality

$$\frac{D_l(\bar{Q}^*)}{\bar{Q}^*} = D'_l(\bar{Q}^*), \tag{57}$$

then the local welfare-maximizing slot quantity equals the first-best slot quantity, that is, $\bar{Q}^* = \bar{Q}^{**}$*;*

(ii) if the left-hand side exceeds the right-hand side, then the local welfare-maximizing slot quantity is too low relative to the first-best slot quantity, that is, $\bar{Q}^{*} < \bar{Q}^{**}$ *; and*

(iii) if the left-hand side is smaller than the right-hand side, then the local welfare-maximizing slot quantity is too high relative to the first-best slot quantity, that is, $\bar{Q}^{*} > \bar{Q}^{**}$.

The left-hand side of (57) shows the share of the locals' passenger quantity relative to the total passenger quantity, which we call the *share of inframarginal locals*. The right-hand side shows the increase in locals associated with a marginal increase in the slot quantity, which we call the *share of marginal locals*. If the local welfare-maximizing solution implies that these two shares are equal, then the local welfare-maximizing solution leads to the first best outcome.

For an intuition, expand (57) by multiplying both sides with $vT'(\bar{Q}^{*})/r^{*}(S)$ and rearrange, which yields

$$\frac{\bar{Q}^{*}\cdot vT'(\bar{Q}^{*})}{r^{*}(S)} = \frac{D_l(\bar{Q}^{*})\cdot vT'(\bar{Q}^{*})}{D_l'(\bar{Q}^{*})\cdot r^{*}(S)}. \tag{58}$$

Both the locals' and non-locals' marginal benefits and marginal external congestion costs are increasing in the slot quantity. The left-hand side shows the cost-benefit ratio of a marginal increase in the slot quantity in terms of the marginal external congestion cost and the ticket price from the first-best viewpoint. The right-hand side shows the cost-benefit ratio of a marginal increase in the slot quantity in terms of the marginal external congestion cost and the ticket price from the airport's viewpoint (which is equal to one in the local-welfare maximum). If these cost-benefit ratios are equal in the local welfare-maximum, which is true if the shares of inframarginal and marginal locals are equal in the local welfare-maximum as mentioned in (57), then the local welfare-maximizing solution coincides with the first-best outcome.

If a marginal increase in the slot quantity leads to a higher cost-benefit ratio of the airport relative to the first-best viewpoint, then the airport is too reluctant to increase slot quantity. In local welfare-maximum, slot policy becomes too strict in the sense that slot quantity is too low relative to the first-best outcome. If a marginal increase in the slot quantity leads to a lower cost-benefit ratio of the airport relative to the first-best viewpoint, then the airport is too inclined to increase slot quantity. In local welfare-maximum, slot policy becomes too loose in the sense that slot quantity is too high relative to the first-best outcome.

The shares of inframarginal and marginal locals can be used to inform policy makers in real world practice. The share of inframarginal locals can be identified by dividing, say, the yearly number of locals by the yearly total number of passengers given by the sum of locals and non-locals. The corresponding share of marginal locals can be identified by considering the changes in passenger quantities associated with an increase in the slot quantity. More specifically, this share can be estimated by dividing the increase in the yearly number of locals associated with an increase in the slot quantity by the increase in the yearly total number of passengers associated with an increase in the slot quantity. The relationship between the two estimates can then be used to assess the incentives of a local welfare-maximizing airport from the first-best viewpoint. For instance, if the estimated share of inframarginal locals is higher than the share of marginal locals, then the airport's incentives to expand the slot quantity should be too high from the first-best viewpoint whereas the airport's incentives to increase the slot quantity should be too low from the first-best viewpoint in the reverse case.

3.2.2.3 Local welfare-maximizing pricing policy

Consider $\phi = P$. Substituting the demands of locals and non-locals depending on the price into the welfare function in (48) yields the local welfare depending on the airport charge, that is, $W_l(r) = W_l(D_l(r), D_{nl}(r))$. Assume that the local welfare-maximizing ticket price, $r^*(P)$, is determined by the first-order condition, $W_l'(r^*) = 0$, which can be written as

$$\left(B_l'(D_l(r^*)) - vT(D(r^*))\right) \cdot D'(r^*) - D_l(r^*) \cdot vT'(D(r^*)) \cdot D'(r^*) + D_{nl}(r^*) = 0. \qquad (59)$$

The first and the second terms on the left-hand side capture the benefits and marginal external congestion cost of locals, respectively. The third term on the left-hand side captures the revenue gain from non-locals. Substituting $\left(B_l'(D_l(r^*)) - vT(D(r^*))\right)$ in the parentheses by the airport charge $r^*(P)$ in the local welfare-maximum and solving for the airport charge yield

$$r^*(P) = D(r^*) \cdot vT'(D(r^*)) + \left|\frac{D(r^*)}{D'(r^*)}\right| \cdot \frac{D_{nl}(r^*)}{D(r^*)} \cdot \eta'(r^*). \qquad (60)$$

The first term on the right-hand side is the marginal external congestion cost of all passengers, which is also the first-best price in (53). The second term is a positive markup, which is determined by the semi-price elasticity of demand, $D(r^*)$, with respect to the airport charge weighted by the share of non-locals and the marginal effect of a change in the airport charge on the generalized price. The semi-price elasticity, $\left|D(r^*) / D'(r^*)\right|$, represents the optimal charge in the case of profit maximization. The notion of profit maximization only applies to non-locals when the airport maximizes local welfare, which is why the elasticity measure includes a weight that captures the share of (inframarginal) non-locals. However, the non-locals not only contribute to the airport's profit but also to congestion. Therefore, the marginal change in the generalized price is added as another weight. Altogether, this implies that

Proposition 15 *The local welfare-maximizing airport charge never reaches the first-best outcome in the sense that* $r^*(P) > r^{**}(P)$.

In the absence of non-locals, the markup is zero in (60). Thus, the local welfare-maximizing airport charge equals the first-best price. This implies that the airport's incentive to exploit the non-locals by charging a positive markup on the marginal external congestion cost of locals eliminates the possibility that pricing policy can achieve the first-best outcome.

3.2.2.4 A congestion game in an airport network

The present model considers the role of locals and non-locals and evaluates the local policies in the context of one (active) congested airport and one (passive) uncongested airport. Insights are developed about the role of locals and non-locals, their shares in terms of inframarginal and marginal passengers and how they affect cost-benefit ratios. This part shows that these insights are robust in the sense that they carry over to cases with more complex airport networks in which several local airport authorities choose congestion policies in a decentralized fashion, such as the three-airport network in the previous chapter.

Consider the left-hand side of equation (57), which shows the share of inframarginal locals. The value of the left-hand side that corresponds to the framework of three-airport network in Chapter 2 can be written as $\left(D_{ij}+D_{iC}\right)/D_i$. Consider the right-hand side of equation (57), which shows the share of marginal locals. In a first step, the value of the right-hand side that corresponds to the framework of three-airport network in Chapter 2 would be considered to be equal to the share of marginal locals $\partial D_{ij}/\partial\overline{Q}_i+\partial D_{iC}/\partial\overline{Q}_i$. However, remember that it is the cost-benefit ratios that ultimately matter.

A crucial difference between the present framework and the framework of three-airport network in Chapter 2 is that locals who travelled between airports A and B had to pay two generalized prices because both airports were congested. Therefore, their marginal benefit of locals who travelled between the congested airports was twice as high as the marginal benefit of locals who travelled between airports i and C who utilized only one congested airport. The locals who travelled between the congested airports thus count twice to capture the difference in marginal benefits. The right-hand side in (57), therefore, correctly translates into $2\partial D_{ij} / \partial \overline{Q}_i + \partial D_{iC} / \partial \overline{Q}_i$ in the framework of three-airport network in Chapter 2. By Lemma 4, the effect of a marginal increase in the local price, or equivalently a marginal reduction in local slot quantity, on passengers who travelled between the congested airport was independent of their origins in the sense that $\partial D_{ij} / \partial \overline{Q}_i = \partial D_{ji} / \partial \overline{Q}_i$. Using this equality, $2\partial D_{ij} / \partial \overline{Q}_i + \partial D_{iC} / \partial \overline{Q}_i$ can be simplified as $\partial D_i / \partial \overline{Q}_i = 1$. But, this implies that the equality (57) can never be satisfied in the framework of three-airport network in Chapter 2 because $\left(D_{ij} + D_{iC} \right) / D_i < 1$. Altogether, the cost-benefit ratio associated with a marginal increase in the local slot quantity is always lower from the local viewpoint relative to the first-best viewpoint. Therefore, the local welfare-maximizing slot quantity will be too high relative to the first-best outcome as was shown in Proposition 9.

The local welfare-maximizing slot quantity can be first-best in the framework with one congested airport whereas this is not possible in the framework of three-airport network in Chapter 2. In this sense, the assessment of slot policies depends on the airport networks under consideration. The result that pricing policies lead to excessive pricing from the first-best viewpoint is, however, more robust in the sense it is true both in the present framework and the framework of three-airport network in Chapter 2. This is because local airports have the incentives to exploit the non-locals by charging a positive markup on the first-best price independent of the airport networks under consideration.

3.3 Exclusive versus inclusive air service

The model has been focusing on exclusive air services where local airlines only serve their locals. This subsection discusses a relaxed environment with inclusive air services in the sense that airlines can serve both locals and non-locals. Consider the region of the congested airport. Let θ_l denote the share of locals served by local airlines and θ_{nl} the share of non-locals served by local airlines. Previously, it was assumed that $\theta_l = 1$ and $\theta_{nl} = 0.$ In this section, this assumption is relaxed in the sense that the two shares can take any value between 0 and 1, that is, $0 \le \theta_i \le 1$ for $i = l, nl$. With this notation, the number of the local airlines' passengers is given by $\theta_l q_l + \theta_{nl} q_{nl}$, and the airport's welfare can be written as

$$W_l = CS_l + R(\phi) \cdot Q + \left(r(\phi) - R(\phi)\right) \cdot \left(\theta_l q_l + \theta_{nl} q_{nl}\right). \tag{61}$$

The first term on the right-hand side is the locals' consumer surplus. The second term is the airport profit. The third term is the local airlines' profit from both locals and non-locals.

In the case of pricing policy $\phi = P,\ r(P) = R(P)$. This implies that the third term on the right-hand side of (61), which is the local airlines' profit, is zero. The airport's welfare is equal to the sum of the locals' consumer surplus and the airport profit, which is identical to the airport's welfare in (48). Therefore,

Proposition 16 *The local welfare-maximizing pricing policies are independent of whether air services are exclusive or inclusive in the sense that the local welfare-maximizing airport charge is given by* $r^*(P)$ *in* (60) for all $\theta_l, \theta_{nl} \in [0,1]$.

In the case of pricing policy, perfectly competitive airline markets imply zero airline profits. Therefore, airlines do not contribute to local welfares and, hence, it is of no importance for the local welfare-maximizer whether airlines serve locals or non-locals.

The picture changes in the case of slot policy in which $\phi = S$ and $R(S) = 0$. In this scenario, the second term on the right-hand side of (61) representing the airport's profit is equal to zero whereas the third term representing the local airlines' profit is positive. It is useful to recognize that what matters from the airport's viewpoint is the total number of passengers served by local airlines, not the shares of locals and non-locals. This is because this allows substituting the total number of flights $\theta_l q_l + \theta_{nl} q_{nl}$ by θQ where θ represents the market share of local airlines. In the case of exclusive air services, the total number of passengers is equal to the total number of locals, that is, $\theta Q = q_l$. In the case of inclusive air services, the total number of flights may or may not be equal to the total number of locals, which is dependent on θ.

Consider the market share of local airlines, θ, as exogenously given.[20] Substituting $\theta_l q_l + \theta_{nl} q_{nl}$ by θQ and Q by $\bar{Q}$ in (61) yields the airport's welfare depending on the market share of the local airlines θ and slot quantity $\bar{Q}$, which can be written as

$$W_l = CS_l + r(S) \cdot \theta \bar{Q}. \tag{62}$$

Assume that the local welfare-maximizing slot quantity is determined by the first-order condition $W_l'(\bar{Q}^*) = 0$, which can be written as

$$-\eta'(\bar{Q}^*) \cdot D_l(\bar{Q}^*) + r(\bar{Q}^*) \cdot \theta + r'(\bar{Q}^*) \cdot \theta \bar{Q}^* = 0. \tag{63}$$

The first term on the left-hand side captures the consumer surplus gain of locals associated with an increase in the slot quantity. This term is (the absolute value of) the product of the marginal change in the generalized price associated with an increase in the slot quantity and the locals' demand. Lemma 8 shows that $r'(\bar{Q}) < 0$ and Lemma

[20] In the case of exclusive air services, the airline market share can be considered as given only if the shares of inframarginal and marginal locals are equal.

10 shows that $0 < \eta'(r) < 1$. Together this implies that $\eta'(\bar{Q}^*) < 0$ because $\eta'(\bar{Q}^*) = \eta'(r) \cdot r'(\bar{Q}^*)$, which means that an increase in the slot quantity increases consumer surplus. The second term captures the local airlines' gain in revenue associated with the increase in the slot and passenger quantity. Lemma 8 shows that $r'(\bar{Q}) < 0$. Therefore, the third term captures the local airlines' loss in revenue from the decrease in the ticket price. Altogether, the local welfare-maximizing slot quantity optimally balances consumer surplus and airline profit effects for the local economy.

Totally differentiating the first-order condition in (63) with respect to $\bar{Q}$ and θ yields:

Lemma 11 *In the case of inclusive air services, for a given market share of the local airlines, θ, and given that the local welfare-maximizing slot quantity is determined by the first-order condition in* (63), *the local welfare-maximizing slot quantity is decreasing in θ, that is,* $\frac{\partial \bar{Q}^*}{\partial \theta} < 0$.

If θ decreases, then local airlines generate less profit and, therefore, the local airlines' profit becomes less significant relative to the locals' consumer surplus to the airport. The lemma shows that in this scenario, the airport has the incentive to increase the slot quantity to allow more locals to travel because the locals' consumer surplus is increasing in the slot quantity as implied by Lemma 9. This relationship exists if the local welfare-maximizing slot quantity is determined by the first-order condition in (63), which does not always need to be true.

If θ is small enough, the local welfare-maximizing slot quantity is so high that the non-negativity constraint associated with the ticket price becomes binding. Consider the extreme case in which θ is equal to zero. In this case, the local welfare is equal to the local consumer surplus which is strictly increasing in the passenger quantity implying a binding non-negativity constraint for the ticket price. In the case of a binding non-negativity constraint, the local welfare-maximizing slot quantity is not unique because any high enough slot quantity can imply a zero ticket price and, therefore, be optimal.

Consider the extreme case in which the local airlines serve all passengers, that is, θ=1. In this case, the airport's welfare is independent of the policy choice because the airport can earn from all passengers by either the airport charge under pricing policy or the local airlines' ticket price under slot policy. This implies that the local welfare-maximizing slot quantity is given by a local welfare-maximizing ticket price that is equal to the local welfare-maximizing airport charge in the case of pricing policy, that is, $r^*(S) = r^*(P)$ when $\theta = 1$ where $r^*(P)$ is given by (60). Together with Lemma 8 and Lemma 11, this implies:

Proposition 17 *In the case of inclusive air services and slot policy, there exists an upper bound for the local welfare-maximizing ticket price* $r^*(S)$ *that is equal to* $r^*(P)$ *given by (60).*

3.4 Slot policy: the case of linear functional forms

This section considers linear functional forms and concentrates on the ambiguous relationships between the local welfare-maximizing slot quantity and the first-best outcome. The discussion of pricing policy is omitted because it involves complex mathematical expressions but provides little insight to justify the mentioning given that the consideration of general functional forms demonstrated that it unambiguously fails to implement the first-best outcome.

The benefits of travelling are given by the quadratic function

$$B_i(q_i) = \alpha_i \cdot q_i - \frac{1}{2}\beta_i \cdot q_i^2 \tag{64}$$

with $\alpha_i, \beta_i > 0$ and $i = l, nl$, where α_i are called the maximum reservation prices.

Average delays are given by $T(Q)$ with $T(Q)=Q$. Demands $D_l(r)$ and $D_{nl}(r)$ are determined by the demand equilibrium conditions $B_i'(q_i)=r+vT(Q)$. Simultaneously solving these conditions yields the demands of locals and non-locals depending on the price r, which can be written as

$$D_i(r)=\frac{\alpha_i\beta_j+\left(\alpha_i-\alpha_j\right)v-\beta_j\cdot r}{\beta_l\beta_{nl}+\left(\beta_l+\beta_{nl}\right)v}. \tag{65}$$

The right-hand side shows that demands are decreasing in price r.[21] Using the demands in (65), the total demand at the airport is given by

$$D(r)=\frac{\alpha_l\beta_{nl}+\alpha_{nl}\beta_l-\left(\beta_l+\beta_{nl}\right)\cdot r}{\beta_l\beta_{nl}+\left(\beta_l+\beta_{nl}\right)v}. \tag{66}$$

Substituting $D(r)$ on the left-hand side of (66) with slot quantity $\bar{Q}$ and solving yield the ticket price, which can be written as

$$r(\bar{Q})=\frac{\alpha_l\beta_{nl}+\alpha_{nl}\beta_l}{\beta_l+\beta_{nl}}-\frac{\beta_l\beta_{nl}+\left(\beta_l+\beta_{nl}\right)v}{\beta_l+\beta_{nl}}\cdot\bar{Q}. \tag{67}$$

The right-hand side shows that the ticket price $r(\bar{Q})$ is decreasing in the slot quantity $\bar{Q}$. Substituting price r on the right-hand side of (65) with the ticket price in (67) yields the demands depending on slot quantity, which can be written as

$$D_i(\bar{Q})=\frac{\alpha_i-\alpha_j+\beta_j\cdot\bar{Q}}{\beta_l+\beta_{nl}}. \tag{68}$$

The right-hand side shows that demands are increasing in slot quantity $\bar{Q}$.

Using $T'(Q)=1$, the first-best ticket price in (52) can be rewritten as $r^{**}(S)=v\cdot\bar{Q}^{**}$. Substituting the left-hand side in (67) by $r(\bar{Q})$ evaluated at the first-best slot quantity yields the condition

[21] It is a necessary condition that $\alpha_i>2v\left(\alpha_j-\alpha_i\right)/\beta_j$ to ensure that all demands are positive.

$$v \cdot \bar{Q}^{**} = \frac{\alpha_l \beta_{nl} + \alpha_{nl} \beta_l}{\beta_l + \beta_{nl}} - \frac{\beta_l \beta_{nl} + (\beta_l + \beta_{nl}) v}{\beta_l + \beta_{nl}} \cdot \bar{Q}^{**}. \tag{69}$$

Solving for the first-best slot quantity $\bar{Q}^{**}$ yields

$$\bar{Q}^{**} = \frac{\alpha_l \beta_{nl} + \alpha_{nl} \beta_l}{\beta_l \beta_{nl} + 2(\beta_l + \beta_{nl}) v}. \tag{70}$$[22]

The local welfare-maximizing slot quantity in the case of slot policy is determined by the first-order condition $W_l'(\bar{Q}^{*}) = 0$ and can be written as

$$\bar{Q}^{*} = \bar{Q}^{**} - (\alpha_l - \alpha_{nl}) \frac{(\beta_l + \beta_{nl}) v}{\beta_{nl} (\beta_l \beta_{nl} + 2(\beta_l + \beta_{nl}) v)} \tag{71}$$

The first term on the right-hand side is given by the first-best slot quantity. The second term is the product of the difference in maximum reservation prices, $(\alpha_l - \alpha_{nl})$ and a positive term, which implies the following relationships between local welfare-maximizing slot quantities and first-best passenger quantities:

Proposition 18 *The consideration of linear functional forms implies:*

(i) If the maximum reservation prices of locals and non-locals are equal, that is, $\alpha_l = \alpha_{nl}$, then the local welfare-maximizing slot quantity equals the first-best slot quantity, that is, $\bar{Q}^{*} = \bar{Q}^{**}$;

(ii) if the maximum reservation price of locals is smaller than the maximum reservation price of non-locals, that is, $\alpha_l < \alpha_{nl}$, then the local welfare-maximizing slot quantity exceeds the first-best slot quantity, that is, $\bar{Q}^{*} > \bar{Q}^{**}$; and

(iii) if the maximum reservation price of locals exceeds the maximum reservation price of non-locals, that is, $\alpha_l > \alpha_{nl}$, then the local welfare-maximizing slot quantity is smaller than the first-best slot quantity, that is, $\bar{Q}^{*} < \bar{Q}^{**}$.

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[22] Together with equation (53), the first-best airport charge is given by $r^{**}(P) = v \cdot \bar{Q}^{**}$.

Proposition 18 highlights that the maximum reservation prices determine whether local welfare-maximizing slot policy can reach first-best outcome. For an intuition, first consider the share of marginal locals, which can be written as

$$D_l'(\bar{Q}) = \frac{\beta_{nl}}{\beta_l + \beta_{nl}}. \tag{72}$$

The right-hand side is positive and independent of slot quantity, which means that the share of marginal locals is independent of the slot quantity. Second, consider the share of inframarginal locals, which can be written as

$$\frac{D_l(\bar{Q})}{\bar{Q}} = \frac{\alpha_l - \alpha_{nl}}{(\beta_l + \beta_{nl})\bar{Q}} + D_l'(\bar{Q}). \tag{73}$$

The first term on the right-hand side contains the difference in maximum reservation prices, $(\alpha_l - \alpha_{nl})$. This difference determines the difference between the demand elasticities of locals and non-locals with respect to the generalized price because these demand elasticities are given by

$$D_i'(\eta) \cdot \frac{\eta}{D_i(\eta)} = -\frac{\eta}{\alpha_i - \eta}. \tag{74}$$

If $\alpha_l = \alpha_{nl}$, then the first term on the right-hand side of (73) is zero and independent of slot quantity, implying that the share of inframarginal locals is always equal to the share of marginal locals. In this scenario, the local welfare-maximizing slot policy reaches the first-best outcome. For an intuition, consider equation (74). The locals' and non-locals' demands are equally elastic in the generalized price. This means that in local welfare-maximum, a reduction in the generalized price that corresponds to an increase in slot quantity will lead to an equal proportionally increase in the locals and non-locals' demands which implies that the share of inframarginal and marginal locals are equal. These shares are not equal if the maximum reservation prices and the corresponding price elasticities of the passenger demands differ.

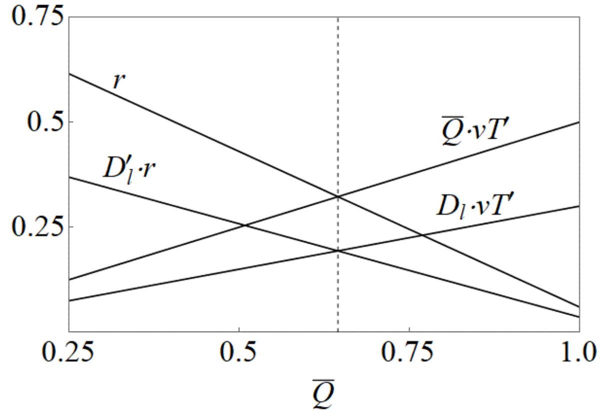

Figure 7: Ticket price r and the weighted ticket price $D_l' \cdot r$, and marginal external congestion costs, $\bar{Q} \cdot vT'$ and $D_l \cdot vT'$, depending on slot quantity when maximum reservation prices are equal, that is, $\alpha_l = \alpha_{nl}$.

Figure 7 and Figure 8 are used to illustrate why local welfare-maximizing slot quantities can or cannot reach the first-best outcome depending on the difference between maximum reservation prices, $(\alpha_l - \alpha_{nl})$. Parameters are given by $\alpha_l = 7/10$ (Figure 8 on the left), $4/5$ (Figure 7), $9/10$ (Figure 8 on the right), $\alpha_{nl} = 4/5$, $\beta_l = 2/5$, $\beta_{nl} = 3/5$ and $v = 1/2$. Slope parameters β_i are distinct to highlight that only the differences in maximum reservation prices determine whether local-welfare maximization can implement the first-best outcome.

In Figure 7, maximum reservation prices of locals and non-locals are equal and given by $\alpha_l = \alpha_{nl} = 4/5$. The upward sloping lines depict the marginal external congestion costs $\bar{Q} \cdot vT'$ and $D_l \cdot vT'$ from the first-best and the airport's viewpoints, respectively, depending on the slot quantity. The downward sloping lines depict the ticket price r and the weighted ticket price $D_l' \cdot r$, respectively, depending on the slot quantity. The minimum and maximum slot quantities are chosen at $\bar{Q} = 1/4$ and $\bar{Q} = 1$, respectively, to ensure that both locals and non-locals' demands are non-negative across the figures.

The intersection point of the two lines on the top determines the first-best slot quantity. The intersection point of the two lines on the bottom determine the slot

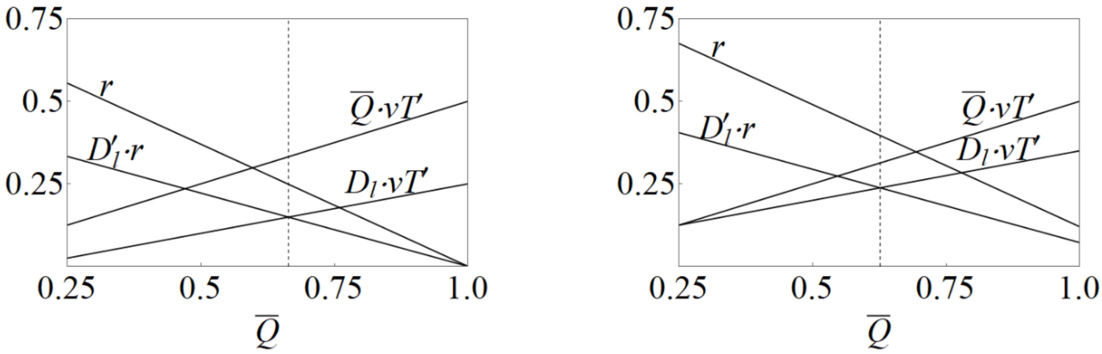

Figure 8: Ticket price r and the weighted ticket price $D_l' \cdot r$, and marginal external congestion costs, $\bar{Q} \cdot vT'$ and $D_l \cdot vT'$, depending on slot quantity with a smaller ($\alpha_l < \alpha_{nl}$ on the left) and a bigger locals' maximum reservation price ($\alpha_l > \alpha_{nl}$ on the right) respectively.

quantity that maximizes the airport's welfare. The vertical dashed line depicts the local welfare-maximizing slot quantity. The slot quantities determined by the intersection points of the two lines on the top and the two lines on the bottom are equal and given by $\bar{Q} = 20/31$. This shows that, in this scenario, local-welfare maximization is consistent with the first-best outcome. The reason is that, evaluated at the optimal slot quantity, the cost-benefit ratios associated with an increase in the slot quantity are equal from the airport's and first-best viewpoints as required by (58).

In Figure 8, maximum reservation prices of locals are given by $\alpha_l = 7/10$ ($< \alpha_{nl} = 4/5$) on the left and $\alpha_l = 9/10$ ($> \alpha_{nl} = 4/5$) on the right. The figure on the left shows that if $\alpha_l < \alpha_{nl}$, then the local welfare-maximizing slot quantity, indicated by the dashed vertical line, implies that the marginal external congestion cost $\bar{Q} \cdot vT'$ exceeds the marginal benefit r from the first-best viewpoint. This leads to a higher cost-benefit ratio associated with an increase in the slot quantity from the first-best viewpoint relative to the airport's viewpoint. Therefore, the local welfare-maximizing slot quantity exceeds the first-best slot quantity, that is, $\bar{Q}^* > \bar{Q}^{**}$. The figure on the right shows that if $\alpha_l > \alpha_{nl}$, then the local welfare-maximizing slot quantity, indicated by the dashed vertical line, implies that the marginal external congestion cost $\bar{Q} \cdot vT'$ is smaller than the marginal benefit r from the first-best viewpoint. This leads to a lower cost-benefit ratio associated with an increase in the slot quantity from the first-best viewpoint relative to the airport's viewpoint. Therefore, the local welfare-maximizing slot quantity is smaller than the first-best slot quantity, that is, $\bar{Q}^{*} < \bar{Q}^{**}$.

3.5 Summary

This chapter developed a stylized but rich enough model to analyze the role of locals and non-locals for the assessment of local welfare-maximizing airport congestion policies by comparing the local welfare-maximizing solutions with the first-best outcome. To capture the presence of non-locals, it was sufficient to consider a network with only two airports. Furthermore, to analyze the role of non-locals for congestion policies, it was sufficient to assume that only one of the two airports was congested.

The congested airport could use slot or pricing policies to mitigate the congestion problem for locals by choosing the slot quantity or the airport charge, respectively. In the case of slot policy, the airport did not earn from selling slots. This captured the notion of grandfather rights established by the Worldwide Scheduling Guidelines of the IATA. In the case of pricing policy, the airport generated a positive profit from locals and non-locals. However, whereas the positive profit derived from non-locals mattered to the local welfare-maximizing airport, the consumer surplus from non-locals was ignored by the local welfare-maximizing airport.

The main part of the analysis was based on the consideration of general functional forms. The analysis showed that the local welfare-maximizing slot quantity could coincide with the first-best outcome whereas, in our framework, this was impossible in the case of pricing policy. The main result was to show that whether the outcomes coincided in the case of slot policy depended on the relationship between two types of shares of locals. The first type represented the share of locals relative to the total number of passengers, which was called the share of inframarginal locals. The second type was related to the effect of a marginal increase in the slot quantity on the quantities of locals, which was called the share of marginal locals. More specifically, the second type of share was equal to the increase in locals relative to the increase in the total passenger quantity, or equivalently, the increase in the slot quantity.

Using these concepts, the analysis showed that the first-best outcome coincided with the local welfare-maximizing slot policy if the implied share of inframarginal locals was equal to the implied share of marginal locals. The intuition was developed with the help of cost-benefit ratios associated with a marginal increase in the slot quantity. The cost-benefit ratios were measured by the marginal external congestion cost divided by the ticket price. If the shares of inframarginal and marginal locals implied by the local welfare-maximum were equal, then the cost-benefit ratios associated with a marginal increase in the slot quantity were equal from the local and the first-best viewpoints. It was shown that the intuition based on cost-benefit ratios carried over to the more complicated case with multiple congested airports. The difference between the exclusive and inclusive airline services were discussed to shed lights on how the share of passengers served by the local airlines affects the assessment of local welfare-maximizing policies. Linear functional forms were used to further illustrate the role of locals and non-locals for the policy comparison and derive analytical solutions.

CHAPTER 4

SUBSTITUTE AIR SERVICES FOR LOCAL PASSENGERS

This chapter extends the three-airport network in Czerny and Lang (2019)'s study by considering an airport network in which passengers can choose between two alternative origin-destination connections as imperfect substitutes. The main insight of the analysis is that the presence of substitute air services is a necessary condition for equilibrium slot quantities to reach the first-best outcome. This is because in the presence of substitute air services, an increase in the local slot quantity leads to a stronger increase in the demand of non-locals than the demand of locals who travel between the two congested airports. This implies that non-locals are taking up more of the additional slot quantities and therefore are the main beneficiaries of the local airport's slot expansion, which reduces the local airport's incentive to increase the slot quantity as they would have in the absence of substitute air services. The presence of substitute air services implies that slot policies are stricter relative to the case in which substitute air services are absent. Equilibrium slot quantities can thus possibly achieve the first-best passenger quantities. The chapter also shows that equilibrium pricing levels will be too high relative to the first-best prices independent of the presence or absence of substitute air services. This is because if profits matter, the local airport will always charge a markup on the first-best price independent of the presence or the absence of substitute air services.

Numerical examples are used to illustrate how the level of substitutability affects the total welfare achieved under equilibrium slot and pricing policies relative to the first-best welfare. These instances show that the welfare performance of pricing policies is better than that of slot policies when the level of substitutability is relatively low or high. In the middle range of substitutability, the welfare performance of slot policies is better than that of pricing policies and can even implement the first-best outcome.

The chapter is organized as follows. The model will be presented in Subchapter 4.1. Subchapter 4.2 4.2 discusses the demand relationships which are crucial for the policy assessment in Subchapter 4.3. At the end of Subchapter 4.3, numerical examples are used to illustrate how the level of substitutability affects the total welfare achieved under equilibrium slot and pricing policies relative to the first-best welfare. Subchapter 4.4 concludes this chapter.

4.1 The Model

This subchapter extends the three airport networks in Chapter 2 by considering substitute air services in the airport congestion policies. All the model settings in Subchapter 2.4 and 2.5 carry over here. To capture that air services are imperfect substitutes, $\partial^2 B_i / \partial q_{ij} \partial q_{iC} < 0$ is assumed to be true with $\partial^2 B_i / \partial q_{iC}^2, \partial^2 B_i / \partial q_{ij}^2 < \partial^2 B_i / \partial q_{ij} \partial q_{iC} < 0$.

The model considers a one-shot game, where airports independently and simultaneously choose between slot and pricing policies as well as respective slot quantities and pricing levels. Equilibrium policies depend on whether airport profits do not matter (slots are equilibrium policies because then consumer surplus is higher with slots than with pricing policies) or do matter (pricing are equilibrium policies because then airports can exploit non-locals) as highlighted by Czerny and Lang (2019) and this dependency is unaffected by the presence of substitute air services.

4.2 Demand relationships

This subchapter analyzes the relationships between (i) airport charges and passenger demands and (ii) slot quantities and passenger demands, and how the presence of substitute air services affects them. An increase in one airport charge will affect both airports' total traffic whereas an increase in one airport's slot quantity will keep the other airport's total air traffic unchanged. This affects equilibrium pricing and slot policies and makes their outcomes different.

The following first considers airport charges and finds that, in the presence of substitute air services, demand of locals who travel between airports A and B can be increasing in the local airport charge. To determine the necessary conditions for such an increase, the relationship between generalized prices and demands is discussed in a second step. The relationship between slot quantities and slot prices is discussed in a third step, which helps analyze the relationship between slot quantities and demands of locals and non-locals in the final step. Altogether, this entire subchapter is crucial for the understanding of the outcomes of equilibrium congestion policies, which will be discussed in the subsequent subchapter.

4.2.1 The effect of airport charges on local and non-local demands

Passengers who travel between airports A and B experience delays at both airports whereas passengers who travel from their local airport to airport C only experience delays once. Let η_{ij} and η_{iC} with

$$\eta_{AB} = r_A + r_B + v(T_A + T_B) \text{ and } \eta_{iC} = r_i + vT_i \tag{75}$$

denote the generalized prices for passengers travelling between airports A and $B,$ and between their local airport and airport C, respectively. Passengers consider generalized prices as given. Demands of locals who travel between airports A and $B,$ and between their local airport and airport C, denoted as $D_{ij}(r_A, r_B)$ and $D_{iC}(r_A, r_B)$, respectively, are determined by the equilibrium conditions

$$\frac{\partial B_i}{\partial q_{ij}} - \eta_{ij} = 0 \text{ and } \frac{\partial B_i}{\partial q_{iC}} - \eta_{iC} = 0. \tag{76}$$

Passengers will travel as long as their marginal benefits from travelling are at least as high as the generalized prices. Applying Cramer's rule to the system of equations in

(76) and using symmetry yield:

Lemma 12 *A marginal increase in airport charge* r_i *implies:*

$$(i)\ \frac{\partial\left(D_{ji}+D_{ij}\right)}{\partial r_i}<0,\ (ii)\ \frac{\partial D_{iC}}{\partial r_i}<0<\frac{\partial D_{jC}}{\partial r_i},\ (iii)\frac{\partial D_{ji}}{\partial r_i}<0,\ (iv)\ \frac{\partial D_{ji}}{\partial r_i}<\frac{\partial D_{ij}}{\partial r_i},$$
$$(v)\ \frac{\partial\left(D_{ij}+D_{iC}\right)}{\partial r_i}<\frac{\partial\left(D_{ji}+D_{jC}\right)}{\partial r_i}\ and\ (vi)\ \frac{\partial D_i}{\partial r_i}<\frac{\partial D_j}{\partial r_i}<0. \qquad (77)$$

This lemma is discussed at length because it will later be used to develop the intuition for the main results on equilibrium pricing policies. It is helpful to understand the following effects of an increase in the local airport charge: an increase in the local airport charge directly affects all locals who travel between airports A and B, and between their local airport and airport C; whereas an increase in the local airport charge only directly affects non-locals who travel between airports A and B, and indirectly on non-locals who travel between the non-local airport and airport C.

Part (i) shows that the overall demand for trips between airports A and B is decreasing in local airport charge. This is because trips between airports A and B become more expensive for both locals and non-locals due to the increase in local airport charge and accordingly reduces the overall demand for such trips.

Part (ii) firstly shows that a marginal increase in the local airport charge reduces the locals' demand for trips between the local airport and airport C. There are two sources for this demand reduction. The first source is that some passengers who travelled before between the local airport and airport C stop travelling now due to an increase in the local airport charge. This effect exists in both cases of non-substitute and substitute air services. The second source only exists in the case of substitute air services. This source captures that locals who travelled before between the local airport and airport C now may want to switch to trips between airports A and B. Whether this switch will happen is unclear because the airport charge increases for all locals, including the locals who travel between airports A and B.

Part (ii) secondly shows that a marginal increase in the local airport charge increases the non-locals' demand for trips between the non-local airport and airport C. There are also two sources that lead to this demand increase. The first source is related to congestion. Part (i) implies that the non-local airport becomes less congested because an increase in the local airport charge reduces the overall demand for trips between airports A and B. Some passengers who did not travel between the non-local airport and airport C before, therefore start to travel because of the congestion reduction. This effect exists both in the cases of non-substitute and substitute air services. The second source only exists in the case of substitute air services. This source captures that some non-locals who travelled before between airports A and B switch to trips between the non-local airport and airport C because traveling between airports A and B has become more expensive due to the increase in the local airport charge.

Part (iii) shows that a marginal increase in the local airport charge reduces the non-locals' demand for trips between airports A and B. There are also two sources for this demand reduction. The first source is that some passengers who travelled before between airports A and B stop travelling now due to an increase in the local airport charge. This effect exists both in the cases of non-substitute and substitute air services. The second source only exists in the case of substitute air services. This source captures again that non-locals who travelled before between airports A and B now switch to trips between the non-local airport and airport C.

Part (iv) shows that a marginal increase in the local airport charge reduces the non-locals' demand by more than the locals' demand for trips between airports A and B (the locals' demand for these trips may actually increase under certain conditions, which will be discussed below). This follows naturally from the discussion of parts (ii) and (iii). Some locals and non-locals who travelled before between airports A and B stop travelling between airports A and B due to an increase in the local airport charge. On the one hand, those locals who travelled before between the local airport and airport C now may want to switch to trips between airports A and B, which would soften the effect of a reduction in the locals' demand for trips between airports A and B. On the other hand, those non-locals who travelled before between airports A and B now may want to switch to trips between the non-local airport and airport C, which would strengthen the effect of a reduction in the non-locals' demand for trips between airports A and B. Therefore, an increase in local airport charge leads to a relatively weak reduction in the locals' demand for trips between A and B compared with the reduction in the non-locals' demand for such trips.

Part (v) shows that a marginal increase in the local airport charge has a greater impact on the total locals' demand than the total non-locals' demand. This is because non-locals who travelled before between airports A and B may switch to trips between the non-local airport and airport C and thus the total demand of non-locals are less affected by an increase in the local airport charge.

Part (vi) shows that a marginal increase in the local airport charge reduces traffic at both local and non-local airports, whereas the effect of the local airport charge is stronger on local traffic than non-local traffic. This is because an increase in the local airport charge affects all locals but only some non-locals.

4.2.2 The relationship between airport charges and generalized prices

It seems natural that an increase in the number of passengers traveling between airports A and B would be associated with a reduction in the corresponding generalized price. The following analysis shows that, in the presence of substitute air services, this relationship may or may not apply. Consider the effect of airport charges on generalized prices. Substituting passenger quantities q_{ij} and q_{iC} with the demands D_{ij}

and D_{iC}, respectively, in the generalized prices in (75), taking the derivatives with respect to the airport charge r_i and using Lemma 12 yield:

Lemma 13 *A marginal increase in airport charge r_i implies:*

$$(i)\ \frac{\partial \eta_{jC}}{\partial r_i} < 0 \ and \ (ii)\ 0 < \frac{\partial \eta_{ij}}{\partial r_i} < \frac{\partial \eta_{iC}}{\partial r_i} < 1. \tag{78}$$

Part (i) shows that an increase in the local airport charge reduces the generalize price for trips between the non-local airport and airport C. This is intuitive because the total traffic and thus congestion are reduced at both airports while the non-local airport charge remains unchanged. Therefore, the generalize price is reduced.

Part (ii) shows that an increase in the local airport charge always increases the generalized prices for trips between airports A and B, and between the local airport and airport C, but by less than 1. The latter is true because an increase in the local airport charge reduces the local and non-local total traffic and thus congestion costs as highlighted by part (vi) in Lemma 12, which softens the effect of an increase in the generalized prices. It further shows that the generalized price for trips between airports A and B is increasing by less than the generalized price for trips between the local airport and airport C. This is because an increase in the local airport charge reduces both airports' total traffic and thus congestion costs as highlighted by part (vi) in Lemma 12 and the generalized price for trips between airports A and B involves two congestion costs reduction whereas the generalized price for trips between the local airport and airport C only involves one congestion costs reduction.

Part (ii) is inconsistent with the notion that a demand increase must be associated with a reduction in the corresponding generalized price. According to Lemma 12, the demand of locals traveling between airports A and B can be increasing in the local airport charge although, according to Lemma 13, the locals' generalized prices are always increasing in the local airport charge. The presence of substitute air services is crucial for this result as shown by the following proposition:

Proposition 19 *(i) The presence of substitute air services with strong enough substitutability in the sense that*

$$\frac{\partial^2 B_i}{\partial q_{ij} \partial q_{iC}} < \frac{1}{2} \frac{\partial^2 B_i}{\partial q_{ij}^2} \tag{79}$$

and (ii) airport congestion are necessary conditions for the demand of locals who travel between airports A and B to be increasing in the local airport charge.

The inequality in (79) can never be satisfied in the absence of substitute air services because the left-hand side of (79) equals zero whereas the right-hand side of (79) is strictly negative by the concavity of the benefit function. This shows that the presence of substitute air services is a necessary condition for the demand of locals who travel between airports A and B to be increasing in the local airport charge.[23] The intuition is that the generalized price for trips between airports A and B is increasing by less than the generalized price for trips between the local airport and airport C in the local airport charge as highlighted by Lemma 13. If the substitutability is strong enough, there will be many locals who travelled before between the local airport and airport C switching to trips between airports A and B in the presence of substitute air services. This may lead an overall increase in the local demand for trips between airports A and B.

The assumption that airports are congested is also crucial for Proposition 19 to be true. Consider otherwise that airports are not congested but air services are substitutes. An increase in the local airport charge leads to $\partial \eta_{ij} / \partial r_i = \partial \eta_{iC} / \partial r_i = 1$.

[23] Following the setup in the analysis using general functional forms, quadratic functional forms can be used and show that demand of local passengers who travel between airport A and B is indeed increasing in local airport charge.

This means that the generalized prices for both trips are increasing in local airport charge by the same amount, that is, 1. There is no incentive for locals who travelled before between the local airport and airport C to switch to trips between airports A and B. Therefore, in the absence of congestion, the demand of locals who travel between airports A and B will not be increasing in the local airport charge.

4.2.3 The relationship between slot prices and slot quantities

Slot prices are the shadow prices under slots that would have to be implemented to ensure that airport passenger demands equal the desired slot quantities. It is assumed that slot constraints are always binding. The slot price $r_i(S)$ is implicitly determined by

$$\bar{Q}_i - D_i\left(r_A(S), r_B(S)\right) = 0. \tag{80}$$

Applying the Gale-Nikaido Theorem (Gale and Nikaido, 1965) and Cramer's rule to the system of equations in (80) yields:

Lemma 14 *(i) There is a unique pair of slot prices matched with each pair of slot quantities; (ii) local airports' slot prices are decreasing in local airport's slot quantities; and (iii) non-local airports' slot prices are increasing in local airport's slot quantities, that is,*

$$\frac{\partial r_i}{\partial \bar{Q}_i} < 0 < \frac{\partial r_j}{\partial \bar{Q}_i} < \left|\frac{\partial r_i}{\partial \bar{Q}_i}\right|. \tag{81}$$

The unique one-to-one pairing relationship between slot prices and slot quantities means that Cramer's rule can be applied to derive the following relationships. The first inequality in (81) shows that local airport's slot price is decreasing in the local airport's slot quantity. Equation (80) implies that an increase in the local slot quantity increases the local airport's demand by the same amount. This is associated with a reduction in the local airport's slot price to ensure that the passenger demand equals the slot quantity by Lemma 12, which shows that demand

D_i is decreasing in r_i. Lemma 12 also implies that the non-local airport's demand is increasing in the local airport's slot quantities. This is because the reduction in the local airport's slot price increases the demand for the non-local airport. To keep the non-local airport's demand unchanged despite an increase in the local's slot quantity and the corresponding reduction in the local airport's slot price, the non-local airport's slot price must be increasing in the local airport's slot quantity. The increase in the non-local airport's slot price is smaller in absolute value than the reduction in the local airport's slot price, which means that the sum of slot prices for flights between airports A and B is reduced by an increase in the local slot quantity.

4.2.4 The effect of slot quantities on local and non-local demands

Airport charges are the decision variables under pricing policies, whereas slot quantities are the decision variables under slot policies. Using Lemma 12 and Lemma 14, the relationships between slot quantities and demands can be described in the following way:

Corollary 4 *A marginal increase in slot quantity* $\bar{Q}_i$ *implies:*

$$(i)\ \frac{\partial\left(D_{ij}+D_{ji}\right)}{\partial\bar{Q}_i}>0,\ (ii)\ \frac{\partial D_{jC}}{\partial\bar{Q}_i}<0<\frac{\partial D_{iC}}{\partial\bar{Q}_i},\ (iii)\ 0<\frac{\partial D_{ji}}{\partial\bar{Q}_i},\ and\ (iv)\ \frac{\partial D_{ij}}{\partial\bar{Q}_i}<\frac{\partial D_{ji}}{\partial\bar{Q}_i}.\ (82)$$

This corollary is also discussed at length because it will later be used to develop the intuition for the main results on equilibrium slot policies. It is helpful to understand the following effects of an increase in the local slot quantity: an increase in the local slot quantity directly affects all locals who travel between airports A and B, and between their local airport and airport C; whereas an increase in the local slot quantity only directly affects non-locals who travel between airports A and B, and indirectly on non-locals who travel between the non-local airport and airport C.

Part (i) shows that the overall demand for trips between airports A and B is increasing in local airport's slot quantity. This is because trips between airports A and B become more attractive due to the relaxed local slot policy and accordingly increases the overall demand for such trips.

Part (ii) firstly shows that a marginal increase in the local slot quantity reduces the non-locals' demand for trips between the non-local airport and airport C. There are two sources for this demand reduction. The first source is related to non-local airport's slot constraint. Part (i) implies that an increase in the local slot quantity increases the overall demand for trips between airports A and B. Whereas the non-local airport's slot quantity and thus total demand remains unchanged, some passengers who travelled before between the non-local airport and airport C stop travelling now. This effect exists both in the cases of non-substitute and substitute air services. The second source only exists in the case of substitute air services. This source captures that non-locals who travelled before between the non-local airport and airport C now may want to switch to trips between airports A and B because traveling between airports A and B has become more attractive due to the relaxed local slot policy.

Part (ii) secondly shows that a marginal increase in the local slot quantity increases the locals' demand for trips between airports A and B. There are also two sources for this demand increase. The first source is that passengers who did not travel before between the local airport and airport C start to travel now because of the relaxed local slot policy. This effect exists both in the cases of non-substitute and substitute air services. The second source only exists in the case of substitute air services. This source captures that some passengers who travelled before between airports A and B now may want to switch to trips between the local airport and airport C. Whether this switch will happen is unclear because the slot quantity increases for all locals, including the locals who travel between airports A and B.

Part (iii) shows that a marginal increase in the local airport's slot quantity increases the non-locals' demand for trips between airports A and B. There are also two sources for this demand increase. The first source is that some passengers who did not travel before between airports A and B start to travel now due to the relaxed local slot policy. This effect exists both in the cases of non-substitute and substitute air services. The second source only exists in the case of substitute air services. This source captures again that non-locals who travelled before between the non-local airport and airport C now may want to switch to trips between airports A and B.

Part (iv) shows that a marginal increase in the local airport slot quantity increases non-locals' demand by more than locals' demand for trips between airports A and B. This follows naturally from the discussion of parts (ii) and (iii). Some locals and non-locals who did not travel before between airport A and B start to travel now between airports A and B due to the relaxed local slot policy. On the one hand, those locals who travelled before between airports A and B now may want to switch to trips between the local airport and airport C, which would soften the effect of an increase in the locals' demand for trips between airports A and B. On the other hand, those non-locals who travelled before between the non-local airport and airport C now may want to switch to trips between airports A and, which would strengthen the effect of an increase in the non-locals' demand for trips between airports A and B. Therefore, an increase in local slot quantity leads to a relatively weak increase in the locals' demand for trips between A and B compared with the increase in the non-locals' demand for such trips.

4.3 Equilibrium Policies

The first-best outcome in Subchapter 2.5 carries over here in the sense that the first-best prices remain unchanged with $r_A = D_A v T_A'$ and $r_B = D_B v T_B'$. This is because the structure of the current model is almost identical to the one in Subchapter 2.4 and

Subchapter 2.5. The only difference is the benefit function where $\partial^2 B_i / \partial q_{ij} \partial q_{iC} < 0$ in this chapter to capture that air services are imperfect substitutes as opposed to $\partial^2 B_i / \partial q_{ij} \partial q_{iC} = 0$ in Chapter 2. The difference in benefit functions does not change the first-best outcomes but change the equilibrium local welfare-maximizing solutions drastically in terms of slot policies, which will be shown in detail as follows.

4.3.1 Equilibrium slot quantities

Consider $\phi_A = \phi_B = S$. Assume that the best responses in terms of slot quantities are determined by the first-order conditions, $\partial W_i / \partial \bar{Q}_i = 0$ and that the map of best responses in terms of the slot quantity is a contraction, which are maintained assumptions here and hereafter. Using the equilibrium conditions (76) and symmetry in the sense that $r_A(S) = r_B(S)$ in equilibrium, the first-order conditions for the best responses in terms of the slot quantities can be written as

$$r_i(S) \cdot \left(2\frac{\partial D_{ij}}{\partial \bar{Q}_i} + \frac{\partial D_{iC}}{\partial \bar{Q}_i} \right) - \left(D_{ij} + D_{iC} \right) v T_i' = 0. \tag{83}$$

The first term on the left-hand side shows how an increase in local slot quantity and the corresponding increase in locals' demands for trips between airports A and B, and their local airport and C affect the locals' benefits from travelling. The benefits for trips between A and B are weighted by two because these passengers use two airports and passengers therefore have to pay two prices. Correspondingly the marginal benefits of traveling are equal to twice of the slot price for these passengers. The following result implies that the first term on the left-hand side is positive:

Lemma 15 *The locals' demands imply*

$$2\frac{\partial D_{ij}}{\partial \bar{Q}_i} + \frac{\partial D_{iC}}{\partial \bar{Q}_i} > 0. \tag{84}$$

The second term on the left-hand side of (83) shows the locals' marginal external congestion cost. The best responses in terms of slot quantities ensure that the locals' marginal benefits are equal to the locals' marginal external congestion cost.

Solving the first-order condition (83) for the equilibrium slot price yields

$$r_i(S) = D_i vT_i' - D_{ji} vT_i' + \frac{\frac{\partial D_{ji}}{\partial \bar{Q}_i} - \frac{\partial D_{ij}}{\partial \bar{Q}_i}}{2\frac{\partial D_{ij}}{\partial \bar{Q}_i} + \frac{\partial D_{iC}}{\partial \bar{Q}_i}}\left(D_{ij} + D_{iC}\right) vT_i'. \tag{85}$$

The right-hand side can be used to show that equilibrium slot prices are high in the presence of substitute air services relative to the case where substitute air services are absent. The first term is the marginal external congestion cost of all passengers at local airport, which is also the first-best price. The second term is the marginal external congestion cost of the non-locals. The third term is a weighted marginal external congestion cost of locals. In the presence of substitute air services, the effect of slot quantities is stronger for non-local than for locals in the sense that $0 < \partial D_{ij} / \partial \bar{Q}_i < \partial D_{ji} / \partial \bar{Q}_i$, whereas in the absence of substitute air services this effect is equal for non-local and locals. These two relationships together imply that in the presence of substitute air services, in equilibrium, the local airport internalizes more than its locals' part of the marginal external congestion cost in the sense that $r_i(S) > D_i vT_i' - D_{ji} vT_i' = \left(D_{ij} + D_{iC}\right) vT_i'$ because the third term is positive. By contrast, in the absence of substitute air services, the third term is zero because $0 < \partial D_{ij} / \partial \bar{Q}_i = \partial D_{ji} / \partial \bar{Q}_i$. Therefore, the airport would, in equilibrium, exactly internalize the locals' part of the marginal external congestion cost as was shown by Czerny and Lang (2019). The intuition is that, an increase in the local slot quantity stimulates non-locals who travelled before between the non-local airport and airport C to switch to trips between airports A and B. Consequently, a marginal increase in the local slot quantity leads to a relatively strong increase in non-local passenger numbers at the local airport because $\partial D_{ij} / \partial \bar{Q}_i < \partial D_{ji} / \partial \bar{Q}_i$, which means that non-locals are the main beneficiaries of the local slot expansion. The local airport therefore ends up internalizing more than its locals' part of the marginal external congestion cost. The following shows that the equilibrium slot quantities can in effect lead to the first-best outcome or even too few slots relative to the first-best outcome, whereas neither of these two equilibrium outcomes would be possible in the absence of substitute air services.

To evaluate the equilibrium slot policies, consider the first-best slot policy that maximizes the total welfares of airports A and B by the choice of the local slot quantity, which is given by

$$\frac{\partial W_i}{\partial \bar{Q}_i} + \frac{\partial W_j}{\partial \bar{Q}_i} = 0. \tag{86}$$

The first term on the left-hand side captures the impact of the local airport's response in terms of slot quantity on the local airport's welfare whereas the second term captures the corresponding *welfare externality* on the other airport. Specifically, the best responses in equilibrium imply that the first term is equal to zero. Given that the contraction condition for best responses in terms of slot quantities is satisfied, this leads to:

Proposition 20 *(i) If the unique equilibrium in slot quantities implies zero welfare externalities, then this unique equilibrium implements the first-best outcome;*

(ii) if welfare externalities are negative in equilibrium, equilibrium slot quantities are too high relative to the first-best slot quantities; and

(iii) if welfare externalities are positive in equilibrium, equilibrium slot quantities are too low relative to the first-best slot quantities.

This proposition is true independent of the presence or absence of substitute air services. However, in the absence of substitute air services, the unique equilibrium in slot quantities always implies negative welfare externalities and equilibrium slot quantities are therefore always too high relative to the first-best slot quantities. In the presence of substitute air services, the unique equilibrium in slot quantities may, however, implies zero welfare-externalities and equilibrium slot quantities can be first-best if the condition in the following proposition is satisfied:

Proposition 21 *If airport profits do not matter and quantities are the decision variables, the presence of substitute air services is a necessary condition for zero welfare externalities in the equilibrium. Specifically, (i) if the equilibrium slot quantities imply the demand condition*

$$\frac{D_{ij} + D_{iC}}{D_i} = 2\frac{\partial D_{ij}}{\partial \bar{Q}_i} + \frac{\partial D_{iC}}{\partial \bar{Q}_i}, \tag{87}$$

then welfare externalities are zero; (ii) if the left-hand side exceeds the right-hand side in equilibrium. the welfare externalities are negative in equilibrium, and (iii) if the left-hand side is lower than the right-hand side in equilibrium, the welfare externalities are positive in equilibrium.

The concept of the share of inframarginal and marginal locals developed in Chapter 3 can be used to derive a better understanding for this proposition. Consider the share of inframarginal locals, which corresponds to the left-hand side of equation (87). Consider the share of marginal locals, which is equal to $\partial D_{ij} / \partial \bar{Q}_i + \partial D_{iC} / \partial \bar{Q}_i$. However, remember that it is the cost-benefit ratios that ultimately matter. This is important in the sense that locals who travel between airports A and B have to pay two generalized prices because both airports are congested. Therefore, the marginal benefit of locals who travel between the congested airports is twice as high as the marginal benefit of locals who travel between airports i and C who utilize only one congested airport. This means the locals who travel between the congested airports count twice to capture the difference in marginal benefits associated with an increase in the local slot quantity. The right-hand side in (87), therefore, correctly translates into $2\partial D_{ij} / \partial \bar{Q}_i + \partial D_{iC} / \partial \bar{Q}_i$.

In the absence of substitute air services, the right-hand side would be equal to 1. This is because an increase in the local slot quantity, or equivalently a reduction in the local slot price, increases non-locals' and locals' demands for trips between airports A and B by the same amount by Lemma 4. The cost-benefit ratio associated with a marginal increase in the local slot quantity is always lower from the local viewpoint relative to the first-best viewpoint. Therefore, the local airports are more inclined to increase the local slot quantities. In equilibrium, slot quantity will always be too high relative to the first-best outcome, leading to negative welfare externalities.

In the presence of substitute air services, the right-hand side is less than 1. This is because an increase in the local airport's slot quantity increases the non-locals' demand for trips between airports A and B by more than the locals' demand for such trips by Corollary 4. The cost-benefit ratios associated with a marginal increase in the local slot quantity can be equal from the local and the first-best viewpoints. Therefore, the local airports are more reluctant to increase the local slot quantities as they would have in the absence of substitute air services. If the condition in (87) is satisfied in equilibrium, local slot quantities are optimal relative to the first-best outcome, leading to zero welfare externalities.

The assessment of equilibrium slot policies changes because the share of marginal locals changes in the presence of substitute air services. The intuition is that, in the absence of substitute air services, when the local slot quantity increases, non-locals who travel between the non-local airport and airport C do not want to switch to trips between airports A and B. Therefore, non-locals and locals who travel between airports A and B are increasing in local slot quantity by the same amount, leading to the share of marginal locals that is equal to 1 and always exceeds the share of inframarginal locals with $\left(2\partial D_{ij}+\partial D_{iC}\right)/\partial\bar{Q}_i=1>\left(D_{ij}+D_{iC}\right)/\bar{Q}_i$. Welfare externalities are always negative and equilibrium slot quantities are too always too high relative to the first-best outcome. In the presence of substitute air services, when the local slot quantity increases, some non-locals who travelled before between the non-local airport and airport C now switch to trips between airports A and B. Therefore, non-locals who travel between airports A and B are increasing in local slot quantity by more than the locals, leading to the share of marginal locals that is smaller than 1 and possibly equals the share of inframarginal locals with $\left(2\partial D_{ij}+\partial D_{iC}\right)/\partial\bar{Q}_i=\left(D_{ij}+D_{iC}\right)/\bar{Q}_i<1$. Welfare externalities can be zero and thus equilibrium slot quantities can reach the first-best outcome.

4.3.2 Equilibrium slot prices

Consider $\phi_A=\phi_B=SP$. Assume that the best responses in terms of slot prices are determined by the first-order conditions $\partial W_i/\partial r_i=0$ and that the map of best responses in terms of the slot price is a contraction, which are maintained assumptions here and hereafter. Using the equilibrium conditions (76) and symmetry in the sense that $r_A(SP)=r_B(SP)$, the first-order conditions for the best responses in terms of the slot prices can be written as

$$r_i(SP)\cdot\left(2\frac{\partial D_{ij}}{\partial r_i}+\frac{\partial D_{iC}}{\partial r_i}\right)-D_{ij}vT_i'\frac{\partial\left(D_i+D_j\right)}{\partial r_i}-D_{iC}vT_i'\frac{\partial D_i}{\partial r_i}=0. \tag{88}$$

The first term on the left-hand side shows how an increase in local slot price and the corresponding reduction in locals' demand for trips between airports A and B, and their local airport and C affect the locals' benefits from travelling. The benefits for trips between A and B are weighted by two again because these passengers pay the slot prices twice, one at each airport. The following result implies that the first term on the left-hand side is negative:

Lemma 16 *The locals' demands imply*

$$2\frac{\partial D_{ij}}{\partial r_i}+\frac{\partial D_{iC}}{\partial r_i}<0. \tag{89}$$

The second term on the left-hand of (88) shows how an increase in the local slot price and the corresponding reduction in locals' demand affect the marginal external congestion cost for trips between airports A and B. Compared with the second term in the first order condition (83), the difference is that when slot quantities are the decision variables, an increase in local slot quantity only affects the local airport's demand and, thus, congestion whereas the other airport's total traffic and, thus, congestion remains unchanged. The picture changes when slot prices are the decision variables. In this case, an increase in local slot price reduces traffic and, thus, congestion at both congested airports. The third term shows how an increase in local slot price and the corresponding reduction in locals' demand affect the marginal external congestion cost for trips between the local airport and airport C. The best responses in terms of slot prices ensure that the locals' marginal benefits are equal to the locals' marginal external congestion cost.

Solving the first-order condition (88) for the equilibrium slot price yields

$$r_i(SP)=D_i vT_i'-\frac{\frac{\partial\left(D_{ij}+D_{iC}\right)}{\partial r_i}-\frac{\partial\left(D_{ji}+D_{jC}\right)}{\partial r_i}}{2\frac{\partial D_{ij}}{\partial r_i}+\frac{\partial D_{iC}}{\partial r_i}}D_{ji}vT_i'+\frac{\frac{\partial D_{ji}}{\partial r_i}-\frac{\partial D_{ij}}{\partial r_i}}{2\frac{\partial D_{ij}}{\partial r_i}+\frac{\partial D_{iC}}{\partial r_i}}\left(D_{iC}+D_{ij}\right)vT_i'. \tag{90}$$

The first term on the right-hand side is the marginal external congestion cost of all passengers at local airport, which is also the first-best price. The second term is a weighted marginal external congestion cost of the non-locals. The third term is a weighted marginal external congestion cost of locals. Lemma 12 mentions that $\partial D_i/\partial r_i<\partial D_j/\partial r_i<0$ and $\partial D_{ji}/\partial r_i<\partial D_{ij}/\partial r_i$, which implies that

$\partial D_i / \partial r_i = \partial\left(D_{ij} + D_{ji} + D_{iC}\right) / \partial r_i < \partial\left(2D_{ij} + D_{iC}\right) / \partial r_i < 0$. Lemma 12 also mentions that $\partial\left(D_{ij} + D_{iC}\right) / \partial r_i < \partial\left(D_{ji} + D_{jC}\right) / \partial r_i$, which altogether implies that the second term is negative, and third term is positive. By contrast, in the absence of substitute air services, the second term is negative whereas the third term disappears because $\partial D_{ji} / \partial r_i = \partial D_{ij} / \partial r_i$ by Lemma 4. Therefore, the airport would, in equilibrium, never internalizes all the passengers' marginal external congestion cost as was shown by Czerny and Lang (2019). In the presence of substitute air services, an increase in the local airport's slot price $r_i(SP)$ stimulates non-locals who travelled before between airports A and B to switch to trips between their local airport and airport C. Consequently, a marginal increase in local slot price leads to a relatively stronger decrease in the demand of non-locals at the local airport because $\partial D_{ji} / \partial r_i < \partial D_{ij} / \partial r_i$. This means that locals are the main beneficiaries of the increase in local slot price. The local airport therefore ends up internalizing more than its locals' part of the marginal external congestion cost. The following shows that the equilibrium slot prices can in effect lead to the first-best outcome or even too high slot prices relative to the first-best outcome, whereas neither of these two equilibrium outcomes would be possible in the absence of substitute air services.

To evaluate the equilibrium slot policies, consider the first-best slot policy that maximizes the total welfares of airports A and B by the choice of the local slot price, which is given by

$$\frac{\partial W_i}{\partial r_i} + \frac{\partial W_j}{\partial r_i} = 0. \tag{91}$$

The first term on the left-hand side captures the impact of the local airport's response in terms of slot price on the local airport's welfare whereas the second term captures the corresponding welfare externality on the other airport. Specifically, the best responses in equilibrium imply that the first term is equal to zero. Given that the contraction condition for best responses in terms of slot prices is satisfied, this leads to:

Proposition 22 *(i) If the unique equilibrium in slot prices implies zero welfare externalities, then this unique equilibrium implements the first-best outcome;*

(ii) if welfare externalities are negative in equilibrium, equilibrium slot prices are too high relative to the first-best slot prices; and

(iii) if welfare externalities are positive in equilibrium, equilibrium slot prices are too low relative to the first-best slot prices.

This proposition is true independent of the presence or absence of substitute air services. However, in the absence of substitute air services, the unique equilibrium in slot prices always implies positive welfare externalities and equilibrium slot prices are therefore always too low relative to the first-best slot prices. In the presence of substitute air services, the unique equilibrium in slot prices may, however, implies zero welfare externalities and equilibrium slot prices can be first-best if the condition in the following proposition is satisfied:

Proposition 23 *If airport profits do not matter and prices are the decision variables, the presence of substitute air services is a necessary condition for zero welfare externalities in the equilibrium. Specifically, (i) if the equilibrium in slot prices satisfies the demand condition*

$$\frac{D_{ij}\frac{\partial\left(D_i+D_j\right)}{\partial r_i}+D_{iC}\frac{\partial D_i}{\partial r_i}}{D_i}=2\frac{\partial D_{ij}}{\partial r_i}+\frac{\partial D_{iC}}{\partial r_i}, \tag{92}$$

then welfare externalities are zero; (ii) if the left-hand side exceeds the right-hand side in equilibrium, the welfare externalities are positive in equilibrium, and (iii) if the left-hand side is lower than the right-hand side in equilibrium, the welfare externalities *are negative in equilibrium.*

The demand condition in (92) also relates the welfare externalities to the share of inframarginal and marginal locals. Again, remember that it is the cost-benefit ratios that ultimately matter. This is important in the sense that locals who travel between airports A and B are using two congested and have to pay two generalized prices. Therefore, their marginal external congestion cost as well as marginal benefit are counted at both airports. By contrast, the locals who travel between airports i and C are using only one congested airport and have to pay one generalized price. Therefore, their marginal external congestion cost as well as marginal benefit are counted at the local airport only. The share of inframarginal locals correctly translate to the left-hand side of (92) whereas the share of marginal locals correctly translate to the right-hand side of (92). The intuition is related to cost-benefit ratios and similar to the case in which quantities are used as decision variables in the previous sub subchapter. Thus, the discussion is omitted.

Proposition 21 and Proposition 23 together show that if airport profits do not matter, using quantities and prices as decision variables can both lead to first-best outcome. Lemma 14 mentions that there is a unique pair of slot prices matched with each pair of slot quantities, this implies that:

Proposition 24 *If airport profits do not matter, regardless of the choices of quantities or prices as decision variables, the demand condition for welfare externalities to be zero is unique.*

To clearly identify the variable effect, consider the following lemma:

Lemma 17 *(i) If equilibrium slot prices are too low relative to the first-best prices, then* $D_i v T_i' > r_i(SP) > r_i(S)$ *; (ii) if equilibrium slot prices are too high relative to the first-best prices, then* $D_i v T_i' < r_i(SP) < r_i(S)$ *; and (iii) if slot prices are first best, then*

$D_i v T_i' = r_i(SP) = r_i(S)$.

This lemma shows that in equilibrium, slot prices $r_i(SP)$ and $r_i(S)$ are always lying on the same side to the first-best price but $r_i(SP)$ is always closer to the first-best price than $r_i(S)$. Only when slots are first-best, equilibrium $r_i(SP)$, $r_i(S)$ and first-best price coincide, which is highlighted by Proposition 24. Given that the contraction conditions are satisfied for both best responses in terms of slot quantities and best responses in terms of slot prices, this altogether leads to:

Proposition 25 *If airport profits do not matter, then the variable effect is negative, that is,* $W_i(S) - W_i(SP) \leq 0$. *Specifically, the variable effect is zero, that is,* $W_i(S) - W_i(SP) = 0$ *if equilibrium slot policies are first best.*

This proposition first shows that a change of policy from slots to pricing indeed brings a negative variable effect. It second shows that if equilibrium slot policies are first best, the choices of the different variables do not matter. This resembles a scenario where a central regulator is present under perfect information and first-best results can be achieved by either the choice of price or quantity.

4.3.3 Equilibrium prices

Consider $\phi_A = \phi_B = P$. Assume that the best responses in terms of prices are determined by the first-order conditions, $\partial W_i / \partial r_i = 0$ and that the map of best responses in terms of the price is a contraction, which are maintained assumptions here and hereafter. Using the equilibrium conditions (76) and symmetry in the sense that $r_A(P) = r_B(P)$, the first-order conditions for the best responses in terms of the prices can be written as

$$r_i(P) \cdot \frac{\partial D_i}{\partial r_i} - D_{ij} v T_i' \frac{\partial \left(D_i + D_j \right)}{\partial r_i} - D_{iC} v T_i' \frac{\partial D_i}{\partial r_i} + D_{ji} = 0. \tag{93}$$

The first term on the left-hand side shows how an increase in local price and the corresponding reduction in local airports' total traffic affect the local airport's profit. Compared with the first term in the first order condition (88), the difference is that local airports now care about the airport profits rather than locals' benefits. The second term shows how an increase in local price and the corresponding reduction in locals' demand affect the marginal external congestion cost for trips between airports A and B. The third term shows how an increase in local price and the corresponding reduction in locals' demand affect the marginal external congestion cost for trips between their local airport and airport C. The fourth term is the non-locals' demand for trips between airports A and B. Compared with the first order condition (88), the fourth term is present because airport profits do matter and non-locals who travel to local airport can bring extra profits. The first and fourth terms together show that if prices are the same decision variables, a change of policies from slots to pricing indeed distorts the airports' behaviors in terms of best responses because of the distribution effect, which will be discussed in detail. In equilibrium, the local airport's marginal profits are equal to the locals' marginal external congestion cost plus the non-locals' demand for trips between airports A and B.

Solving the first-order condition (93) for the equilibrium price yields

$$r_i(P) = \left(D_{ij} + D_{iC}\right)vT_i' + D_{ji}vT_i'\frac{\partial D_j / \partial r_i}{\partial D_i / \partial r_i} + \left|\frac{D_i}{\partial D_i / \partial r_i}\right| \cdot \frac{D_{ji}}{D_i}. \tag{94}$$

The first term on the right-hand side is the marginal external congestion cost of locals. The second term is a weighted marginal external congestion cost of non-locals. Lemma 12 mentions that $\partial D_i / \partial r_i < \partial D_j / \partial r_i < 0$. Therefore, $\partial D_i / \partial r_i / \partial D_j / \partial r_i < 1$, which implies that local airport only internalizes partially the marginal external congestion cost of non-locals who travel between airports A and B if profits matter. The third term is a positive markup, which is the product of the semi-price elasticity of demand, D_i, with respect to the local price and the share of other passengers at the local airport.

The semi-price elasticity, $\left|D_i / \partial D_i / \partial r_i\right|$, represents the optimal price in the case of airport profit maximization. The notion of profit maximization only applies to non-locals when the airport maximizes local welfare, which is why the elasticity measure is weighted by the share of non-locals at the local airport. By contrast, in the absence of non-locals, the equilibrium price is equal to the first term, which is also the first-best price. In the presence of non-locals, if profits matter, local airport will still charge a price that internalize entirely the marginal external congestion cost of locals. Meanwhile, local airport also has the incentive to exploit the non-locals by charging a markup which is weighted by the share of non-locals at the local airport. In order to obtain the profits from this part of non-locals, the local airport also has to internalize the marginal external congestion cost of these non-locals, but only partially as shown in the second term. This leads to:

Proposition 26 *If airport profits do matter, equilibrium prices are too high relative to the first-best prices, leading to negative welfare externalities.*

The notion of welfare externality and Proposition 22 under $\phi_A = \phi_B = SP$ carry over here because under both policies prices are the same decision variables and the sum of welfares are the same because profits are cancelled out in the calculation of total welfare under both $\phi_A = \phi_B = SP,\ P$. This proposition shows that equilibrium prices are always too high relative to the first-best prices independent of the airport networks as long as the non-locals are present. This is because local airports always have the incentives to exploit non-locals if airport profits do matter.

Although prices are the same decision variables under $\phi_A = \phi_B = SP$ and P, a change of polices from slots to pricing involves airport profits and thus brings in the distribution effect. Given that the contraction condition is satisfied for both best responses in terms of slot prices and best responses in terms of prices, the distribution

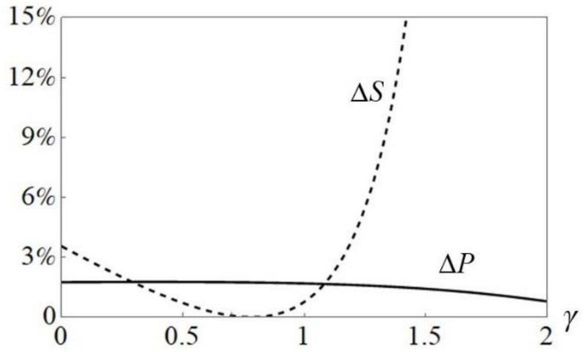

Figure 9: Welfare losses under slots, $\Delta(S)$ (dashed line), and pricing, $\Delta(P)$ (solid line), relative to first-best in percent depending on substitution parameter γ. Parameters: $\alpha_1 = 1$, $\alpha_2 = 3/5$, $\beta_1 = 2$, $\beta_2 = 4$ and $v = 9/4$.

effect is not clear-cut. This is because equilibrium price $r_i(P)$ is always greater than the first-best price by Proposition 26 whereas equilibrium slot price $r_i(SP)$ may be smaller, equal to or greater than the first-best price by Lemma 17. Therefore, it is impossible to compare equilibrium $r_i(P)$ with equilibrium $r_i(SP)$ because the two prices are not lying on the same side to the first-best price.

The following example illustrates how the presence of imperfect substitute air services affects the relative performance of slot and pricing policies relative to the first-best outcome and the role of variable and distribution effect.

Example 4 The benefit of travelling is given by

$$B_i(q_{ij}, q_{iC}) = \alpha_1 \cdot q_{ij} + \alpha_2 \cdot q_{iC} - \frac{1}{2}\left(\beta_1 \cdot q_{ij}^2 + \beta_2 \cdot q_{iC}^2\right) - \gamma \cdot q_{ij} \cdot q_{iC} \tag{95}$$

for airports A and B. Specifically, $\beta_1 = -\partial^2 B_i / \partial q_{ij}^2$, $\beta_2 = -\partial^2 B_i / \partial q_{iC}^2$ and $\gamma = -\partial^2 B_i / \partial q_{ij} \partial q_{iC}$. Parameter γ is used to capture the level of substitutability of the air services. To illustrate the relative performance of slot and pricing policies, the following notations are used. Using symmetry, the aggregate welfare is denoted as W with $W = W(\phi_i) = 2W_i(\phi_i)$. Let W^* denote the aggregate welfare under first-best prices $r_i = D_i v T_i'$. The relative welfare loss of slot policies, denoted as $\Delta(S)$, is given

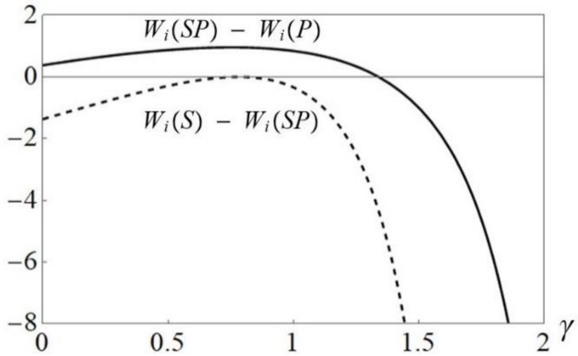

Figure 10: The variable effect, $W_i(S) - W_i(SP)$ (dashed line), and distribution effect, $W_i(SP) - W_i(P)$ (solid line), depending on substitution parameter γ (welfare values are multiplied by $1,000$ for scaling reasons). Parameters: $\alpha_1 = 1$, $\alpha_2 = 3/5$, $\beta_1 = 2$, $\beta_2 = 4$ and $v = 9/4$.

by $\Delta(S) = \left(W^* - W(S)\right)/W^*$, whereas the relative welfare loss of pricing policies, denoted as $\Delta(P)$, is given by $\Delta(P) = \left(W^* - W(P)\right)/W^*$.

Figure 9 illustrates the welfare losses of slot and pricing policies depending on substitution parameter γ in percent for parameters $\alpha_1 = 1$, $\alpha_2 = 3/5$, $\beta_1 = 2$, $\beta_2 = 4$ and $v = 9/4$. The solid line and dashed line represent the welfare losses when airport profits matter, $\Delta(P)$, and do not matter, $\Delta(S)$, respectively. The figure illustrates that given a time valuation, as substitution parameter γ increases, slots are becoming less and less loose. When the substitution parameter $\gamma \approx 0.7$, slots become first best with $\Delta(S) = 0$, and then becoming more and more excessive. Furthermore, $\Delta(P)$ is always positive, which suggests that there is always a welfare loss relative to the first-best welfare under pricing. The figure also provides a policy implication that pricing performs better than slots when the level of substitutability is relatively low or high. In the middle range of substitutability, slots performs better than pricing and can even implement the first-best outcome.

Figure 10 illustrates how substitution parameter γ affects the variable effect, $W_i(S) - W_i(SP)$ (dashed line), and the distribution effect, $W_i(SP) - W_i(P)$ (solid line). Given a time valuation, the variable effect is always non-positive. Only when the substitution parameter $\gamma \approx 0.7$, the variable effect is zero and slots become first best. This means the choices of different decision variables do not matter. By contrast, the distribution effect is first positive and then negative as substitution parameter γ increases. This shows that distribution effect is indeed not clear-cut. ■

4.4 Summary

The present chapter analyzed an airport network in which passengers chose between two alternative origin-destination connections which they considered as imperfect substitutes. The network involved two symmetric congested airports with locals and one uncongested airport without locals, thus, a three-airport network. Locals travelled to either the other congested airport or alternatively to the uncongested airport. The two congested airports independently and simultaneously chose between slot and pricing policies and their respective slot quantities and pricing levels to mitigate the congestion problem for the locals. This captured that most airports are under localized rather than centralized government controls. In the case of slot policies, airports did not earn from selling slots. This captured the notion of grandfather rules. By contrast, in the case of pricing policies, airports earned positive profits.

The present study found that the presence of substitute air services was a necessary condition for equilibrium slot quantities to reach the first-best passenger quantities. This was because an increase in the local slot quantity led to a stronger increase in the demand of non-locals than the demand of locals who travelled between the two congested airports. This implied that non-locals were taking up more of the additional slot quantities and were the main beneficiaries of the local airport's slot expansion, which reduced the local airport's incentive to increase the slot quantity as they would have in the absence of substitute air services. Slot policies thus became stricter in the presence of substitute air services than in the absence of substitute air services. This could possibly lead to first-best passenger quantities in equilibrium.

Specifically, if equilibrium slot quantities were first best, it implies that the welfare externalities of slot-quantity choices were zero. This explained why the variable effect was equal to zero in this case. Equilibrium pricing levels would be too high relative to the first-best prices independent of the presence or the absence of substitute air services. This was because if profits matter, the local airport would always charge a markup on the first-best price independent of the presence or the absence of substitute air services.

Numerical examples were used to illustrate how the level of substitutability between the alternative connections affected the total welfare achieved under equilibrium slot and pricing policies relative to the first-best outcome. These instances showed that the welfare performance of pricing policies was better than slot policies when the level of substitutability was relatively low or high. In the middle range of substitutability, the welfare performance of slot policies was better than pricing policies and could even implement the first-best outcome.

CHAPTER 5

AIRPORT COMPETITION FOR NON-LOCAL PASSENGERS

This chapter considers airport competition in the presence of substitute air services for non-local origin-destination passengers. One more symmetric congested airport with locals is added to the model in Chapter 3, thus forming a three-airport network. All passengers are origin-destination passengers and take return flights. Locals from the two congested airports only fly between their local airports and the uncongested airport. There is no connection between the two congested airports. Non-locals from the uncongested airports consider the two congested airports as alternatives and fly between the uncongested airport and the congested airport. The two congested airports independently and simultaneously choose between slot and pricing policies and their respective slot quantity and pricing levels to mitigate congestion problem.

By contrast with the model in Chapter 3, the presence of one more congested airport leads to airport competition. More specifically, two congested airports are competing via the non-locals who consider these two congested airports as substitute destinations. Consider the case in which airport profits do not matter. Slots control becomes more effective in the sense that a reduction in local slot quantity can drive more non-locals to use the other congested airport. Therefore, local airports are more inclined to reduce local slot quantities. Consider the case in which airport profits do matter. Local airports are more inclined to reduce the price to attract more non-locals to use local airports because non-locals generate extra profits. This however hurts the other congested airport's profit.

The analysis shows that equilibrium slot quantities are too low to maximize the total welfare of the two congested airports and possibility lead to first-best outcome because of airport competition. The former is true because the local airport has the incentives to drive more non-locals to use the other congested airport by reducing local slot quantity. The latter is true because non-locals are atomistic and, thus, would make excessive use of congested airports in the case of laissez faire. A tightening in the slots can be optimal from the first-best viewpoint. Furthermore, non-locals benefit from airport competition in the sense that the share of inframarginal non-locals at the local airport implied by the first-best slot policies is higher relative to the case in which airport competition is absent.

The analysis also shows that the equilibrium prices in the case of pricing policies are too low to maximize the total welfare of the two airports and too high relative to the first-best prices. The former is true because the local airport has the incentive to attract more non-locals to use local airport by reducing the local airport charge. The latter is true because local airports exploit the non-locals by charging a positive markup on the first-best prices.

Numerical examples are used to illustrate how the presence of airport competition affects the outcomes of slot and pricing policies. It shows that when the level of substitutability is relatively small, slot policies performs better than pricing policies and can even reach the first-best outcome. It has been shown that there may also exist a coordination problem between the two airports.

This chapter is organized as follows. Subchapter 5.1 presents the model. Subchapter 5.2 discusses the demand relationships which are crucial for the policy assessment in Subchapter 5.3. At the end of Subchapter 5.3, numerical examples are used to illustrate how the presence of airport competition affects the outcomes of slot and pricing policies. Subchapter 5.4 concludes this chapter.

5.1 The Model

The model in this chapter extends the two-airport network in Chapter 3 to a three-airport network to focus on how the presence of airport competition affects the equilibrium slot and pricing policies. One more congested airport is added, thus

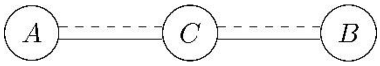

Figure 11: An illustration of the three-airport network. Solid lines: two direct connections for airports A and B 's origin-destination passengers; Dashed lines: two alternative direct connections for airport C 's origin-destination passengers.

forming a three-airport network.

Airports i and j are congested with $\{i, j\} \in \{A, B\}$ and $i \neq j$. Whereas airport C is uncongested. Locals are origin-destination passengers. They only fly between airport i and C, and take return flights. There is no connection between two congested airports in the sense there is no direct flight between airports A and B or transfer flight via C. Passengers originating from airport C consider airports A and B as substitute destinations. Figure 11 illustrates the three-airport network. The solid lines depict the two direct connections for airport i 's origin-destination passengers whereas the dashed lines depict the two alternative direct connections for airport C 's origin-destination passengers.

Passenger quantities of locals and non-locals at airport i are denoted as q_{iC} and q_{Ci} respectively. Passenger quantities are strictly positive on all routes, that is, $q_{iC}, q_{Ci} > 0$. The benefits of locals and non-locals are denoted as $B_i(q_{iC})$ and $B_C(q_{CA}, q_{CB})$, respectively. Benefits are strictly concave in the sense that $\partial^2 B_i / \partial q_{iC}^2 < 0$ and $\partial^2 B_C / \partial q_{Ci}^2 < \partial^2 B_C / \partial q_{CA} \partial q_{CB} < 0$ by assumption. The latter assumption $\partial^2 B_C / \partial q_{CA} \partial q_{CB} < 0$ is used to capture that air services are imperfect substitutes for non-locals.

This chapter continues to compare equilibrium slot with pricing policies. Czerny and Lang (2019) demonstrated that the consideration of both policies can be justified in the sense that slot policies constitute (subgame perfect) equilibrium policies when airport profits do not matter for local governments whereas pricing policies constitute (subgame perfect) equilibrium policies when airport profits matter.

However, before the comparison can be conducted, the rather complicated demand relationships will be analyzed in the next subchapter.

5.2 Demand relationships

This subchapter analyzes the relationships between (i) airport charges and passenger demands and (ii) slot quantities and passenger demands. The following first considers airport charges. The relationship between generalized prices and demands is discussed in a second step for the comparison of the equilibrium prices and first-best prices. The relationship between slot quantities and slot prices are discussed in a third step, which helps analyze the relationship between slot quantities and local and non-local demands in the final step. Altogether, this entire subchapter is crucial for the understanding of the outcomes of equilibrium congestion policies, which will be discussed in the subsequent subchapter.

5.2.1 The effect of airport charges on local and non-local demands

Passengers who travel only use one congested airport. Let η_i with

$$\eta_i = r_i + vT_i \tag{96}$$

denote the generalized prices for passengers who use airport i. Passengers consider generalized prices as given. Demands for trips between airports i and C, denoted as $D_{iC}(r_A, r_B)$ and $D_{Ci}(r_A, r_B)$, respectively, depend on both price r_A and r_B which represent the slot prices in the case of slot policy and the airport charges in the case of pricing policy. The total traffic at local airports is denoted as D_i with $D_i(r_A, r_B) = D_{iC}(r_A, r_B) + D_{Ci}(r_A, r_B)$. Demands are determined by the equilibrium conditions

$$\frac{\partial B_i}{\partial q_{iC}} = \frac{\partial B_C}{\partial q_{Ci}} = \eta_i. \tag{97}$$

Applying Cramer's rule to the equilibrium conditions' system of equations (97) yields:

Lemma 18 *The effect of a marginal increase in* r_i *on demands can be characterized as*

$$(i)\ \frac{\partial D_{iC}}{\partial r_i},\ \frac{\partial D_{Ci}}{\partial r_i} < \frac{\partial D_{jC}}{\partial r_i} < 0 < \frac{\partial D_{Cj}}{\partial r_i},\ (ii)\ \frac{\partial\left(D_{CA}+D_{CB}\right)}{\partial r_i} < 0$$

$$and\ \text{(iii)}\ \frac{\partial D_i}{\partial r_i} < 0 < \frac{\partial D_j}{\partial r_i} < \left|\frac{\partial D_i}{\partial r_i}\right|. \qquad (98)$$

Part (i) first shows that demands of both locals and non-locals at local airport are decreasing in the local airport charge. It second shows that demand of the congested airport's passengers is also decreasing in the local airport charge but by less. It third shows that demand of non-locals who travel between airport C and the other congested airport is increasing in the local airport charge. This is because of the presence of airport competition. Some non-locals who originally used the local airport now switch to the other congested airport when local airport increases the airport charge. It also explains why the demand of the other congested airport's passengers is decreasing in the local airport charge. This is because more non-locals are using the other congested airport when the local airport charge increases, which makes the other congested airport more congested and thus increases the congestion cost. Part (ii) shows that the total demand of non-locals is decreasing in the local airport charge. Part (iii) shows that the overall traffic at local airport is decreasing whereas the overall traffic at the other congested airport is increasing in the local airport charge. It also shows that the local airport charge has a greater impact on the overall traffic at local airport relative to the other congested airport.

5.2.2 The relationship between airport charges and generalized prices

Consider the effect of airport charges on generalized prices. Substituting passenger quantities q_{iC} and q_{Ci} with the demands D_{iC} and D_{Ci} respectively in the generalized prices and taking the derivatives with respect to the airport charge r_i yield:

Lemma 19 *A marginal increase in airport charge* r_i *implies:*

$$0 < \frac{\partial \eta_j}{\partial r_i} < \frac{\partial \eta_i}{\partial r_i} < 1. \tag{99}$$

This lemma first shows that the generalized price for the passengers using the other congested airport is increasing but by less than the generalized price for the passengers using the local airport in the local airport charge. It second shows that the generalized price for the passengers using the local airport is increasing in the local airport charge by less than 1. The generalized price for the passengers using the local airport is the sum of the airport charge and the congestion cost. Whereas the local airport charge is increasing by 1, the local airport's congestion cost is decreasing in the local airport charge. Altogether, the generalized price for the passengers using the local airport is increasing in the local airport charge by less than 1. Whereas the other congested airport charge is independent of local airport charge, but the other congested airport's congestion cost is increasing in the local airport charge. Altogether, the generalized price for the passengers using the other congested airport is increasing in the local airport charge but by less than the generalized price for the passengers using the local airport.

The results seem natural expect that the generalized price for the passengers using the other congested airport is actually increasing in the local airport charge. Lemma 18 mentions that the other congested airport's total traffic is increasing in the local airport charge as well, which implies that the other congested airport's total traffic is increasing in the generalized price for the passengers using the other congested airport. This is only possible in the presence of airport competition because a reduction in the number of non-locals at the local airport increases the marginal benefit of non-locals at the other congested airport. Although the generalized price for the passengers using the other congested airport is increasing in local airport charge, the increase in the marginal benefit exceeds the increase in generalized price, which altogether leads to an increase in the number of non-locals at the other congested airport and thus an overall increase in the total traffic at the other congested airport.

5.2.3 The relationship between slot prices and slot quantities

Slot prices are the shadow prices under slots that would have to be implemented to ensure that airport passenger demands equal the desired slot quantities. The slot price $r_i(S)$ is implicitly determined by

$$\bar{Q}_i - D_i\left(r_A(S), r_B(S)\right) = 0. \tag{100}$$

Applying the Gale-Nikaido Theorem (Gale and Nikaido, 1965) and Cramer's rule to the system of equations (100) yields:

Lemma 20 *(i) There is a unique pair of slot prices matched with each pair of slot quantities and (ii) both local and the other congested airports' slot prices are decreasing in local airport's slot quantities;* and (iii) *non-local airports' slot prices are increasing by less than local airport's slot prices in local airport's slot quantities in absolute value, that is,*

$$\frac{\partial r_i}{\partial \bar{Q}_i} < \frac{\partial r_j}{\partial \bar{Q}_i} < 0. \tag{101}$$

The unique one-to-one pairing relationship between slot prices and slot quantities means that Cramer's rule can be applied to derive the following relationships. The first inequality in (101) shows that local airports' slot prices are decreasing in the local airports' slot quantities. Local airport's total traffic is increasing in slot quantities, which is associated with a reduction in the local airport's slot price to ensure that the passenger demand equals the slot quantity by Lemma 18. Lemma 18 also implies that the other congested airport's demand is decreasing in the local airport's slot quantity. This is because the reduction in the local airport's slot price decreases the other congested airport's demand. To keep the other congested airport's demand unchanged despite the increase in the local airport's slot quantity and the corresponding reduction in the local airport's slot price, the other congested airport's slot price must be decreasing in the local airport's slot quantity. The reduction in the other congested airport's slot price is smaller in absolute value than the reduction in the local airport's slot price.

5.2.4 The effect of slot quantities on local and non-local demands

Airport charges are the decision variables under pricing policies, whereas slot quantities are the decision variables under slot policies. Using Lemma 18 and Lemma 20, the relationships between slot quantities and demands can be described in the following way:

Lemma 21 *A marginal increase of slot quantity* $\bar{Q}_i$ *implies:*

$$(i)\ \frac{\partial D_{Cj}}{\partial \bar{Q}_i} < 0 < \frac{\partial D_{jC}}{\partial \bar{Q}_i} < \frac{\partial D_{iC}}{\partial \bar{Q}_i}, \frac{\partial D_{Ci}}{\partial \bar{Q}_i} < 1 \text{ and } (ii)\ 0 < \frac{\partial \left(D_{CA} + D_{CB}\right)}{\partial \bar{Q}_i}. \tag{102}$$

Part (i) first shows that demand of non-locals at the other congested airport is decreasing in the local airport's slot quantity. This is because of the presence of airport competition. Some non-locals who originally used the other congested airport now switch to the local airport when local airport increases the slot quantity. It also explains why the demand of the other congested airport's passengers is increasing in the local airport's slot quantity, as second shown in part (i). This is because fewer non-locals are using the other congested airport when the local airport slot quantity increases, which allows more passengers originating from the other congested airport to travel. Part (i) third shows that the demands for both locals and non-locals are increasing in the local airport's slot quantity by more than the demand of passengers originating from the other congested airport but by less than 1. Part (ii) shows that the total demand of non-locals are increasing in the local airport's slot quantity.

5.3 Equilibrium Policies

Consumer surplus of locals originating from airport i, denoted as CS_i, is equal to the differences between the benefits and the sum of airport payment and delays costs, which can be written as

$$CS_i(q_i) = B_i(q_i) - q_i \cdot R(\phi_i) - q_i \cdot vT_i(Q_i). \tag{103}$$

The welfare of airport i, denoted as W_i, is equal to the sum of the locals' consumer surplus and the airport's profit (that is, $Q_i \cdot R_i$), which can be simplified and written as

$$W_i(q_{iC}, q_{Ci}) = B_i(q_i) + q_{Ci} \cdot R(\phi_i) - q_{iC} \cdot vT_i(Q_i). \tag{104}$$

Airport C's welfare is equal to consumer surplus. This is because airport C is uncongested and charges a zero price. Therefore, airport C's welfare, denoted as W_C, and non-locals' consumer surplus, denoted as CS_C, can be written as

$$W_C = CS_C = B_C(q_{CA}, q_{CB}) - q_{CA} \cdot R_A(\phi_A) - q_{CB} \cdot R_B(\phi_B) - q_{CA} \cdot vT_A - q_{CB} \cdot vT_B, \tag{105}$$

in which the right-hand side of the second equality are equal to the difference between the total benefits and the sum of total airport payment and delays costs.

The aggregate welfare of the three populated airports, $W_A + W_B + W_C$, is given by the difference between the sum of benefits, $B_A(q_{AC}) + B_B(q_{BC}) + B_C\left(q_{CA}, q_{CB}\right)$, and the sum of local congestion costs, $Q_A vT_A + Q_B vT_B$. The first-best passenger quantities are determined by the first-order conditions $\partial B_i / \partial q_{iC} - \partial(Q_A \cdot vT_A + Q_B \cdot vT_B) / \partial q_{iC} = \partial B_C / \partial q_{Ci} - \partial(Q_A \cdot vT_A + Q_B \cdot vT_B) / \partial q_{Ci} = 0.$ This together with the equilibrium conditions for demands in (97) implies the first-best prices $r_A = D_A vT'_A$, $r_B = D_B vT'_B$. The first-best prices $D_i vT'_i$ represent the marginal external congestion costs for passengers who use airport i.

Assume that the best responses in terms of slot quantities and prices are determined by the first-order conditions, $\partial W_i / \partial \overline{Q}_i = 0$ and $\partial W_i / \partial r_i = 0$. Using the equilibrium conditions for demands in (97), the first-order conditions for the best responses and thus the equilibrium slot quantities and prices in airport competition are analogue to the first-order conditions and welfare-maximizing slot quantities and prices in Chapter 3 in structure. Therefore, the results and proofs of Proposition 14 and Proposition 15 carry over here in the sense that

Proposition 27 *Assessments of equilibrium slot policies and pricing policies are unaffected by the presence of airport competition.*

The only difference between the current model and the model in Chapter 3 is the presence of airport competition, which implies that one congested airport's congestion policy will produce externality on the other congested airport. This has been reflected by the demand relationships in the previous subchapter and will be discussed in detail as follows.

5.3.1 Welfare externality under equilibrium slot policies

Consider $\phi_A = \phi_B = S$. To capture the externality of local airport's congestion policy, especially the welfare externality of the local airport's slot policy on the other congested airport, $\partial W_j / \partial \bar{Q}_i$ is used when quantities are the decision variables. Using the equilibrium conditions for demands in (97), in equilibrium, the welfare externality $\partial W_j / \partial \bar{Q}_i$ is given by

$$\frac{\partial W_j}{\partial \bar{Q}_i} = r_i(S)\frac{\partial D_{jC}}{\partial \bar{Q}_i}, \tag{106}$$

in which the right-hand side is strictly positive if $r_i(S) > 0$ because Lemma 21 mentions that $\partial D_{jC} / \partial \bar{Q}_i > 0$. The slot quantity $\bar{Q}_i$ is assumed to be finite, which implies that $r_i(S)$ is indeed positive. This means that local airports' slot policies always lead to positive welfare externalities. The best responses in equilibrium imply that $\partial W_i / \partial \bar{Q}_i = 0$. Given that the contraction condition for best responses in terms of slot quantities is satisfied, it implies that

Proposition 28 *The welfare externalities are positive and equilibrium slot quantities are too low to maximize the total welfare of the two congested airports, that is,*

$$\frac{\partial\left(W_A + W_B\right)}{\partial \bar{Q}_i} > 0. \tag{107}$$

This proposition is true because of the presence of non-locals and the airport competition. Consider the case in which non-locals are present but airport competition is absent. This case is equivalent to the model in Chapter 3, which shows that non-locals are taking up the local slot resources but not contributing to the local welfare. Therefore, local airport has the incentive to reduce local slot quantity relative to the case in which non-locals would be absent. Given symmetry, this means both airports would have tightened slot quantities in the absence of airport competition. Consider the case in which non-locals and airport competition are both present. In this case, non-locals will not stop traveling in response to a tightening of local slot quantity. Instead, some non-locals can switch to travelling to the other congested airport, making slot controls more effective tools for controlling local congestion. In equilibrium, slot quantities are too low to maximize the total welfare of two congested airports.

Non-locals are atomistic and, thus, make excessive use of congested airports in the case of laissez faire. The equilibrium slot quantities that are too low to maximize the total welfare of two congested airports can, therefore, lead to the first-best outcome. Proposition 14 carries over here in the sense that it is still the share of inframarginal and marginal locals that matter in the assessment of slot policies. The only difference is that, in airport competition, local airport's slot policy has an impact on the other congested airport, which is captured by welfare externalities.

Interestingly, when slot policies are first-best, the share of inframarginal non-locals at the local airport is higher. To see this, consider the share of inframarginal and marginal non-locals implied by the first-best slot policies, which are equal by

Proposition 27 and can be written as

$$\frac{D_{Ci}}{D_i} = \frac{\partial D_{Ci}}{\partial r_i}\frac{\partial r_i}{\partial \overline{Q}_i} + \frac{\partial D_{Ci}}{\partial r_j}\frac{\partial r_j}{\partial \overline{Q}_i}. \tag{108}$$

The left-hand side captures the share of inframarginal non-locals. The right-hand side captures the share of marginal non-locals. The first-best slot policies in equilibrium implies that the two shares are equal. Specifically, the first term on the right-hand side is present both in absence of airport competition as shown in Chapter 3 and in the presence of airport competition. It captures how an increase in the local airport's slot quantity reduces local airport's slot price and the corresponding increase in the demand of non-locals. The second term is only present in the presence of airport competition, which captures how an increase in the local airport's slot quantity reduces the other airport's slot price and the corresponding increase in the demand of non-locals. Lemma 18 mentions that $\partial D_{Ci} / \partial r_j > 0$ and Lemma 20 mentions that $\partial \overline{Q}_i / \partial r_j < 0$, which altogether implies that the second term is positive. This leads to:

Proposition 29 *The share of inframarginal non-locals implied by the first-best slot policies in the presence of airport competition is higher relative to the case in which airport competition is absent.*

This is because, in the presence of airport competition, non-locals do not stop travelling in response to a tightening of local airport's slot policy. Some non-locals can switch to travelling to the other congested airport. Therefore, the share of non-locals is higher in airport competition relative to the case in which airport competition is absent.

5.3.2 Welfare externality under equilibrium pricing policies

Consider $\phi_A = \phi_B = P$. To capture the externality of local airport's congestion policy, especially the welfare externality of the local airport's pricing policy on the other congested airport, $\partial W_j / \partial r_i$ is used when prices are the decision variables. Using the equilibrium conditions for demands in (97), in equilibrium, the welfare externality $\partial W_j / \partial r_i$ is given by

$$\frac{\partial W_j}{\partial r_i} = D_{Cj}. \tag{109}$$

The right-hand side is strictly positive. This means that local pricing policies always lead to positive welfare externalities. The best responses in equilibrium imply that $\partial W_i / \partial r_i = 0$. Given that the contraction condition for best responses in terms of prices is satisfied, it implies that

Proposition 30 *The welfare externalities are positive and equilibrium prices are too low to maximize the total welfare of the two congested airports, that is,*

$$\frac{\partial \left(W_A + W_B\right)}{\partial r_i} > 0. \tag{110}$$

The intuition is that, if airport profits do matter, two congested airports are competing for non-locals in the sense that both congested airports have the incentives to lower the airport charges to attract more non-locals to use local airports by Lemma 18. Therefore, equilibrium prices are relatively lower in the presence of non-locals and airport competition.

Equilibrium airport charges are analogue in structure to the welfare-maximizing airport charge in Chapter 3, which are equal to the sum of first-best price and a positive markup. However, the markup in the presence of airport competition is smaller. Consider the model in Chapter 3 in the absence of airport competition. The local airport represents a monopoly. Non-locals who want to fly do not have alternatives but to use the only congested airport. This implies that the price elasticity of demand of non-locals is low in the absence of airport competition, which allows the congested airport to charge a high markup. The presence of airport competition forms a Bertrand competition between the two congested airports in a duopoly. Non-locals who want to fly have alternatives to choose from. Both congested airports care about profits and thus compete for non-local passengers. This implies that the price elasticity of demand of non-locals is relatively higher in the presence of airport competition in absolute value, which only allows the two congested airports to charge a lower markup. Therefore,

Proposition 31 *In the presence of airport competition, equilibrium prices are too high relative to first-best prices but lower relative to the case in which airport competition is absent.*

The following example illustrates how the presence of non-locals and airport competition affect the relative performance of slot and pricing policies from the two congested airports' and first-best viewpoints.

Example 5 The benefits of travelling are given by

$$B_i(q_{iC}) = \alpha \cdot q_{iC} - \frac{1}{2}\beta \cdot q_{iC}^2 \tag{111}$$

and

$$B_C(q_{CA}, q_{CB}) = \alpha_1 \cdot q_{CA} + \alpha_2 \cdot q_{CB} - \frac{1}{2}\left(\beta_1 \cdot q_{CA}^2 + \beta_2 \cdot q_{CB}^2\right) - \gamma \cdot q_{CA} \cdot q_{CB} \tag{112}$$

for airports i and C, respectively. Parameters $\beta = -\partial^2 B_i / \partial q_{iC}^2$, $\beta_1 = -\partial^2 B_C / \partial q_{CA}^2$, $\beta_2 = -\partial^2 B_C / \partial q_{CB}^2$ and $\gamma = -\partial^2 B_C / \partial q_{CA} \partial q_{CB}$ are used and given by $\alpha = 4/5$, $\beta = 3/2$, $\alpha_1 = \alpha_2 = 1$, $\beta_1 = \beta_2 = 2$, and $v = 3/5$. Parameter γ is used to capture the level of substitutability of the air services for the non-locals. To illustrate the relative performance of slot and pricing policies under different scenarios, symmetry and the following notations are used: (i) the total welfare of the two congested airports given the slot quantities or prices that maximize the total welfare of the two congested airports is denoted as $W_2^*(\phi_i)$, (ii) the first-best welfare is denoted as W_3^* and (iii) the

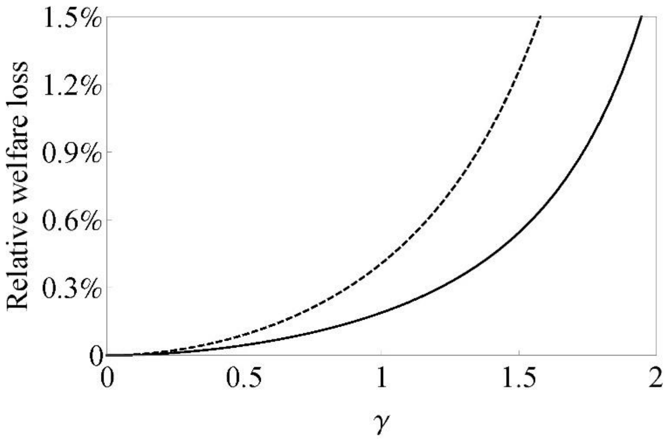

Figure 12: Relative welfare loss in percent in the presence of airport competition under slots (dashed line) and pricing (solid line) from the two airports' viewpoint depending on substitution parameter γ relative to the absence of airport competition.

equilibrium local welfares are denoted as $W_i(\phi_i)$ and $W_C(\phi_i)$ for airports i and C, respectively.

Figure 12 illustrates the relative welfare losses of slot (dashed line) and pricing policies (solid line) depending on substitution parameter γ in percent from the two congested airports' viewpoint relative to the absence of airport competition. Specifically, the relative welfare losses are captured by $\left(W_2^*(\phi_i) - 2W_i(\phi_i)\right) / W_2^*(\phi_i)$. The dashed and solid lines show that the relative welfare loss of slot policies and pricing policies are positive except when $\gamma = 0$. This means that in the presence of airport competition, equilibrium congestion policies can never maximize the total welfare of the two congested airports. When $\gamma = 0$ which means that two congested airports are operating in isolation, both policies lead to zero welfare loss from the two congested airports' viewpoint. The figure also shows that the relative welfare loss of pricing policies is lower than slot policies. This is at the cost of non-locals who pay to local airports under pricing policies.

Figure 13 illustrates the relative welfare losses of slot (dashed line) and pricing policies (solid line) depending on substitution parameter γ in percent from the first-best viewpoint. Specifically, the relative welfare losses are captured by

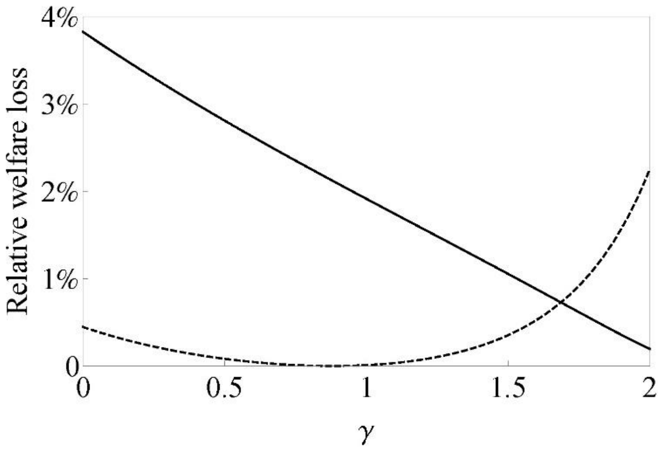

Figure 13: Relative welfare loss in percent under slots (dashed line) and pricing (solid line) from the first-best viewpoint depending on substitution parameter γ.

$\left(W_3^* - 2W_i(\phi_i) - W_C(\phi_i)\right)/W_3^*$. The dashed line shows that the relative welfare loss of slot policies is positive. When $\gamma = \left(\sqrt{3661} - 35\right)/29$ (≈ 0.88), the relative welfare loss of slot policies is zero, leading to first-best outcome. The solid line shows that the relative welfare loss of pricing policies is always positive. This figure also shows that there is a critical point at $\gamma \approx 1.69$ where relative welfare losses of slot and pricing policies are the same. Any other value of γ implies that there might be a coordination problem between the two congested airports in the sense that: (i) if profits matter and γ is on the left-hand side of the critical point, the two congested airports will choose pricing polices although they should have chosen slot policies. This is because slot policies perform better than pricing policies and can even reach first-best outcome; (ii) if profits do not matter and γ is on the right-hand side of the critical point, the two congested airports will choose slot polices although they should have chosen pricing policies. This is because pricing policies perform better than slot policies. ■

5.4 Summary

This chapter considered airport competition in the presence of substitute air services for non-local origin-destination passengers. One more symmetric congested airport with locals was added introduced to the model in Chapter 3, thus forming a three-airport network. All passengers were origin-destination passengers and took return flights. Locals from the two congested airports only flew between their local airports and the uncongested airport. There was no connection between the two congested airports. Non-locals from the uncongested airports considered the two congested airports as alternatives and fly between the uncongested airport and the congested airport. The two congested airports independently and simultaneously chose between slot and pricing policies and their respective slot quantity and pricing levels to mitigate congestion problem.

By contrast with the model in Chapter 3, the presence of one more congested airport led to airport competition. More specifically, two congested airports were competing via the non-locals who considered these two congested airports as substitute destinations. The results showed that equilibrium slot quantities were too low to maximize the total welfare of the two congested airports and possibility led to first-best outcome because of airport competition. The former was true because the local airport had the incentives to drive more non-locals to use the other congested airport by reducing local slot quantity. The latter was true because non-locals were atomistic and, thus, would make excessive use of congested airports in the case of laissez faire. A tightening in the slots could be optimal from the first-best viewpoint. Furthermore, non-locals benefited from airport competition in the sense that the share of inframarginal non-locals at the local airport implied by the first-best slot policies was higher relative to the case in which airport competition was absent.

The results also showed that the equilibrium prices in the case of pricing policies were too low to maximize the total welfare of the two airports and too high relative to the first-best prices. The former was true because the local airport had the incentive to attract more non-locals to use local airport by reducing the local airport charge. The latter was true because local airports exploited the non-locals by charging a positive markup on the first-best prices.

Numerical examples were used to illustrate how the presence of airport competition affected the outcomes of slot and pricing policies. It showed that when the level of substitutability was relatively small, slot policies performed better than pricing policies and could even reach the first-best outcome. It has been shown that there might also exist a coordination problem between the two airports.

CHAPTER 6

CONCLUSIONS

This dissertation consisted of four studies on the assessment of decentralized welfare-maximizing airport congestion policies involving slot policy and pricing policy. The studies concentrated on origin-destination passengers who could be locals or non-locals. Passengers could choose from one or two destinations, which might or might not be considered as substitutes. It has been shown that even a small variation in these dimensions could fundamentally change the analysis and the assessment of the congestion policies.

Chapter 2 arose from Czerny and Lang (2019) and considered networks with two or three complementary airports. In each case, two congested airports were present and independently chose between slot and pricing policies. The results showed that equilibrium policies involved slots when airport profits did not matter and pricing policies when airport profits did matter. This justified the consideration of slots and pricing policies in the whole dissertation. The results further showed that the equilibrium slot policies reached the first-best passenger quantities when congestion effects were absent. Otherwise, equilibrium slot policies would lead to excessive and equilibrium pricing policies to too low passenger quantities relative to the first best outcome. The analysis formally distinguished the sources for the different outcomes under slot and pricing policies by distinguishing between a variable effect and a distribution effect. The variable effect captured that decision variables were quantities in the case of slot policies and prices in the case of pricing policies. The distribution effect captured that airport slot allocation was based on grandfather rules.

Chapter 3 arose from Lang and Czerny (2020a) and considered a stylized airport network with two airports designed to clearly identify the role of local and non-local passengers. The results showed that the local welfare-maximizing slot quantity could coincide with the first-best outcome whereas this was impossible in the case of pricing policy. Whether the outcomes coincided in the case of slot policy depended on the shares of inframarginal and marginal local and non-local passengers. The intuition was developed based on cost-benefit ratio as measured by the marginal external congestion cost divided by the ticket price. The results provided clear insights on the reasons why slot quantities were found to be excessive in the three-airport network considered in Chapter 2.

Chapter 4 arose from Lang and Czerny (2020b). It developed and analyzed an extended framework of the three-airport network considered in Chapter 2. This extended framework involved a variation of the demand structure in the sense that the air services offered at the congested airports were considered as imperfect substitutes whereas they were not considered as substitutes in Chapter 2. The results showed that the presence of substitute air services was a necessary condition for equilibrium slot quantities to reach the first-best outcome. The results derived from Chapter 3 helped understand the reasons why equilibrium slot quantities could lead to first-best outcome. Whereas equilibrium pricing levels would always be too high relative to the first-best prices independent of the presence or absence of substitute air services.

By contrast with Chapter 4, Chapter 5 arose from Lang and Czerny (2020c) and proceeded with the consideration of substitute air services for non-local passengers in a three-airport network to concentrate on the role of airport competition. The results showed that airport competition would lead to too low equilibrium slot quantities in the case of slot policies, or too low equilibrium prices in the case of pricing policies, to maximize the total welfare of the two congested airports. The non-local passengers benefited from the airport competition compared with the case in which airport competition was absent. The results further showed that slot policies could lead to first-best outcome. Whereas pricing policies were too strict with too high equilibrium prices relative to the first-best outcome.

This dissertation has been considering perfectly competitive airline markets. There are many situations in which airline markets are oligopolistic and airlines internalize the congestion. One avenue for future research could be looking into the role of airline market power for the welfare implications of slot and pricing policies. Another avenue for future research would be to investigate airport networks with (non-local) transfer passengers. Capturing transfer passengers requires a different set of assumptions because they use the congested airport twice as often as origin-destination passengers, and airports typically discriminate between origin-destination and transfer passengers in terms of airport charges (for example, Lin and Zhang, 2016). Airport physical capacity investment is abstracted away from this dissertation, which, however, could be incorporated into the future study. There are many airports such as London Heathrow Airport (LHR) and Hong Kong International Airport (HKIA) are constructing new runways, aiming to mitigate the congestion problems in the long run. This suggests that airport profits are important and thus pricing policy becomes more relevant. In this dissertation, non-aeronautical revenue has been abstracted away. The presence of non-aeronautical revenues in many airports in practice deserve attention in the future study. Because this may change the assessment of congestion policies in the sense that local airport has the incentive to attract the non-locals to boost the non-aeronautical revenues and therefore must balance among the congestion costs, aeronautical revenues and non-aeronautical revenues arising from the non-locals. Finally, it would be useful to empirically estimate the shares of inframarginal and marginal locals of congested airports to derive a better understanding of their incentives to implement slot policies.

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APPENDIX

A. 1 Proof of Lemma 1

Let x and y represent the equilibrium conditions:

$$x = Q_i - q_{ij} - q_{ji} = 0, \tag{a.1}$$
$$y = B_i' - B_j' = 0. \tag{a.2}$$

Totally differentiating leads to

$$dx = dQ_i - dq_{ij} - dq_{ji} = 0, \tag{a.3}$$
$$dy = B_i'' \cdot dq_{ij} - B_j'' \cdot dq_{ji} = 0. \tag{a.4}$$

After rearranging, this system of equations can be written in matrix form as

$$\begin{pmatrix} -1 & -1 \\ B_i'' & -B_j'' \end{pmatrix} \begin{pmatrix} dq_{ij} \\ dq_{ji} \end{pmatrix} = dQ_i \begin{pmatrix} -1 \\ 0 \end{pmatrix}. \tag{a.5}$$

Cramer's Rule can be applied to derive how local passenger quantities change in total passenger quantities:

$$\frac{dq_{ij}}{dQ_i} = \frac{dq_{ij}}{dQ_j} = \frac{B_j''}{B_A'' + B_B''} > 0. \tag{a.6}$$

Substituting passenger quantities with demands completes the proof.

A. 2 Proof of Proposition 2

The (Nash) equilibrium slot quantities are defined by the airports' best responses where airports have no incentive to either increase or decrease slot quantities when their objectives are to maximize local consumer surplus. First, consider $\bar{Q}_A = \bar{Q}_B < Q^*$. In this case, airports have no incentive to individually increase slot quantities because the own total passenger quantity would be limited and determined by the other airport's slot quantity and, thus, remains unchanged. Airports also have no incentive to decrease slot quantities because this would further reduce their already too low local passenger quantities. Therefore, a scenario where both airports choose the same slot quantities and these slot quantities imply total passenger quantities that are smaller than the first-best total passenger quantity, constitutes an equilibrium solution. Second, consider $\bar{Q}_A, \bar{Q}_B \geq Q^*$. In this case, the first-best passenger quantities are implemented, and slot prices are equal to zero. This means that an increase in slot quantities cannot further reduce slot prices and, thus, leaves local welfares unchanged. Airports also have no incentive to decrease slot quantities beyond the first-best passenger quantity because this would reduce local welfares. This shows that both cases $\bar{Q}_A = \bar{Q}_B < Q^*$ and $\bar{Q}_A, \bar{Q}_B \geq Q^*$ constitute equilibrium constellations.

To show that these constellations determine the full set of equilibrium cases, consider $\bar{Q}_i < \bar{Q}_j < Q^*$. In this case, airport i could increase slot quantity all the way to $\bar{Q}_j$, which would increase local welfare because $\bar{Q}_j < Q^*$. Thus, this is not an equilibrium constellation. Finally, consider $\bar{Q}_i < Q^* \leq \bar{Q}_j$. In this case, airport i could increase its slot quantity all the way to first-best passenger quantity Q^*, or even beyond first-best total passenger quantity, to increase and maximize local welfare. Thus, this cannot be an equilibrium constellation, which completes the proof.

A. 3 Proof of Lemma 2

Let x_{AB}, x_{AC}, x_{BA}, and x_{BC} represent the equilibrium conditions:

$$x_{AB} = \frac{\partial B_A}{\partial q_{AB}} - \left(r_A + r_B\right) = 0, \tag{a.7}$$

$$x_{AC} = \frac{\partial B_A}{\partial q_{AC}} - r_A = 0, \tag{a.8}$$

$$x_{BA} = \frac{\partial B_B}{\partial q_{BA}} - \left(r_A + r_B\right) = 0, \tag{a.9}$$

$$x_{BC} = \frac{\partial B_B}{\partial q_{BC}} - r_B = 0. \tag{a.10}$$

Totally differentiating leads to

$$dx_{AB} = \frac{\partial x_{AB}}{\partial q_{AB}} dq_{AB} + \frac{\partial x_{AB}}{\partial q_{AC}} dq_{AC} + \frac{\partial x_{AB}}{\partial q_{BA}} dq_{BA} + \frac{\partial x_{AB}}{\partial q_{BC}} dq_{BC} + \frac{\partial x_{AB}}{\partial r_A} dr_A = 0, \tag{a.11}$$

$$dx_{AC} = \frac{\partial x_{AC}}{\partial q_{AB}} dq_{AB} + \frac{\partial x_{AC}}{\partial q_{AC}} dq_{AC} + \frac{\partial x_{AC}}{\partial q_{BA}} dq_{BA} + \frac{\partial x_{AC}}{\partial q_{BC}} dq_{BC} + \frac{\partial x_{AC}}{\partial r_A} dr_A = 0, \tag{a.12}$$

$$dx_{BA} = \frac{\partial x_{BA}}{\partial q_{AB}} dq_{AB} + \frac{\partial x_{BA}}{\partial q_{AC}} dq_{AC} + \frac{\partial x_{BA}}{\partial q_{BA}} dq_{BA} + \frac{\partial x_{BA}}{\partial q_{BC}} dq_{BC} + \frac{\partial x_{BA}}{\partial r_A} dr_A = 0, \tag{a.13}$$

$$dx_{BC} = \frac{\partial x_{BC}}{\partial q_{AB}} dq_{AB} + \frac{\partial x_{BC}}{\partial q_{AC}} dq_{AC} + \frac{\partial x_{BC}}{\partial q_{BA}} dq_{BA} + \frac{\partial x_{BC}}{\partial q_{BC}} dq_{BC} + \frac{\partial x_{BC}}{\partial r_A} dr_A = 0. \tag{a.14}$$

After rearranging, this system of equations can be written in matrix form as

$$\begin{pmatrix} \frac{\partial x_{AB}}{\partial q_{AB}} & \frac{\partial x_{AB}}{\partial q_{AC}} & \frac{\partial x_{AB}}{\partial q_{BA}} & \frac{\partial x_{AB}}{\partial q_{BC}} \\ \frac{\partial x_{AC}}{\partial q_{AB}} & \frac{\partial x_{AC}}{\partial q_{AC}} & \frac{\partial x_{AC}}{\partial q_{BA}} & \frac{\partial x_{AC}}{\partial q_{BC}} \\ \frac{\partial x_{BA}}{\partial q_{AB}} & \frac{\partial x_{BA}}{\partial q_{AC}} & \frac{\partial x_{BA}}{\partial q_{BA}} & \frac{\partial x_{BA}}{\partial q_{BC}} \\ \frac{\partial x_{BC}}{\partial q_{AB}} & \frac{\partial x_{BC}}{\partial q_{AC}} & \frac{\partial x_{BC}}{\partial q_{BA}} & \frac{\partial x_{BC}}{\partial q_{BC}} \end{pmatrix} \begin{pmatrix} dq_{AB} \\ dq_{AC} \\ dq_{BA} \\ dq_{BC} \end{pmatrix} = dr_A \begin{pmatrix} -\frac{\partial x_{AB}}{\partial r_A} \\ -\frac{\partial x_{AC}}{\partial r_A} \\ -\frac{\partial x_{BA}}{\partial r_A} \\ -\frac{\partial x_{BC}}{\partial r_A} \end{pmatrix} = dr_A \begin{pmatrix} 1 \\ 1 \\ 1 \\ 0 \end{pmatrix}. \tag{a.15}$$

Let Ψ denote the determinant of the Jacobian on the left-hand side of first equality, which can be written as

$$\Psi = \det \begin{pmatrix} \frac{\partial x_{AB}}{\partial q_{AB}} & \frac{\partial x_{AB}}{\partial q_{AC}} & \frac{\partial x_{AB}}{\partial q_{BA}} & \frac{\partial x_{AB}}{\partial q_{BC}} \\ \frac{\partial x_{AC}}{\partial q_{AB}} & \frac{\partial x_{AC}}{\partial q_{AC}} & \frac{\partial x_{AC}}{\partial q_{BA}} & \frac{\partial x_{AC}}{\partial q_{BC}} \\ \frac{\partial x_{BA}}{\partial q_{AB}} & \frac{\partial x_{BA}}{\partial q_{AC}} & \frac{\partial x_{BA}}{\partial q_{BA}} & \frac{\partial x_{BA}}{\partial q_{BC}} \\ \frac{\partial x_{BC}}{\partial q_{AB}} & \frac{\partial x_{BC}}{\partial q_{AC}} & \frac{\partial x_{BC}}{\partial q_{BA}} & \frac{\partial x_{BC}}{\partial q_{BC}} \end{pmatrix} = \det \begin{pmatrix} \frac{\partial^2 B_A}{\partial q_{AB}^2} & 0 & 0 & 0 \\ 0 & \frac{\partial^2 B_A}{\partial q_{AC}^2} & 0 & 0 \\ 0 & 0 & \frac{\partial^2 B_B}{\partial q_{BA}^2} & 0 \\ 0 & 0 & 0 & \frac{\partial^2 B_B}{\partial q_{BC}^2} \end{pmatrix}$$

$$= \frac{\partial^2 B_A}{\partial q_{AB}^2} \frac{\partial^2 B_A}{\partial q_{AC}^2} \frac{\partial^2 B_B}{\partial q_{BA}^2} \frac{\partial^2 B_B}{\partial q_{BC}^2} > 0. \tag{a.16}$$

To derive how demands change in airport price r_A, Cramer's Rule can be applied:

$$\frac{dq_{AB}}{dr_A}=\frac{1}{\Psi}\det\begin{pmatrix}-\frac{\partial x_{AB}}{\partial r_A} & \frac{\partial x_{AB}}{\partial q_{AC}} & \frac{\partial x_{AB}}{\partial q_{BA}} & \frac{\partial x_{AB}}{\partial q_{BC}}\\ -\frac{\partial x_{AC}}{\partial r_A} & \frac{\partial x_{AC}}{\partial q_{AC}} & \frac{\partial x_{AC}}{\partial q_{BA}} & \frac{\partial x_{AC}}{\partial q_{BC}}\\ -\frac{\partial x_{BA}}{\partial r_A} & \frac{\partial x_{BA}}{\partial q_{AC}} & \frac{\partial x_{BA}}{\partial q_{BA}} & \frac{\partial x_{BA}}{\partial q_{BC}}\\ -\frac{\partial x_{BC}}{\partial r_A} & \frac{\partial x_{BC}}{\partial q_{AC}} & \frac{\partial x_{BC}}{\partial q_{BA}} & \frac{\partial x_{BC}}{\partial q_{BC}}\end{pmatrix}=\frac{1}{\Psi}\det\begin{pmatrix}1 & 0 & 0 & 0\\ 1 & \frac{\partial^2 B_A}{\partial q_{AC}^2} & 0 & 0\\ 1 & 0 & \frac{\partial^2 B_B}{\partial q_{BA}^2} & 0\\ 0 & 0 & 0 & \frac{\partial^2 B_B}{\partial q_{BC}^2}\end{pmatrix}$$

$$=\frac{1}{\Psi}\frac{\partial^2 B_A}{\partial q_{AC}^2}\frac{\partial^2 B_B}{\partial q_{BA}^2}\frac{\partial^2 B_B}{\partial q_{BC}^2}=1/\frac{\partial^2 B_A}{\partial q_{AB}^2}<0. \tag{a.17}$$

Similarly,

$$\frac{dq_{AC}}{dr_A}=1/\frac{\partial^2 B_A}{\partial q_{AC}^2}<0, \tag{a.18}$$

$$\frac{dq_{BA}}{dr_A}=1/\frac{\partial^2 B_B}{\partial q_{BA}^2}<0, \tag{a.19}$$

$$\frac{dq_{BC}}{dr_A}=0. \tag{a.20}$$

Substituting passenger quantities with demands completes the proof. Analogous results hold for how demands change in r_B.

A. 4 Proof of Lemma 3

Totally differentiating (18) yields

$$d\left(\bar{Q}_A-D_A\right)=\frac{\partial\left(\bar{Q}_A-D_A\right)}{\partial r_A}dr_A+\frac{\partial\left(\bar{Q}_A-D_A\right)}{\partial r_B}dr_B+\frac{\partial\left(\bar{Q}_A-D_A\right)}{\partial \bar{Q}_A}d\bar{Q}_A \tag{a.21}$$

$$=-\frac{\partial D_A}{\partial r_A}dr_A-\frac{\partial D_A}{\partial r_B}dr_B+d\bar{Q}_A=0, \tag{a.22}$$

$$d\left(\bar{Q}_B-D_B\right)=\frac{\partial\left(\bar{Q}_B-D_B\right)}{\partial r_A}dr_A+\frac{\partial\left(\bar{Q}_B-D_B\right)}{\partial r_B}dr_B+\frac{\partial\left(\bar{Q}_B-D_B\right)}{\partial \bar{Q}_A}d\bar{Q}_A \tag{a.23}$$

$$=-\frac{\partial D_B}{\partial r_A}dr_A-\frac{\partial D_B}{\partial r_B}dr_B=0. \tag{a.24}$$

In matrix form, this can be rewritten as

$$\begin{pmatrix}-\frac{\partial D_A}{\partial r_A} & -\frac{\partial D_A}{\partial r_B}\\ -\frac{\partial D_B}{\partial r_A} & -\frac{\partial D_B}{\partial r_B}\end{pmatrix}\begin{pmatrix}dr_A\\ dr_B\end{pmatrix}=-\begin{pmatrix}1\\ 0\end{pmatrix}d\bar{Q}_A. \tag{a.25}$$

The 2×2 matrix on the left-hand side is positive definite, which ensures that each pair of slots is mapped with a unique pair of slot prices by the Gale-Nikaido Theorem (Gale and Nikaido, 1965). This proves part (i).

Applying Cramer's rule shows that an increase in the own airport's slot quantity reduces the own slot price and increases the other airport's slot price:

$$\frac{dr_i}{d\bar{Q}_i} = \frac{\dfrac{\partial D_j}{\partial r_j}}{\dfrac{\partial D_A}{\partial r_A}\dfrac{\partial D_B}{\partial r_B} - \dfrac{\partial D_B}{\partial r_A}\dfrac{\partial D_A}{\partial r_B}} < 0 \text{ and } \frac{dr_j}{d\bar{Q}_i} = \frac{-\dfrac{\partial D_j}{\partial r_i}}{\dfrac{\partial D_A}{\partial r_A}\dfrac{\partial D_B}{\partial r_B} - \dfrac{\partial D_B}{\partial r_A}\dfrac{\partial D_A}{\partial r_B}} > 0, \tag{a.26}$$

where the right-hand of the first equation is greater than the right-hand side of the second equation in absolute values by Lemma 2.

A. 5 Proof of Lemma 4

Let y_{AB}, y_{AC}, y_{BA}, and y_{BC} represent the equilibrium conditions:

$$y_{AB} = \frac{\partial B_A}{\partial q_{AB}} - \left(r_A + r_B + v\left(T_A + T_B\right)\right) = 0, \tag{a.27}$$

$$y_{AC} = \frac{\partial B_A}{\partial q_{AC}} - \left(r_A + vT_A\right) = 0, \tag{a.28}$$

$$y_{BA} = \frac{\partial B_B}{\partial q_{BA}} - \left(r_A + r_B + v\left(T_A + T_B\right)\right) = 0, \tag{a.29}$$

$$y_{BC} = \frac{\partial B_B}{\partial q_{BC}} - \left(r_B + vT_B\right) = 0. \tag{a.30}$$

Totally differentiating, and after rearranging, this leads to a system of equations in matrix form as

$$\begin{pmatrix} \dfrac{\partial y_{AB}}{\partial q_{AB}} & \dfrac{\partial y_{AB}}{\partial q_{AC}} & \dfrac{\partial y_{AB}}{\partial q_{BA}} & \dfrac{\partial y_{AB}}{\partial q_{BC}} \\ \dfrac{\partial y_{AC}}{\partial q_{AB}} & \dfrac{\partial y_{AC}}{\partial q_{AC}} & \dfrac{\partial y_{AC}}{\partial q_{BA}} & \dfrac{\partial y_{AC}}{\partial q_{BC}} \\ \dfrac{\partial y_{BA}}{\partial q_{AB}} & \dfrac{\partial y_{BA}}{\partial q_{AC}} & \dfrac{\partial y_{BA}}{\partial q_{BA}} & \dfrac{\partial y_{BA}}{\partial q_{BC}} \\ \dfrac{\partial y_{BC}}{\partial q_{AB}} & \dfrac{\partial y_{BC}}{\partial q_{AC}} & \dfrac{\partial y_{BC}}{\partial q_{BA}} & \dfrac{\partial y_{BC}}{\partial q_{BC}} \end{pmatrix} \begin{pmatrix} dq_{AB} \\ dq_{AC} \\ dq_{BA} \\ dq_{BC} \end{pmatrix} = dr_A \begin{pmatrix} -\dfrac{\partial y_{AB}}{\partial r_A} \\ -\dfrac{\partial y_{AC}}{\partial r_A} \\ -\dfrac{\partial y_{BA}}{\partial r_A} \\ -\dfrac{\partial y_{BC}}{\partial r_A} \end{pmatrix} = dr_A \begin{pmatrix} 1 \\ 1 \\ 1 \\ 0 \end{pmatrix}. \tag{a.31}$$

Using symmetry, the Jacobian on the left-hand side of first equality can be rewritten as

$$
\begin{pmatrix}
\frac{\partial y_{AB}}{\partial q_{AB}} & \frac{\partial y_{AB}}{\partial q_{AC}} & \frac{\partial y_{AB}}{\partial q_{BA}} & \frac{\partial y_{AB}}{\partial q_{BC}} \\
\frac{\partial y_{AC}}{\partial q_{AB}} & \frac{\partial y_{AC}}{\partial q_{AC}} & \frac{\partial y_{AC}}{\partial q_{BA}} & \frac{\partial y_{AC}}{\partial q_{BC}} \\
\frac{\partial y_{BA}}{\partial q_{AB}} & \frac{\partial y_{BA}}{\partial q_{AC}} & \frac{\partial y_{BA}}{\partial q_{BA}} & \frac{\partial y_{BA}}{\partial q_{BC}} \\
\frac{\partial y_{BC}}{\partial q_{AB}} & \frac{\partial y_{BC}}{\partial q_{AC}} & \frac{\partial y_{BC}}{\partial q_{BA}} & \frac{\partial y_{BC}}{\partial q_{BC}}
\end{pmatrix}
= \begin{pmatrix}
\frac{\partial^2 B_A}{\partial q_{AB}^2} - 2vT_A' & -vT_A' & -2vT_A' & -vT_A' \\
-vT_A' & \frac{\partial^2 B_A}{\partial q_{AC}^2} - vT_A' & -vT_A' & 0 \\
-2vT_A' & -vT_A' & \frac{\partial^2 B_A}{\partial q_{AB}^2} - 2vT_A' & -vT_A' \\
-vT_A' & 0 & -vT_A' & \frac{\partial^2 B_A}{\partial q_{AC}^2} - vT_A'
\end{pmatrix}. \tag{a.32}
$$

The determinant of the Jacobian can be written as

$$
\det\begin{pmatrix}
\frac{\partial y_{AB}}{\partial q_{AB}} & \frac{\partial y_{AB}}{\partial q_{AC}} & \frac{\partial y_{AB}}{\partial q_{BA}} & \frac{\partial y_{AB}}{\partial q_{BC}} \\
\frac{\partial y_{AC}}{\partial q_{AB}} & \frac{\partial y_{AC}}{\partial q_{AC}} & \frac{\partial y_{AC}}{\partial q_{BA}} & \frac{\partial y_{AC}}{\partial q_{BC}} \\
\frac{\partial y_{BA}}{\partial q_{AB}} & \frac{\partial y_{BA}}{\partial q_{AC}} & \frac{\partial y_{BA}}{\partial q_{BA}} & \frac{\partial y_{BA}}{\partial q_{BC}} \\
\frac{\partial y_{BC}}{\partial q_{AB}} & \frac{\partial y_{BC}}{\partial q_{AC}} & \frac{\partial y_{BC}}{\partial q_{BA}} & \frac{\partial y_{BC}}{\partial q_{BC}}
\end{pmatrix}
= \left(vT_A' - \frac{\partial^2 B_A}{\partial q_{AC}^2}\right)\left(\left(\frac{\partial^2 B_A}{\partial q_{AB}^2} + 4\frac{\partial^2 B_A}{\partial q_{AC}^2}\right)vT_A' - \frac{\partial^2 B_A}{\partial q_{AB}^2}\frac{\partial^2 B_A}{\partial q_{AC}^2}\right)\frac{\partial^2 B_A}{\partial q_{AB}^2} \tag{a.33}
$$

where the right-hand side is strictly positive. Applying Cramer’s rule yields:

$$
\frac{dq_{AB}}{dr_A} = \frac{dq_{BA}}{dr_A} = -\frac{1}{vT_A'\left(\frac{\partial^2 B_A}{\partial q_{AB}^2} / \frac{\partial^2 B_A}{\partial q_{AC}^2}\right) + 4vT_A' - \frac{\partial^2 B_A}{\partial q_{AB}^2}} < 0, \tag{a.34}
$$

$$
\frac{dq_{AC}}{dr_A} = -\frac{\left(\frac{\partial^2 B_A}{\partial q_{AB}^2} + 2\frac{\partial^2 B_A}{\partial q_{AC}^2}\right)vT_A' - \frac{\partial^2 B_A}{\partial q_{AB}^2}\frac{\partial^2 B_A}{\partial q_{AC}^2}}{\left(vT_A' - \frac{\partial^2 B_A}{\partial q_{AC}^2}\right)\left(\left(\frac{\partial^2 B_A}{\partial q_{AB}^2} + 4\frac{\partial^2 B_A}{\partial q_{AC}^2}\right)vT_A' - \frac{\partial^2 B_A}{\partial q_{AB}^2}\frac{\partial^2 B_A}{\partial q_{AC}^2}\right)} < 0, \tag{a.35}
$$

$$\frac{dq_{BC}}{dr_A} = \frac{2vT'_A}{\left(vT'_A - \frac{\partial^2 B_A}{\partial q_{AC}^2}\right)\left(vT'_A\left(\frac{\partial^2 B_A}{\partial q_{AB}^2} / \frac{\partial^2 B_A}{\partial q_{AC}^2}\right) + 4vT'_A - \frac{\partial^2 B_A}{\partial q_{AB}^2}\right)} > 0. \tag{a.36}$$

Substituting passenger quantities with demands completes the proof.

A. 6 Proof of Proposition 11

Consider the equilibrium prices in (34) and the first-best prices $r_i = D_i vT'_i$ for $i = A, B$. These prices can be used to show that in the presence of congestion and symmetry, and if airports pursue local welfare objectives, the equilibrium prices exceed the first-best price if

$$\left(D_{ij}\frac{\partial\left(D_A + D_B\right)}{\partial r_i} / \frac{\partial D_i}{\partial r_i} + D_{iC}\right)vT'_i - D_{ji} / \frac{\partial D_i}{\partial r_i} > D_i vT'_i. \tag{a.37}$$

This condition is equivalent to the condition

$$\left(\frac{\partial D_{jC}}{\partial r_i} - \frac{\partial D_{iC}}{\partial r_i}\right)vT'_i < 1. \tag{a.38}$$

Using (a.35) and (a.36), it can be shown that

$$\left(\frac{dD_{jC}}{dr_i} - \frac{dD_{iC}}{dr_i}\right)vT'_i = \frac{vT'_i}{vT'_i - \frac{\partial^2 B_i}{\partial D_{iC}^2}}, \tag{a.39}$$

where the right-hand side is indeed strictly smaller than 1.

A. 7 Proof of Lemma 7

Let x_l and x_{nl} represent the conditions:

$$x_l = B'_l(q_l) - \eta = 0, \tag{a.40}$$

$$x_{nl} = B'_{nl}(q_{nl}) - \eta = 0. \tag{a.41}$$

Totally differentiating, and after rearranging, this leads to a system of equations in matrix form as

$$\begin{pmatrix} \frac{\partial x_l}{\partial q_l} & \frac{\partial x_l}{\partial q_{nl}} \\ \frac{\partial x_{nl}}{\partial q_l} & \frac{\partial x_{nl}}{\partial q_{nl}} \end{pmatrix} \begin{pmatrix} dq_l \\ dq_{nl} \end{pmatrix} = dr \begin{pmatrix} -\frac{\partial x_l}{\partial r} \\ -\frac{\partial x_{nl}}{\partial r} \end{pmatrix} = dr \begin{pmatrix} 1 \\ 1 \end{pmatrix}. \tag{a.42}$$

Using symmetry, the Jacobian on the left-hand side can be rewritten as

$$\begin{pmatrix} \frac{\partial x_l}{\partial q_l} & \frac{\partial x_l}{\partial q_{nl}} \\ \frac{\partial x_{nl}}{\partial q_l} & \frac{\partial x_{nl}}{\partial q_{nl}} \end{pmatrix} = \begin{pmatrix} B_l''(q_l) - vT' & -vT' \\ -vT' & B_{nl}''(q_{nl}) - vT' \end{pmatrix}. \tag{a.43}$$

The determinant of the Jacobian, denoted as Ψ, can be written as

$$\Psi = B_l''(q_l) \cdot B_{nl}''(q_{nl}) - vT'(B_l''(q_l) + B_{nl}''(q_{nl})) \tag{a.44}$$

in which the right-hand side is positive. Applying Cramer's rule yields:

$$q_l'(r) = \frac{B_{nl}''(q_{nl})}{\Psi}, \tag{a.45}$$

$$q_{nl}'(r) = \frac{B_l''(q_l)}{\Psi}. \tag{a.46}$$

Both right-hand sides are negative. Substituting passenger quantities with demands completes the proof.

A. 8 Proof of Lemma 8

Totally differentiating (43) yields

$$d(\bar{Q} - D(r)) = \frac{\partial(\bar{Q} - D(r))}{\partial r} dr + \frac{\partial(\bar{Q} - D(r))}{\partial \bar{Q}} d\bar{Q} = -D'(r) \cdot dr + d\bar{Q} = 0. \tag{a.47}$$

An increase in slot quantity changes ticket price in the following way:

$$r'(\bar{Q}) = \frac{1}{D'(r)}. \tag{a.48}$$

Lemma 7 mentions that $D_l'(r), D_{nl}'(r) < 0$, which implies that $D'(r) = D_l'(r) + D_{nl}'(r) < 0$. Therefore, the right-hand side of (a.48) is negative, which completes the proof.

A. 9 Proof of Lemma 9

To show that the demands of both locals and non-locals are increasing in the slot quantity by less than 1, use Lemma 7 and Lemma 8, which yields

$$D_l'(\bar{Q}) = D_l'(r) \cdot r'(\bar{Q}) = \frac{B_{nl}''(q_{nl})}{B_l''(q_l) + B_{nl}''(q_{nl})}, \tag{a.49}$$

$$D_{nl}'(\bar{Q}) = D_{nl}'(r) \cdot r'(\bar{Q}) = \frac{B_l''(q_l)}{B_l''(q_l) + B_{nl}''(q_{nl})}. \tag{a.50}$$

Both right-hand sides of second equality are positive and less than 1.

To show that the total traffic is increasing in the slot quantity by 1, use (a.49) and (a.50), which yields

$$D'(\bar{Q}) = D_l'(\bar{Q}) + D_{nl}'(\bar{Q}) = 1. \tag{a.51}$$

A. 10 Proof of Lemma 10

To show that the generalized price is increasing in price r, substitute quantities with demands and use (a.45) and (a.46), which yields

$$\eta'(r) = 1 + vT'(D(r)) \cdot D'(r) = \frac{B_l''(D_l(r)) \cdot B_{nl}''(D_{nl}(r))}{\Psi} \tag{a.52}$$

where the right-hand side of second equality is positive.

To show that the generalized price is increasing in the price r by less than 1, consider $\eta'(r) = 1 + vT'(D(r)) \cdot D'(r)$. Lemma 7 mentions that $D'(r) = D_l'(r) + D_{nl}'(r) < 0$. Therefore, $vT'(D(r)) \cdot D'(r) < 0$ and $1 + vT'(D(r)) \cdot D'(r) < 1$ because $vT'(D(r)) > 0$ by assumption.

A. 11 Proof of Proposition 14

Consider equation (56). Replace the local welfare-maximizing ticket price $r^*(S)$ on the left-hand side by the marginal external congestion cost evaluated at the local welfare maximizing slot quantity, which yields

$$\bar{Q}^* \cdot vT'(\bar{Q}^*) = D_l(\bar{Q}^*) \cdot vT'(\bar{Q}^*) + \frac{D_{nl}'(\bar{Q}^*)}{D_l'(\bar{Q}^*)} \cdot D_l(\bar{Q}^*) \cdot vT'(\bar{Q}^*). \tag{a.53}$$

Dividing $vT'(\bar{Q}^*)$ at both sides, replacing $\bar{Q}^*$ by $D_l(\bar{Q}^*) + D_{nl}(\bar{Q}^*)$, simplifying and rearranging yield

$$\frac{D_l(\bar{Q}^*)}{D_{nl}(\bar{Q}^*)} = \frac{D_l'(\bar{Q}^*)}{D_{nl}'(\bar{Q}^*)}. \tag{a.54}$$

Adding one to both sides, substituting $D_l(\bar{Q}^*) + D_{nl}(\bar{Q}^*)$ with $\bar{Q}^*$ and rearranging yield (57), which completes the proof. Too high and too low welfare-maximizing slot quantity relative to the first-best slot quantity can be proved similarly by using greater-than and less-than signs in (a.53) respectively.

A. 12 Proof of Lemma 11

Totall differentiating the first-order condition in (63) yields

$$d\,\frac{\partial W_l(\bar{Q}^*)}{\partial \bar{Q}} = \frac{\partial^2 W_l(\bar{Q}^*)}{\partial \bar{Q}\partial\theta}\,d\bar{Q}^* + \frac{\partial^2 W_l(\bar{Q}^*)}{\partial \bar{Q}^2}\,d\theta = 0. \tag{a.55}$$

Rearranging (a.55) and subsitituting $d\bar{Q}^* / d\theta$ by $\partial\bar{Q}^* / \partial\theta$ yields

$$\frac{\partial \bar{Q}^*}{\partial\theta} = -\frac{\partial^2 W_l(\bar{Q}^*) / \partial\bar{Q}\partial\theta}{\partial^2 W_l(\bar{Q}^*) / \partial\bar{Q}^2}. \tag{a.56}$$

By assumption, the airport's welfare is concave in slot quantity, implying that $\partial^2 W_l(\bar{Q}^*) / \partial\bar{Q}^2 < 0.$ To prove that the local welfare-maximizing slot quantity is decreasing in θ, it is equivalent to proving that $\partial^2 W_l(\bar{Q}^*) / \partial\bar{Q}\partial\theta < 0.$ Consider $\partial^2 W_l(\bar{Q}^*) / \partial\bar{Q}\partial\theta,$ which can be written as

$$\frac{\partial^2 W_l(\bar{Q}^*)}{\partial\bar{Q}\partial\theta} = r(\bar{Q}^*) + r'(\bar{Q}^*)\cdot\bar{Q}^*. \tag{a.57}$$

The right-hand side is negative. To see this, consider Lemma 8 which shows that $r'(\bar{Q}) < 0$ and Lemma 10 which shows that $0 < \eta'(r) < 1$. Together this implies that $\eta'(\bar{Q}^*) < 0$ because $\eta'(\bar{Q}^*) = \eta'\left(r(\bar{Q}^*)\right)\cdot r'(\bar{Q}^*)$. The first term on the left-hand side of (63) is positive, implying that the sum of the second and third term, $\theta\cdot\left(r(\bar{Q}^*) + r'(\bar{Q}^*)\cdot\bar{Q}^*\right),$ is negative. This implies that $r(\bar{Q}^*) + r'(\bar{Q}^*)\cdot\bar{Q}^* < 0$ because

$\theta > 0$. This completes the proof.

A. 13 Proof of Lemma 12

Let y_{AB}, y_{AC}, y_{BA}, and y_{BC} represent the equilibrium conditions:

$$y_{AB} = \frac{\partial B_A}{\partial q_{AB}} - \left(r_A + r_B + v\left(T_A + T_B\right)\right) = 0, \tag{a.58}$$

$$y_{AC} = \frac{\partial B_A}{\partial q_{AC}} - \left(r_A + vT_A\right) = 0, \tag{a.59}$$

$$y_{BA} = \frac{\partial B_B}{\partial q_{BA}} - \left(r_A + r_B + v\left(T_A + T_B\right)\right) = 0, \tag{a.60}$$

$$y_{BC} = \frac{\partial B_B}{\partial q_{BC}} - \left(r_B + vT_B\right) = 0. \tag{a.61}$$

Totally differentiating, and after rearranging, this leads to a system of equations in matrix form as

$$\begin{pmatrix} \frac{\partial y_{AB}}{\partial q_{AB}} & \frac{\partial y_{AB}}{\partial q_{AC}} & \frac{\partial y_{AB}}{\partial q_{BA}} & \frac{\partial y_{AB}}{\partial q_{BC}} \\ \frac{\partial y_{AC}}{\partial q_{AB}} & \frac{\partial y_{AC}}{\partial q_{AC}} & \frac{\partial y_{AC}}{\partial q_{BA}} & \frac{\partial y_{AC}}{\partial q_{BC}} \\ \frac{\partial y_{BA}}{\partial q_{AB}} & \frac{\partial y_{BA}}{\partial q_{AC}} & \frac{\partial y_{BA}}{\partial q_{BA}} & \frac{\partial y_{BA}}{\partial q_{BC}} \\ \frac{\partial y_{BC}}{\partial q_{AB}} & \frac{\partial y_{BC}}{\partial q_{AC}} & \frac{\partial y_{BC}}{\partial q_{BA}} & \frac{\partial y_{BC}}{\partial q_{BC}} \end{pmatrix} \begin{pmatrix} dq_{AB} \\ dq_{AC} \\ dq_{BA} \\ dq_{BC} \end{pmatrix} = dr_A \begin{pmatrix} -\frac{\partial y_{AB}}{\partial r_A} \\ -\frac{\partial y_{AC}}{\partial r_A} \\ -\frac{\partial y_{BA}}{\partial r_A} \\ -\frac{\partial y_{BC}}{\partial r_A} \end{pmatrix} = dr_A \begin{pmatrix} 1 \\ 1 \\ 1 \\ 0 \end{pmatrix}. \tag{a.62}$$

Using symmetry, the Jacobian on the left-hand side of first equality can be rewritten as

$$\begin{pmatrix} \frac{\partial y_{AB}}{\partial q_{AB}} & \frac{\partial y_{AB}}{\partial q_{AC}} & \frac{\partial y_{AB}}{\partial q_{BA}} & \frac{\partial y_{AB}}{\partial q_{BC}} \\ \frac{\partial y_{AC}}{\partial q_{AB}} & \frac{\partial y_{AC}}{\partial q_{AC}} & \frac{\partial y_{AC}}{\partial q_{BA}} & \frac{\partial y_{AC}}{\partial q_{BC}} \\ \frac{\partial y_{BA}}{\partial q_{AB}} & \frac{\partial y_{BA}}{\partial q_{AC}} & \frac{\partial y_{BA}}{\partial q_{BA}} & \frac{\partial y_{BA}}{\partial q_{BC}} \\ \frac{\partial y_{BC}}{\partial q_{AB}} & \frac{\partial y_{BC}}{\partial q_{AC}} & \frac{\partial y_{BC}}{\partial q_{BA}} & \frac{\partial y_{BC}}{\partial q_{BC}} \end{pmatrix}$$

$$
= \begin{pmatrix} \frac{\partial^2 B_A}{\partial q_{AB}^2} - 2vT'_A & \frac{\partial^2 B_A}{\partial q_{AB}\partial q_{AC}} - vT'_A & -2vT'_A & -vT'_A \\ \frac{\partial^2 B_A}{\partial q_{AB}\partial q_{AC}} - vT'_A & \frac{\partial^2 B_A}{\partial q_{AC}^2} - vT'_A & -vT'_A & 0 \\ -2vT'_A & -vT'_A & \frac{\partial^2 B_A}{\partial q_{AB}^2} - 2vT'_A & \frac{\partial^2 B_A}{\partial q_{AB}\partial q_{AC}} - vT'_A \\ -vT'_A & 0 & \frac{\partial^2 B_A}{\partial q_{AB}\partial q_{AC}} - vT'_A & \frac{\partial^2 B_A}{\partial q_{AC}^2} - vT'_A \end{pmatrix}. \tag{a.63}
$$

The determinant of the Jacobian, denoted as Ψ, can be written as

$$
\Psi = \det \begin{pmatrix} \frac{\partial y_{AB}}{\partial q_{AB}} & \frac{\partial y_{AB}}{\partial q_{AC}} & \frac{\partial y_{AB}}{\partial q_{BA}} & \frac{\partial y_{AB}}{\partial q_{BC}} \\ \frac{\partial y_{AC}}{\partial q_{AB}} & \frac{\partial y_{AC}}{\partial q_{AC}} & \frac{\partial y_{AC}}{\partial q_{BA}} & \frac{\partial y_{AC}}{\partial q_{BC}} \\ \frac{\partial y_{BA}}{\partial q_{AB}} & \frac{\partial y_{BA}}{\partial q_{AC}} & \frac{\partial y_{BA}}{\partial q_{BA}} & \frac{\partial y_{BA}}{\partial q_{BC}} \\ \frac{\partial y_{BC}}{\partial q_{AB}} & \frac{\partial y_{BC}}{\partial q_{AC}} & \frac{\partial y_{BC}}{\partial q_{BA}} & \frac{\partial y_{BC}}{\partial q_{BC}} \end{pmatrix}
$$

$$
= \Bigg[\left(\frac{\partial^2 B_A}{\partial q_{AB}^2} \frac{\partial^2 B_A}{\partial q_{AC}^2} - \frac{\partial^2 B_A}{\partial q_{AB}\partial q_{AC}}^2 - vT'_A \frac{\partial^2 B_A}{\partial q_{AB}^2} \right)
$$

$$
-4vT'_A \left(\frac{\partial^2 B_A}{\partial q_{AC}^2} - \frac{\partial^2 B_A}{\partial q_{AB}\partial q_{AC}} \right) \left(\frac{\partial^2 B_A}{\partial q_{AB}^2} \frac{\partial^2 B_A}{\partial q_{AC}^2} - \frac{\partial^2 B_A}{\partial q_{AB}\partial q_{AC}}^2 - vT'_A \frac{\partial^2 B_A}{\partial q_{AB}^2} \right) \Bigg]. \tag{a.64}
$$

in which the right-hand side is positive. Applying Cramer's rule yields

$$
\frac{dq_{AB}}{dr_A} = \frac{1}{\Psi} \left(\frac{\partial^2 B_A}{\partial q_{AB}\partial q_{AC}} - \frac{\partial^2 B_A}{\partial q_{AC}^2} \right)
$$

$$
\left[vT'_A \left(\frac{\partial^2 B_A}{\partial q_{AB}^2} - 2 \frac{\partial^2 B_A}{\partial q_{AB}\partial q_{AC}} \right) - \left(\frac{\partial^2 B_A}{\partial q_{AB}^2} \frac{\partial^2 B_A}{\partial q_{AC}^2} - \frac{\partial^2 B_A}{\partial q_{AB}\partial q_{AC}}^2 \right) \right] \tag{a.65}
$$

in which the right-hand side is undetermined in sign;

$$
\frac{dq_{AC}}{dr_A} = \frac{1}{\Psi} \Bigg[-vT'_A \frac{\partial^2 B_A}{\partial q_{AB}^2} \left(2 \left(\frac{\partial^2 B_A}{\partial q_{AC}^2} - \frac{\partial^2 B_A}{\partial q_{AB}\partial q_{AC}} \right) + \left(\frac{\partial^2 B_A}{\partial q_{AB}^2} - \frac{\partial^2 B_A}{\partial q_{AB}\partial q_{AC}} \right) \right)
$$

$$
+ \left(\frac{\partial^2 B_A}{\partial q_{AB}^2} - \frac{\partial^2 B_A}{\partial q_{AB}\partial q_{AC}} \right) \left(\frac{\partial^2 B_A}{\partial q_{AB}^2} \frac{\partial^2 B_A}{\partial q_{AC}^2} - \frac{\partial^2 B_A}{\partial q_{AB}\partial q_{AC}}^2 \right) \Bigg] \tag{a.66}
$$

in which the right-hand side is negative;

$$\frac{dq_{BA}}{dr_A}=\frac{1}{\Psi}\left[-vT_A'\left(2\frac{\partial^2 B_A}{\partial q_{AB}\partial q_{AC}}\left(\frac{\partial^2 B_A}{\partial q_{AC}^2}-\frac{\partial^2 B_A}{\partial q_{AB}\partial q_{AC}}\right)+\frac{\partial^2 B_A}{\partial q_{AB}^2}\frac{\partial^2 B_A}{\partial q_{AC}^2}\right)\right.$$
$$\left.+\frac{\partial^2 B_A}{\partial q_{AC}^2}\left(\frac{\partial^2 B_A}{\partial q_{AB}^2}\frac{\partial^2 B_A}{\partial q_{AC}^2}-\frac{\partial^2 B_A}{\partial q_{AB}\partial q_{AC}}^2\right)\right] \quad \text{(a.67)}$$

in which the right-hand side is negative; and

$$\frac{dq_{BC}}{dr_A}=\frac{1}{\Psi}\left[-\frac{\partial^2 B_A}{\partial q_{AB}\partial q_{AC}}\left(\frac{\partial^2 B_A}{\partial q_{AB}^2}\frac{\partial^2 B_A}{\partial q_{AC}^2}-\frac{\partial^2 B_A}{\partial q_{AB}\partial q_{AC}}^2\right)\right.$$
$$\left.-vT_A'\frac{\partial^2 B_A}{\partial q_{AB}^2}\left(\frac{\partial^2 B_A}{\partial q_{AB}\partial q_{AC}}-\frac{\partial^2 B_A}{\partial q_{AB}^2}-\frac{\partial^2 B_A}{\partial q_{AC}^2}\right)\right] \quad \text{(a.68)}$$

in which the right-hand side is positive.

To show that the total demand of passengers who travel between airports A and B is decreasing in local airport charge in part (i), use (a.65) and (a.67), which yields

$$\frac{dq_{AB}}{dr_A}+\frac{dq_{BA}}{dr_A}=-\frac{1}{\Psi}\left(2\frac{\partial^2 B_A}{\partial q_{AC}^2}-\frac{\partial^2 B_A}{\partial q_{AB}\partial q_{AC}}\right)\left(\frac{\partial^2 B_A}{\partial q_{AB}\partial q_{AC}}^2-\frac{\partial^2 B_A}{\partial q_{AB}^2}\frac{\partial^2 B_A}{\partial q_{AC}^2}+vT_A'\frac{\partial^2 B_A}{\partial q_{AB}^2}\right) \quad \text{(a.69)}$$

in which the right-hand side is negative.

To show that a marginal increase in the local airport charge reduces the locals' demand for trips between the local airport and airport C whereas increases the non-locals' demand for trips between the non-local airport and airport C in part (ii), consider (a.66) and (a.68).

To show that a marginal increase in the local airport charge reduces the non-locals' demand for trips between airports A and B in part (iii), consider (a.67).

To show that a marginal increase in the local airport charge reduces the non-locals' demand by more than the locals' demand for trips between airports A and B in part (iv), use (a.65) and (a.67), which yields

$$\frac{dq_{AB}}{dr_A}-\frac{dq_{BA}}{dr_A}=\frac{1}{\Psi}\frac{\partial^2 B_A}{\partial q_{AB}\partial q_{AC}}\left[\left(\frac{\partial^2 B_A}{\partial q_{AB}\partial q_{AC}}^2-\frac{\partial^2 B_A}{\partial q_{AB}^2}\frac{\partial^2 B_A}{\partial q_{AC}^2}\right)\right. \quad \text{(a.70)}$$

$$-vT_A'\left(4\frac{\partial^2 B_A}{\partial q_{AB}\partial q_{AC}}-\frac{\partial^2 B_A}{\partial q_{AB}^2}-4\frac{\partial^2 B_A}{\partial q_{AC}^2}\right)\Bigg] \tag{a.71}$$

in which the right-hand side is positive.

To show that a marginal increase in the local airport charge has a greater impact on the total locals' demand than the total non-locals' demand in part (v), use (a.65), (a.66), (a.67) and (a.68), which yields

$$\frac{dq_{AB}}{dr_A}+\frac{dq_{AC}}{dr_A}-\frac{dq_{BA}}{dr_A}-\frac{dq_{BC}}{dr_A}=-\frac{1}{\Psi}\left(\frac{\partial^2 B_A}{\partial q_{AB}^2}-\frac{\partial^2 B_A}{\partial q_{AB}\partial q_{AC}}\right)\Bigg[\frac{\partial^2 B_A}{\partial q_{AB}\partial q_{AC}}^2-\frac{\partial^2 B_A}{\partial q_{AB}^2}\frac{\partial^2 B_A}{\partial q_{AC}^2}$$

$$-vT_A'\left(4\frac{\partial^2 B_A}{\partial q_{AB}\partial q_{AC}}-\frac{\partial^2 B_A}{\partial q_{AB}^2}-4\frac{\partial^2 B_A}{\partial q_{AC}^2}\right)\Bigg] \tag{a.72}$$

in which the right-hand side is negative.

To show that a marginal increase in the local airport charge reduces total traffic at the local airport in part (vi), use (a.66) and (a.69), which yields

$$\frac{dQ_A}{dr_A}=\frac{dq_{AB}}{dr_A}+\frac{dq_{BA}}{dr_A}+\frac{dq_{AC}}{dr_A} \tag{a.73}$$

in which the right-hand side is negative.

To show that a marginal increase in the local airport charge reduces total traffic at non-local airport in part (vi), use (a.68) and (a.69), which yields

$$\frac{dQ_B}{dr_A}=\frac{dq_{AB}}{dr_A}+\frac{dq_{BA}}{dr_A}+\frac{dq_{BC}}{dr_A} \tag{a.74}$$

$$=\frac{2}{\Psi}\left(\frac{\partial^2 B_A}{\partial q_{AB}\partial q_{AC}}^2-\frac{\partial^2 B_A}{\partial q_{AB}^2}\frac{\partial^2 B_A}{\partial q_{AC}^2}\right)\left(\frac{\partial^2 B_A}{\partial q_{AB}\partial q_{AC}}-\frac{\partial^2 B_A}{\partial q_{AC}^2}\right) \tag{a.75}$$

in which the right-hand side of (a.75) is negative.

To show that a marginal increase in the local airport charge reduce the local airport's traffic by more than the non-local airport's traffic in part (vi), use (a.66) and (a.68), which yields

$$\frac{dQ_A}{dr_A}-\frac{dQ_B}{dr_A}=\left(\frac{dq_{AB}}{dr_A}+\frac{dq_{BA}}{dr_A}+\frac{dq_{AC}}{dr_A}\right)-\left(\frac{dq_{AB}}{dr_A}+\frac{dq_{BA}}{dr_A}+\frac{dq_{BC}}{dr_A}\right) \tag{a.76}$$

$$= \frac{dq_{AC}}{dr_A} - \frac{dq_{BC}}{dr_A} \tag{a.77}$$

in which the right-hand side of (a.77) is negative.

Substituting quantities above with demands completes the proof.

A. 14 Proof of Lemma 13

To show that the generalized price for trips between the non-local airport and airport C is decreasing in local airport charge in part (i), use the generalized price in (75), which yields

$$\frac{\partial \eta_{BC}}{\partial r_A} = \frac{\partial \left(r_B + vT_B \right)}{\partial r_A} \tag{a.78}$$

$$= vT_B' \frac{\partial D_B}{\partial r_A} \tag{a.79}$$

in which the right-hand side of (a.79) is negative because vT_B' is positive by assumption and $\partial D_B / \partial r_A$ is negative by Lemma 12.

To show that the generalized price for trips between airports A and B is increasing in local airport charge in part (ii), use the generalized price in (75), which yields

$$\frac{\partial \eta_{AB}}{\partial r_A} = \frac{\partial \eta_{BA}}{\partial r_A} \tag{a.80}$$

$$= \frac{\partial \left(r_A + r_B + vT_A + vT_B \right)}{\partial r_A} \tag{a.81}$$

$$= vT_A' \left(\frac{\partial D_A}{\partial r_A} + \frac{\partial D_B}{\partial r_A} \right) + 1. \tag{a.82}$$

Using (a.65), (a.66), (a.67) and (a.68), the right-hand side of (a.82) can be rewritten as

$$vT_A' \left(\frac{\partial D_A}{\partial r_A} + \frac{\partial D_B}{\partial r_A} \right) + 1$$

$$= \frac{\left(\frac{\partial^2 B_A}{\partial q_{AB} \partial q_{AC}} \right)^2 - \frac{\partial^2 B_A}{\partial q_{AB}^2} \frac{\partial^2 B_A}{\partial q_{AC}^2}}{\left(\frac{\partial^2 B_A}{\partial q_{AB} \partial q_{AC}} \right)^2 - \frac{\partial^2 B_A}{\partial q_{AB}^2} \frac{\partial^2 B_A}{\partial q_{AC}^2} + vT_A' \left(\frac{\partial^2 B_A}{\partial q_{AB}^2} + 4 \frac{\partial^2 B_A}{\partial q_{AC}^2} - 4 \frac{\partial^2 B_A}{\partial q_{AB} \partial q_{AC}} \right)} \tag{a.83}$$

in which the right-hand side is positive.

To show that the generalized price for trips between the local airport and airport C is increasing in local airport charge by more than the generalized price for trips between airports A and B in part (ii), use the generalized price in (75), which yields

$$\frac{\partial \eta_{AC}}{\partial r_A} = \frac{\partial \eta_{AB}}{\partial r_A} - \frac{\partial \eta_{BC}}{\partial r_A} \tag{a.84}$$

in which the right-hand side is larger than $\partial \eta_{AB} / \partial r_A$ because $\partial \eta_{BC} / \partial r_A < 0$ as proved by (a.79).

To show that the generalized price for passengers travelling between the local airport and airport C is increasing in local airport charge by less than 1, use the generalized price in (75), which yields

$$\frac{\partial \eta_{AC}}{\partial r_A} = \frac{\partial \left(r_A + vT_A \right)}{\partial r_A} \tag{a.85}$$

$$= 1 + vT_A' \frac{\partial D_A}{\partial r_A} \tag{a.86}$$

in which the right-hand side of (a.86) is smaller than 1 because the second term is negative by Lemma 12.

A. 15 Proof of Proposition 19

Substitute q_{AB} with D_{AB} and use (a.65), which yields

$$\frac{\partial D_{AB}}{\partial r_A} = \frac{1}{\Psi}\left(\frac{\partial^2 B_A}{\partial q_{AB} \partial q_{AC}} - \frac{\partial^2 B_A}{\partial q_{AC}^2} \right)\left[vT_A' \left(\frac{\partial^2 B_A}{\partial q_{AB}^2} - 2\frac{\partial^2 B_A}{\partial q_{AB} \partial q_{AC}} \right) - \left(\frac{\partial^2 B_A}{\partial q_{AB}^2} \frac{\partial^2 B_A}{\partial q_{AC}^2} - \frac{\partial^2 B_A}{\partial q_{AB} \partial q_{AC}}^2 \right) \right]. \tag{a.87}$$

When demand D_{AB} is increasing in airport charge r_A, it requires that the third term in parentheses

$$vT_A' \left(\frac{\partial^2 B_A}{\partial q_{AB}^2} - 2\frac{\partial^2 B_A}{\partial q_{AB} \partial q_{AC}} \right) - \left(\frac{\partial^2 B_A}{\partial q_{AB}^2} \frac{\partial^2 B_A}{\partial q_{AC}^2} - \frac{\partial^2 B_A}{\partial q_{AB} \partial q_{AC}}^2 \right) \tag{a.88}$$

to be positive because $\Psi > 0$ and $\partial^2 B_A / \partial q_{AB} \partial q_{AC} - \partial^2 B_A / \partial q_{AC}^2 > 0$. Consider the second term in parentheses in (a.88), $\partial^2 B_A / \partial q_{AB}^2 \cdot \partial^2 B_A / \partial q_{AC}^2 - \left(\partial^2 B_A / \partial q_{AB} \partial q_{AC}\right)^2$, which is positive, and T_A', which is also positive by assumption. If time valuations v are zero, which means that there is no congestion, then demand D_{AB} can never be increasing in airport charge r_A because it violates the condition that (a.88) must be positive. Therefore, congestion is a necessary condition for $\partial D_{AB} / \partial r_A > 0$. When time valuations v are positive which means that airports are congested, $\partial^2 B_A / \partial q_{AB}^2 - 2\partial^2 B_A / \partial q_{AB} \partial q_{AC} > 0$ is a necessary condition for $\partial D_{AB} / \partial r_A > 0$. This means that $\partial^2 B_A / \partial q_{AB} \partial q_{AC}$ has to be not only negative but also lower than half of $\partial^2 B_A / \partial q_{AB}^2$, which implies a strong level of substitutability. Therefore, strong enough substitutability is a necessary condition for $\partial D_{AB} / \partial r_A > 0$.

A. 16 Proof of Lemma 14

Totally differentiating (80) yields

$$d\left(\bar{Q}_A - D_A\right) = \frac{\partial\left(\bar{Q}_A - D_A\right)}{\partial r_A} dr_A + \frac{\partial\left(\bar{Q}_A - D_A\right)}{\partial r_B} dr_B + \frac{\partial\left(\bar{Q}_A - D_A\right)}{\partial \bar{Q}_A} d\bar{Q}_A \tag{a.89}$$

$$= -\frac{\partial D_A}{\partial r_A} dr_A - \frac{\partial D_A}{\partial r_B} dr_B + d\bar{Q}_A = 0, \tag{a.90}$$

$$d\left(\bar{Q}_B - D_B\right) = \frac{\partial\left(\bar{Q}_B - D_B\right)}{\partial r_A} dr_A + \frac{\partial\left(\bar{Q}_B - D_B\right)}{\partial r_B} dr_B + \frac{\partial\left(\bar{Q}_B - D_B\right)}{\partial \bar{Q}_A} d\bar{Q}_A \tag{a.91}$$

$$= -\frac{\partial D_B}{\partial r_A} dr_A - \frac{\partial D_B}{\partial r_B} dr_B = 0. \tag{a.92}$$

In matrix form, this can be rewritten as

$$\begin{pmatrix} -\dfrac{\partial D_A}{\partial r_A} & -\dfrac{\partial D_A}{\partial r_B} \\ -\dfrac{\partial D_B}{\partial r_A} & -\dfrac{\partial D_B}{\partial r_B} \end{pmatrix} \begin{pmatrix} dr_A \\ dr_B \end{pmatrix} = -\begin{pmatrix} 1 \\ 0 \end{pmatrix} d\bar{Q}_A. \tag{a.93}$$

The 2×2 matrix on the left-hand side is positive definite, which ensures that each pair of slots is mapped with a unique pair of slot prices by the Gale-Nikaido Theorem (Gale and Nikaido, 1965). Given that

$$\frac{dr_i}{d\bar{Q}_i} = \frac{\partial r_i}{\partial \bar{Q}_i} + \frac{\partial r_i}{\partial \bar{Q}_j}\frac{d\bar{Q}_j}{d\bar{Q}_i} = \frac{\partial r_i}{\partial \bar{Q}_i} \tag{a.94}$$

and

$$\frac{dr_j}{d\bar{Q}_i} = \frac{\partial r_j}{\partial \bar{Q}_i} + \frac{\partial r_j}{\partial \bar{Q}_j}\frac{d\bar{Q}_j}{d\bar{Q}_i} = \frac{\partial r_j}{\partial \bar{Q}_i}, \tag{a.95}$$

applying Cramer's rule, an increase in the local airport's slot quantity changes the local slot price and the other airport's slot price in the sense that

$$\frac{\partial r_i}{\partial \bar{Q}_i} = \frac{\dfrac{\partial D_i}{\partial r_i}}{\dfrac{\partial D_A}{\partial r_A}\dfrac{\partial D_B}{\partial r_B} - \dfrac{\partial D_B}{\partial r_A}\dfrac{\partial D_A}{\partial r_B}} \tag{a.96}$$

and

$$\frac{\partial r_j}{\partial \bar{Q}_i} = \frac{-\dfrac{\partial D_j}{\partial r_i}}{\dfrac{\partial D_A}{\partial r_A}\dfrac{\partial D_B}{\partial r_B} - \dfrac{\partial D_B}{\partial r_A}\dfrac{\partial D_A}{\partial r_B}}. \tag{a.97}$$

Lemma 12 mentions that $\partial D_i / \partial r_i < \partial D_j / \partial r_i < 0$, therefore $\partial D_A / \partial r_A \cdot \partial D_B / \partial r_B - \partial D_B / \partial r_A \cdot \partial D_A / \partial r_B > 0$. This implies that the right-hand side of (a.96) is negative whereas the right-hand side of (a.97) is positive.

To show that the increase in the non-local airport's slot price in local slot quantity is smaller in absolute value than the reduction in the local airport's slot price in local slot quantity, it is equivalent to showing that $\partial r_i / \partial \bar{Q}_i + \partial r_j / \partial \bar{Q}_i < 0$. Use (a.96) and (a.97), which yields

$$\frac{\partial r_i}{\partial \bar{Q}_i} + \frac{\partial r_j}{\partial \bar{Q}_i} = \frac{\dfrac{\partial D_i}{\partial r_i} - \dfrac{\partial D_j}{\partial r_i}}{\dfrac{\partial D_A}{\partial r_A}\dfrac{\partial D_B}{\partial r_B} - \dfrac{\partial D_B}{\partial r_A}\dfrac{\partial D_A}{\partial r_B}}. \tag{a.98}$$

Using symmetry in the sense that $\partial D_A / \partial r_A = \partial D_B / \partial r_B$ and $\partial D_B / \partial r_A = \partial D_A / \partial r_B$, and substituting $\partial D_A / \partial r_A$ and $\partial D_B / \partial r_A$ with $\partial D_i / \partial r_i$ and $\partial D_j / \partial r_i$ respectively, the right-hand side of (a.98) can be written as

$$\frac{\dfrac{\partial D_i}{\partial r_i} - \dfrac{\partial D_j}{\partial r_i}}{\dfrac{\partial D_A}{\partial r_A}\dfrac{\partial D_B}{\partial r_B} - \dfrac{\partial D_B}{\partial r_A}\dfrac{\partial D_A}{\partial r_B}} = \frac{\dfrac{\partial D_i}{\partial r_i} - \dfrac{\partial D_j}{\partial r_i}}{\left(\dfrac{\partial D_i}{\partial r_i} + \dfrac{\partial D_j}{\partial r_i}\right)\left(\dfrac{\partial D_i}{\partial r_i} - \dfrac{\partial D_j}{\partial r_i}\right)} \tag{a.99}$$

$$= \frac{1}{\dfrac{\partial D_i}{\partial r_i} + \dfrac{\partial D_j}{\partial r_i}} \tag{a.100}$$

in which the right-hand side of (a.100) is negative by Lemma 12 and thus completes the proof.

A. 17 Proof of Corollary 4

To show that the overall demand for trips between airports A and B is increasing in local airport's slot quantity in part (i), using symmetry in the sense that $\partial\left(D_{ij} + D_{ji}\right) / \partial r_i = \partial\left(D_{ij} + D_{ji}\right) / \partial r_j$ yields

$$\frac{\partial\left(D_{ij} + D_{ji}\right)}{\partial \bar{Q}_i} = \frac{\partial\left(D_{ij} + D_{ji}\right)}{\partial r_i}\frac{\partial r_i}{\partial \bar{Q}_i} + \frac{\partial\left(D_{ij} + D_{ji}\right)}{\partial r_j}\frac{\partial r_j}{\partial \bar{Q}_i} \tag{a.101}$$

$$= \frac{\partial\left(D_{ij} + D_{ji}\right)}{\partial r_i}\left(\frac{\partial r_i}{\partial \bar{Q}_i} + \frac{\partial r_j}{\partial \bar{Q}_i}\right) \tag{a.102}$$

in which the right-hand side of (a.102) is positive by Lemma 12 and Lemma 14.

To show that demand for trips between the non-local airports j and C is decreasing in local slot quantity in part (ii), using symmetry in the sense that $\partial D_{jC} / \partial r_j = \partial D_{iC} / \partial r_i$ yields

$$\frac{\partial D_{jC}}{\partial \bar{Q}_i} = \frac{\partial D_{jC}}{\partial r_i}\frac{\partial r_i}{\partial \bar{Q}_i} + \frac{\partial D_{jC}}{\partial r_j}\frac{\partial r_j}{\partial \bar{Q}_i} \tag{a.103}$$

$$= \frac{\partial D_{jC}}{\partial r_i}\frac{\partial r_i}{\partial \bar{Q}_i} + \frac{\partial D_{iC}}{\partial r_i}\frac{\partial r_j}{\partial \bar{Q}_i} \tag{a.104}$$

in which the right-hand side (a.104) is negative by Lemma 12 and Lemma 14.

To show that demand for trips between the local airport and airport C is increasing in local slot quantity in part (ii), using symmetry in the sense that $\partial D_{iC} / \partial r_j = \partial D_{jC} / \partial r_i$ yields

$$\frac{\partial D_{iC}}{\partial \bar{Q}_i} = \frac{\partial D_{iC}}{\partial r_i}\frac{\partial r_i}{\partial \bar{Q}_i} + \frac{\partial D_{iC}}{\partial r_j}\frac{\partial r_j}{\partial \bar{Q}_i} \tag{a.105}$$

$$= \frac{\partial D_{iC}}{\partial r_i}\frac{\partial r_i}{\partial \bar{Q}_i} + \frac{\partial D_{jC}}{\partial r_i}\frac{\partial r_j}{\partial \bar{Q}_i} \tag{a.106}$$

in which the right-hand side (a.106) is positive by Lemma 12 and Lemma 14.

To show that the non-local's demand for trips between airports A and B is increasing in local slot quantity in part (iii), using symmetry in the sense that $\partial D_{ji} / \partial r_j = \partial D_{ij} / \partial r_i$ yields

$$\frac{\partial D_{ji}}{\partial \bar{Q}_i} = \frac{\partial D_{ji}}{\partial r_i}\frac{\partial r_i}{\partial \bar{Q}_i} + \frac{\partial D_{ji}}{\partial r_j}\frac{\partial r_j}{\partial \bar{Q}_i} \tag{a.107}$$

$$= \frac{\partial D_{ji}}{\partial r_i}\frac{\partial r_i}{\partial \bar{Q}_i} + \frac{\partial D_{ij}}{\partial r_i}\frac{\partial r_j}{\partial \bar{Q}_i} \tag{a.108}$$

$$> -\frac{\partial D_{ji}}{\partial r_i}\frac{\partial r_j}{\partial \bar{Q}_i} + \frac{\partial D_{ij}}{\partial r_i}\frac{\partial r_j}{\partial \bar{Q}_i} \tag{a.109}$$

$$= \left(\frac{\partial D_{ij}}{\partial r_i} - \frac{\partial D_{ji}}{\partial r_i}\right)\frac{\partial r_j}{\partial \bar{Q}_i} \tag{a.110}$$

in which the right-hand side of (a.110) is positive by Lemma 12 and Lemma 14.

To show that a marginal increase in the local airport slot quantity increases non-locals' demands by more than the locals' demands for trips between airports A and B in part (iv), using symmetry in the sense that $\partial D_{ji} / \partial r_j = \partial D_{ij} / \partial r_i$ and $\partial D_{ij} / \partial r_j = \partial D_{ji} / \partial r_i$ yields

$$\frac{\partial D_{ji}}{\partial \bar{Q}_i} - \frac{\partial D_{ij}}{\partial \bar{Q}_i} = \frac{\partial D_{ji}}{\partial r_i}\frac{\partial r_i}{\partial \bar{Q}_i} + \frac{\partial D_{ji}}{\partial r_j}\frac{\partial r_j}{\partial \bar{Q}_i} - \left(\frac{\partial D_{ij}}{\partial r_i}\frac{\partial r_i}{\partial \bar{Q}_i} + \frac{\partial D_{ij}}{\partial r_j}\frac{\partial r_j}{\partial \bar{Q}_i}\right) \tag{a.111}$$

$$= \left(\frac{\partial D_{ij}}{\partial r_i} - \frac{\partial D_{ji}}{\partial r_i}\right)\left(\frac{\partial r_j}{\partial \bar{Q}_i} - \frac{\partial r_i}{\partial \bar{Q}_i}\right) \tag{a.112}$$

in which the right-hand side of (a.112) is positive by Lemma 12 and Lemma 14.

A. 18 Proof of Lemma 15

Using (a.112), $2\partial D_{ij}/\partial\bar{Q}_i + \partial D_{iC}/\partial\bar{Q}_i$ can be rewritten as

$$2\frac{\partial D_{ij}}{\partial\bar{Q}_i}+\frac{\partial D_{iC}}{\partial\bar{Q}_i}=\left(\frac{\partial D_{ij}}{\partial\bar{Q}_i}+\frac{\partial D_{iC}}{\partial\bar{Q}_i}+\frac{\partial D_{ji}}{\partial\bar{Q}_i}\right)-\left(\frac{\partial D_{ji}}{\partial\bar{Q}_i}-\frac{\partial D_{ij}}{\partial\bar{Q}_i}\right) \tag{a.113}$$

$$=1-\left(\frac{\partial D_{ij}}{\partial r_i}-\frac{\partial D_{ji}}{\partial r_i}\right)\left(\frac{\partial r_j}{\partial\bar{Q}_i}-\frac{\partial r_i}{\partial\bar{Q}_i}\right). \tag{a.114}$$

Using (a.96) and (a.97), and symmetry in the sense that $\partial D_A/\partial r_A = \partial D_B/\partial r_B$ and $\partial D_B/\partial r_A = \partial D_A/\partial r_B$, and substituting $\partial D_A/\partial r_A$ and $\partial D_B/\partial r_A$ with $\partial D_i/\partial r_i$ and $\partial D_j/\partial r_i$ respectively yield

$$1-\left(\frac{\partial D_{ij}}{\partial r_i}-\frac{\partial D_{ji}}{\partial r_i}\right)\left(\frac{\partial r_j}{\partial\bar{Q}_i}-\frac{\partial r_i}{\partial\bar{Q}_i}\right)=1+\frac{\left(\frac{\partial D_{ij}}{\partial r_i}-\frac{\partial D_{ji}}{\partial r_i}\right)\left(\frac{\partial D_i}{\partial r_i}+\frac{\partial D_j}{\partial r_i}\right)}{\frac{\partial D_A}{\partial r_A}\frac{\partial D_B}{\partial r_B}-\frac{\partial D_B}{\partial r_A}\frac{\partial D_A}{\partial r_B}} \tag{a.115}$$

$$=1+\frac{\left(\frac{\partial D_{ij}}{\partial r_i}-\frac{\partial D_{ji}}{\partial r_i}\right)\left(\frac{\partial D_i}{\partial r_i}+\frac{\partial D_j}{\partial r_i}\right)}{\left(\frac{\partial D_i}{\partial r_i}+\frac{\partial D_j}{\partial r_i}\right)\left(\frac{\partial D_i}{\partial r_i}-\frac{\partial D_j}{\partial r_i}\right)} \tag{a.116}$$

$$=1+\frac{\frac{\partial D_{ij}}{\partial r_i}-\frac{\partial D_{ji}}{\partial r_i}}{\frac{\partial D_i}{\partial r_i}-\frac{\partial D_j}{\partial r_i}} \tag{a.117}$$

$$=\frac{\left(\frac{\partial D_{ij}}{\partial r_i}+\frac{\partial D_{iC}}{\partial r_i}\right)-\left(\frac{\partial D_{ji}}{\partial r_i}+\frac{\partial D_{jC}}{\partial r_i}\right)}{\frac{\partial D_i}{\partial r_i}-\frac{\partial D_j}{\partial r_i}}. \tag{a.118}$$

Lemma 12 mentions that $\partial\left(D_{ij}+D_{iC}\right)/\partial r_i < \partial\left(D_{ji}+D_{jC}\right)/\partial r_i$ and $\partial D_i/\partial r_i < \partial D_j/\partial r_i$. Therefore, the right-hand side of (a.118) is positive, which completes the proof.

A. 19 Proof of Proposition 21

Consider equation (85). Replace the equilibrium slot price $r_i(S)$ on the left-hand side by the marginal external congestion cost evaluated at the first-best price, which yields

$$D_i vT_i' = D_i vT_i' - D_{ji} vT_i' + \frac{\frac{\partial D_{ji}}{\partial \bar{Q}_i} - \frac{\partial D_{ij}}{\partial \bar{Q}_i}}{2\frac{\partial D_{ij}}{\partial \bar{Q}_i} + \frac{\partial D_{iC}}{\partial \bar{Q}_i}} \left(D_{ij} + D_{iC} \right) vT_i'. \quad \text{(a.119)}$$

Dividing vT_i' at both sides and rearranging yield

$$D_{ji} \left(2\frac{\partial D_{ij}}{\partial \bar{Q}_i} + \frac{\partial D_{iC}}{\partial \bar{Q}_i} \right) = \left(\frac{\partial D_{ji}}{\partial \bar{Q}_i} - \frac{\partial D_{ij}}{\partial \bar{Q}_i} \right) \left(D_{ij} + D_{iC} \right) vT_i'. \quad \text{(a.120)}$$

Replacing D_{ji} with $D_i - (D_{ij} + D_{iC})$ on the right-hand side and rearranging completes the proof. Negative and positive welfare externalities can be proved similarly by using greater-than and less-than signs in (a.119) respectively.

A. 20 Proof of Lemma 16

Using Lemma 12, $2\partial D_{ij} / \partial r_i + \partial D_{iC} / \partial r_i$ can be rewritten as

$$2\frac{\partial D_{ij}}{\partial r_i} + \frac{\partial D_{iC}}{\partial r_i} = \frac{\partial D_{ij}}{\partial r_i} + \frac{\partial D_{iC}}{\partial r_i} + \frac{\partial D_{ij}}{\partial r_i} \quad \text{(a.121)}$$

$$< \frac{\partial D_{ji}}{\partial r_i} + \frac{\partial D_{jC}}{\partial r_i} + \frac{\partial D_{ij}}{\partial r_i} \quad \text{(a.122)}$$

$$= \frac{\partial D_j}{\partial r_i} \quad \text{(a.123)}$$

in which the right-hand side of (a.123) is negative by Lemma 12.

A. 21 Proof of Proposition 23

Consider equation (90). Replace the equilibrium slot price $r_i(SP)$ on the left-hand side by the marginal external congestion cost evaluated at the first-best price, which yields

$$D_i vT_i' = D_i vT_i' - \frac{\frac{\partial \left(D_{ij} + D_{iC} \right)}{\partial r_i} - \frac{\partial \left(D_{ji} + D_{jC} \right)}{\partial r_i}}{2\frac{\partial D_{ij}}{\partial r_i} + \frac{\partial D_{iC}}{\partial r_i}} D_{ji} vT_i' + \frac{\frac{\partial D_{ji}}{\partial r_i} - \frac{\partial D_{ij}}{\partial r_i}}{2\frac{\partial D_{ij}}{\partial r_i} + \frac{\partial D_{iC}}{\partial r_i}} \left(D_{iC} + D_{ij} \right) vT_i'. \quad \text{(a.124)}$$

Dividing vT_i' at both sides and rearranging yield

$$\left(\frac{\partial\left(D_{ij}+D_{iC}\right)}{\partial r_i}-\frac{\partial\left(D_{ji}+D_{jC}\right)}{\partial r_i}\right)D_{ji}=\left(\frac{\partial D_{ji}}{\partial r_i}-\frac{\partial D_{ij}}{\partial r_i}\right)\left(D_{iC}+D_{ij}\right) \tag{a.125}$$

Replacing D_{ji} with $D_i-(D_{ij}+D_{iC})$ on the right-hand side and rearranging completes the proof. Negative and positive welfare externalities can be proved similarly by using less-than and greater-than signs in (a.124) respectively.

A. 22 Proof of Lemma 17

Use the equilibrium slot prices in (85) and (90), which yields

$$r_i(SP)-r_i(S)$$

$$=\frac{1}{2\frac{\partial D_{ij}}{\partial r_i}+\frac{\partial D_{iC}}{\partial r_i}}\left(\left(D_{ij}+D_{iC}\right)\frac{\partial D_i}{\partial r_i}+D_{ji}\frac{\partial D_j}{\partial r_i}\right)vT_i'-\frac{1}{2\frac{\partial D_{ij}}{\partial \bar{Q}_i}+\frac{\partial D_{iC}}{\partial \bar{Q}_i}}\left(D_{ij}+D_{iC}\right)vT_i'. \tag{a.126}$$

Using (a.118) in the sense that

$$2\frac{\partial D_{ij}}{\partial \bar{Q}_i}+\frac{\partial D_{iC}}{\partial \bar{Q}_i}=\frac{\frac{\partial\left(D_{ij}+D_{iC}\right)}{\partial r_i}-\frac{\partial\left(D_{ji}+D_{jC}\right)}{\partial r_i}}{\frac{\partial\left(D_i-D_j\right)}{\partial r_i}}, \tag{a.127}$$

the right-hand side of (a.126) can be rewritten as

$$r_i(SP)-r_i(S)=\frac{1}{2\frac{\partial D_{ij}}{\partial r_i}+\frac{\partial D_{iC}}{\partial r_i}}\left(\left(D_{ij}+D_{iC}\right)\frac{\partial D_i}{\partial r_i}+D_{ji}\frac{\partial D_j}{\partial r_i}\right)vT_i'$$

$$-\frac{\frac{\partial\left(D_i-D_j\right)}{\partial r_i}}{\frac{\partial\left(D_{ij}+D_{iC}\right)}{\partial r_i}-\frac{\partial\left(D_{ji}+D_{jC}\right)}{\partial r_i}}\left(D_{ij}+D_{iC}\right)vT_i' \tag{a.128}$$

$$=\lambda\cdot\left(\frac{D_{ij}\frac{\partial\left(D_i+D_j\right)}{\partial r_i}+D_{iC}\frac{\partial D_i}{\partial r_i}}{D_i}-\left(2\frac{\partial D_{ij}}{\partial r_i}+\frac{\partial D_{iC}}{\partial r_i}\right)\right)D_i vT_i' \tag{a.129}$$

where

$$\lambda = \frac{\dfrac{\partial D_j}{\partial r_i}\dfrac{\partial\left(D_i - D_j\right)}{\partial r_i}}{\left(\dfrac{\partial\left(D_{ij} + D_{iC}\right)}{\partial r_i} - \dfrac{\partial\left(D_{ji} + D_{jC}\right)}{\partial r_i}\right)\left(2\dfrac{\partial D_{ij}}{\partial r_i} + \dfrac{\partial D_{iC}}{\partial r_i}\right)}. \tag{a.130}$$

and $\lambda > 0$ by Lemma 12 and Lemma 16.

Proposition 23 mentions that if equilibrium slot prices are too low, that is, $D_i v T_i' > r_i(SP),\ r_i(S)$, then it is true that

$$\frac{D_{ij}\dfrac{\partial\left(D_i + D_j\right)}{\partial r_i} + D_{iC}\dfrac{\partial D_i}{\partial r_i}}{D_i} > 2\frac{\partial D_{ij}}{\partial r_i} + \frac{\partial D_{iC}}{\partial r_i}. \tag{a.131}$$

Therefore, the right-hand side of (a.129) is positive and completes the proof of part (i). Part (ii) and (iii) can be proved similarly by considering less-than and equal sign in (a.131).

A. 23 Proof of Lemma 18

Let y_{CA}, y_{CB}, y_{AC}, and y_{BC} represent the equilibrium conditions:

$$y_{CA} = \frac{\partial B_C}{\partial q_{CA}} - \left(r_A + vT_A\right) = 0, \tag{a.132}$$

$$y_{CB} = \frac{\partial B_C}{\partial q_{CB}} - \left(r_B + vT_B\right) = 0, \tag{a.133}$$

$$y_{AC} = \frac{\partial B_A}{\partial q_{AC}} - \left(r_A + vT_A\right) = 0, \tag{a.134}$$

$$y_{BC} = \frac{\partial B_B}{\partial q_{BC}} - \left(r_B + vT_B\right) = 0, \tag{a.135}$$

Totally differentiating and rearranging, this leads to a system of equations in matrix form as

$$\begin{pmatrix} \frac{\partial y_{CA}}{\partial q_{CA}} & \frac{\partial y_{CA}}{\partial q_{CB}} & \frac{\partial y_{CA}}{\partial q_{AC}} & \frac{\partial y_{CA}}{\partial q_{BC}} \\ \frac{\partial y_{CB}}{\partial q_{CA}} & \frac{\partial y_{CB}}{\partial q_{CB}} & \frac{\partial y_{CB}}{\partial q_{AC}} & \frac{\partial y_{CB}}{\partial q_{BC}} \\ \frac{\partial y_{AC}}{\partial q_{CA}} & \frac{\partial y_{AC}}{\partial q_{CB}} & \frac{\partial y_{AC}}{\partial q_{AC}} & \frac{\partial y_{AC}}{\partial q_{BC}} \\ \frac{\partial y_{BC}}{\partial q_{CA}} & \frac{\partial y_{BC}}{\partial q_{CB}} & \frac{\partial y_{BC}}{\partial q_{AC}} & \frac{\partial y_{BC}}{\partial q_{BC}} \end{pmatrix} \begin{pmatrix} dq_{CA} \\ dq_{CB} \\ dq_{AC} \\ dq_{BC} \end{pmatrix} = dr_A \begin{pmatrix} -\frac{\partial y_{CA}}{\partial r_A} \\ -\frac{\partial y_{CB}}{\partial r_A} \\ -\frac{\partial y_{AC}}{\partial r_A} \\ -\frac{\partial y_{BC}}{\partial r_A} \end{pmatrix} = dr_A \begin{pmatrix} 1 \\ 0 \\ 1 \\ 0 \end{pmatrix}. \tag{a.136}$$

Using symmetry, the Jacobian on the left-hand side of first equality can be rewritten as

$$\begin{pmatrix} \frac{\partial y_{CA}}{\partial q_{CA}} & \frac{\partial y_{CA}}{\partial q_{CB}} & \frac{\partial y_{CA}}{\partial q_{AC}} & \frac{\partial y_{CA}}{\partial q_{BC}} \\ \frac{\partial y_{CB}}{\partial q_{CA}} & \frac{\partial y_{CB}}{\partial q_{CB}} & \frac{\partial y_{CB}}{\partial q_{AC}} & \frac{\partial y_{CB}}{\partial q_{BC}} \\ \frac{\partial y_{AC}}{\partial q_{CA}} & \frac{\partial y_{AC}}{\partial q_{CB}} & \frac{\partial y_{AC}}{\partial q_{AC}} & \frac{\partial y_{AC}}{\partial q_{BC}} \\ \frac{\partial y_{BC}}{\partial q_{CA}} & \frac{\partial y_{BC}}{\partial q_{CB}} & \frac{\partial y_{BC}}{\partial q_{AC}} & \frac{\partial y_{BC}}{\partial q_{BC}} \end{pmatrix}$$

$$= \begin{pmatrix} \frac{\partial^2 B_C}{\partial q_{CA}^2} - vT_A' & \frac{\partial^2 B_C}{\partial q_{CA}\partial q_{CB}} & -vT_A' & 0 \\ \frac{\partial^2 B_C}{\partial q_{CA}\partial q_{CB}} & \frac{\partial^2 B_C}{\partial q_{CA}^2} - vT_A' & 0 & -vT_A' \\ -vT_A' & 0 & \frac{\partial^2 B_A}{\partial q_{AC}^2} - vT_A' & 0 \\ 0 & -vT_A' & 0 & \frac{\partial^2 B_A}{\partial q_{AC}^2} - vT_A' \end{pmatrix}. \tag{a.137}$$

The determinant of the Jacobian, denoted as Ψ, can be written as

$$\Psi = \left[\left(\left(vT_A' - \frac{\partial^2 B_A}{\partial q_{AC}^2} \right) \left(\frac{\partial^2 B_C}{\partial q_{CA}^2} + \frac{\partial^2 B_C}{\partial q_{CA}\partial q_{CB}} \right) + vT_A' \frac{\partial^2 B_A}{\partial q_{AC}^2} \right) \right.$$
$$\left. \left(\left(vT_A' - \frac{\partial^2 B_A}{\partial q_{AC}^2} \right) \left(\frac{\partial^2 B_C}{\partial q_{CA}^2} - \frac{\partial^2 B_C}{\partial q_{CA}\partial q_{CB}} \right) + vT_A' \frac{\partial^2 B_A}{\partial q_{AC}^2} \right) \right] \tag{a.138}$$

in which the right-hand side is positive. Applying Cramer's rule yields:

$$\frac{dq_{CA}}{dr_A} = \frac{1}{\Psi} \frac{\partial^2 B_A}{\partial q_{AC}^2} \left(\frac{\partial^2 B_A}{\partial q_{AC}^2} \frac{\partial^2 B_C}{\partial q_{CA}^2} - vT_A' \left(\frac{\partial^2 B_A}{\partial q_{AC}^2} + \frac{\partial^2 B_C}{\partial q_{CA}^2} \right) \right) \tag{a.139}$$

in which the right-hand side is negative;

$$\frac{dq_{CB}}{dr_A}=\frac{1}{\Psi}\frac{\partial^2 B_A}{\partial q_{AC}^2}\frac{\partial^2 B_C}{\partial q_{CA}\partial q_{CB}}\left(vT_A'-\frac{\partial^2 B_A}{\partial q_{AC}^2}\right) \tag{a.140}$$

in which the right-hand side is positive;

$$\frac{dq_{AC}}{dr_A}=\frac{1}{\Psi}\left(\left(\frac{\partial^2 B_A}{\partial q_{AC}^2}-vT_A'\right)\left({\frac{\partial^2 B_C}{\partial q_{CA}^2}}^2-{\frac{\partial^2 B_C}{\partial q_{CA}\partial q_{CB}}}^2\right)-vT_A'\frac{\partial^2 B_A}{\partial q_{AC}^2}\frac{\partial^2 B_C}{\partial q_{CA}^2}\right) \tag{a.141}$$

in which the right-hand side is negative;

$$\frac{dq_{BC}}{dr_A}=-\frac{1}{\Psi}vT_A'\frac{\partial^2 B_A}{\partial q_{AC}^2}\frac{\partial^2 B_C}{\partial q_{CA}\partial q_{CB}} \tag{a.142}$$

in which the right-hand side is negative.

To show that demands for both locals and non-locals who travel at local airport are decreasing in the local airport charge in part (i), consider (a.139) and (a.141).

To show that demand of the passengers from the other congested airport is decreasing in the local airport charge but by less than passengers using the local airport in part (i), use (a.139), (a.141) and (a.142), which yields

$$\frac{dq_{BC}}{dr_A}-\frac{dq_{AC}}{dr_A}=\frac{1}{\Psi}\left(\left(vT_A'-\frac{\partial^2 B_A}{\partial q_{AC}^2}\right)\left(\frac{\partial^2 B_C}{\partial q_{CA}^2}+\frac{\partial^2 B_C}{\partial q_{CA}\partial q_{CB}}\right)+vT_A'\frac{\partial^2 B_A}{\partial q_{AC}^2}\right)\left(\frac{\partial^2 B_C}{\partial q_{CA}^2}-\frac{\partial^2 B_C}{\partial q_{CA}\partial q_{CB}}\right) \tag{a.143}$$

and

$$\frac{dq_{BC}}{dr_A}-\frac{dq_{CA}}{dr_A}=-\frac{1}{\Psi}\frac{\partial^2 B_A}{\partial q_{AC}^2}\left(\frac{\partial^2 B_A}{\partial q_{AC}^2}\frac{\partial^2 B_C}{\partial q_{CA}^2}-vT_A'\cdot\left(\frac{\partial^2 B_C}{\partial q_{CA}^2}-\frac{\partial^2 B_C}{\partial q_{CA}\partial q_{CB}}+\frac{\partial^2 B_A}{\partial q_{AC}^2}\right)\right) \tag{a.144}$$

in which both right-hand sides are positive.

To show that demand of non-locals who use the other congested airport is increasing in the local airport charge in part (i), consider (a.140).

To show that the total demand of non-locals from airport C is decreasing in the local airport charge in part (ii), use (a.139) and (a.140), which yields

$$\frac{dq_{CA}}{dr_A}+\frac{dq_{CB}}{dr_A}=-\frac{1}{\Psi}\frac{\partial^2 B_A}{\partial q_{AC}^2}\left(\left(vT_A'-\frac{\partial^2 B_A}{\partial q_{AC}^2}\right)\left(\frac{\partial^2 B_C}{\partial q_{CA}^2}-\frac{\partial^2 B_C}{\partial q_{CA}\partial q_{CB}}\right)+vT_A'\frac{\partial^2 B_A}{\partial q_{AC}^2}\right) \tag{a.145}$$

in which the right-hand side is negative.

To show that the total traffic at local airport is decreasing in the local airport charge in part (iii), use (a.139) and (a.141), which yields

$$\frac{dQ_A}{dr_A}=\frac{dq_{CA}}{dr_A}+\frac{dq_{AC}}{dr_A} \tag{a.146}$$

in which the right-hand side is negative.

To show that the total traffic at the other congested airport is increasing in the local airport charge in part (iii), use (a.140) and (a.142), which yields

$$\frac{dQ_B}{dr_A}=\frac{dq_{CB}}{dr_A}+\frac{dq_{BC}}{dr_A} \tag{a.147}$$

$$=-\frac{1}{\Psi}\frac{\partial^2 B_A}{\partial q_{AC}^2}^{2}\frac{\partial^2 B_C}{\partial q_{CA}\partial q_{CB}} \tag{a.148}$$

in which the right-hand side of (a.148) is positive.

To show that the a marginal change in local airport charge has a greater impact on the total traffic at local airport relative to the other congested airport in part (iii), use (a.139), (a.140), (a.141) and (a.142), which yields

$$\frac{dQ_A}{dr_A}+\frac{dQ_B}{dr_A}=\left(\frac{dq_{CA}}{dr_A}+\frac{dq_{AC}}{dr_A}\right)+\left(\frac{dq_{CB}}{dr_A}+\frac{dq_{BC}}{dr_A}\right) \tag{a.149}$$

$$=-\frac{1}{\Psi}\left[\left(\frac{\partial^2 B_A}{\partial q_{AC}^2}+\frac{\partial^2 B_C}{\partial q_{CA}^2}+\frac{\partial^2 B_C}{\partial q_{CA}\partial q_{CB}}\right)\left(\left(vT_A'-\frac{\partial^2 B_A}{\partial q_{AC}^2}\right)\left(\frac{\partial^2 B_C}{\partial q_{CA}^2}-\frac{\partial^2 B_C}{\partial q_{CA}\partial q_{CB}}\right)+vT_A'\frac{\partial^2 B_A}{\partial q_{AC}^2}\right)\right] \tag{a.150}$$

in which the right-hand side of (a.150) is negative. Together with $dQ_A/dr_A<0<dQ_B/dr_A$, this implies that dQ_A/dr_A is bigger in absolute value.

Substituting quantities above with demands completes the proof.

A. 24 Proof of Lemma 19

To show that the generalized price for the passengers using the other congested airport is increasing in the local airport charge, use the generalized price in (96), which yields

$$\frac{\partial \eta_j}{\partial r_i} = \frac{\partial\left(r_j + vT_j\right)}{\partial r_i} \tag{a.151}$$

$$= vT_j' \frac{\partial D_j}{\partial r_i} \tag{a.152}$$

in which the right-hand side of (a.152) is positive because vT_j' is positive by assumption and $\partial D_j / \partial r_i$ is positive by Lemma 18.

To show that the generalized price for the passengers using the local airport is increasing by more than the generalized price for the passengers using the other congested airport in the local airport charge, use symmetry in the sense that $T_i' = T_j'$ and (a.139), (a.140), (a.141) and (a.142), which yields

$$\frac{\partial \eta_i}{\partial r_i} - \frac{\partial \eta_j}{\partial r_i} = \left(1 + vT_i' \frac{\partial D_i}{\partial r_i}\right) - vT_j' \frac{\partial D_j}{\partial r_i} \tag{a.153}$$

$$= \frac{\left(\dfrac{\partial^2 B_C}{\partial q_{CA} \partial q_{CB}} - \dfrac{\partial^2 B_C}{\partial q_{CA}^2}\right) \dfrac{\partial^2 B_A}{\partial q_{AC}^2}}{\left(\dfrac{\partial^2 B_A}{\partial q_{AC}^2} - vT_A'\right)\left(\dfrac{\partial^2 B_C}{\partial q_{CA} \partial q_{CB}} - \dfrac{\partial^2 B_C}{\partial q_{CA}^2}\right) + vT_A' \dfrac{\partial^2 B_A}{\partial q_{AC}^2}} \tag{a.154}$$

in which the right-hand side of (a.154) is positive.

To show that the generalized price for the passengers using the local airport is increasing in the local airport charge by less than 1, use the generalized price in (96), which yields

$$\frac{\partial \eta_i}{\partial r_i} = \frac{\partial\left(r_i + vT_i\right)}{\partial r_i} \tag{a.155}$$

$$= 1 + vT_i' \frac{\partial D_i}{\partial r_i}. \tag{a.156}$$

Lemma 18 mentions that $\partial D_i / \partial r_i < 0$ and vT_i' is positive by assumption, which implies that the right-hand side of (a.156) is less than 1 and thus completes the proof.

A. 25 Proof of Lemma 20

Totally differentiating (100) yields

$$d\left(\bar{Q}_A - D_A\right) = \frac{\partial\left(\bar{Q}_A - D_A\right)}{\partial r_A} dr_A + \frac{\partial\left(\bar{Q}_A - D_A\right)}{\partial r_B} dr_B + \frac{\partial\left(\bar{Q}_A - D_A\right)}{\partial \bar{Q}_A} d\bar{Q}_A \tag{a.157}$$

$$= -\frac{\partial D_A}{\partial r_A} dr_A - \frac{\partial D_A}{\partial r_B} dr_B + d\bar{Q}_A = 0, \tag{a.158}$$

$$d\left(\bar{Q}_B - D_B\right) = \frac{\partial\left(\bar{Q}_B - D_B\right)}{\partial r_A} dr_A + \frac{\partial\left(\bar{Q}_B - D_B\right)}{\partial r_B} dr_B + \frac{\partial\left(\bar{Q}_B - D_B\right)}{\partial \bar{Q}_A} d\bar{Q}_A \tag{a.159}$$

$$= -\frac{\partial D_B}{\partial r_A} dr_A - \frac{\partial D_B}{\partial r_B} dr_B = 0. \tag{a.160}$$

In matrix form, this can be rewritten as

$$\begin{pmatrix} -\dfrac{\partial D_A}{\partial r_A} & -\dfrac{\partial D_A}{\partial r_B} \\ -\dfrac{\partial D_B}{\partial r_A} & -\dfrac{\partial D_B}{\partial r_B} \end{pmatrix} \begin{pmatrix} dr_A \\ dr_B \end{pmatrix} = -\begin{pmatrix} 1 \\ 0 \end{pmatrix} d\bar{Q}_A. \tag{a.161}$$

The 2×2 matrix on the left-hand side is positive definite, which ensures that each pair of slots is mapped with a unique pair of slot prices by the Gale-Nikaido Theorem (Gale and Nikaido, 1965). Given that

$$\frac{dr_i}{d\bar{Q}_i} = \frac{\partial r_i}{\partial \bar{Q}_i} + \frac{\partial r_i}{\partial \bar{Q}_j}\frac{d\bar{Q}_j}{d\bar{Q}_i} = \frac{\partial r_i}{\partial \bar{Q}_i} \tag{a.162}$$

and

$$\frac{dr_j}{d\bar{Q}_i} = \frac{\partial r_j}{\partial \bar{Q}_i} + \frac{\partial r_j}{\partial \bar{Q}_j}\frac{d\bar{Q}_j}{d\bar{Q}_i} = \frac{\partial r_j}{\partial \bar{Q}_i}, \tag{a.163}$$

applying Cramer's rule, an increase in the local airport's slot quantity changes the local slot price and the other airport's slot price in the sense that

$$\frac{\partial r_i}{\partial \bar{Q}_i} = \frac{\dfrac{\partial D_i}{\partial r_i}}{\dfrac{\partial D_A}{\partial r_A}\dfrac{\partial D_B}{\partial r_B} - \dfrac{\partial D_B}{\partial r_A}\dfrac{\partial D_A}{\partial r_B}} \tag{a.164}$$

and

$$\frac{\partial r_j}{\partial \bar{Q}_i} = \frac{-\dfrac{\partial D_j}{\partial r_i}}{\dfrac{\partial D_A}{\partial r_A}\dfrac{\partial D_B}{\partial r_B} - \dfrac{\partial D_B}{\partial r_A}\dfrac{\partial D_A}{\partial r_B}}. \tag{a.165}$$

Lemma 13 mentions that $\partial D_i / \partial r_i < 0 < \partial D_j / \partial r_i < \left|\partial D_i / \partial r_i\right|$, therefore $\partial D_A / \partial r_A \cdot \partial D_B / \partial r_B - \partial D_B / \partial r_A \cdot \partial D_A / \partial r_B > 0$. This implies that both right-hand sides of (a.164) and (a.165) are negative.

To show that the reduction in the non-local airport's slot price is smaller than the reduction in the local airport's slot price in local slot quantity, use (a.164) and (a.165), which yields

$$\frac{\partial r_i}{\partial \bar{Q}_i} - \frac{\partial r_j}{\partial \bar{Q}_i} = \frac{\dfrac{\partial D_i}{\partial r_i} + \dfrac{\partial D_j}{\partial r_i}}{\dfrac{\partial D_A}{\partial r_A}\dfrac{\partial D_B}{\partial r_B} - \dfrac{\partial D_B}{\partial r_A}\dfrac{\partial D_A}{\partial r_B}}. \tag{a.166}$$

Using symmetry in the sense that $\partial D_A / \partial r_A = \partial D_B / \partial r_B$ and $\partial D_B / \partial r_A = \partial D_A / \partial r_B$, and substituting $\partial D_A / \partial r_A$ and $\partial D_B / \partial r_A$ with $\partial D_i / \partial r_i$ and $\partial D_j / \partial r_i$ respectively, the right-hand side of (a.166) can be rewritten as

$$\frac{\partial r_i}{\partial \bar{Q}_i} - \frac{\partial r_j}{\partial \bar{Q}_i} = \frac{1}{\dfrac{\partial D_i}{\partial r_i} - \dfrac{\partial D_i}{\partial r_i}} \tag{a.167}$$

in which the right-hand size is negative and thus completes the proof.

A. 26 Proof of Lemma 21

To show that demand of non-locals who use the other congested airport is decreasing in the local airport's slot quantity in part (i), use (a.164) and (a.165), which yields

$$\frac{\partial D_{Cj}}{\partial \bar{Q}_i} = \frac{\partial D_{Cj}}{\partial r_i}\frac{\partial r_i}{\partial \bar{Q}_i} + \frac{\partial D_{Cj}}{\partial r_j}\frac{\partial r_j}{\partial \bar{Q}_i} \tag{a.168}$$

$$= \frac{\dfrac{\partial D_{Cj}}{\partial r_i}\dfrac{\partial D_{iC}}{\partial r_i} - \dfrac{\partial D_{Ci}}{\partial r_i}\dfrac{\partial D_{jC}}{\partial r_i}}{\dfrac{\partial D_A}{\partial r_A}\dfrac{\partial D_B}{\partial r_B} - \dfrac{\partial D_B}{\partial r_A}\dfrac{\partial D_A}{\partial r_B}}. \tag{a.169}$$

Lemma 18 mentions that $\partial D_i / \partial r_i < 0 < \partial D_j / \partial r_i < |\partial D_i / \partial r_i|$, therefore $\partial D_A / \partial r_A \cdot \partial D_B / \partial r_B - \partial D_B / \partial r_A \cdot \partial D_A / \partial r_B > 0$. Lemma 18 also mentions that $\partial D_{iC} / \partial r_i < 0$ and $\partial D_{Ci} / \partial r_i < \partial D_{jC} / \partial r_i < 0 < \partial D_{Cj} / \partial r_i$, therefore $\partial D_{Cj} / \partial r_i \cdot \partial D_{iC} / \partial r_i - \partial D_{Ci} / \partial r_i \cdot \partial D_{jC} / \partial r_i < 0$. Altogether, the right-hand side of (a.169) is negative.

To show that the demand of the other congested airport's passengers is increasing in the local airport's slot quantity in part (i), using symmetry in the sense that $\partial D_{jC} / \partial r_i = \partial D_{iC} / \partial r_j$ yields

$$\frac{\partial D_{jC}}{\partial \bar{Q}_i} = \frac{\partial D_{jC}}{\partial r_i}\frac{\partial r_i}{\partial \bar{Q}_i} + \frac{\partial D_{jC}}{\partial r_j}\frac{\partial r_j}{\partial \bar{Q}_i} \tag{a.170}$$

$$= \frac{\partial D_{jC}}{\partial r_i}\frac{\partial r_i}{\partial \bar{Q}_i} + \frac{\partial D_{iC}}{\partial r_i}\frac{\partial r_j}{\partial \bar{Q}_i}. \tag{a.171}$$

Lemma 18 mentions that $\partial D_{iC} / \partial r_i < \partial D_{jC} / \partial r_i < 0$ whereas Lemma 20 mentions that $\partial r_i / \partial \bar{Q}_i < \partial r_j / \partial \bar{Q}_i < 0$, which altogether implies that the right-hand side of (a.171) is positive.

To show that the demand of locals is increasing in the local airport's slot quantity by more than the demand of passengers originating from the other congested airport in the local airport's slot quantity in part (i), using symmetry in the sense that $\partial D_{iC} / \partial r_i = \partial D_{jC} / \partial r_j$ and $\partial D_{jC} / \partial r_i = \partial D_{iC} / \partial r_j$ yields

$$\frac{\partial D_{iC}}{\partial \bar{Q}_i} - \frac{\partial D_{jC}}{\partial \bar{Q}_i} = \left(\frac{\partial D_{iC}}{\partial r_i}\frac{\partial r_i}{\partial \bar{Q}_i} + \frac{\partial D_{iC}}{\partial r_j}\frac{\partial r_j}{\partial \bar{Q}_i}\right) - \left(\frac{\partial D_{jC}}{\partial r_i}\frac{\partial r_i}{\partial \bar{Q}_i} + \frac{\partial D_{jC}}{\partial r_j}\frac{\partial r_j}{\partial \bar{Q}_i}\right) \tag{a.172}$$

$$= \left(\frac{\partial D_{iC}}{\partial r_i} - \frac{\partial D_{jC}}{\partial r_i}\right)\left(\frac{\partial r_i}{\partial \bar{Q}_i} - \frac{\partial r_j}{\partial \bar{Q}_i}\right). \tag{a.173}$$

Lemma 18 mentions that $\partial D_{iC} / \partial r_i < \partial D_{jC} / \partial r_i$ whereas Lemma 20 mentions that $\partial r_i / \partial \bar{Q}_i < \partial r_j / \partial \bar{Q}_i < 0$, which altogether implies that the right-hand side of (a.173) is positive.

To show that the demand of non-locals who use the local airport is increasing in the local airport's slot quantity by more than the demand of passengers originating from the other congested airport in the local airport's slot quantity in part (i), using symmetry in the sense that $\partial D_{Cj} / \partial r_i = \partial D_{Ci} / \partial r_j$ and $\partial D_{jC} / \partial r_i = \partial D_{iC} / \partial r_j$ yields

$$\frac{\partial D_{Ci}}{\partial \bar{Q}_i} - \frac{\partial D_{jC}}{\partial \bar{Q}_i} = \left(\frac{\partial D_{Ci}}{\partial r_i} \frac{\partial r_i}{\partial \bar{Q}_i} + \frac{\partial D_{Ci}}{\partial r_j} \frac{\partial r_j}{\partial \bar{Q}_i} \right) - \left(\frac{\partial D_{jC}}{\partial r_i} \frac{\partial r_i}{\partial \bar{Q}_i} + \frac{\partial D_{jC}}{\partial r_j} \frac{\partial r_j}{\partial \bar{Q}_i} \right) \tag{a.174}$$

$$= \left(\frac{\partial D_{Ci}}{\partial r_i} - \frac{\partial D_{jC}}{\partial r_i} \right) \frac{\partial r_i}{\partial \bar{Q}_i} + \left(\frac{\partial D_{Cj}}{\partial r_i} - \frac{\partial D_{iC}}{\partial r_i} \right) \frac{\partial r_j}{\partial \bar{Q}_i}. \tag{a.175}$$

Using (a.164) and (a.165), the right-hand side of (a.175) can be rewritten as

$$\frac{\partial D_{Ci}}{\partial \bar{Q}_i} - \frac{\partial D_{jC}}{\partial \bar{Q}_i} = \frac{1}{\frac{\partial D_A}{\partial r_A} \frac{\partial D_B}{\partial r_B} - \frac{\partial D_B}{\partial r_A} \frac{\partial D_A}{\partial r_B}} \left(\frac{\partial D_i}{\partial r_i} - \frac{\partial D_j}{\partial r_i} \right) \left(\frac{\partial D_{Ci}}{\partial r_i} + \frac{\partial D_{Cj}}{\partial r_i} \right). \tag{a.176}$$

Lemma 18 mentions that $\partial D_i / \partial r_i < 0 < \partial D_j / \partial r_i < \left| \partial D_i / \partial r_i \right|$, therefore $\partial D_A / \partial r_A \cdot \partial D_B / \partial r_B - \partial D_B / \partial r_A \cdot \partial D_A / \partial r_B > 0$. Lemma 18 also mentions that $\partial \left(D_{CA} + D_{CB} \right) / \partial r_i < 0$, which altogether implies that the right-hand side of (a.176) is positive.

To show that the demands for both locals and non-locals who use local airport are increasing in the local airport's slot quantity by less than 1 in part (i), consider the local airport's total traffic which is the sum of the two demands and is increasing in the local airport's slot quantity by 1. Since the two demands have been proved to be increasing in the local airport's slot quantity, each of the two demands is increasing in the local airport's slot quantity by less than 1.

To show that the total demand of non-locals from airport C is increasing in the local airport's slot quantity in part (ii), using symmetry in the sense that $\partial \left(D_{CA} + D_{CB} \right) / \partial r_i = \partial \left(D_{CA} + D_{CB} \right) / \partial r_j$ yields

$$\frac{\partial\left(D_{CA}+D_{CB}\right)}{\partial\bar{Q}_i}=\frac{\partial\left(D_{CA}+D_{CB}\right)}{\partial r_i}\frac{\partial r_i}{\partial\bar{Q}_i}+\frac{\partial\left(D_{CA}+D_{CB}\right)}{\partial r_j}\frac{\partial r_j}{\partial\bar{Q}_i} \tag{a.177}$$

$$=\frac{\partial\left(D_{CA}+D_{CB}\right)}{\partial r_i}\left(\frac{\partial r_i}{\partial\bar{Q}_i}+\frac{\partial r_j}{\partial\bar{Q}_i}\right). \tag{a.178}$$

Lemma 18 mentions that $\partial\left(D_{CA}+D_{CB}\right)/\partial r_i<0$ whereas Lemma 20 mentions that $\partial r_i/\partial\bar{Q}_i<\partial r_j/\partial\bar{Q}_i<0$, which altogether implies that the right-hand side of (a.178) is positive.