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**Modeling airport networks for theoretical policy analyses**

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**Abstract:** More than in almost any other transport industry, air transport is globally connected. This paper provides an overview over theoretical studies considering network structures involving two or more airports. Beyond conveying study results, the goal is to offer guidance on how to *theoretically* cover and analyze specific issues in the most effective way. Effectiveness is measured in terms of the complexity needed to address the specific issues. The selected issues discussed in this paper include ownership structures and privatization, congestion, beggar-thy-neighbor, and competition. We demonstrate that the analysis of these issues requires networks of different sizes and structures. We measure the airport size by the number of airports involved. We determine the network structure by (i) the number of regions and by distinguishing between regions which are just passively present or actively involved in policy making, and (ii) the involvement of local and non-local passengers.

**Keywords:** *Airport networks;Congestion;Privatization;Beggar-thy-neighbor;Competition*

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# 1. Introduction

More than in almost any other transport industry, air transport is globally connected. According to The World Factbook of the US Central Intelligence Agency, 41,820 airports existed in the world in 2021. If each of these airports would be connected with a direct flight, this would create a massive network with around 1.75 billion direct connections. The Airports Council International, the airports' global trade association, counts 1,925 member airports. Connecting only these member airports would already create a network with around 3.7 million direct connections. And, the number of existing airports continues to grow. In China alone, ten new airports will be constructed on average every year until 2035. Airport networks involve continents, countries, cities and other types of economic and political regions. Not all airport regions are large enough in terms of population or economic importance to allow for the supply of direct connections, or airlines may not be allowed to offer direct connections because air space access is restricted by bilateral agreements between the regions of origin and destination. Therefore, many airports may be connected to other airports only indirectly requiring passengers or cargo to switch aircraft at so-called hub airports. This further adds to the complexity of airport networks.

The goal of this paper is to offer guidance on how to *theoretically* cover and analyze specific topics in an effective way. Effectiveness is measured in terms of the complexity needed to address the specific topics. The regulation and management of airport networks involves many issues. In this paper, we concentrate on ownership structures and privatization, congestion externalities, beggar-thy-neighbor, and competition. Many of these issues may exist and/or may be more or less problematic depending on the size and the structure of the airport networks involved. We measure the network size by the number of airports involved. We determine the network structure by (i) the number of regions and by distinguishing between regions which are just passively present or actively involved in policy making, and (ii) the involvement of local and non-local passengers. A proper theoretical analysis requires a good understanding of how airport networks can be developed along these dimensions. We do not attempt to provide a complete overview over the relevant literature, which is huge. Selected (theoretical) studies will be used and the most relevant aspects of those studies, for the purpose of this paper, will be discussed as examples for specific airport networks and how they are applied to analyze the above-listed issues. The selection of studies is intended to provide a good overview over the most relevant insights derived by the literature. Empirical studies or studies applying a complex system perspective using network science tools are not the focus of this paper.[1]

[1]For instance, Sun, Wandelt and Zhang (2020) have applied a complex system perspective using network science tools to study how Covid-19 impacted air transportation.

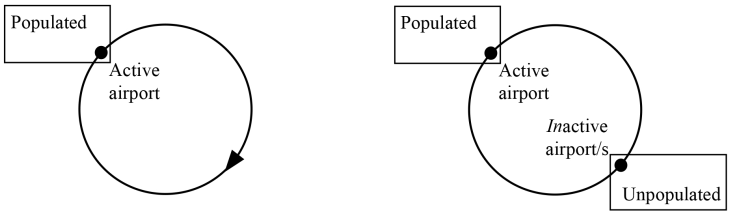


***Figure 1:*** *Basic networks: "sightseeing" network (left) and more complex alternative version (right)*

This paper consists of three main parts. Section 2 develops and discusses the simplest possible network version called the "sightseeing network" as well as more complicated structures such as hub-and-spoke networks. Section 3 introduces what we call "beggar" networks involving airports located in different regions with local governments and populations. Section 4 separately discusses networks for the analyses of airport competition for origin-destination and transfer passengers. Section 5 provides conclusions and develops avenues for future research.

## 2. Basic and hub-and-spoke networks

Figure 1 illustrates two "basic" networks which are considered in this section. The reason for calling them basic is that they could be considered as the building blocks for other more complex networks.

The most basic network is what we call the "sightseeing network" (see the network on the left of Figure 1). It is called this way because it involves "flights to nowhere" in the sense that the origin and destination airports are identical. Although not important from the modeling viewpoint, such services indeed existed; they have been invented by airlines during the Covid-19 pandemic as a means to make use of their aircraft fleet despite the many flight restrictions. Alternatively, one could use a network in which an arbitrary number of inactive airports located in unpopulated regions are added to the network (see the network on the right of Figure 1). Adding inactive airports in unpopulated regions is not always necessary or useful although their consideration could possibly comfort the reader because with them included the network may be appearing more realistic. To avoid unnecessary complications, we recommend adding network components only if they serve a special purpose beyond comforting the reader, that is, without them the analysis would lose relevant insights. Anyway, this paper is developed in a way which is intended to help the reader get used to the notion of active/inactive and populated/unpopulated airports and appreciate the benefits of these concepts from the modeling perspective.

The sightseeing network on the left of Figure 1 can be used to analyze an extensive number of management and policy topics. Examples for the most popular topics involve congestion, non-aeronautical revenues, and price regulation. Consider an airport which is congested and where average passenger delays depend on the number of passengers because either terminal capacity is limited or runway capacity is limited (higher passenger numbers will typically be associated with an increase in aircraft take-offs and landings). These passengers could be on a "flight to nowhere" or on a flight to other airports which are uncongested and charge a normalized price of zero for their capacity use. The results will be independent which of the two approaches would be used. This is why we recommend resorting to the "sightseeing network" because of its simplicity. Excellent survey papers are available providing an overview over the contributions in these areas of research. A recent one is written by D'Alfonso et al. (2023). Basso and Zhang (2007), Zhang and Czerny (2012), and Gillen et al. (2016) are other recommended survey papers for readers who are interested in studies of these topics in which airport networks are not of main interest.

Our contribution is to provide an overview over studies using structures which are more complex than the sightseeing network in the sense that at least two airports are involved. Hub-and-spoke networks are a great example for this. Serving airport pairs non-stop with direct connections may not be economic in terms of profit or even welfare when demand is low. In such cases, airlines serve thin markets in terms of demand by collecting passengers at their main or hub airports and indirectly flying them from their origin airport to their destination airport. Passengers who change aircraft at the hub airport are called transfer passengers. Maertens et al. (2020) find that transfer passengers are the main source of aeronautical revenue for many large airports (although the overall share of transfer passengers has declined over time globally).

Oum et al. (1996) highlight that transfer passengers make heavy use of the runway infrastructure because they land and take-off on each leg of their journey whereas origin-destination passengers use the runway infrastructure only once on each leg. This can be captured by a simple network with one active hub airport and one inactive spoke airport in one region and a third unpopulated region with another inactive spoke airport. The inactive spoke airports can be representative for an arbitrary number of spoke airports. Considering only one spoke airport at the edges of the network economizes the notations. The left network of Figure 2 illustrates such an airport network. In this network, the airport located in the center is the hub airport where passengers originating from the populated spoke airport at the one edge of the network travel to the spoke airport located at the other edge of the network by changing aircraft at the hub.

Brueckner (2002) demonstrates that the pricing of congested airports should be based on market shares by considering a network structure equivalent to that of a sightseeing network. This is an ambiguous result in the sense that market shares

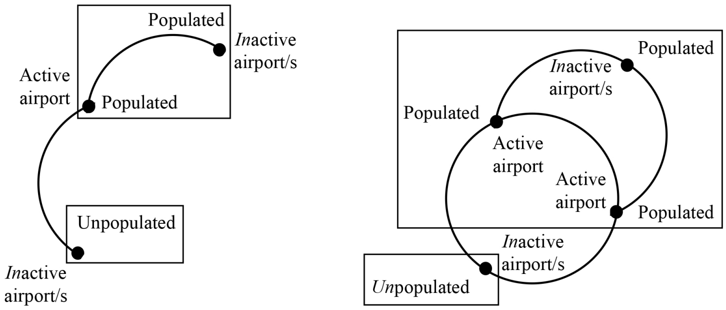


***Figure 2:*** *Hub-and-spoke networks: Network without (left) and with (right) hub-to-hub connection*

reflect the share in traffic as well as market power. Brueckner (2005) considers an extended version of a hub-and-spoke network to study this ambiguity. The network at the bottom right of Figure 2 can be used to illustrate his approach. Importantly, this network involves two hub airports, both congested, allowing for the consideration of connections between hub airports. Brueckner (2005) considers two airlines, each operating one of the two hub airports. Assuming symmetry, this implies that these airlines do not differ in terms of market power while their traffic shares at the two hub airports do differ because the "home carrier" does not only operate the hub-to-hub connections at its hub airport but also the spoke-to-hub and hub-to-spoke connections. As shown by Brueckner (2005), the welfare-maximizing airport charges at the hub airports are not equal for the two airlines but depend on their traffic shares in terms of flights, solving the previously mentioned ambiguity.

Passengers care about not only ticket prices, congestion delays but also about schedule delays defined as the difference between the preferred and actual departure times by Douglas and Miller (1974). Flores-Fillol (2010) uses a type of network similar to the one considered by Oum et al. (1996) to study frequency supplies when the hub airport is congested. Using fixed demands in the spirit of Brueckner and Van Dender (2008) to abstract away from airline market power, he shows, amongst other results, that without proper aeronautical charges airlines will be flying too often to boost their frequency supply and reduce passenger schedule delay costs. Considering a similar network setting but with endogenous demands, Lin (2013) finds that the privatization of all airports including hub and spoke airports is the least desirable policy in terms of welfare. Flores-Fillol (2010) distinguishes between passenger- and flight-based airport charges. This distinction is relevant for several reasons as highlighted by, for example, Czerny and Zhang, (2015), one of them being that passenger-based charges can be differentiated by distinguishing between origin-destination and transfer passengers. Lin and Zhang (2016) highlight that discriminatory passenger charges of this type are widespread in Asia, Canada and Europe. They use the type of network depicted on the left of Figure 2 to demonstrate that such pricing flexibility can be welfare enhancing.

# 3. Beggar-thy-neighbor

Infrastructure charges are sometimes raised to exploit non-locals (for simplicity, local and non-local passengers are called locals and non-locals respectively here and hereafter). This can be characterized as "beggar thy neighbour" strategies (Montolio and Trillas, 2013). Such strategies seem highly relevant in aviation markets which often involve pairs of airports which are located in different regions, countries or even continents. This section describes networks suitable for the analysis of the "beggar thy neighbour" phenomenon in air transport.

## 3.1. One beggar

We distinguish among three types of beggar networks. The first and simplest involves only one active airport (see top-left network in Figure 3) whereas many studies use two or more active airports to avoid considering populated regions which are non-active (see the other two networks in Figure 3 as examples). In this part, we highlight that simplifying the network structure by considering two populated airport regions in which only one airport is active can have the advantage of helping concentrate on the effect of non-locals on local policies without the need to consider equilibrium airport behaviors.

In the one-beggar network, it is convenient to define users from the perspective of the active airport. The total passenger quantity, denoted by $q$, is given by the sum of locals and non-locals denoted by $q_l$ and $q_{nl}$, respectively, that is, $q = q_l + q_{nl}$. The total benefit from flying is additive separable so that it can be written as the sum of the locals' benefit denoted by $B_l(q_l)$ and the non-locals' benefit denoted by $B_{nl}(q_{nl})$, that is, $B(q_l, q_{nl}) = B_l(q_l) + B_{nl}(q_{nl})$. Lang and Czerny (2022b) use such a simple approach with two populated regions of which only one is active to compare and evaluate the price- and slot-based solutions when the congested airport is used by locals and non-locals. They found that pricing solutions will never achieve a (first-best) result that will maximize the total welfare of all regions including the non-locals' region of origin because the airport not only internalizes the marginal external congestion costs but also charges a premium on them to exploit non-locals. A different result is obtained for quantity-based solutions involving airport slots which are allocated to airlines based on grandfather rules. An important implication is that such a system does not involve airport revenues

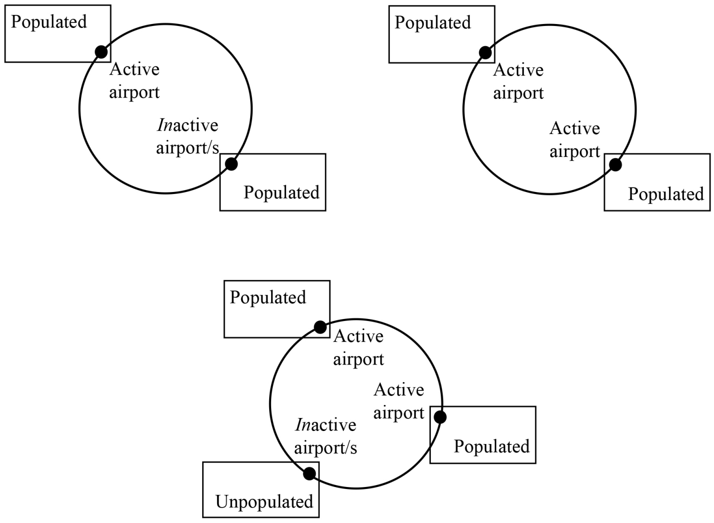


***Figure 3:*** *Beggar networks: one-beggar network (top left), base version of a two-beggar network (top right), and expanded version of a two-beggar network (bottom)*

from allocating slots to non-locals because grandfathering involves no payments. Accordingly, the airport maximizes local welfare by balancing the benefits and congestion costs of locals via changing the slot quantity denoted by $\bar{Q}$. Non-locals complicate the problem because they will use up some slot capacity.

To understand how the local-welfare maximizing slot quantity denoted by $\bar{Q}^*$ relates to the first-best slot quantity, Lang and Czerny (2022b) distinguish between the share of locals in terms of inframarginal and marginal passengers. Let $q_i'(\bar{Q})$ denote the change in the number of passengers of type $i$ with $i = l, nl$ caused by a marginal increase in the slot quantity. The inframarginal and marginal shares of locals can then be written as $q_l(\bar{Q})/(q_l(\bar{Q}) + q_{nl}(\bar{Q}))$ and $q_l'(\bar{Q})/(q_l'(\bar{Q}) + q_{nl}'(\bar{Q}))$, respectively.[2] They show that the local welfare-maximizing solution replicates the first-best result when those shares are equal in the local welfare-maximizing solution, that is,

$$\frac{q_l(\bar{Q}^*)}{q_l(\bar{Q}^*) + q_{nl}(\bar{Q}^*)} = \frac{q_l'(\bar{Q}^*)}{q_l'(\bar{Q}^*) + q_{nl}'(\bar{Q}^*)} \tag{1}$$

whereas $\bar{Q}^*$ is smaller or greater than the first-best slot quantity depending on whether the inframarginal share of locals is higher or smaller than the corresponding share of marginal locals. As we will again highlight later, these results are also valid for more complex networks involving several active airports, showing that fundamental results can be obtained by using the most simplified one-beggar network.

## 3.2. Two beggars: base version

The two-beggar network displayed on the top-right of Figure 3 is, relative to the one-beggar network, a more commonly considered network structure. This network involves two regions each of them populated and each of them equipped with one active and congested airport; thus, there is one congested and active airport in each of the two populated regions.

In the base version of the two-beggar network (as well as in the expanded version), it is no longer appropriate to define passengers from the perspective of a particular airport because both airports are active. In this case, airports may be denoted by $A$ and $B$ and the quantity of passengers who originate from $i$ with $i = A, B$ could be denoted by $q_{ij}$ with $j \neq i$. As highlighted by Czerny and Lang (2019), this notation could be economized by choosing $q_i$ instead of $q_{ij}$. The more complex notation is, however, maintained because it is useful in the extended version of the two-beggar network. With symmetry, the total benefit from flying is given by $B(q_{AB}) + B(q_{BA})$.

Pels and Verhoef (2004) use a two-beggar network to analyze the regional airport authorities' incentives to independently implement pricing policies versus laissez faire in which the airport would be charging zero tolls. They highlight that keeping airport charges low is not attractive from the perspective of local governments because not only the local airlines benefit from low charges but also foreign airlines. They use numerical illustrations to demonstrate the possibility of prisoner's dilemma situation in which regions charge positive prices although they would be better off in terms of local welfares with zero tolls. Using a two-beggar network, Lin (2020) further highlights the existence of foreign airlines as a source for policy failure in terms of airport pricing. Basso (2008) considers a two-beggar network to capture scenarios in which airports would be privatized separately and not in a system. He highlights that profit-maximizing airports which are complements

[2]The share of marginal locals can be simplified to $q_l(\bar{Q})/\bar{Q}$ because $q_l(\bar{Q}) + q_{nl}(\bar{Q})$ equals $\bar{Q}$ whereas the share of inframarginal locals can be simplified to $q_l'(\bar{Q})$ because $q_l'(\bar{Q}) + q_{nl}'(\bar{Q})$ equals 1.

and act independently suffer from double marginalization leading to excessive pricing from the social viewpoint. He further highlights that airports have incentives to excessively invest in capacity. Given that capacities are determined before prices and prices are strategic substitutes in the sense of Bulow et al. (1985), capacity investments improve the strategic position at the pricing stage causing the counterpart to reduce prices. Following the terminology of Fudenberg and Tirole (1984), airports are found to use so-called top-dog strategies. This is an important result which is complementary to the findings by De Borger and Van Dender (2006) who consider airports which are substitutes as will be discussed in Section 4 concerning competitive airport networks.

Whereas Basso (2008) considers privatization policies as given, Mantin (2012) uses a two-beggar network to analyze endogenous ownership decisions by regional and independent policy makers. He finds that both airports would privatize their airports ending up in a prisoner's dilemma with both regions being worse off with private airports than with publicly owned airports in terms of their welfare positions. The intuition can be developed along the lines developed by Basso (2008). Privatization can be considered a top-dog strategy because the prices of a profit-maximizing airport typically exceed those of a government who is not only concerned about airport profits but also about consumer surplus and airline profits. Privatization can, therefore, be used as a tool to commit to a tougher strategic position in the pricing stage. Because both airports follow the top-dog strategies, price levels are excessive and social welfare is lower than with publicly owned airports. Czerny and Lang (2019) use the two-beggar network to compare price- and slot-based congestion policies by independent local decision makers. This study is similar to the above-mentioned study by Lang and Czerny (2022b), who used a one-beggar network, except that Czerny and Lang (2019) use the two-beggar network to study properties of equilibrium policy solutions. They highlight a specific complication arising from the use of a two-beggar network for the analysis of equilibrium slot policies which is the existence of multiple equilibrium solutions or, in other words, the lack of a unique equilibrium slot-policy solution. The ambiguity arises because an increase in the slot quantity of one airport may or may not result in an increase in that airport's output depending on whether the other airport's slot constraint is binding or not, respectively. For instance, if passengers only fly between airports, say, A and B, and airport A imposes an upper limit of ten flights on airport operations, the other airport cannot independently accommodate more than ten flights. They suggest considering the below-mentioned expanded two-beggar network constellation to address this issue.

### 3.3. Two beggars: expanded version

The expanded version of the two-beggar network is displayed at the bottom of Figure 3. It adds one unpopulated and inactive airport, which can be representative for an arbitrary number of unpopulated and inactive airports. This third airport may be denoted by $C$ and the quantity of passengers who originate from $i$ with $i = A, B$ could be denoted by $q_{ij}$ for those who fly to the other active airport and by $q_{iC}$ for those who fly to the airport located in the unpopulated region. With symmetry, the total benefit from flying is given by $B(q_{AB}, q_{AC}) + B(q_{BA}, q_{BC})$.

Recall that the two-beggar network produced ambiguous equilibrium results in the case of slot policies. The reason was that an increase in one airport's slot number increased traffic at this airport only if traffic had not yet reached the maximum slot capacity set by the other airport. With the existence of the third airport, this problem is solved leading to objective functions in terms of local welfares which are smooth in slot quantities in the relevant ranges. For illustration, consider a situation in which the other airport's traffic reached the capacity limit but that some of the slots are used for flights to the new third airport. In this case, an increase in the slot quantity can translate into higher traffic at the airport because the extra slots could either be used for trips to the new third airport or they could even be used to increase flights to the slot constrained airport because they can replace flights from the other airport to the third airport. Czerny and Lang (2019) and Lang and Czerny (2022a) use the expanded version of the two-beggar network and symmetry to show that equilibrium slot quantities can reach the first-best outcome depending on the equilibrium shares of marginal and inframarginal locals. They further show that a necessary condition for equilibrium slot quantities to be first-best is that passengers consider flights between their airport and airport $C$ as substitutes for flights between their airport and the other active airport in the sense that $\partial^2 B(q_{ij}, q_{iC})/\partial q_{ij}\partial q_{iC} < 0$.

## 4. Competition

This section discusses pure competition networks as well as networks which combine properties of beggar and competition networks. Sun et al. (2017) find that there are many regions in which origin-destination passengers can choose among multiple airports for their flight trips.Two network instances are used to study airport competition for origin-destination passengers. One network instance is used to study airport competition for transfer passengers.

### 4.1. Competition for origin-destination passengers

The perhaps simplest competition network combines two sightseeing types of networks displayed in Figure 1. It involves one populated region and two active and neighboring airports (see left network in Figure 4). All passengers can visit each of the two airports by ground transport indicated by the dashed line connecting the two airports. Airports may again be denoted by $A$ and $B$ and the quantity of passengers who originate from $i$ with $i = A, B$ is simply denoted by $q_i$.

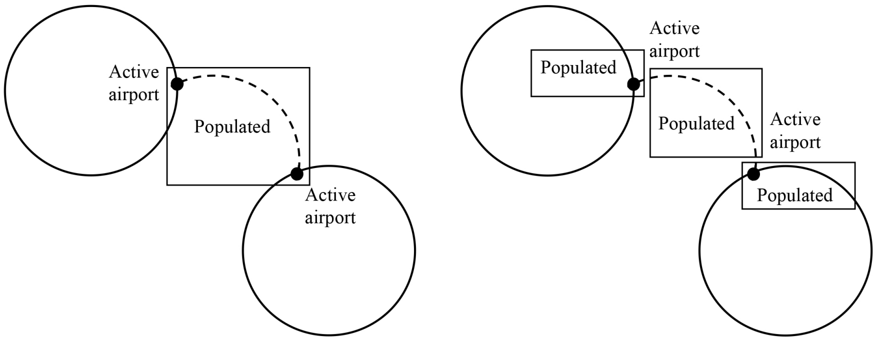


***Figure 4:*** *Competition for origin-destination passengers: Left network is used to study duopolistic competition whereas the right network is used to compare pricing and slot policies.*

De Borger and Van Dender (2006) consider a generic economic environment with the duopolistic interaction between congested facilities which could be interpreted as airports. They assume that users consider the services of the two facilities as perfect substitutes, that is, $B(q_A, q_B) = B(q_A + q_B)$. This assumption implies that the prices of the facilities are strategic complements in the sense of Bulow et al. (1985), which has an interesting implication for equilibrium investments. It is useful to understand that congestion softens price competition leading to strictly positive markups on marginal cost in equilibrium. This is for the following reason and holds although services are perfect substitutes in the sense that $B(q_A, q_B) = B(q_A + q_B)$. Congestion implies that even though one company charges a lower price than the rival, not all users will be demanding the lower-priced service, as would be the case without congestion (and in the absence of any other capacity constraints), because the higher demand will increase congestion at the more attractive facility. This already indicates that congestion softens competition, which is desirable from the companies' perspective. De Borger and Van Dender (2006) show that companies actually have incentives to strategically reduce capacity investments so that congestion is increased and price competition is softened in the subsequent stage. Using the terminology of Fudenberg and Tirole (1984), companies follow puppy-dog strategies.

Czerny, Höffler and Mun (2014) consider a network structure which combines elements of beggar and competition networks. They use a version of the two-sightseeing network to study endogenous port privatization policies when there are local and non-local users. Their version contains three populated regions only two of them containing an active port (see right network in Figure 4). There are no capacity limits, thus, congestion and delays are absent. Ports could be interpreted as airports. Let $q_{iu}$ denote the quantities of local and non-local users and $B_{iu}$ the corresponding user benefits with $i = A, B$, $u = l, nl$ and $B_{il}(q_{il})$ and $B_{nl}(q_{Anl} + q_{Bnl})$, respectively. Passengers prefer using their nearby airport to save travel time (Wiltshire, 2018; Adler et al., 2022). For simplicity, local users are assumed to have zero travel cost when they use their own port and prohibitively large travel costs when they use the other region's port. The travel costs of non-local users depend on their location within the third region. Let $T_i(q_{iu})$ denote the marginal travel costs of port $i$'s users with $T'_{iu} > 0$, and let $\tau_i$ denote port $i$'s user charge. The non-local users' demand for ports $A$ and $B$ is implicitly determined by the system of equations $\tau_A + T(q_{Anl}) = \tau_B + T(q_{Bnl})$ and $\tau_A + T(q_{Anl}) = B'_{Anl}(q_{Anl} + q_{Bnl})$ ensuring that users cannot be better off by using a different port or by not using the ports, respectively. Similar to De Borger and Van Dender (2006), prices are strategic complements in this scenario and privatization could be interpreted as a puppy-dog strategy because, by privatizing, the regions commit to charging higher prices softening competition for non-local users in the pricing stage. The authors demonstrate that local policy makers, especially if they govern the smaller region in terms of their local population, can be inclined to privatize their ports although in equilibrium local welfare might be higher with public ownership. Partial privatization strategies are considered by Noruzoliaee et al. (2015).

Leisure traffic seems of growing importance for aviation. For instance, the share of leisure passengers at London Airports increased from 63 percent in 1978 to 81 percent in 2019 (Airport Council International, 2021). The non-local users in the network setting considered by Czerny, Höffler and Mun (2014) can be interpreted as leisure travelers. Lang and Czerny (2023) use a network with almost the same properties as the one developed and analyzed by Czerny, Höffler and Mun (2014) to study congestion policies in a network, capturing airport competition for non-locals, which could be interpreted as leisure passengers. The only substantial difference between the settings (beyond notation and interpretations) is that Lang and Czerny (2023) consider active facilities which are congested whereas Czerny, Höffler and Mun (2014) consider uncongested facilities. Recall that Czerny and Lang (2019) and Lang and Czerny (2022a) find that, in equilibrium, prices are too high relative to the first-best prices whereas slot quantities can reach the first-best outcome (assuming that airports cannot earn from selling slots). Lang and Czerny (2023) reproduce this result in their network setting but further find that, from the viewpoint of the two active and congested airports, both the equilibrium prices as well as the the equilibrium slot quantities were too low to maximize their total welfare. The incentive to exploit non-locals provides an intuition for the too high prices. The intuition for the too low slot quantities is that a reduction in the local slot quantity increases the non-locals'

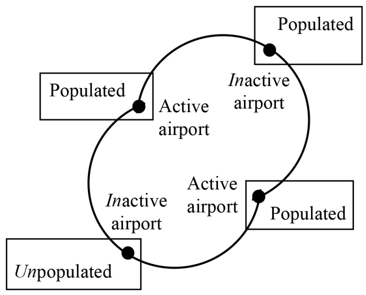


***Figure 5:*** *Competition for transfer passengers.*

incentives to use the alternative congested airport. Limited slot supply can therefore protect locals from congestion caused by non-locals.

### 4.2. Competition for transfer passengers

The previous part considered competition for origin-destination passengers. Many of the results carry over to scenarios in which airports compete for transfer passengers. Consider the network in Figure 5. Similar to Brueckner (2005), four airports are used to model the hub airports' competition for transfer passengers. The network in Figure 5 is designed to analyze competition; therefore, compared with the corresponding network in Figure 1 there is (i) no need for having the connection between hub airports and (ii) all airports are located in different regions implying that different governments are in control. Lang and Czerny (2023) use such a network assuming that the inactive, populated airport is the destination for locals whereas the inactive, unpopulated airport is the destination for the non-locals. This is to reduce complexity. Comparing the equilibrium policies derived for origin-destination passengers (the right network of Figure 4) with those derived for transfer passengers shows that some results are robust whereas other results are new.

The following results are robust. Consider slot policies. In this case, the qualitative results derived for origin-destination passengers carry over to the results derived for transfer passengers. Lang and Czerny (2023) demonstrate that in both environments equilibrium slot quantities are too low from the active and congested airports' point of view whereas they could be first-best. Consider pricing policies. Another result that carries over is that the equilibrium prices charged to non-locals are too low to maximize the total welfare of the two regions in which the congested airports are located and too high relative to the first-best prices. Recall that transfer passengers can be charged differently from origin-destination passengers. This is where the new result appears. The equilibrium prices charged to locals are actually too high from the active and congested airports' point of view and too low relative to the first-best prices. The intuition is that the airports try to attract the non-local transfer passengers because they bring extra profit to the local economy. Two strategies are used to increase attractiveness. The first is to reduce the price for the non-local transfer passengers. The second is more unexpected and involves increasing the price for local origin-destination passengers. The goal is to reduce demand and congestion, thus, increase the convenience for transfer passengers. Airports still care about locals' consumer surpluses, implying that they will not too aggressively charge their locals.

## 5. Conclusions

This paper surveyed and discussed theoretical studies involving relatively complex airport networks in which "complex" was applied to all settings which require the consideration of at least two airports. We distinguished between sightseeing, hub-and-spoke, beggar and competition networks and discussed how they can be modeled so that the researcher avoids being distracted by unnecessary model features. We described how various policy and managerial issues can be analyzed by varying the size and structure of airport networks. Size was measured by the number of airports involved. Structure was determined by the number of regions involved and by distinguishing between regions which are just passively present or actively involved in policy making. Another factor determining the network structure was the involvement of locals and non-locals.

The discussion of beggar and competition networks abstracted away from the discussion of airline market structures. This is by purpose. The reason is that these networks involve airports located in different regions used by local and non-local users. This substantially complicates the analysis of airport policies as has been demonstrated by Lang and Czerny (2022b). They distinguished between *exclusive* and *inclusive* airline services. The consideration of exclusive airline services requires that each region has its own home carriers. In this case, airline services are "exclusive" if passengers fly with their home airlines only. Inclusive services are such that home carriers serve locals and non-locals. This distinction matters for the policy analysis even if airline markets are assumed to be perfectly competitive. For instance, Lang and Czerny (2022b) show that pricing and slot policies lead to the same outcome in terms of local welfare when the corresponding home carriers offer exclusive air services whereas these policies lead to different outcomes when this is not the case. Hou et al. (2022) is another study which integrates airline market structures into the analysis of airport competition. They capture the Civial Aviation Industry of China (CAAC) can deter airline operations from specific airports and show that policy decisions depend on the weights policy makers attach to airline profits. Altogether, this indicates that integrating airline market structures into the analysis of beggar and competition networks offers plenty of opportunities for future research. Another issue which has been entirely abstracted away from are intermodal aspects of airport networks. A recent survey paper, though not with a special focus on airport networks, is provided by Zhang et al. (2019). Given the growing importance of high-speed rail in China and elsewhere, this is another area which needs further research.

Finally, one objective in modeling airport networks was to consider the minimum number of airports necessary to capture the relevant policy issues. In some cases, policy outcomes may depend on the network size. Czerny (2009) provides an example considering a hub-and-spoke network and the welfare effects of code-sharing agreements with antitrust immunity depending on the number of spoke airports. He shows that antitrust immunity could reduce welfare even though airline networks are perfectly complementary when the airport network in terms of the number of spoke airports is sufficiently large. This illustrates that results can depend on the network size requiring models of variable network size allowing comparative statics analysis in the network size.


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