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Price Competition of Airports and its Effects on the Airline's Network when the Short Haul Trip Demand Exists

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Abstract:

This paper deals with the price competition of airport operators and its effect on airlines' networks when the short haul trip demand between the competitors exists. We extend the model of Teraji and Morimoto (2014) by introducing the passengers' scheduling cost and the short haul trip demand. By using this model, we address the following two questions: i) how the price competition of airport operators affects the airline's network choice; and ii) how the short haul trip demand affects the price competition and the consequent airline's network choice. The results show that the price competition distorts the airline's network choice in the following two ways: i) it causes the airline to choose a point-to-point network instead of a hub-spoke one; and ii) it forces the airline to choose an airport at a relatively small city as its hub. Furthermore, although the short haul trip demand loosens the price competition of airport operators, the point-to-point network inefficiently sustains at the equilibrium.

Keywords: Airport Competition, Network Choice, Hub-Spoke, Point-to-Point, Short Haul Trip

1. Introduction

Airline deregulation and "Open Skies" agreements enhance the freedom of the airline's network choice, which airport to be served. Observing these liberalizations in the aviation industry, Graham (2008) argues that the low airport charge is one of the key factors when airlines determine the served airports. As claimed by Graham (2008), this situation motivates airport operators to discount their airport charges; consequently, the airport operators face the more intense competition. For example, East Asian airports such as Narita (NRT), Kansai (KIX), Incheon (ICN), and Hong Kong (HKG) offer the discounts of the airport charges when airlines start the flight service along the new routes, or increase the flight volume to the existing destinations. In case of KIX, the airport operator has started the discount program in 2012,[1] and as a result of this program, KIX has experienced a significant growth in the traffic volume during the succeeding four years from 2012.[2] This shows that operators can induce the airlines to form a favorable network for them by discounting their charges.

By incorporating these facts, Teraji and Morimoto (2014) firstly develop a model that enables to analyze the interaction between the competition of airports and the airline's network choice.[3] They have shown that the airport in a relatively small city has an incentive to discount its airport charge more aggressively than the one in a large city. Consequently, the price competition of airports distorts the airline's network by hubbing at the airport in a relatively small city. Their model, however, has the following shortcomings. First, they do not consider the short haul (or domestic) trip between the competitors' airports, which may enhance the scale economy in providing the

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[1] New Kansai International Airport Company (NKIAC) has been offering the following discount program. First, NKIAC cuts the landing fee for the international flights by 5 %. Furthermore, in order to motivate airlines to serve more flights, NKIAC discounts the landing fee for airlines which increase the number of flights or start the service at KIX.

[2] From 2011 to 2015, KIX experienced 57 % increase in the number of flights, and 74 % increase in the number of departing passengers.

[3] After the seminal works of Starr and Stinchcombe (1992) and Hendricks et al. (1995), several studies have focused on the carrier's network choice (for example, Brueckner, 2004; Kawasaki, 2008; Flores-Fillol, 2009). Brueckner (2004) analyzes the topic using three airports and a monopolistic carrier model. The carrier chooses a hub-spoke network when the fixed cost for a flight is high relative to the marginal cost for a seat and when passengers place a high value on flight frequency. Kawasaki (2008) extends the model of Bruechner (2004) by introducing the heterogeneity in value of time among passengers, leisure and business demands. Flores-Fillol (2009) extends the model by considering the duopoly case and shows that asymmetric equilibria may arise, namely one carrier chooses a point-to-point network while the other chooses a hub-spoke network.

connecting flights between the hub and spoke. In addition, the short haul trip may play the role to disturb the formation of the hub-spoke network. When setting the airport charges, operators face the problem whether to offer a discount to airlines. Once offering a discount, they can expand their airports' network sizes through becoming the airlines' hub. When the short haul trip demand is sufficiently large relative to the trip demands to newly connected airports, operators may have no incentives to discount. Consequently, there exists a possibility such that no hub-spoke network emerges at the equilibrium. Second, they ignore the scheduling cost of passengers, which might be significant under the hub-spoke network. Furthermore, this is one of the major sources for the scale economy of hubbing.

By incorporating these two factors, this paper addresses the question such that i) how the price competition affects the airline's network choice; and ii) how the existence of the short haul trip demand affects the behaviors of the airport operators and the consequent airline's network. The rest of the paper is organized as follows: Section 2 explains the model, and Section 3 describes the optimal network configuration, which is the benchmark for evaluating the equilibrium network configuration. In Section 4, we first summarize the network choice of airlines under the circumstance where positive airport charges are levied. This section also describes the equilibrium of the game between airport operators, and derives the equilibrium network configuration as a result of the price competition of airport operators. In Section 5, we compare the two network configurations, the optimum and the equilibrium, and evaluate the welfare effect of the price competition of airport operators. More specifically, we explain how the price competition of airport operators distorts the airline's network choice. In addition, we examine how the size of the short haul trip demand affects the two network configurations. Finally, Section 6 concludes.

2. The Model

2.1. The Basic Setting

Suppose a country which is consisted from the two cities, Cities 1 and 2, and we call it Country H. The population of the country is normalized to unity, and without loss of generality, we assume that City 1 is larger than City 2. To sum up, since the total population of this country is unity, we denote by $n > 1/2$ the population of City 1, and that of City 2 is $1 - n$. Each City i has an airport, and we call the one at City i Airport i. By using the airport, residents in each city travel to the other city and a foreign country (hereafter, we name this foreign destination Country F). Figure 1 summarizes the geography of the economy, and l_{ij} represents the distance between i

and j. We assume that the two airports are equidistant from Country F, and the distance to F is normalized to unity (that is, $l_{iF} = 1$).[4] The distance between the two airports, 1 and 2, is denoted by $l_{12} = l < 1$.

<<FIGURE 1: ABOUT HERE>>

We assume that a single airline provides the domestic and the international flight services to the two airports, 1 and 2, of Country H, and hereafter, we simply call it Airline. The domestic flight is the service for travelers between the two cities, and is named service D. The international flight is the service for travelers between each City i and Country F, and is called service I. In addition, when providing service I, Airline has the two choices as in Figure 2. The left side of Figure 2 corresponds to the point-to-point network: that is, the direct flight service to Country F is provided at the two airports. The right side of Figure 2 draws the hub-spoke network: namely, the direct flight to Country F is served at one of the two airports. In this type of network, Airline also chooses its hub from the two airports.

The difference among the three networks in Figure 2 is captured by whether Airline provides the direct international flight service to each of the two airports. Therefore, in order to express Airline's network formally, we define by δ_i the binary variable which

[4] The asymmetric case is studied in Teraji and Morimoto (2014), and in order to reduce the complexity, in this paper, we limit our focus to the symmetric case.

shows Airline's choice on the international service to Airport i. Namely, $\delta_i = 1$ if Airline operates the direct international flights at Airport i; $\delta_i = 0$, otherwise. The economy has the three types of agents, airport operators, Airline, and households. The sequence of decision among the three types of agents as follows. First, airport operators set their airport charges, and then Airline determines its network configuration, $\boldsymbol{\delta} = (\delta_1, \delta_2)$, airfares and aircraft sizes. Finally, households decide whether to travel. Hereafter, we track back this sequence of the decisions.

<<FIGURE 2: ABOUT HERE>>

2.2. Households

Households choose to travel by using service S $(S = I, D)$ flights unless the trip cost exceeds the reservation price, v^S. We assume that the reservation prices for the two services, I and D, are identical, and we normalize the reservation price for each service to unity $(v^I = v^D = 1)$.[5] The trip frequency also differs between the two services: households in each City i travel to Country F once while they travel to the other city j $\bar{d} \geq 1$ times.

The trip cost for each trip includes two components such as the airfare and the scheduling cost. The trip cost for domestic passengers, g^D, is given by:

[5] We limit our focuses to the case where Country F is neighboring to Country H. Under this circumstance, the difference in the reservation price between the domestic and the international trips is negligible; consequently, this assumption has a rationale.

$$g^D = p^D + \frac{1}{4f_{12}}, \qquad (1)$$

where p^D and f_{12} are the airfare for service D and the flight frequency between the two airports, 1 and 2, respectively. In Eq. (1), the second term of the RHS captures the scheduling cost.[6] Each household in City i travels to the other city, j, if $1 \geq g^D$. When this condition holds, the aggregate demand for service D, Q^D, is $\bar{d}$; otherwise, $Q^D = 0$.

In contrast, the trip cost for the international passengers from City i, g_i^I, depends on the Airline's network configuration. In other words, the trip cost is written as the function of δ_i: that is, $g_i^I = g_i^I(\delta_i)$. If $\delta_i = 1$,

$$g_i^I(1) = p_i + \frac{1}{4f_{iF}}, \qquad (2.1)$$

while if $\delta_i = 0$,

$$g_i^I(0) = p_i + \frac{1}{4f_{12}} + \frac{1}{4f_{jF}}. \qquad (2.2)$$

In Eqs. (2), p_i is the airfare for travelers from City i to Country F while f_{iF} represents the flight frequency between i and F. In case of $\delta_i = 0$, travelers between City i and Country F must access to Airport j, at which the direct flights to Country F is operated; therefore, in Eq. (2.2), the scheduling cost for the flights between the two cities, $1/4f_{12}$, is included. Each household decides to travel to Country F if

[6] This expression of the average waiting time is based on the assumption that trip demand is uniformly distributed across the time of day.

$1 \geq g_i^I(\delta_i)$. Under this circumstance, the aggregate demand between City i and Country F, Q_{iF}, is equal to the population of City i, n_i; otherwise, $Q_{iF} = 0$.

The number of passengers on each route r ($r = 12, 1F, 2F$), q_r, however, may differ from the aggregate demand since it depends on the network choice by Airline, $\boldsymbol{\delta} = (\delta_1, \delta_2)$: that is, $q_r(\boldsymbol{\delta})$. In case of $\boldsymbol{\delta} = (1, 1)$, the number of passengers on each route is given by:

$$q_{12}(1,1) = Q^D \text{ and } q_{iF}(1,1) = Q_{iF}.$$

If Airline chooses Airport 1 as its hub (that is, $\boldsymbol{\delta} = (1, 0)$):

$$q_{12}(1,0) = Q_{2F} + Q^D,\ q_{1F}(1,0) = \sum_{i=1,2} Q_{iF},\ \text{and } q_{2F}(1,0) = 0.$$

Finally, for the case of hubbing at Airport 2 (namely, $\boldsymbol{\delta} = (0, 1)$),

$$q_{12}(0,1) = Q_{1F} + Q^D,\ q_{1F}(0,1) = 0,\ \text{and } q_{2F}(0,1) = \sum_{i=1,2} Q_{iF}.$$

2.3. Airline

Airline incurs the two types of costs when providing the service such as the operating cost of flights and the airport charge payments for each route r. The marginal flight operating cost on route r is constant and given by cl_r. That is, the marginal cost is proportional to the cruising distance. In sum, for route r, the operating cost is computed as $cl_r f_r$ where $l_{12} = l$ and $l_{1F} = l_{2F} = 1$. We assume that all the flights on route r are fully seated, and operated with the same capacity s_r. Therefore, the flight frequency for route r must suffice the following relation:

$$s_r f_r = q_r(\boldsymbol{\delta}) \Leftrightarrow f_r(\boldsymbol{\delta}) = \frac{q_r(\boldsymbol{\delta})}{s_r}. \tag{3}$$

The airport charge is paid on a per passenger basis, and we denote by a_i the charge at Airport i; the airport charge payments of routes 12 and iF are respectively computed as $(a_1 + a_2)q_{12}(\boldsymbol{\delta})$ and $a_i q_{iF}(\boldsymbol{\delta})$. In summary, the Airline's total cost, $C(\mathbf{s}, \boldsymbol{\delta}; \mathbf{a})$, is:

$$C(\mathbf{s}, \boldsymbol{\delta}; \mathbf{a}) = \left(\frac{cl}{s_{12}} + a_1 + a_2\right) q_{12}(\boldsymbol{\delta}) + \sum_{i=1,2}\left(\frac{c}{s_{iF}} + a_i\right) q_{iF}(\boldsymbol{\delta}), \tag{4}$$

where $\mathbf{s} = (s_{12}, s_{1F}, s_{2F})$ and $\mathbf{a} = (a_1, a_2)$.

Airline maximizes its profit by choosing the airfare, the size of aircraft, and its network configuration. Since Airline can exercise their market power when determining the airfare, Airline chooses the airfare so that it fully exploits the consumer's gain, the reservation price net of the trip cost. According to these, the airfare for each service is computed as $p_i^I(\mathbf{s}, \boldsymbol{\delta})$ and $p^D(\mathbf{s}, \boldsymbol{\delta})$.[7] Under this pricing, $Q^D = \bar{d}$ and $Q_{iF} = n_i$. Therefore, the traffic volume for three routes under the three alternative networks are computed as follows:

$$q_{12}(1,1) = Q^D = \bar{d} \text{ and } q_{iF}(1,1) = Q_{iF} = n_i,$$

$$q_{12}(1,0) = Q_{2F} + Q^D = 1 - n + \bar{d},\ q_{1F}(1,0) = \sum_{i=1,2} Q_{iF} = 1, \text{ and } q_{2F}(1,0) = 0,$$

$$q_{12}(0,1) = Q_{1F} + Q^D = n + \bar{d},\ q_{1F}(0,1) = 0, \text{ and } q_{2F}(0,1) = \sum_{i=1,2} Q_{iF} = 1.$$

[7] The detailed expression is summarized in Appendix A.

By using these, the Airline's profit, $\pi(\boldsymbol{\delta}, \mathbf{s}; \mathbf{a})$, is computed as:

$$\pi(\mathbf{s}, \boldsymbol{\delta}; \mathbf{a}) = \sum_{i=1,2} p_i^I(\mathbf{s}, \boldsymbol{\delta}) Q_{iF} + p^D(\mathbf{s}, \boldsymbol{\delta}) Q^D - C(\mathbf{s}, \boldsymbol{\delta}; \mathbf{a}). \tag{5}$$

Given the airport charges, $\mathbf{a}$, Airline chooses the aircraft size for each route under the three alternative networks. Formally, this is written as follows:

$$\max_{\mathbf{s}} \pi(\mathbf{s}, \boldsymbol{\delta}; \mathbf{a}),$$

The size of aircrafts for each route is derived as:

$$\frac{\partial \pi(\mathbf{s}, \boldsymbol{\delta}; \mathbf{a})}{\partial s_r} = -\frac{1}{4} + \frac{c l_r q_r(\boldsymbol{\delta})}{s_r^{\,2}} = 0 \Leftrightarrow s_r^*(\boldsymbol{\delta}) = 2\sqrt{c l_r q_r(\boldsymbol{\delta})} \text{ for } r = 12, 1F, 2F. \tag{6}$$

By using Eqs. (3) and (6), the flight frequency of route r is computed as:

$$f_r^*(\boldsymbol{\delta}) = \frac{1}{2}\sqrt{\frac{q_r(\boldsymbol{\delta})}{c l_r}}.$$

Substituting Eq. (6) into Eq. (5), the Airline's profit for each of the three network is written as the function of airport charges, $\mathbf{a}$:

$$\pi(1,0;\mathbf{a}) = 1 + \bar{d} - a_1 - (a_1 + a_2)(1 - n + \bar{d}) - \sqrt{c}\left(1 + \sqrt{l(1 - n + \bar{d})}\right), \tag{7.1}$$

$$\pi(0,1;\mathbf{a}) = 1 + \bar{d} - a_2 - (a_1 + a_2)(n + \bar{d}) - \sqrt{c}\left(1 + \sqrt{l(n + \bar{d})}\right), \tag{7.2}$$

$$\pi(1,1;\mathbf{a}) = 1 + \bar{d} - \sum_{i=1,2} a_i (n_i + \bar{d}) - \sqrt{c}\left(\sum_{i=1,2} \sqrt{n_i} + \sqrt{l\bar{d}}\right). \tag{7.3}$$

In addition, we assume that Airline provides the service for each market r if the profit from the market r is non-negative: that is, $\pi_r(\boldsymbol{\delta}; \mathbf{a}) \geq 0$.[8]

2.4. Airport Operators

[8] The detailed expression for $\pi_r(\boldsymbol{\delta}; \mathbf{a})$ is summarized in Appendix A.

Each airport is operated by a different private authority, and they maximize their airport charge revenue. The airport charge revenue, however, varies with the network choice of Airline, $\boldsymbol{\delta}$. If Airline chooses to operate the international flights at a single airport, i, all the revenue from the international passengers flows into operator i's revenue, and the revenues from domestic and connecting passengers are shared between the two operators. In contrast, if Airline chooses the point-to-point network, with respect to the international flights, each operator earns the revenue from its home city demand. Formally, the airport charge revenue is written as follows:

$$R_i(\boldsymbol{\delta}) = a_i\left[q_{12}(\boldsymbol{\delta}) + q_{iF}(\boldsymbol{\delta})\right].$$

3. The Optimal Network Configuration

This section describes the optimal network configuration. Since the demands for the two types of services are inelastic, the profit of Airline is equivalent to the social surplus. Furthermore, since there are no externalities at the airports such as the congestion, at the optimum, the airport charges should be zero. In summary, the social surplus under the network $\boldsymbol{\delta}$ is computed as:

$$SS(1,0) = \pi\left(1,0;\mathbf{a}^{\mathbf{O}}\right) = 1+\bar{d} - \sqrt{c}\left(1+\sqrt{l\left(1-n+\bar{d}\right)}\right),$$

$$SS(0,1) = \pi\left(0,1;\mathbf{a}^{\mathbf{O}}\right) = 1+\bar{d} - \sqrt{c}\left(1+\sqrt{l\left(n+\bar{d}\right)}\right),$$

$$SS(1,1) = \pi(1,1;\mathbf{a^o}) = 1 + \bar{d} - \sqrt{c}\left(\sum_{i=1,2}\sqrt{n_i} + \sqrt{l\bar{d}}\right),$$

where $\mathbf{a^o} = (0,0)$ is the vector of the optimal airport charge.

The optimal network configuration, $\boldsymbol{\delta}^{\mathbf{o}}$, is characterized by the network which maximizes the social surplus. Since, under the assumption of the inelastic demand, the gross benefit is constant, the maximizing the social surplus is equivalent to minimizing the social cost of providing the flight services, $SC(\boldsymbol{\delta})$:

$$SC(1,0) = \sqrt{c}\left(1 + \sqrt{l\left(1 - n + \bar{d}\right)}\right), \tag{8.1}$$

$$SC(0,1) = \sqrt{c}\left(1 + \sqrt{l\left(n + \bar{d}\right)}\right), \tag{8.2}$$

$$SC(1,1) = \sqrt{c}\left(\sum_{i=1,2}\sqrt{n_i} + \sqrt{l\bar{d}}\right). \tag{8.3}$$

Hereafter, we derive the optimal network configuration, $\boldsymbol{\delta}^{\mathbf{o}}$, by comparing the social costs, Eqs. (8). Let us start with the comparison of hubbing at Airports 1 ($\boldsymbol{\delta} = (1,0)$) and 2 ($\boldsymbol{\delta} = (0,1)$):

$$SC(1,0) - SC(0,1) = \sqrt{cl}\left(\sqrt{1 - n + \bar{d}} - \sqrt{n + \bar{d}}\right) < 0. \tag{9}$$

The RHS of Eq. (9) is the cost differential in the connecting flights along route 12. Since $n > 1/2$, the sign of Eq. (9) is always negative. This is summarized in Lemma 1:

Lemma 1

When the two airports are equidistant from Country F, *hubbing at Airport 2* (*that is,* $\boldsymbol{\delta} = (0,1)$) *is always socially inferior to hubbing at Airport 1* ($\boldsymbol{\delta} = (1,0)$).

Lemma 1 states that hubbing at the airport in the larger city always minimizes the social cost compared to hubbing at the airport in the smaller city. In our setting, the hub-spoke network generates the flight operating cost for connecting passengers along route 12. Since this cost is increasing in the number of connecting passengers, hubbing at Airport 1 always reduces this additional cost compared to choosing Airport 2 as the Airline's hub.

Now, we derive the optimal network configuration $\boldsymbol{\delta}^{\mathbf{O}}$. In comparison of the social costs between hubbing at Airport 1 ($\boldsymbol{\delta} = (1,0)$) and point-to-point ($\boldsymbol{\delta} = (1,1)$), the point-to-point network becomes the optimal network configuration if:

$$SC(1,0) - SC(1,1) = \sqrt{c}\left(1 - \sum_i \sqrt{n_i}\right) + \sqrt{cl}\left(\sqrt{1-n+\bar{\bar{d}}} - \sqrt{\bar{\bar{d}}}\right) > 0. \tag{10}$$

Solving Eq. (10) for $\sqrt{l}$, we obtain the threshold l^O, and by using this threshold, we obtain Proposition 1, which summarizes the optimal network configuration, $\boldsymbol{\delta}^{\mathbf{O}}$.

Proposition 1

The optimal network configuration, $\boldsymbol{\delta}^{\mathbf{O}}$, *is summarized as follows:*

$$\boldsymbol{\delta}^{\mathbf{O}} = \begin{cases} (1,1) & \text{if } \sqrt{l} > l^O, \\ (1,0) & \text{if } \sqrt{l} \le l^O, \end{cases} \tag{11.1}$$

where

$$l^O \equiv \frac{\sum_i \sqrt{n_i} - 1}{\sqrt{1-n+\bar{\bar{d}}} - \sqrt{\bar{\bar{d}}}}. \tag{11.2}$$

Proposition 1 states that the optimal network configuration falls into hubbing at Airport 1 if the two airports in Country H are sufficiently close (that is, $\sqrt{l} \leq l^{O}$). This is because the scale economy in gathering all the international passengers to a single airport dominates the additional cost for serving the connecting flights between Airports 1 and 2. As the distance between the two airports increases, the optimal network configuration changes from the hub-spoke to the point-to-point since the additional cost for connecting passengers outweighs the scale economy of hubbing. Hereafter, in order to simplify the analysis, we consider the case where all the routes generate the surplus. Let us denote by $SS_r(\boldsymbol{\delta})$ the surplus of market r under network $\boldsymbol{\delta}$: then it is computed by evaluating $\pi_r(\boldsymbol{\delta}; \mathbf{a})$ at $\mathbf{a} = \mathbf{a^O} = (0,0)$. Namely,[9]

$$SS_r\left(\boldsymbol{\delta}\right) = \pi_r\left(\boldsymbol{\delta}; \mathbf{a^O}\right) \geq 0.$$

4. The Equilibrium

This section derives the equilibrium network configuration as a result of the game among Airline and the two airport operators. This section tracks back this sequence of decisions. Namely, Subsection 4.1 deals with the Airline's decision, and Subsection 4.2 explains how we discretize the two airports' strategies. In addition, we summarize the

[9] Appendix B summarizes the range of parameter values.

relationship between the two operators' choices and the network formation by Airline. In Subsection 4.3, by using the results in Subsection 4.2, we describe the Nash equilibrium airport charge, and the equilibrium network configuration.

4.1. The Airline's Choices

Given the airport charges, $\mathbf{a} = (a_1, a_2)$, Airline chooses its network, $\boldsymbol{\delta}^*(\mathbf{a})$, in order to maximize its profit. Formally, this problem is stated as:

$$\boldsymbol{\delta}^*(\mathbf{a}) = \arg\max_{\boldsymbol{\delta}} \pi(\boldsymbol{\delta}, \mathbf{a}).$$

When deriving $\boldsymbol{\delta}^*(\mathbf{a})$, we compare the profits under the three alternative network configurations:

$$\pi(1,0;\mathbf{a}) = 1 + \bar{d} - a_1 - (a_1 + a_2)(1 - n + \bar{d}) - \sqrt{c}\left(1 + \sqrt{l(1 - n + \bar{d})}\right), \tag{12.1}$$

$$\pi(0,1;\mathbf{a}) = 1 + \bar{d} - a_2 - (a_1 + a_2)(n + \bar{d}) - \sqrt{c}\left(1 + \sqrt{l(n + \bar{d})}\right), \tag{12.2}$$

$$\pi(1,1;\mathbf{a}) = 1 + \bar{d} - \sum_{i=1,2} a_i (n_i + \bar{d}) - \sqrt{c}\left(\sum_{i=1,2} \sqrt{n_i} + \sqrt{l\bar{d}}\right). \tag{12.3}$$

For example, when $\boldsymbol{\delta}^*(\mathbf{a}) = (1,1)$, the following must hold:

$$\frac{1}{2}\left[\pi(1,1;\mathbf{a}) - \pi(1,0;\mathbf{a})\right] = a_1(1-n) + \frac{\sqrt{c}}{2}\left[1 - \sum_{i=1,2}\sqrt{n_i} + \sqrt{l}\left(\sqrt{1-n+\bar{d}} - \sqrt{\bar{d}}\right)\right] > 0, \tag{13.1}$$

$$\frac{1}{2}\left[\pi(1,1;\mathbf{a}) - \pi(0,1;\mathbf{a})\right] = a_2 n + \frac{\sqrt{c}}{2}\left[1 - \sum_{i=1,2}\sqrt{n_i} + \sqrt{l}\left(\sqrt{n+\bar{d}} - \sqrt{\bar{d}}\right)\right] > 0. \tag{13.2}$$

Prior to deriving the condition such that Airline prefers the point-to-point network to the hub-spoke, we define the two variables, X^I and X_i^D, as follows:

$$X^I \equiv \sum_{i=1,2}\sqrt{n_i}-1 \text{ and } X_i^D \equiv \sqrt{n_i+\bar{d}}-\sqrt{\bar{d}}.$$

These two variables capture the Airline's tradeoff when changing its network from point-to-point to hubbing at Airport j. Namely, X^I captures the scale economy for service I, the cost reduction of service I through gathering all the demand to a single airport. In contrast, X_i^D is the incremental cost for service D, the additional cost for the operation along route 12 due to the connecting. By using these expressions and solving Eqs. (13) for a_i, we obtain:

$$a_i > h_i \equiv \frac{\sqrt{c}\left(X^I-\sqrt{l}\times X_j^D\right)}{2n_j} \text{ for } i=1,2,\ j\neq i. \tag{14}$$

In addition to the condition (14), the two airport operators must assure that Airline earns the non-negative profits from each of the three markets r ($r = 1F, 2F, 12$): $\pi_r(1,1;\mathbf{a}) \geq 0$. Exercising the similar procedures for the other two networks, we obtain Lemma 2, which summarizes the Airline's network choice.

Lemma 2

Suppose that $\pi_r(\delta) \geq 0$ *for* $\forall\delta$ *and* r. *Given the airport charges,* $\mathbf{a}$, *the network choice by Airline,* $\boldsymbol{\delta}^*(\mathbf{a})$, *is derived as: i)* $\boldsymbol{\delta}^*(\mathbf{a}) = (1,1)$ *if* $a_1 > h_1$ *and* $a_2 > h_2$; *ii)* $\boldsymbol{\delta}^*(\mathbf{a}) = (1,0)$ *if* $a_1 \leq \min\{h_1, f_1(a_2)\}$; *iii)* $\boldsymbol{\delta}^*(\mathbf{a}) = (0,1)$ *if* $a_2 \leq \min\{h_2, f_2(a_1)\}$ *where*

$$f_i\left(a_j\right) \equiv \frac{a_j n_i}{n_j} - \frac{\sqrt{cl}\left(X_j^D - X_i^D\right)}{2n_j}. \tag{15}$$

Proof: Eq. (14) summarizes the condition where $\boldsymbol{\delta}^*(\mathbf{a}) = (1,1)$ is realized. In case of $\boldsymbol{\delta}^*(\mathbf{a}) = (1,0)$, according to Eq. (14), $\pi(1,0;\mathbf{a}) \geq \pi(1,1;\mathbf{a})$ if $a_1 \leq h_1$. Furthermore, according to the comparison of the profits under the two alternative hub-spoke networks,

$$\frac{1}{2}\left[\pi\left(1,0;\mathbf{a}\right) - \pi\left(0,1;\mathbf{a}\right)\right] = a_1\left(1-n\right) - a_2 n + \frac{\sqrt{cl}}{2}\left(\sqrt{1-n+\bar{d}} - \sqrt{n+\bar{d}}\right) > 0.$$

Solving this for a_1,

$$a_1 \leq f_1\left(a_2\right) \equiv \frac{a_2 n}{1-n} - \frac{\sqrt{cl}\left(X_2^D - X_1^D\right)}{2\left(1-n\right)}.$$

In sum, $\boldsymbol{\delta}^*(\mathbf{a}) = (1,0)$ if $a_1 \leq \min\{h_1, f_1(a_2)\}$. For the case of $\boldsymbol{\delta}^*(\mathbf{a}) = (0,1)$, the similar discussion is applied, and the sufficient condition is characterized by $a_2 \leq \min\{h_2, f_2(a_1)\}$.

QED

In order to understand the statement of Lemma 2, we plot $f_i(a_j)$ and h_i in (a_1, a_2) space in Figure 3. It shows that as the airport charges increase, the Airline's network changes from the hub-spoke to the point-to-point. In addition, for $0 < a_1 < f_1(0)$ in Figure 3, Airline chooses Airport 1 as its hub even when operator 2 sets the airport charge equal to zero. This indicates the advantage of Airport 1; namely, since City 1 has the larger demand, Airline chooses Airport 1 as its hub in order to reduce the cost for operating connecting flights even when operator 2 offers the free airport use.

<<FIGURE 3: ABOUT HERE>>

By using Lemma 2, we limit our focus on the case where Airline always has the three alternative choices: that is,

$$1-\sqrt{\frac{c}{n_i}} \geq h_i = \frac{\sqrt{c}\left(X^I - \sqrt{l} \times X_j^D\right)}{2n_j}. \tag{16.1}$$

In addition, we set the assumption for the domestic route:

$$1-\sqrt{\frac{cl}{\bar{d}}} \geq \left(1-\sqrt{\frac{c}{n}}\right)+\left(1-\sqrt{\frac{c}{1-n}}\right). \tag{16.2}$$

This condition assures that Airline provides the domestic flight service even when the two operators exploit the profits from the international flight services at their airports.[10]

4.2. The Airports Operator' Choices and Airline's Network

The two operators simultaneously determine their airport charges. By using the network choice, $\boldsymbol{\delta}^*(\mathbf{a})$, in Lemma 2, the revenue of operator i is computed as:

$$R_i\left(a_i, a_j\right) = R_i\left(\boldsymbol{\delta}^*\left(\mathbf{a}\right)\right) = a_i\left[q_{12}\left(\boldsymbol{\delta}^*\left(\mathbf{a}\right)\right) + q_{iF}\left(\boldsymbol{\delta}^*\left(\mathbf{a}\right)\right)\right].$$

In order to simplify the analysis, as in Teraji and Morimoto (2014), we limit our focus on the case where the strategy of each airport operator is discrete; that is, the discount

[10] Further details of the parameter ranges are summarized in Appendix B.

(represented by the superscript d) or the exploiting strategy (represented by the superscript e). Formally, the problem of operator i is expressed as:

$$\max_{a_i \in \{a_i^e, a_i^d\}} R_i\left(a_i, a_j\right),$$

where a_i^e and a_i^d respectively represent the airport charges under the exploiting and the discount strategies. Under the assumptions (16), the Airline's network falls into the point-to-point if the two airport operators choose to exploit the Airline's profit. The exploiting strategy, a_i^e, is computed as:

$$\pi_{iF}\left(1,1;a_i^e\right) = n_i\left(1-a_i^e-\sqrt{\frac{c}{n_i}}\right) = 0 \Leftrightarrow a_i^e = 1-\sqrt{\frac{c}{n_i}}. \tag{17}$$

In contrast, the discount strategy, a_i^d, does not necessarily imply that operator i discounts its airport charge to zero. This is because, once choosing the exploiting strategy, operator i can earn the revenue:

$$R_i\left(a_i^e, a_j\right) = a_i^e\left(n_i+\bar{d}\right) = \left(n_i+\bar{d}\right)\left(1-\sqrt{\frac{c}{n_i}}\right) = \bar{R}_i.$$

This implies that when discounting, the revenue earned under the exploiting strategy, $\bar{R}_i$, becomes the reference point. That is, operator i discounts its airport charge as long as the revenue under the discount strategy is at least equal to $\bar{R}_i$. Let us denote by $\underline{a}_i$ the lower bound of the discount strategy: it is computed as,

$$\underline{a}_i\left(1+n_j+\bar{d}\right) = a_i^e\left(n_i+\bar{d}\right) \Leftrightarrow \underline{a}_i = \frac{n_i+\bar{d}}{1+n_j+\bar{d}}\left(1-\sqrt{\frac{c}{n_i}}\right). \tag{18}$$

Since $n \geq 1/2$, note that the lower bound of the discount of operator 2 is always lower than that of operator 1:

$$\underline{a}_1 = \frac{n+\bar{d}}{2-n+\bar{d}}\left(1-\sqrt{\frac{c}{n}}\right) > \frac{1-n+\bar{d}}{1+n+\bar{d}}\left(1-\sqrt{\frac{c}{1-n}}\right) = \underline{a}_2.$$

The two operators know that Airline has the three alternative network choices, and that the network falls into the point-to-point ($\boldsymbol{\delta}^*(\mathbf{a^e}) = (1,1)$) once they play the exploiting strategy. Therefore, each operator recognizes its competitor's reservation revenue, $\bar{R}_i$, and the lower bound of the discount airport charge, $\underline{a}_i$. Furthermore, as in Lemma 2, operator i takes into account the fact such that Airline sets Airport i as its hub if operator i chooses its airport charge as $a_i = \min\{f_i(a_j), h_i\}$. Together with these information, the discount strategy is characterized by:

$$a_i^d = \min\left\{ f_i\left(\underline{a}_j\right), h_i\right\}. \tag{19}$$

In comparison of $f_i(\underline{a}_j)$ and h_i, the discount strategy of operator i is characterized as in Lemma 3.

Lemma 3

The discount strategy of operator i, a_i^d, *is characterized as:*

$$a_i^d = \begin{cases} h_i & \text{if } \sqrt{l} > l_{i,j}^d, \\ f_i\left(\underline{a}_j\right) & \text{if } \sqrt{l} \leq l_{i,j}^d, \end{cases}$$

where

$$l_{i,j}^{d} \equiv \left(\frac{X^{I}}{X_{i}^{D}} - \frac{n_{i}\underline{a}_{j}}{\sqrt{c}X_{i}^{D}} \right).$$

Proof: According to the comparison of $f_i(\underline{a}_i)$ and h_i, $a_i^d = h_i$ if:

$$f_{i}\left(\underline{a}_{j}\right) - h_{i} = \frac{n_{i}\underline{a}_{j}}{n_{j}} - \frac{\sqrt{cl}\left(X_{j}^{D} - X_{i}^{D}\right)}{2n_{j}} - \frac{\sqrt{c}\left(X^{I} - \sqrt{l} \times X_{j}^{D}\right)}{2n_{j}} = \frac{n_{i}\underline{a}_{j}}{n_{j}} + \frac{\sqrt{cl}X_{i}^{D}}{2n_{j}} - \frac{\sqrt{c}X^{I}}{2n_{j}} > 0$$

$$\Leftrightarrow \sqrt{l} > \left(\frac{X^{I}}{X_{i}^{D}} - \frac{2n_{i}\underline{a}_{j}}{\sqrt{c}X_{i}^{D}} \right) = l_{i,j}^{d}.$$

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<<TABLE 1: ABOUT HERE>>

By using the two strategies characterized by Eqs. (17) and (19), we can summarize the payoff matrix in Table 1. Based on Table 1, we derive the equilibrium airport charge, and the equilibrium network configuration. In Table 1, when $\mathbf{a} = (a_1^e, a_2^e)$, the equilibrium network configuration falls into the point-to-point: that is, $\boldsymbol{\delta}^*(a_1^e, a_2^e) = (1,1)$. In contrast, if one of the two operators play the discount strategy while the other plays the exploiting, the equilibrium network configuration falls into the hub-spoke. Airline chooses the airport whose operator plays the discount strategy as its hub: that is, $\boldsymbol{\delta}^*(a_1^d, a_2^e) = (1,0)$ and $\boldsymbol{\delta}^*(a_1^e, a_2^d) = (0,1)$. However, the Airline's network is indeterminate if both operators play the discount strategy. Therefore, we start with showing the Airline's network choice in case of $\mathbf{a} = \left(a_1^d, a_2^d\right)$:

Lemma 4

Suppose that the two operators play the discount strategy (that is, $\mathbf{a} = \left(a_1^d, a_2^d\right)$*). In such case, the network choice of Airline is summarized as follows:*

$$\boldsymbol{\delta}^*\left(a_1^d, a_2^d\right) = \begin{cases} (1,0) \text{ if } \sqrt{l} \le \min\left\{l_{1,2}^d, \tilde{l}\right\} \text{ or } \sqrt{l} \le l_{2,1}^d, \\ (0,1) \text{ if } \tilde{l} \le \sqrt{l} \le l_{2,1}^d \text{ or } \sqrt{l} \le l_{1,2}^d, \\ (1,1) \text{ otherwise.} \end{cases}$$

where

$$\tilde{l} \equiv \frac{2\left[n\underline{a}_2 - (1-n)\underline{a}_1\right]}{\sqrt{c}\left(X_1^D - X_2^D\right)}.$$

Proof: see Appendix C.

4.3. The Equilibrium Network Configuration

By using Table 1 and the results summarized in Subsection 4.2, we derive the equilibrium network configuration. This subsection is organized as follows: first, we describe the best response of the two operators, and then we derive the Nash equilibrium airport charges, $\mathbf{a}^* = (a_1^*, a_2^*)$. Finally, substituting $\mathbf{a}^* = (a_1^*, a_2^*)$ into $\boldsymbol{\delta}^*(\mathbf{a})$, the equilibrium network configuration is derived. First, we consider the best response of operator i against the competitor j's exploiting strategy. In such case, the network falls into hubbing at Airport i if operator i plays the discount strategy while it becomes the point-to-point if it plays the exploiting. Therefore, operator i plays the discount strategy if:

$$R_i\left(a_i^d, a_j^e\right) - R_i\left(a_i^e, a_i^e\right) = a_i^d\left(1 + n_j + \bar{d}\right) - a_i^e\left(n_i + \bar{d}\right) \geq 0.$$

Since the second term of the LHS equals to $\bar{R}_i$, this relation is rewritten as:

$$R_i\left(a_i^d, a_j^e\right) - R_i\left(a_i^e, a_i^e\right) = R_i\left(a_i^d, a_j^e\right) - \bar{R}_i = \left(a_i^d - \underline{a}_i\right)\left(1 + n_j + \bar{d}\right) \geq 0. \quad (20)$$

This indicates that the discount strategy becomes operator i's the best response against j's exploiting strategy if $a_i^d \geq \underline{a}_i$.

In case where operator j plays the discount strategy, the difference of operator i's revenue varies with the Airline's network choice $\boldsymbol{\delta}^*\left(a_1^d, a_2^d\right)$ summarized in Lemma 4. If $\boldsymbol{\delta}^*\left(a_1^d, a_2^d\right)$ results in hubbing at the competitor's airport, the revenue differential is computed as:

$$R_i\left(a_i^d, a_j^d\right) - R_i\left(a_i^e, a_i^e\right) = \left(a_i^d - a_i^e\right)\left(n_i + \bar{d}\right). \quad (21)$$

By the assumption such that $a_i^e > h_i$ and the definition of a_i^d (that is, $a_i^d \equiv \min\{h_i, f_i(\underline{a}_j)\}$), the sign of Eq. (21) is definitely negative; therefore, in such situation, operator i's best response is the exploiting. In contrast, if $\boldsymbol{\delta}^*\left(a_1^d, a_2^d\right)$ is hubbing at Airport i, the revenue differential is:

$$R_i\left(a_i^d, a_j^d\right) - R_i\left(a_i^e, a_i^d\right) = R_i\left(a_i^d, a_j^d\right) - \bar{R}_i = \left(a_i^d - \underline{a}_i\right)\left(1 + n_j + d\right).$$

Therefore, in this case, as in Eq. (20), the best response of operator i against the competitor's discount strategy is determined according to the relation between a_i^d and $\underline{a}_i$.

By comparing a_i^d and $\underline{a}_i$, we obtain operator i's best responses against the competitor j's discount and the exploiting strategies as in Lemma 5.

Lemma 5

i) Suppose that the competitor j plays the exploiting strategy. Airport i's best response, $a_i^r\left(a_j^e\right)$, is derived as follows:

$$a_1^r\left(a_2^e\right) = a_1^e, \tag{22.1}$$

$$a_2^r\left(a_1^e\right) = \begin{cases} a_2^d & \text{if } \sqrt{l} \le l_{1,2}^d, \\ a_2^e & \text{otherwise.} \end{cases} \tag{22.2}$$

ii) Suppose that the competitor j plays the discount strategy. Airport i's best response is always the exploiting strategy: namely, $a_i^r\left(a_j^d\right) = a_i^e$.

Proof: see Appendix C.

Lemma 5 shows that operator 1 never plays the discount strategy whereas operator 2 discounts its airport charge if the distance is close. This is interpreted as follows. When the distance between the two airports is close, the additional operating cost for connecting passengers is less significant; consequently, Airline attaches the weight on forming the hub-spoke network rather than choosing which airport to be its hub. This implies that, in order to become the Airline's hub, the operators must discount their airport charges more. In such situation, operator 1 chooses to enjoy exploiting the Airline's profit since it has the large demand from its home city. In contrast, due to the small demand, the discount strategy augments the payoff of operator 2; therefore, operator 2 has an incentive to play the discount strategy.

However, the importance of the additional operating cost increases as the distance between the two airports increases. In such case, for each operator i, in order to attract Airline to choose Airport i as its hub, it is necessary to offer a significant discount. Hence, compared to the exploiting strategy, the discount strategy becomes less profitable; consequently, both operators play the exploiting strategy. By using Lemma 5, we obtain the equilibrium airport charge, $\mathbf{a}^*$, and the consequent equilibrium network configuration, $\boldsymbol{\delta}^*(\mathbf{a}^*)$, as in Proposition 2.

Proposition 2

The equilibrium airport charges, $\mathbf{a}^*$, *are derived as follows:*

$$\mathbf{a}^* = \begin{cases} \left(a_1^e, a_2^d\right) \text{ if } \sqrt{l} \le l_{1,2}^d, \\ \left(a_1^e, a_2^e\right) \text{ if } l_{1,2}^d < \sqrt{l} \ . \end{cases} \tag{23.1}$$

Consequently, the equilibrium network is determined as:

$$\boldsymbol{\delta}^*\left(\mathbf{a}^*\right) = \begin{cases} (0,1) \text{ if } \sqrt{l} \le l_{1,2}^d, \\ (1,1) \text{ if } l_{1,2}^d < \sqrt{l} \ . \end{cases} \tag{23.2}$$

Proof: First, Lemma 5 shows that operator 1's dominant strategy is the exploiting (that is, $a_1^r(a_2) = a_1^e$). Eq. (22.2) characterizes the operator 2's best response against the operator 1's exploiting. According to these, the equilibrium airport charges, $\mathbf{a}^*$, are computed as:

$$\mathbf{a}^* = \begin{cases} \left(a_1^e, a_2^d\right) \text{ if } \sqrt{l} \le l_{1,2}^d, \\ \left(a_1^e, a_2^e\right) \text{ if } l_{1,2}^d < \sqrt{l} \ . \end{cases}$$

Therefore, the equilibrium network configuration, $\boldsymbol{\delta}^*(\mathbf{a}^*)$ falls into hubbing at Airport 2 if $\sqrt{l} \le l_{1,2}^d$ whereas the point-to-point emerges at the equilibrium if $\sqrt{l} > l_{1,2}^d$.

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Proposition 2 shows that, as the distance between the two airports, l, increases, the network configuration changes from the hub-spoke to the point-to-point. Figure 4 plots the threshold in Proposition 2 against the population of City 1, n, in case of $\bar{d} = 1$. In this figure, for $\sqrt{l} > l_{1,2}^d$, the equilibrium network falls into the point-to-point while, for $\sqrt{l} \le l_{1,2}^d$, the hub-spoke network emerges at the equilibrium. In case of $\sqrt{l} > l_{1,2}^d$, the equilibrium characterized by $\mathbf{a}^* = (a_1^e, a_2^e)$ and $\boldsymbol{\delta}^*(\mathbf{a}^*) = (1,1)$. This is because, under the private operation, for $\sqrt{l} > l_{1,2}^d$, the additional operating cost for connecting passengers outweighs the scale economy in hubbing. In this situation, the two operators have to discount more if they want to become the Airline's hub; consequently, they play the exploiting strategy and Airline chooses the point-to-point network.

<<FIGURE 4: ABOUT HERE>>

For $\sqrt{l} \leq l_{1,2}^{d}$, since operator 2 plays the discount strategy, Airline always chooses Airport 2 as its hub. As explained in Lemma 5, the difference in the choices of the two operators is attributed to the one in the gains from the hubbing. Let us denote by Δ_i the ratio of the traffic volume at Airport i between the hubbing and the point-to-point; namely,

$$\Delta_i = \frac{1 + n_j + \bar{d}}{n_i + \bar{d}} \text{ for } i = 1, 2, \ j \neq i. \tag{24}$$

Since $1/2 < n < 1$ and $\bar{d} \geq 1$,

$$\Delta_1 = \frac{2 - n + \bar{d}}{n + \bar{d}} \leq \frac{1 + n + \bar{d}}{1 - n + \bar{d}} = \Delta_2.$$

It is obvious that operator 2 always experiences the larger increase in the passengers from becoming the Airline's hub compared to operator 1. In other words, operator 2 receives the larger gain from discounting the airport charges than operator 1 does. For $\sqrt{l} \leq l_{1,2}^{d}$, the operator 2's gain from the discount outweighs the loss; consequently, operator 2 plays the discount strategy. In contrast, since the gain from becoming the Airline's hub is small, operator 1 chooses never to play the discount strategy. As a result, for $\sqrt{l} \leq l_{1,2}^{d}$, hubbing at Airport 2 becomes the equilibrium network configuration.

5. Discussion

This section compares the two types of the network configuration, the optimum and the equilibrium. It is shown how the private operation of airports and consequent airport competition distort the Airline's network choice. Specifically, we evaluate the welfare effects of the price competition and consequent equilibrium network by comparing the thresholds summarized in Propositions 1 and 2. In this section, we also deal with how the results differ from those obtained in Teraji and Morimoto (2014). This study extends the model of Teraji and Morimoto (2014) in the two aspects, the formulation of the scale economy and the existence of the short haul trip demand. We conduct the comparative statics with respect to the size of the short haul demand. This section is organized as follows: in Subsection 5.1, we compare the optimal and the equilibrium thresholds at which the network changes from the hub-spoke to the point-to-point. Then, Subsection 5.2 reports the effect of the short haul trip demand on the two network configurations.

5.1. Equilibrium vs. Optimum

As in Proposition 2, at the equilibrium, the threshold, $l_{1,2}^{d}$, divides the domains of the hub-spoke and the point-to-point whereas l^{O} characterizes the boundary of the two domains at the optimum. Proposition 3 compares the two thresholds and summarizes the inefficiencies of the equilibrium network:

Proposition 3

At the equilibrium, it is more difficult for Airline to choose the hub-spoke network *compared to at the optimum; namely,* $l^O > l_{1,2}^d$. *Furthermore, at the equilibrium, the efficient hub-spoke network never emerges.*

Proof: see Appendix D.

Figures 5 plots the two thresholds, l^O and $l_{1,2}^d$, in $\left(n, \sqrt{l}\right)$ space under in case of $\bar{d} = 1$. It shows that the optimal network configuration is always the hub-spoke since $l^O > 1$. In contrast, at the equilibrium, the network configuration still depends on both the distance between the two cities, l, and the population of City 1, n. Namely, as the population of City 1 increases, the equilibrium network falls into hubbing at Airport 2 more easily. However, the two cities are sufficiently distant, the competition results in the point-to-point.

<<FIGURE 5: ABOUT HERE>>

Proposition 3 and Figure 5 report the two inefficiencies of the equilibrium network configuration $\boldsymbol{\delta}^*(\mathbf{a}^*)$. First, for $\min\{l^O, 1\} \geq \sqrt{l} > l_{1,2}^d$, the game among the two operators and Airline results in the formation of the point-to-point network although the hub-spork network is the most efficient. As in Teraji and Morimoto (2014), this is due to the positive airport charge. Namely, since our setting has no source of the externalities such as airport congestion, the optimal airport charge is equal to zero. At the equilibrium, however, the private operation of airports imposes the positive airport charge on Airline.

In such situation, other than the flight operating cost for the connecting passengers, Airline must incur the airport charge payment for the connecting passengers. Therefore, even when the scale economy of hubbing dominates the flight operating cost for the connecting passengers, Airline wants to avoid the airport charge payment at the hub; consequently, the point-to-point network is more easily chosen at the equilibrium.

Second, for $l_{1,2}^{d} \geq \sqrt{l}$, although the forms of the network are identical between the optimum and the equilibrium, the equilibrium hub location is inefficient: at the equilibrium, Airport 2 always becomes the Airline's hub. As in Teraji and Morimoto (2014), this is explained by the difference in the attitude toward the airport competition. Namely, due to the smaller home demand, the reservation revenue of operator 2 becomes smaller than the one of operator 1. This implies that since the lower bound of the discount, $\underline{a}_2$, becomes too low, operator 1 must discount more in order to become the Airline's hub. Consequently, for operator 1, the loss of the discount dominates the gain from becoming the hub, and operator 1 never plays the discount strategy. In contrast, since the gain from the discount dominates its loss, operator 2 has an incentive to play the discount strategy if the additional operating cost for connecting becomes negligible (that is, the two airports are sufficiently close). This indicates that, in our setting, in order to become the Airline's hub, only operator 2 offers the discount in the airport charge. Therefore, the inefficient network, hubbing at Airport 2, emerges at the equilibrium.

5.2. The Effect of the Short Haul Trip Demand

In Teraji and Morimoto (2014), it is shown that the price competition of airports induces the formation of the inefficient network. Proposition 3 confirms that, the similar mechanisms, the difference in the attitude toward the price competition and the market power of the two operators, make Airline choose the inefficient network. Our study extends the model of Teraji and Morimoto (2014) by introducing the scheduling cost of the passengers and the short haul trip demand. As discussed in Subsection 5.1, our formulation of the scale economy, the scheduling cost of passengers, generates the qualitatively similar results in Teraji and Morimoto (2014), in which the scale economy is captured by the reduction in the fixed cost.

This subsection focuses on the effect of the other extension; the short haul trip demand, $\bar{d}$. In order to clarify its effect, we conduct the comparative statics of the thresholds, l^O and $l^d_{1,2}$, with respect to $\bar{d}$. The results are summarized in Proposition 4.

Proposition 4

As the short haul trip demand, $\bar{d}$, increases, the difference between l^O and $l^d_{1,2}$ expands. Namely, $\partial l^O/\partial \bar{d} > \partial l^d_{1,2}/\partial \bar{d}$.

Proof: see Appendix D.

Proposition 4 states that, as the market size of the short haul trip expands, the point-to-point network becomes hard to realize at the optimum whereas the equilibrium network falls into the point-to-point more easily.

This result is interpreted as follows. At the optimum, the expansion of the short haul trip demand reduces the additional operating cost for connecting passengers, X_2^D, while the scale economy of hubbing, X^I, remains constant; therefore, since the scale economy dominates the additional cost, the social planner chooses the hub-spoke network more easily. In contrast, for the airport operators, the expansion of the short haul trip demand rises the reservation revenue, $\bar{R}_i$, and consequently, the lower bound of the discount charge, $\underline{a}_i$: indeed,

$$\frac{\partial \underline{a}_1}{\partial \bar{d}} = \frac{a_1^e}{2-n+\bar{d}}\left(1-\frac{n+\bar{d}}{2-n+\bar{d}}\right) = \frac{2(1-n)a_1^e}{2-n+\bar{d}} > 0,$$

$$\frac{\partial \underline{a}_2}{\partial \bar{d}} = \frac{a_2^e}{1+n+\bar{d}}\left(1-\frac{1-n+\bar{d}}{1+n+\bar{d}}\right) = \frac{2na_2^e}{1+n+\bar{d}} > 0.$$

This implies that the expansion of the short haul trip demand increases the loss when playing the discount strategy whereas the gain from the discount, the revenue from the connecting passengers, is constant. Therefore, the two operators are less motivated to play the discount strategy, and at the equilibrium, the point-to-point network sustains more easily.

6. Conclusion

In this paper, we extend the model of Teraji and Morimoto (2014) by incorporating the short haul trips and the passenger's scheduling cost. By using this model, we address the problems such as: i) how the price competition affects the airline's network choice; and ii) how the existence of the short haul trip demand affects the behaviors of the airport operators and the consequent airline's network. As in Teraji and Morimoto (2014), at the optimum, without any locational advantages, airports at relatively small cities never become the airline's hub.

Conversely, at the equilibrium, airports at relatively small cities always become the airline's hub even if they have no locational advantage. This is because operators of airports at small cities are willing to discount their airport charge since they receive relatively large gains from connecting flights from their spoke nodes. Furthermore, the introduction of the short haul trip between the two cities loosens the price competition of the airport operators. This is because, due to the short haul trip demand between the competitors, the airport operators experience the significant loss due to the discount; hence, they become less motivated to offer the discount in the airport charges to the airline. As a result, the equilibrium network falls into the point-to-point more easily.

In reality, although a discount program offered by an airport operator is one of the key determinants when airlines choose the airports to be served, the number of links which the airport have is also an important factor. In order to compare these two factors, the price competition and the difference in the link size, on the economic welfare, it is necessary to develop a model in which asymmetry in the airports is represented by the number of links. Under this setting, in some situation, operators of the airports with the less links may have no incentives to discount, and consequently, airlines choose the airports with more links as their hubs. Furthermore, this implies that the price competition of operators generates no distortion on the network choice by airlines.

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Appendix A: The Airfares under the Three Alternative Network Configurations

Since each service market is under the monopoly, Airline can fully exploits the consumer's surplus by determining the airfare, p_i^I and p^D. First note that the scheduling cost depends on the aircraft size, $\mathbf{s}$, as in Eq. (3). Furthermore, for service D, the number of passengers on the route 12 depends on the Airline's network choice, $\boldsymbol{\delta}$. Therefore, the trip costs for service D and for service I from Airport i are respectively expressed as $g^D(\mathbf{s},\boldsymbol{\delta})$ and $g_i^I(\mathbf{s},\boldsymbol{\delta})$. By taking into account this, the airfares of the two services, $p_i^I(\mathbf{s},\boldsymbol{\delta})$ and $p^D(\mathbf{s},\boldsymbol{\delta})$, are derived according to the equation, $1 = g_i^I(\mathbf{s},\boldsymbol{\delta})$ and $1 = g^D(\mathbf{s},\boldsymbol{\delta})$ as follows:

$$p_1^I\left(\mathbf{s},1,0\right)=1-\frac{1}{4f_{1F}}=1-\frac{s_{1F}}{4q_{1F}\left(1,0\right)}=1-\frac{s_{1F}}{4}, \tag{A.1.1}$$

$$p_2^I\left(\mathbf{s},1,0\right)=1-\frac{1}{4f_{12}}-\frac{1}{4f_{1F}}=1-\frac{s_{12}}{4q_{12}\left(1,0\right)}-\frac{s_{1F}}{4q_{1F}\left(1,0\right)}=1-\frac{s_{12}}{4\left(1-n+\bar{d}\right)}-\frac{s_{1F}}{4}, \tag{A.1.2}$$

$$p_1^I\left(\mathbf{s},0,1\right)=1-\frac{1}{4f_{12}}-\frac{1}{4f_{2F}}=1-\frac{s_{12}}{4q_{12}\left(0,1\right)}-\frac{s_{2F}}{4q_{2F}\left(0,1\right)}=1-\frac{s_{12}}{4\left(n+\bar{d}\right)}-\frac{s_{2F}}{4}, \tag{A.1.3}$$

$$p_2^I\left(\mathbf{s},0,1\right)=1-\frac{1}{4f_{2F}}=1-\frac{s_{2F}}{4q_{2F}\left(0,1\right)}=1-\frac{s_{2F}}{4}, \tag{A.1.4}$$

$$p_i^I\left(\mathbf{s},1,1\right)=1-\frac{1}{4f_{iF}}=1-\frac{s_{iF}}{4q_{iF}\left(1,1\right)}=1-\frac{s_{iF}}{4n_i}. \tag{A.1.5}$$

$$p^D\left(\mathbf{s},1,0\right)=1-\frac{1}{4f_{12}}=1-\frac{s_{12}}{4q_{12}\left(1,0\right)}=1-\frac{s_{12}}{4\left(1-n+\bar{d}\right)}, \tag{A.1.6}$$

$$p^D(\mathbf{s},0,1) = 1 - \frac{1}{4f_{12}} = 1 - \frac{s_{12}}{4q_{12}(0,1)} = 1 - \frac{s_{12}}{4(n+\bar{d})}, \tag{A.1.7}$$

$$p^D(\mathbf{s},1,1) = 1 - \frac{1}{4f_{12}} = 1 - \frac{s_{12}}{4q_{12}(1,1)} = 1 - \frac{s_{12}}{4\bar{d}}. \tag{A.1.8}$$

By using Eqs. (6) and (A.1), the non-negative profit condition for each route r is summarized as follows. In case of hubbing at Airport 1 (that is, $\boldsymbol{\delta} = (1,0)$):

$$\pi_{1F}(1,0;\mathbf{a}) = n\left(1 - a_1 - \sqrt{c}\right) \geq 0, \tag{A.2.1}$$

$$\pi_{2F}(1,0;\mathbf{a}) = (1-n)\left[1 - 2a_1 - a_2 - \sqrt{c}\left(1 + \sqrt{\frac{l}{1-n+d}}\right)\right] \geq 0, \tag{A.2.2}$$

$$\pi_{12}(1,0;\mathbf{a}) = \bar{d}\left(1 - a_1 - a_2 - \sqrt{\frac{cl}{1-n+\bar{d}}}\right) \geq 0. \tag{A.2.3}$$

For hubbing at Airport 2 ($\boldsymbol{\delta} = (0,1)$),

$$\pi_{1F}(0,1;\mathbf{a}) = n\left[1 - 2a_2 - a_1 - \sqrt{c}\left(1 + \sqrt{\frac{l}{n+\bar{d}}}\right)\right] \geq 0, \tag{A.3.1}$$

$$\pi_{2F}(0,1;\mathbf{a}) = (1-n)\left(1 - a_2 - \sqrt{c}\right) \geq 0, \tag{A.3.2}$$

$$\pi_{12}(0,1;\mathbf{a}) = \bar{d}\left(1 - a_1 - a_2 - \sqrt{\frac{cl}{n+\bar{d}}}\right) \geq 0. \tag{A.3.3}$$

Under the point-to-point network ($\boldsymbol{\delta} = (1,1)$) ,

$$\pi_{iF}(1,1;\mathbf{a}) = n_i\left(1 - a_i - \sqrt{\frac{c}{n_i}}\right) \geq 0, \text{ for } i = 1,2, \tag{A.4.1}$$

$$\pi_{12}(1,1;\mathbf{a}) = \bar{d}\left(1 - a_1 - a_2 - \sqrt{\frac{cl}{\bar{d}}}\right) \geq 0. \tag{A.4.2}$$

Appendix B: Ranges of Parameter Values

The parameter values must suffice the following relations:

$$1-\sqrt{\frac{c}{1-n}} \geq 0, \tag{B.1.1}$$

$$1-\sqrt{\frac{cl}{\bar{\bar{d}}}}-\left(2-\sqrt{\frac{c}{n}}-\sqrt{\frac{c}{1-n}}\right) \geq 0. \tag{B.1.2}$$

The first condition, (B.1.1), requests that the direct flight service for Route $2F$ always generates the non-negative surplus. Once this condition is satisfied, the positive surplus is always assured for the direct flight service for $1F$. By solving Eq. (B.1.1), the sufficient condition is computed as: $n \leq 1-c$.

The second condition, (B.1.2), implies that Airline can earn the non-negative profit from providing the domestic flight service even when the two operators set their airport charges to exploit the Airline's profit from the direct international flight service. In order to derive the sufficient condition where Eq. (B.1.2) is met, we take the following strategy. First, we consider the case where the LHS of Eq. (B.1.2) takes the minimum value, and derive the range of the parameter values in which the minimum value suffices the condition (B.1.2). After that, even when the minimum value of the LHS does not suffice the condition, we compute the range of the parameter values in which Eq. (B.1.2) is satisfied.

Looking at Eq. (B.1.2), the bracket term takes the maximum at $n = 1/2$, and since

$0 < l \leq 1$, the second term is at the peak when $l = 1$. Therefore, Eq. (B.1.2) is minimized at $(l, n) = (1, 1/2)$: that is, the minimum value is computed as

$$1-\sqrt{\frac{c}{\bar{d}}}-2\left(1-\sqrt{2c}\right)=\frac{\sqrt{2}}{2}\left(4\sqrt{c}-\sqrt{2}\right)-\sqrt{\frac{c}{\bar{d}}}. \tag{B.2}$$

The sign of Eq. (B.2) is non-negative if:

$$4\sqrt{c}-\sqrt{2}\geq 0 \Leftrightarrow c\geq \frac{1}{8},$$

Solving (B.2) for $\bar{d}$,

$$\frac{\sqrt{2}}{2}\left(4\sqrt{c}-\sqrt{2}\right)-\sqrt{\frac{c}{\bar{d}}}\geq 0 \Leftrightarrow \bar{d}\geq \frac{2c}{\left(4\sqrt{c}-\sqrt{2}\right)^{2}}.$$

In addition, since $\bar{d} \geq 1$,

$$\frac{2c}{\left(4\sqrt{c}-\sqrt{2}\right)^{2}}\leq 1 \Leftrightarrow c\leq \frac{9-4\sqrt{2}}{49}<\frac{1}{8},\frac{1}{8}<\frac{9+4\sqrt{2}}{49}\leq c.$$

In summary, the first case of the parameter sets is characterized by $0 \leq l \leq 1$, $1 \leq \bar{d}$, $1/2 < n < 1 - c$, and $\left(9 + 4\sqrt{2}\right)/49 \leq c < 1/2$.

In the case where $c < \left(9 + 4\sqrt{2}\right)/49$, the parameters do not suffice the condition (B.1.2) when $\bar{d} = l = 1$. Therefore, solving Eq. (B.1.2) for l,

$$1-\sqrt{\frac{cl}{\bar{d}}}-\left(2-\sqrt{\frac{c}{n}}-\sqrt{\frac{c}{1-n}}\right)=\sqrt{\frac{c}{n}}+\sqrt{\frac{c}{1-n}}-1-\sqrt{\frac{cl}{\bar{d}}}\geq 0 \Leftrightarrow l\leq \frac{\bar{d}}{c}\left(\sqrt{\frac{c}{n}}+\sqrt{\frac{c}{1-n}}-1\right)^{2}\equiv \bar{l}.$$

Other than this condition, the bracket term of the LHS should be positive: that is,

$$\sqrt{\frac{c}{n}}+\sqrt{\frac{c}{1-n}}-1>0 \Leftrightarrow c>\frac{n(1-n)}{\left(\sqrt{n}+\sqrt{1-n}\right)^2}=\frac{n(1-n)}{1+2\sqrt{n}\sqrt{1-n}}. \tag{B.3}$$

The threshold, the RHS of (B.3), is decreasing in n for $1/2 < n$, and, as long as $1/8 < c$, for $1/2 < n < 1-c$, Eq. (B.3) is always satisfied. In other words, for $1/8 < c < (9+4\sqrt{2})/49$, other parameters must satisfy the following: $0 \le l \le \bar{l}$, $1 \le \bar{d}$, and $1/2 < n < 1-c$. For $c \le 1/8$, the exploiting airport charge becomes too high, and Airline no longer provides the domestic service between the two airports 1 and 2; therefore, $Q^D = 0$.

Summarizing the discussion above, we state Lemma B, which summarizes the ranges of the parameter values:

Lemma B

As long as $1/8 \le c \le 1/2$, *the domestic flight service generates the non-negative profit if:*

$$\bar{d} \ge 1,\ 1 \le l \le \min\{\bar{l}, 1\},\ \text{and}\ \frac{1}{2} < \bar{n} \le 1-c,$$

where

$$\bar{l} \equiv \frac{\bar{d}}{c}\left(\sqrt{\frac{c}{n}}+\sqrt{\frac{c}{1-n}}-1\right)^2.$$

However, for $c < 1/8$, *no domestic flights are served* (*that is,* $Q^D = 0$).

Appendix C: Proofs of Lemmas in Section 4

We start with summarizing the relationship of the two thresholds, $l_{1,2}^d$ and $l_{2,1}^d$:

Lemma C1

When the domestic trip is absent ($\bar{d} = 0$), *for* $1/2 < n < 1 - c$, $l_{1,2}^d \geq l_{2,1}^d$.

Proof: In the case where $\bar{d} = 0$, $l_{i,j}^d$ is expressed as:

$$l_{1,2}^d\big|_{\bar{d}=0} = 1 + \frac{3-n}{1+n}\sqrt{\frac{1-n}{n}} - \frac{1}{\sqrt{n}}\left(1 + \frac{2(1-n)^2}{\sqrt{c}(1+n)}\right), \tag{C.1.1}$$

$$l_{2,1}^d\big|_{\bar{d}=0} = 1 + \frac{2+n}{2-n}\sqrt{\frac{n}{1-n}} - \frac{1}{\sqrt{1-n}}\left(1 + \frac{2n^2}{\sqrt{c}(2-n)}\right). \tag{C.1.2}$$

Eqs. (C.1) show that $l_{i,j}^d\big|_{\bar{d}=0}$ is obviously increasing in c; that is, they are maximized at $c = 1/2$ and minimized at $c = 1/8$. Also note that as in Lemma B, the population of City 1, n, must lie in the domain, $1/2 \leq n \leq 1 - c$. In case of $n = 1/2$,

$$l_{1,2}^d\big|_{\bar{d}=0,n=\frac{1}{2}} = l_{2,1}^d\big|_{\bar{d}=0,n=\frac{1}{2}} = \frac{8}{3} - \sqrt{2}\left(1 + \frac{1}{3\sqrt{c}}\right).$$

Differentiating $l_{i,j}^d\big|_{\bar{d}=0}$ with respect to n and evaluating at $n = 1/2$,

$$\left.\frac{\partial l_{1,2}^d\big|_{\bar{d}=0}}{\partial n}\right|_{n=\frac{1}{2}} = \sqrt{2}\left(1 - \frac{11\sqrt{2}}{9}\right) + \frac{5\sqrt{2}}{9\sqrt{c}}, \tag{C.2.1}$$

$$\left.\frac{\partial l_{2,1}^d\big|_{\bar{d}=0}}{\partial n}\right|_{n=\frac{1}{2}} = -\sqrt{2}\left(1 - \frac{11\sqrt{2}}{9}\right) - \frac{5\sqrt{2}}{9\sqrt{c}} = -\left.\frac{\partial l_{1,2}^d\big|_{\bar{d}=0}}{\partial n}\right|_{n=\frac{1}{2}} \tag{C.2.2}$$

Observing Eqs. (C.2), the RHS of Eq. (C.2.1) is decreasing in c whereas that of (C.2.2) is increasing in c. Therefore, the signs of Eqs. (C.2) are determined by evaluating

(C.2.1) at $c = 1/2$;

$$\left.\frac{\partial l_{1,2}^{d}\big|_{\bar{d}=0}}{\partial n}\right|_{n=\frac{1}{2},c=\frac{1}{2}} = \sqrt{2}\left(1-\frac{11\sqrt{2}}{9}\right)+\frac{10}{9} = \sqrt{2}-\frac{4}{3} > 0. \tag{C.3}$$

This implies that, around $n = 1/2$, $l_{1,2}^{d}\big|_{\bar{d}=0}$ is increasing in n while $l_{2,1}^{d}\big|_{\bar{d}=0}$ is decreasing in n.

In case of $n = 1 - c$,

$$l_{1,2}^{d}\big|_{\bar{d}=0,n=1-c} = 1+\sqrt{\frac{c}{1-c}}-\frac{1}{\sqrt{1-c}}, \tag{C.4.1}$$

$$l_{2,1}^{d}\big|_{\bar{d}=0,n=1-c} = 1+\frac{3-c}{1+c}\sqrt{\frac{1-c}{c}}-\frac{1}{\sqrt{c}}\left(1+\frac{2(1-c)^{2}}{\sqrt{c}(1+c)}\right). \tag{C.4.2}$$

Figure C1 below plots the values of Eqs. (C.4) against c, and it is shown that, for $1/8 \le c \le 1/2$, $l_{1,2}^{d}\big|_{\bar{d}=0,n=1-c} \ge l_{2,1}^{d}\big|_{\bar{d}=0,n=1-c}$. Together with Eqs. (C.1), (C.2), and (C.3), we can conclude that when $\bar{d} = 0$, $l_{1,2}^{d} \ge l_{2,1}^{d}$.

<<Figure C1: ABOUT HERE>>

QED

Furthermore, Lemma C2 summarizes how the presence of the domestic trip demand, $Q^{D} = \bar{d} \ge 1$, affects the relation between the two thresholds, $l_{1,2}^{d}$ and $l_{2,1}^{d}$.

Lemma C2

When the domestic trip is present ($\bar{d} \ge 1$), *for* $1/2 < n < 1 - c$ *and* $c \ge 1/8$, $l_{1,2}^{d} \ge l_{2,1}^{d}$.

Proof: First evaluating $l_{i,j}^d$ at $n = 1/2$,

$$l_{1,2}^d\Big|_{n=\frac{1}{2}} = l_{2,1}^d\Big|_{n=\frac{1}{2}} = \frac{2-\sqrt{2}}{\sqrt{1+2\bar{d}}-\sqrt{2\bar{d}}} - \frac{\sqrt{2}\left(1+2\bar{d}\right)\left(1-\sqrt{2c}\right)}{\sqrt{c}\left(3+2\bar{d}\right)\left(\sqrt{1+2\bar{d}}-\sqrt{2\bar{d}}\right)} \equiv \underline{\lambda}^d\left(c,\bar{d}\right), \quad \text{(C.5)}$$

Observing at Eq. (C.5), at $n = 1/2$, $l_{1,2}^d = l_{2,1}^d$. Differentiating $l_{i,j}^d$ with respect to n and evaluating them at $n = 1/2$, we have:

$$\left.\frac{\partial l_{1,2}^d}{\partial n}\right|_{n=\frac{1}{2}} = -\left.\frac{\partial l_{2,1}^d}{\partial n}\right|_{n=\frac{1}{2}}. \quad \text{(C.6)}$$

Furthermore, as in Figure C2, the value of (C.6) is increasing in $\bar{d}$, and is always positive for $\bar{d} \geq 1$.

<<Figure C2: ABOUT HERE>>

At $n = 1 - c$,

$$l_{1,2}^d\Big|_{n=1-c} = \frac{\sqrt{1-c}+\sqrt{c}-1}{\sqrt{1-c+\bar{d}}-\sqrt{\bar{d}}} \equiv \bar{\lambda}_{1,2}^d\left(c,\bar{d}\right) > 0, \quad \text{(C.7.1)}$$

$$l_{2,1}^d\Big|_{n=1-c} = \frac{\sqrt{1-c}+\sqrt{c}-1}{\sqrt{c+\bar{d}}-\sqrt{\bar{d}}} - \frac{2\sqrt{c}\left(1-c+\bar{d}\right)}{\left(1+c+\bar{d}\right)\left(\sqrt{c+\bar{d}}-\sqrt{\bar{d}}\right)}\left(1-\sqrt{\frac{c}{1-c}}\right) \equiv \bar{\lambda}_{2,1}^d\left(c,\bar{d}\right). \quad \text{(C.7.2)}$$

In comparison of Eqs. (C.7),

$$\bar{\lambda}_{1,2}^d\left(c,\bar{d}\right) - \bar{\lambda}_{2.1}^d\left(c,\bar{d}\right) = \frac{\left(\sqrt{1-c}+\sqrt{c}-1\right)\left(\sqrt{c+\bar{d}}-\sqrt{1-c+\bar{d}}\right)}{\left(\sqrt{1-c+\bar{d}}-\sqrt{\bar{d}}\right)\left(\sqrt{c+\bar{d}}-\sqrt{\bar{d}}\right)} + \frac{2\sqrt{c}\left(1-c+\bar{d}\right)\left(1-\sqrt{c/(1-c)}\right)}{\left(1+c+\bar{d}\right)\left(\sqrt{c+\bar{d}}-\sqrt{\bar{d}}\right)}.$$

(C.8)

This is increasing in $\bar{d}$, and as in Lemma C.1, in case of $\bar{d} = 0$, its sign is positive; therefore, for $Q^D = \bar{d} \geq 1$, $\bar{\lambda}^d_{1,2} > \bar{\lambda}^d_{2,1}$. According to Figure C2, and Eqs (C.5), (C.6) and (C.8), when the short haul trip is present, $l^d_{1,2} \geq l^d_{2,1}$.

QED

By using Lemmas C2 and 3, we consider the network configuration under $\mathbf{a} = \left(a^d_1, a^d_2\right)$.

Lemma 4

Suppose that the two operators play the discount strategy (*that is,* $\mathbf{a} = \left(a^d_1, a^d_2\right)$). *In such case, the network choice of Airline is summarized as follows:*

$$\boldsymbol{\delta}^*\left(a_1^d, a_2^d\right) = \begin{cases} (1,0) \text{ if } \sqrt{l} \leq \min\left\{l_{1,2}^d, \tilde{l}\right\} \text{ or } l_{2,1}^d \leq \sqrt{l}, \\ (0,1) \text{ if } \tilde{l} \leq \sqrt{l} \leq l_{2,1}^d \text{ or } l_{1,2}^d \leq \sqrt{l}, \\ (1,1) \text{ otherwise.} \end{cases}$$

where

$$\tilde{l} \equiv \frac{2\left[(1-n)\underline{a}_1 - n\underline{a}_2\right]}{\sqrt{c}\left(X_1^D - X_2^D\right)}.$$

Proof: When the two operators play the discount strategy, according to Lemma 2, Airline chooses Airport i as its hub if:

$$a_i^d \leq \min\left\{h_i, f_i\left(a_j^d\right)\right\}. \tag{C.9}$$

First, we focus on the case where $a_i^d = f\left(\underline{a}_j\right)$. The competitor j has the two alternative strategies: namely, $a_j^d = f_j(\underline{a}_i)$ and $a_j^d = h_j$. Suppose that the competitor's discount airport charge is given by h_j (that is, $a_j^d = h_j$). In this case, through the calculation, $f_i(a_j^d) = f_i(h_j) = h_i$; therefore, the condition (C.9) is automatically satisfied when $(a_i^d, a_j^d) = (f(\underline{a}_j), h_j)$. In case of $a_j^d = f_j(\underline{a}_i)$, Airline chooses Airport i as its hub if $a_i^d = f_i(\underline{a}_j) \leq f_i(a_j^d) = f_i\left(f_j(\underline{a}_i)\right)$. Provided $X_1^D - X_2^D > 0$, for operator 1, this condition is computed as:

$$a_1^d - f_1\left(f_2\left(\underline{a}_1\right)\right) = f_1\left(\underline{a}_2\right) - f_1\left(f_2\left(\underline{a}_1\right)\right) = \frac{n\underline{a}_2 - (1-n)\underline{a}_1}{(1-n)} + \frac{\sqrt{cl}\left(X_1^D - X_2^D\right)}{2(1-n)} \leq 0$$

$$\Leftrightarrow \sqrt{l} \leq \frac{2\left[(1-n)\underline{a}_1 - n\underline{a}_2\right]}{\sqrt{c}\left(X_1^D - X_2^D\right)} \equiv \tilde{l}. \qquad \text{(C.10.1)}$$

For operator 2,

$$a_2^d - f_2\left(f_1\left(\underline{a}_2\right)\right) = f_2\left(\underline{a}_1\right) - f_2\left(f_1\left(\underline{a}_2\right)\right) = \frac{(1-n)\underline{a}_1 - n\underline{a}_2}{n} - \frac{\sqrt{cl}\left(X_1^D - X_2^D\right)}{2n} \leq 0$$

$$\Leftrightarrow \sqrt{l} \geq \frac{2\left[(1-n)\underline{a}_1 - n\underline{a}_2\right]}{\sqrt{c}\left(X_1^D - X_2^D\right)} \equiv \tilde{l}. \qquad \text{(C.10.2)}$$

Then, $f_1(\underline{a}_2) \leq \min\{h_1, f_1(a_2^d)\}$ if $\sqrt{l} \leq \min\{l_{1,2}^d, \tilde{l}\}$. For Airport 2, $f_2(\underline{a}_1) \leq \min\{h_2, f_2(a_1^d)\}$ if $\tilde{l} \leq \sqrt{l} \leq l_{2,1}^d$.

In case of $a_i^d = h_i$, first, we focus on the case where $a_j^d = f_j(\underline{a}_i)$. In such situation, it is necessary to check the condition such that $a_i^d = h_i \leq f_i(a_j^d) = f_i\left(f_j(\underline{a}_i)\right)$. For the two airport operators,

$$h_1 - f_1\left(f_2\left(\underline{a}_1\right)\right) = \frac{\sqrt{c}\left(X^I - \sqrt{l} \times X_2^D\right)}{2(1-n)} - \underline{a}_1 \leq 0 \Leftrightarrow \sqrt{l} \geq \frac{X^I}{X_2^D} - \frac{2(1-n)\underline{a}_1}{\sqrt{c}X_2^D} = l_{2,1}^d, \qquad \text{(C.11.1)}$$

$$h_2 - f_2\left(f_1\left(\underline{a}_2\right)\right) = \frac{\sqrt{c}\left(X^I - \sqrt{l} \times X_1^D\right)}{2n} - \underline{a}_2 \leq 0 \Leftrightarrow \sqrt{l} \geq \frac{X^I}{X_1^D} - \frac{2n\underline{a}_2}{\sqrt{c}X_1^D} = l_{1,2}^d. \quad \text{(C.11.2)}$$

In the second case where the competitor sets $a_j^d = h_j$, since $f_i(a_j^d) = f_i(h_j) = h_i$, the condition (C.9) is automatically satisfied. Hence, $h_1 \leq \min\{h_1, f_1(a_2^d)\}$ if $\sqrt{l} \geq l_{2,1}^d$ and $h_2 \leq \min\{h_2, f_2(a_1^d)\}$ if $\sqrt{l} \geq l_{1,2}^d$. In summary, when both operators play the discount strategy, Airline chooses hubbing at Airport 1 if $\sqrt{l} \leq \min\{l_{1,2}^d, \tilde{l}\}$ or if $l_{2,1}^d \leq \sqrt{l}$; hubbing at Airport 2 if $\tilde{l} \leq \sqrt{l} \leq l_{2,1}^d$ or if $l_{1,2}^d \leq \sqrt{l}$; point-to-point, otherwise.

QED

Lemma 5 summarizes the two operators' best responses against the competitors' two strategies.

Lemma 5

i) Suppose that the competitor j plays the exploiting strategy. Airport i's best response, $a_i^r(a_j^e)$, is derived as follows:

$$a_1^r\left(a_2^e\right) = a_1^e, \quad (22.1)$$

$$a_2^r\left(a_1^e\right) = \begin{cases} a_2^d & \text{if } \sqrt{l} \leq l_{1,2}^d, \\ a_2^e & \text{otherwise.} \end{cases} \quad (22.2)$$

ii) Suppose that the competitor j plays the discount strategy. Airport i's best response is always the exploiting strategy: namely, $a_i^r(a_j^d) = a_i^e$.

Proof: We start with the statement i). As summarized in Eq. (20), the best response is determined according to the relation between a_i^d and $\underline{a}_i$. First, let us consider the case where $a_i^d = h_i$. According to the comparison, the discount strategy becomes the best response against a_j^e if:

$$h_i - \underline{a}_i = \frac{\sqrt{c}\left(X^I - \sqrt{l} \times X_j^D\right)}{2n_j} - \underline{a}_i \geq 0 \Leftrightarrow \sqrt{l} \leq \left(\frac{X^I}{X_j^D} - \frac{2n_j \underline{a}_i}{\sqrt{c} X_j^D}\right) = l_{j,i}^d.$$

In addition, as in Lemma 3, $a_i^d = h_i$ if $\sqrt{l} > l_{i,j}^d$: therefore,

$$a_i^r\left(a_j^e\right) = h_i \text{ if } l_{i,j}^d < \sqrt{l} \leq l_{j,i}^d. \tag{C.12}$$

According to Lemma C2, however, Eq. (C.12) is satisfied only when $i = 2$: namely, operator 2 has a choice to play $a_2^d = h_2$ as the discount strategy whereas operator 1 has no incentives to play $a_1^d = h_1$.

According to Lemma 3, $a_i^d = f_i(\underline{a}_j)$ if $\sqrt{l} \leq l_{i,j}^d$. In addition, each operator plays the discount strategy if $f_i(\underline{a}_j) \geq \underline{a}_i$. For operator 1,

$$f_1\left(\underline{a}_2\right) - \underline{a}_1 = \frac{n\underline{a}_2 - (1-n)\underline{a}_1}{1-n} + \frac{\sqrt{cl}\left(X_1^D - X_2^D\right)}{2(1-n)} \geq 0 \Leftrightarrow \sqrt{l} \geq \frac{2\left[(1-n)\underline{a}_1 - n\underline{a}_2\right]}{\sqrt{c}\left(X_1^D - X_2^D\right)} = \tilde{l}.$$

For operator 2,

$$f_2\left(\underline{a}_1\right) - \underline{a}_2 = \frac{(1-n)\underline{a}_1 - n\underline{a}_2}{n} - \frac{\sqrt{cl}\left(X_1^D - X_2^D\right)}{2n} \geq 0 \Leftrightarrow \sqrt{l} \leq \frac{2\left[(1-n)\underline{a}_1 - n\underline{a}_2\right]}{\sqrt{c}\left(X_1^D - X_2^D\right)} = \tilde{l}.$$

By using Lemma 3,

$$a_1^r\left(a_2^e\right) = f_1\left(\underline{a}_2\right) \text{ if } l_{1,2}^d \geq \sqrt{l} \geq \tilde{l}, \tag{C.13.1}$$

$$a_2^r\left(a_1^e\right)= f_2\left(\underline{a}_1\right) \text{ if } \min\left\{l_{2,1}^d,\tilde{l}\right\}\geq\sqrt{l}. \tag{C.13.2}$$

In comparison of $l_{1,2}^d$ and $\tilde{l}$, according to Lemma C2,

$$\tilde{l}-l_{1,2}^d=\frac{2\left[(1-n)\underline{a}_1-n\underline{a}_2\right]}{\sqrt{c}\left(X_1^D-X_2^D\right)}-\frac{X^I}{X_1^D}+\frac{2n\underline{a}_2}{\sqrt{c}X_1^D}=\frac{X_2^D\left(l_{1,2}^d-l_{2,1}^d\right)}{X_1^D-X_2^D}>0. \tag{C.14}$$

That is, the sufficient condition for $a_1^r(a_2^e)=f_1(\underline{a}_2)$ is never satisfied. Therefore, each operator's best response against its competitor's exploiting is summarized as:

$$a_1^r\left(a_2^e\right)=a_1^e, \tag{C.15.1}$$

$$a_2^r\left(a_1^e\right)=\begin{cases} a_2^d & \text{if } \sqrt{l}\leq l_{1,2}^d, \\ a_2^e & \text{otherwise.}\end{cases} \tag{C.15.2}$$

When the competitor plays the discount strategy, as discussed, Airport i plays the exploiting strategy if one of the following two conditions is satisfied. First, since the discount strategy aims at attracting Airline, operator i plays the exploiting strategy if Airline chooses the competitor's airport as its hub or the point-to-point network: that is, $a_i^r(a_j^d)=a_i^e$. Second, even when Airline chooses its airport as its hub, operator i prefers the exploiting strategy if the revenue from this strategy exceeds the one from discounting. In the first condition, according to Lemma 4, this is the case for operator 1 if $\min\{l_{1,2}^d,\tilde{l}\}<\sqrt{l}<l_{2,1}^d$, and for operator 2 if $\sqrt{l}<\tilde{l}$ or $l_{2,1}^d<\sqrt{l}<l_{1,2}^d$.

Focusing on the second condition, as in Eq. (C.15.1), it is obvious that operator 1 has no incentives to play the discount strategy (that is, $a_1^d<\underline{a}_1$) since the revenue under the exploiting always dominates the one under the discount. In case of operator 2, Lemma 4 shows that Airline chooses Airport 2 as its hub for $\tilde{l} \leq \sqrt{l} \leq l^d_{2,1}$ or if $l^d_{1,2} \leq \sqrt{l}$. From Eq. (C.14) and Lemma C2, since $\tilde{l} > l^d_{1,2} \geq l^d_{2,1}$, the first situation, $\tilde{l} \leq \sqrt{l} \leq l^d_{2,1}$, is never realized. Under the second situation, $l^d_{1,2} \leq \sqrt{l}$, according to Eq. (C.15.2), operator 2 always plays the exploiting strategy (that is, $a^d_2 < \underline{a}_2$). In summary, the exploiting strategy is always the best response against the competitor's discount strategy: that is, $a^r_i\left(a^d_j\right) = a^e_i$.

QED

Appendix D: Proofs of Propositions in Section 5

First, we compare the two thresholds, l^O and $l^d_{1,2}$, which are summarized in Proposition 3.

Proposition 3

At the equilibrium, it is more difficult for Airline to choose the hub-spoke network compared to at the optimum; namely, $l^O > l^d_{1,2}$*. Furthermore, at the equilibrium, the efficient hub-spoke network never emerges.*

Proof: For the first statement, the two thresholds are

$$l^O = \frac{\sum_i \sqrt{n_i} - 1}{\sqrt{1 - n + \bar{d}} - \sqrt{\bar{d}}} = \frac{X^I}{X_2^D},$$

$$l^d_{1,2} = \frac{X^I}{X_1^D} - \frac{n\underline{a}_2}{\sqrt{c} X_1^D}.$$

Since $X_2^D < X_1^D$, $X^I/X_1^D < X^I/X_2^D$. In addition, $\underline{a}_2 \geq 0$. These two facts automatically imply $l^O > l^d_{1,2}$. For the second statement, as in Propositions 1 and 2, although hubbing at Airport 1 is more efficient than hubbing at airport 2, at the equilibrium, only Airport 2 becomes the hub.

QED

By differentiating the two thresholds, we have Proposition 4.

Proposition 4

As the short haul trip demand, $\bar{d}$, increases, the difference between l^O and $l^d_{1,2}$ expands. Namely, $\partial l^O/\partial \bar{d} > \partial l^d_{1,2}/\partial \bar{d}$.

Proof: Differentiating l^O and $l^d_{1,2}$ with respect to $\bar{d}$,

$$\frac{\partial l^O}{\partial \bar{d}} = -\frac{l^O}{2X_2^D}\left(\frac{1}{\sqrt{1-n+\bar{d}}} - \frac{1}{\sqrt{\bar{d}}}\right) = \frac{l^O}{2X_2^D}\left(\frac{1}{\sqrt{\bar{d}}} - \frac{1}{\sqrt{1-n+\bar{d}}}\right) > 0, \tag{D.1}$$

$$\frac{\partial l^d_{1,2}}{\partial \bar{d}} = -\frac{l^d_{1,2}}{2X_1^D}\left(\frac{1}{\sqrt{n+\bar{d}}} - \frac{1}{\sqrt{\bar{d}}}\right) - \frac{n}{X_1^D}\frac{\partial \underline{a}_2}{\partial \bar{d}} = \frac{l^d_{1,2}}{2X_1^D}\left(\frac{1}{\sqrt{\bar{d}}} - \frac{1}{\sqrt{n+\bar{d}}}\right) - \frac{n}{X_1^D}\frac{\partial \underline{a}_2}{\partial \bar{d}}. \tag{D.2}$$

First, since $n + \bar{d} > 1 - n + \bar{d} > \bar{d}$, $\partial l^O/\partial \bar{d} > 0$. Now, let us consider the comparison of Eq. (D.1) and the first term of Eq. (D.2). According to Proposition 3, $l^d_{1,2} < l^O$. The relation between the two is determined by that of the rest. Through the calculation, we have:

$$\frac{1}{2X_2^D}\left(\frac{1}{\sqrt{\bar{d}}} - \frac{1}{\sqrt{1-n+\bar{d}}}\right) = \frac{1}{2\left(\sqrt{1-n+\bar{d}} - \sqrt{\bar{d}}\right)} \times \frac{\sqrt{1-n+\bar{d}} - \sqrt{\bar{d}}}{\sqrt{\bar{d}}\sqrt{1-n+\bar{d}}} = \frac{1}{2\sqrt{\bar{d}}\sqrt{1-n+\bar{d}}},$$

$$\frac{1}{2X_1^D}\left(\frac{1}{\sqrt{\bar{d}}} - \frac{1}{\sqrt{n+\bar{d}}}\right) = \frac{1}{2\left(\sqrt{n+\bar{d}} - \sqrt{\bar{d}}\right)} \times \frac{\sqrt{n+\bar{d}} - \sqrt{\bar{d}}}{\sqrt{\bar{d}}\sqrt{1-n+\bar{d}}} = \frac{1}{2\sqrt{\bar{d}}\sqrt{n+\bar{d}}}.$$

Hence,

$$\frac{l^O}{2X_2^D}\left(\frac{1}{\sqrt{\bar{d}}} - \frac{1}{\sqrt{1-n+\bar{d}}}\right) > \frac{l^d_{1,2}}{2X_1^D}\left(\frac{1}{\sqrt{\bar{d}}} - \frac{1}{\sqrt{n+\bar{d}}}\right).$$

Furthermore, the second term is computed as:

$$\frac{\partial \underline{a}_2}{\partial \bar{d}} = \frac{a_2^e}{1+n+\bar{d}}\left(1-\frac{1-n+\bar{d}}{1+n+\bar{d}}\right) = \frac{2na_2^e}{1+n+\bar{d}} > 0.$$

In summary, we always have $\partial l^O / \partial \bar{d} > \partial l_{1,2}^d / \partial \bar{d}$.

QED

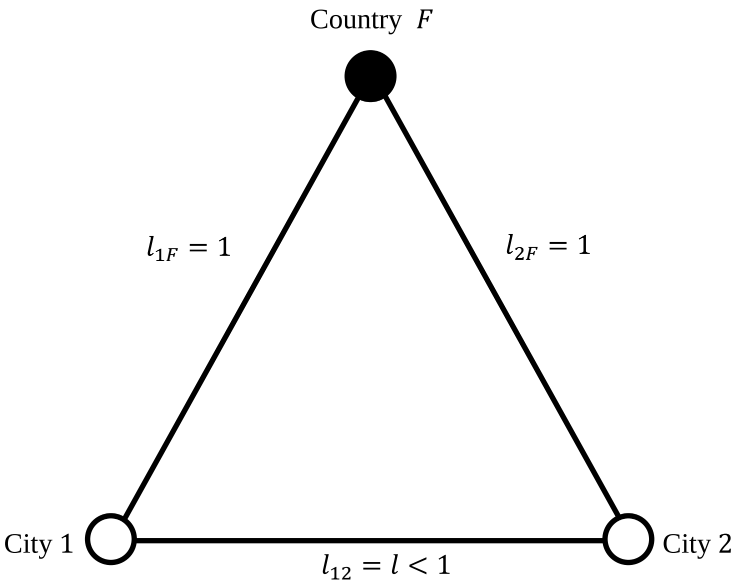

Figure 1: The Geography of the Economy

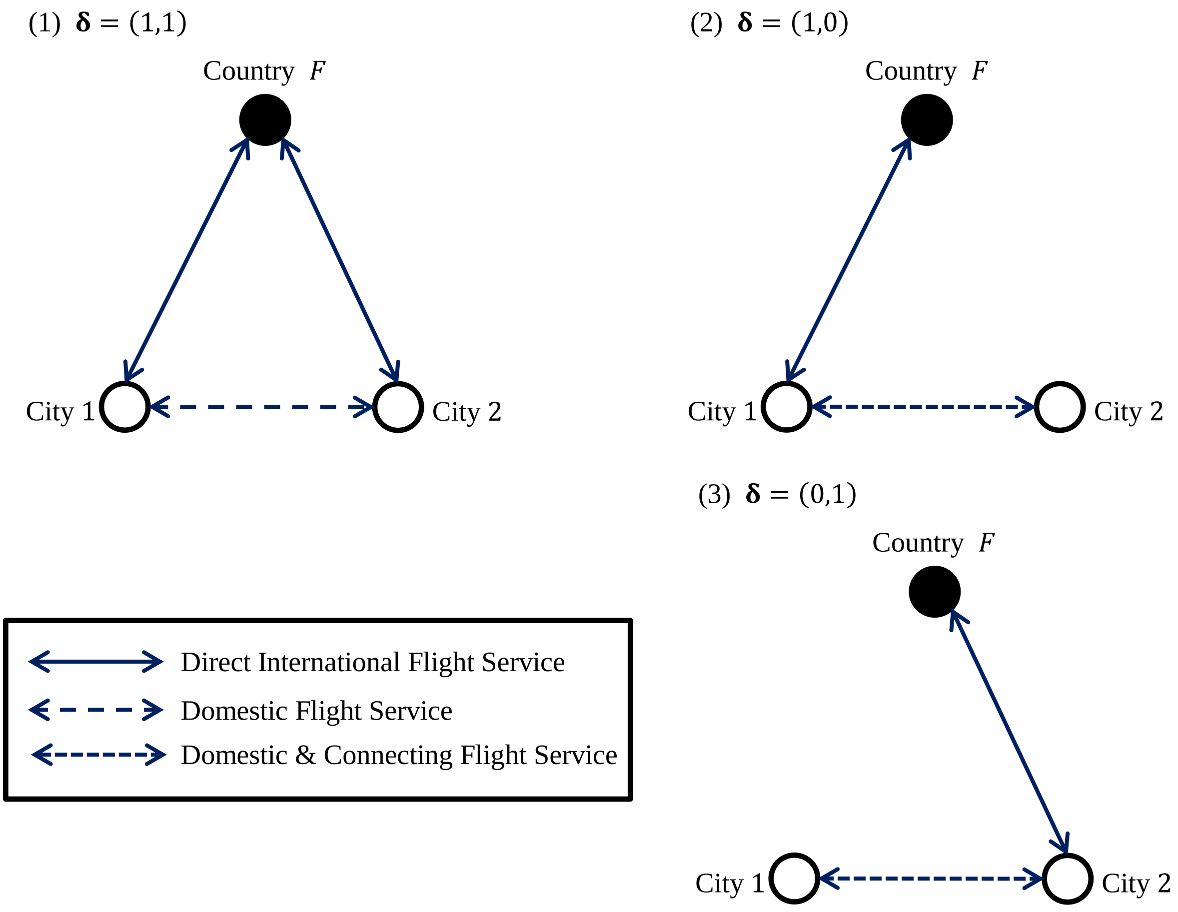

Figure 2: The Airline's Network Choice

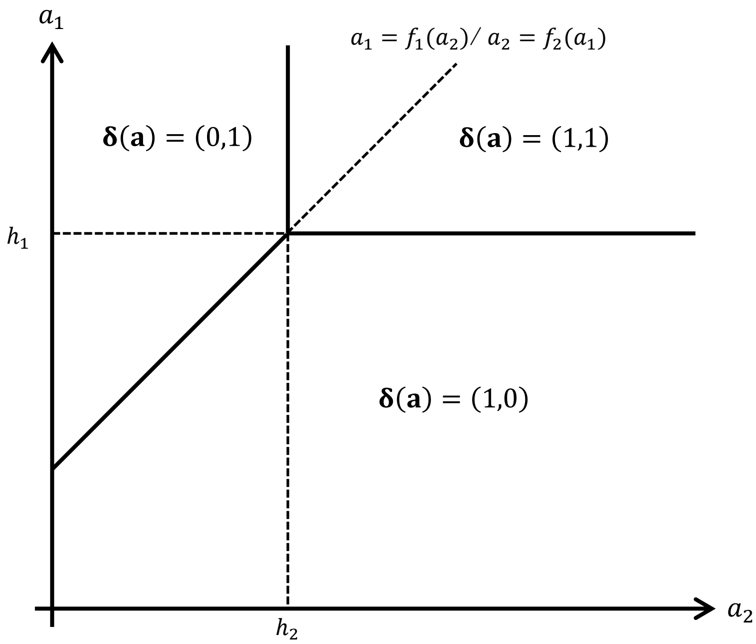

Figure 3: The Airline's Network Choice

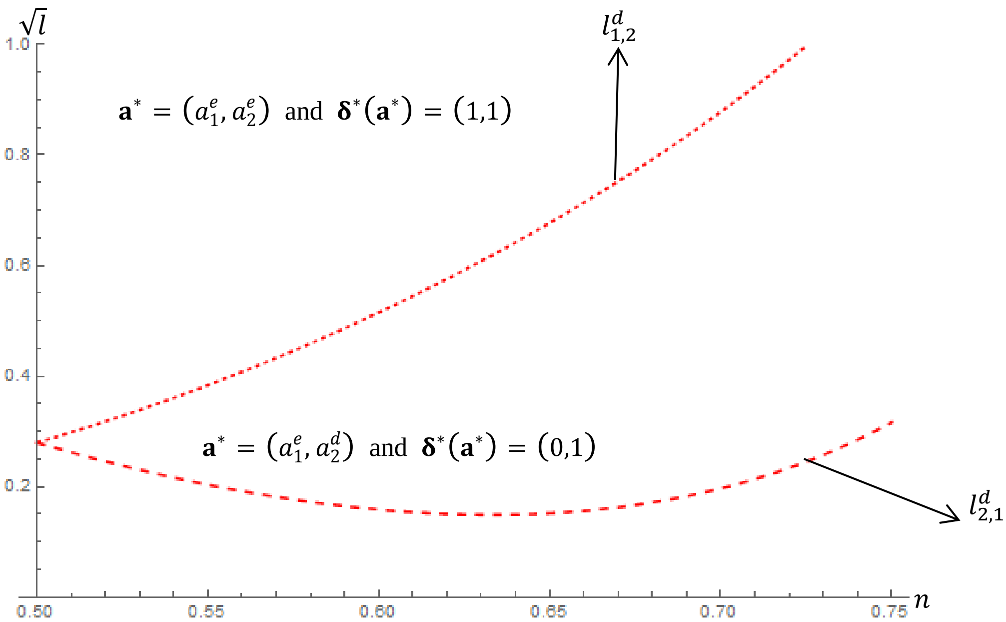

Figure 4: The Equilibrium Network Configurations ($c = 1/4\,, \bar{d} = 1$)

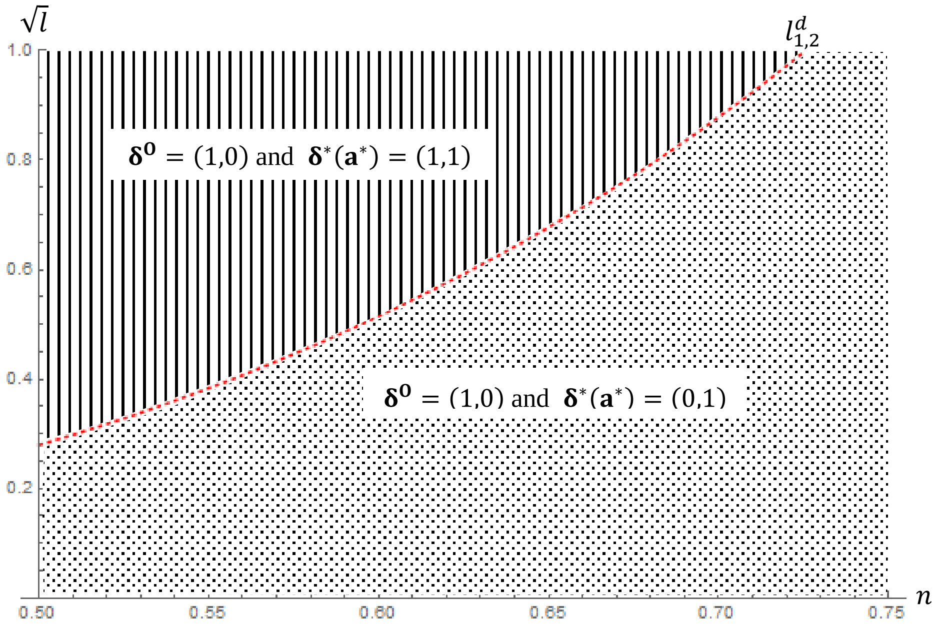

Figure 5: The Equilibrium vs. the Optimum ($c = 1/4$, $\bar{d} = 1$)

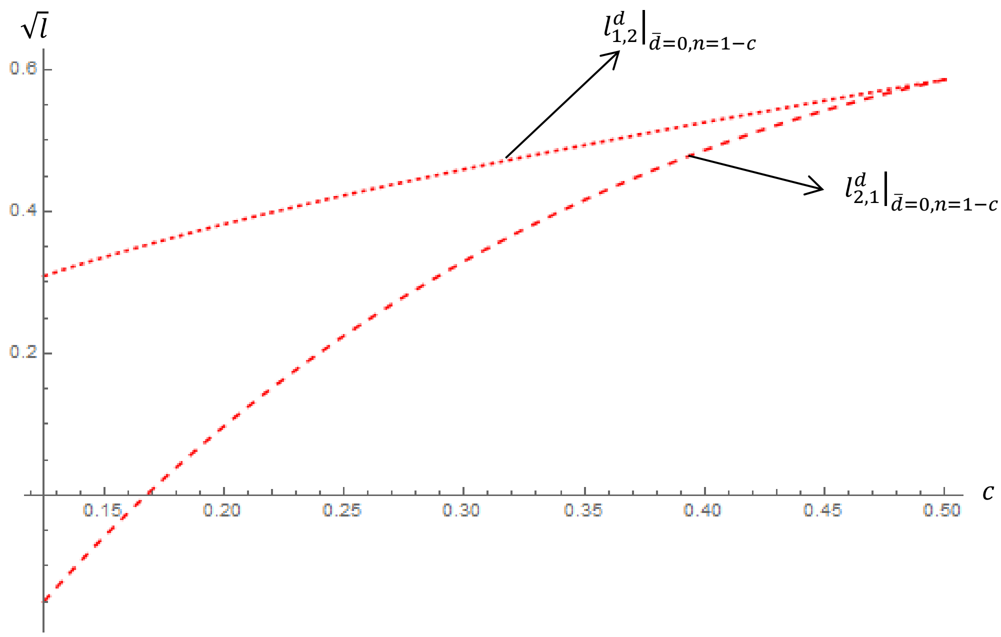

Figure C1: The Marginal Cost and its Effect on the Two Thresholds ($\boldsymbol{n = 1 - c, \bar{d} = 0}$)

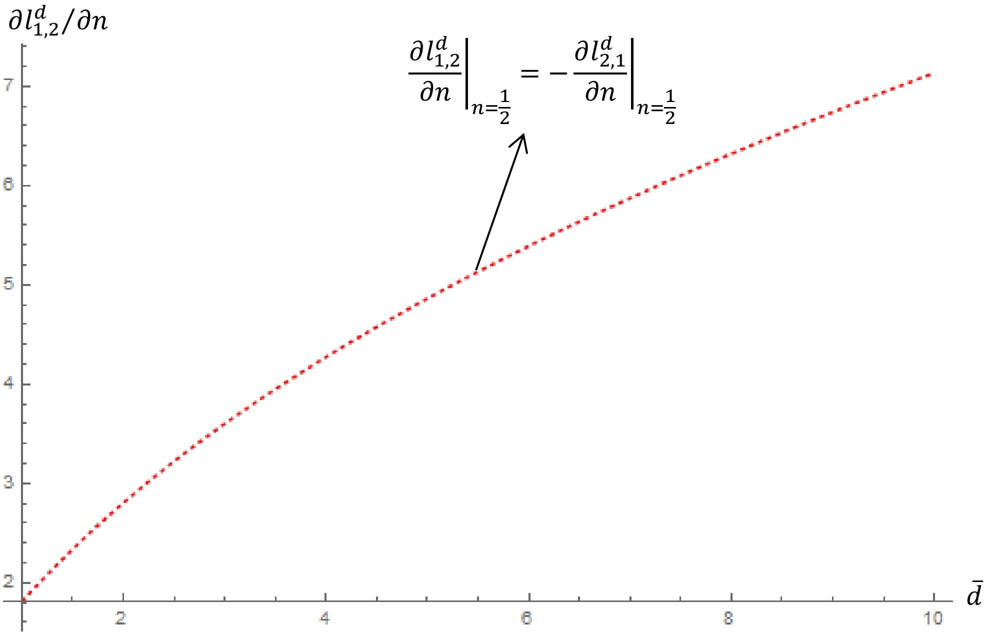

Figure C2: The Domestic Trip and its Effect on the Partial Derivative $\boldsymbol{\partial l_{1,2}^d/\partial n}$ ($\boldsymbol{n = 1/2, c = 1/4}$)

Table 1: Payoff Matrix

Airport 1 \ Airport 2	Exploiting Strategy	Discount Strategy
Exploiting Strategy	$R_1(a_1^e, a_2^e), R_2(a_2^e, a_1^e)$	$R_1(a_1^e, a_2^d), R_2(a_2^d, a_1^e)$
Discount Strategy	$R_1(a_1^d, a_2^e), R_2(a_2^e, a_1^d)$	$R_1(a_1^d, a_2^d), R_2(a_2^d, a_1^d)$