Chapter 8
The Basic Model of Airline Network

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8.1 Introduction

From the viewpoint of regional policy, the hub airport is crucial for developing the regional economy. Because various goods, services, and information are gathered in the hub city, many firms aggregate there. As these firms aggregate, many people are also drawn to the region and regional development ensues.

With regard to the hub problem, Konishi [21] is an important and interesting study. According to Konishi [21], which uses the general equilibrium model, if all transportation technology is the same (i.e., in the symmetric transportation technology setting), hub route does not appear in equilibrium; on the contrary, if transportation technology is different between countries (i.e., in the asymmetric transportation technology setting), hub route occurs when the transportation technology of one country is superior.

Given the importance of hubs, this chapter introduces a model to analyze not only the airline network formation problem but also the hub location problem. Much research has considered the airline network formation problem and hub location problem. Previous studies of airline networks and, especially, hub location problems have used operation research (OR). The main purpose of OR analysis is to develop an algorithm minimizing total transportation costs. However, studies using OR analysis have certain shortcomings, notably failing to internalize carriers' strategies (e.g., pricing, flight frequency). In other words, although carriers want to maximize their profit, previous studies have not considered this problem. Rather, minimizing the number of connecting passengers has been thought to be important

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for hub airports. However, in the actual airline market, carriers may not choose the hub airport in order to minimize the potential number of connecting passengers. For example, Changi International Airport in Singapore aims to be a hub airport in Asia by attracting more connecting passengers in various ways.[1] Another well-known hub airport in Asia is Hong Kong International Airport; however, the number of passengers coming to Hong Kong is not always large.

Considering these shortcomings in previous research, this chapter first derives a carrier's strategies (i.e., related to airfare and flight frequency) to maximize profit and the profit amount. Then, we analyze whether a monopolistic carrier chooses a point-to-point network or a hub–spoke network with one hub airport (and if the latter, which airport serves as the hub). Additionally, we derive the socially preferable network formation and socially preferable hub location. By considering these problems, this chapter aims to explain the strategies of various actual airline networks including the examples of Changi International Airport and Hong Kong International Airport by using the theory of industrial organization (IO)[2].

The theory of IO has previously addressed only airline network formation by explaining those mechanisms that carriers adopt in a hub–spoke network. For example, economies of density was mainly discussed in the 1990s.[3] Because the hub–spoke network can gather the passengers in two markets onto one route, the carrier's marginal cost decreases compared with the point-to-point network due to economies of density. Consequently, to lower operation cost and increase profit, each carrier adopts the hub–spoke network after the deregulation of the airline market. On the contrary, while studies in the 1990s addressed the network effect with suppliers, many researchers after 2000 started to examine the network effect with passengers. Here, by gathering passengers onto one route, the flight frequency of that route increases, which improves passenger convenience. As a result, the passenger's utility increases and potential demand for carriers rises. According to some studies, in this scenario, each carrier adopts the hub–spoke network to obtain these benefits.

However, while studies have used the theory of IO to examine the airline network formation problem, this theory has rarely been used to consider the hub location problem. One such study is Kawasaki [19]. Therefore, to simplify Kawasaki's [19] analysis, the present chapter introduces a model of IO to analyze the hub location problem.

The main results obtained in this chapter are as follows. When the additional travel time cost for connecting passengers is large (small), the monopolistic carrier adopts the point-to-point (hub–spoke) network. This finding concurs with those of previous studies. On the contrary, with regard to the hub location problem, the monopolistic carrier does not always choose the hub airport to minimize the

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[1] For example, it has a games corner, transit hotel, gym, shower room, and swimming pool.

[2] For industrial economic theory, see Tirole [31]. We use the theory of IO to internalize a firm's various strategies.

[3] See Brueckner and Spiller [8], for example.

potential number of connecting passengers. That is, if the potential number of connecting passengers is very large, the monopolistic carrier does not adopt the hub airport to minimize the potential number of connecting passengers. Additionally, the socially preferable hub airport is not always the airport that minimizes the potential number of connecting passengers. Finally, we introduce the per-seat cost to analyze the airline network formation and hub location problems and demonstrate that although the results mentioned above hold when the per-seat cost is small, when this cost is large, the point-to-point network is always adopted.

The remainder of this chapter is organized as follows. In Sect. 8.2, we review previous studies of the airline network problem. Section 8.3 presents the model used in this chapter. In Sect. 8.4, we analyze the model and derive the profit-maximizing flight frequency and airfare. Section 8.5 compares the result of each outcome. In Sect. 8.6, we derive the profit-maximizing network formation and hub location. Section 8.7 derives social welfare and finds the socially preferable hub location. Section 8.8 additionally introduces the per-seat cost and re-analyzes the airline network formation and hub location problems. In Sect. 8.9, the policy implications from this chapter are discussed. Section 8.10 concludes.

8.2 Literature Review

We begin this review of studies of airline networks by discussing those that have used OR analysis. The key aim of studies using OR analysis is to find a location for a hub city such that total transportation costs (e.g., passengers' movement, waiting time) are minimized. A seminal study in this regard is O'Kelly [23]. Thereafter, many researchers developed models that analyze the hub location problem using the OR method. For example, Campbell [10] develops a model to solve a number of hub location problems (see Bryan and O'Kelly [9] for a detailed survey of hub location analyses). Martin and Roman [22] propose a model to solve the hub location problem by considering competition between airlines. Racunica and Wynter [27] formulate a model to solve a hub location problem with intermodal freight, and Rodriguez et al. [28] propose a model with capacity constraints. Similarly, Eiselta and Marianov [13] develop a model to solve the competitive airline market's hub location problem by using gravity-like utility functions for passengers, while De Camargo et al. [11] address the multiple allocation of hub airports under the hub congestion problem.[4]

A representative study of airline network formation using IO is Brueckner and Spiller [8]. By using a quantity competition model with economies of density, they examine whether a monopolistic or competitive market is socially preferable. They find that in the competitive market, although the cost per passenger increases due to the decrease in passengers on one route, airfare decreases. Contrarily, in the

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[4] Other examples include Aykin [2] and Alumur and Kara [1].

monopolistic market, airfare increases. Consequently, a competitive market raises social welfare compared with the monopolistic market.

Another important study is that by Hendricks et al. [16], who analyze which network carriers adopted after the deregulation in 1978, demonstrating that both hub–spoke networks and point-to-point networks were used because of economies of density. Hendricks et al. [17] then address the competition between major carriers that adopt hub–spoke networks and regional carriers. They show that adopting a hub–spoke network becomes a dominant strategy, allowing major carriers to continue to operate in spoke markets even when regional carriers exist.[5]

On the demand-side network effects rather than the supplier side, representative studies are Oum et al. [24] and Brueckner [6]. Oum et al. [24] find that incumbent carriers adopt hub–spoke networks as an entry deterrence strategy. Brueckner [6] assumes a monopolistic airline market and discusses why flight frequency increases in modern airline networks by using a model in which the benefit of traveling is introduced, concluding that the reason for this approach is to adopt a hub–spoke network. In addition, Brueckner [6] discusses whether the monopolistic carrier adopts the hub–spoke network or the point-to-point network and concludes that when the marginal operation cost per flight is small, the hub–spoke network is adopted given that its total flight frequency is larger than that for the point-to-point network. Kawasaki [18] points out the shortcomings of Brueckner's [6] study, notably that its results depend on some assumptions and that its model assumes that all passengers use direct services when the point-to-point network is adopted. Kawasaki [18] argues that even when the point-to-point network is adopted, some passengers may use connecting services. To overcome these shortcomings, Kawasaki [18] uses the model of Berechman and Shy [4] and Berechman et al. [3] to analyze whether the hub–spoke network or point-to-point network is adopted by the monopolistic carrier. The important characteristic of Kawasaki's [18] study is that it introduces heterogeneity into the time value (i.e., some passengers use connecting services even when the carrier adopts the point-to-point network). Kawasaki [18] finds that when the difference in the time value between passengers is small (large), the monopolistic carrier has an (no) incentive to adopt the hub–spoke network to discriminate airfares between passengers.

Thereafter, studies of airline competition were published. Brueckner and Flores-Fillol [7] consider the situation in which two carriers in an economy that both adopt hub–spoke networks compete with each other on flight frequency and airfare. They show that by comparing the market equilibrium flight frequency with the socially preferable one, the market equilibrium becomes the socially inadequate flight frequency. Flores-Fillol [7] analyzes airline network formation in a competitive situation, demonstrating that when cost per passenger (or per seat) is sufficiently small, both carriers adopt hub–spoke networks; however, as this cost increases, the equilibrium that at least one carrier adopts the point-to-point network arises.

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[5] Other examples include Bittlingmayer [5], who discusses airline pricing under a hub–spoke network by considering economies of scope.

Similarly, Flores-Fillol and Fargeda [15] consider airline network formation with airport congestion and demonstrate that carriers prefer the hub–spoke network even though it may not be preferable from the perspective of social welfare.

Finally, only one study except Kawasaki [19] has addressed the hub location problem. Pels et al. [26] use linear demand and cost functions in a three-city model and assume that one city pair's potential number of passengers is smaller than that of the other city pair. Then, by considering the quantity decisions made by two competitive airlines seeking to maximize profits, they show that the hub city is constructed to minimize the potential number of passengers who travel between spoke cities (i.e., connecting passengers).

As seen from this brief review, although IO addresses the airline network formation problem, the hub location problem has rarely been considered by previous researchers. To address this shortcoming, this chapter introduces a model to analyze both network formation and hub location.

8.3 The Model

Following Brueckner [6] and Kawasaki [18], this chapter uses a model with three cities, termed A, B, and C. In this chapter, we assume for simplicity that the airline market is monopolistic. A carrier chooses either a hub–spoke network with hub city h or a point-to-point network. The carrier flies between city pair $ij(i, j = A, B, C,\ i \neq j)$ f_{ij} times. When the carrier operates its service, it incurs an operation cost, which arises from the flights. We assume that the cost per flight is constant and is denoted by K. The cost per passenger is ignored. Further, we assume for simplicity that the capacity of an aircraft is unlimited.

In each city, there exist potential passengers who plan to travel to their destination. When passengers use airline services to travel to their destination, they gain a benefit. Following Brueckner [6], we assume that this benefit is the sum of the travel benefit and the reduction in schedule delay.[6] This chapter assumes that all passengers have a constant and common time value. The travel benefit is expressed as w. It is assumed that potential passengers evaluate airline services differently. Therefore, this chapter assumes that the travel benefit w is uniformly distributed between $-\underline{W}$ and W. Here, we assume that the absolute value $\underline{W}$ is adequately large. This interpretation is as follows. A passenger for whom $w = -\underline{W}$ has a fear of heights and never travels by air. A passenger for whom $w = W$ prefers to travel by air and often flies. With regard to the density of w, this chapter assumes that the density of w in city pair AC equals 1 and that in city pair AB and BC equals $\beta(\geq 0)$.

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[6] The term "schedule delay cost" quantifies the disutility from the difference between passengers' preferred departure or arrival time and the actual departure or arrival time. The schedule delay can be decomposed into the "frequency delay" and the "stochastic delay." Both delays depend on flight frequency. See Douglas and Miller [12] and Panzar [25] for a detailed discussion.

When an airline increases its flight frequency, all passengers enjoy convenience, which subsequently increases passengers' benefit. This means a reduction in schedule delay. For example, in Brueckner [6], when an airline firm increases its flight frequency, the schedule delay cost decreases, thereby increasing passengers' benefit.[7] This chapter uses the Kawasaki-type function [18] for simplicity,[8] that is, $\sqrt{f_{ij}}$.[9] Following Kawasaki [19], we call this reduction in schedule delay (i.e., the increase in convenience) by increasing flight frequency the "scheduling effect."

Further, it is necessary to formulate a benefit function for connecting passengers that differs from that used in previous studies. When connecting passengers travel via a hub city, they need to take two flights on two routes. Consequently, their convenience depends on both routes. Therefore, following Oum et al. [24] Kawasaki [19], and Kawasaki and Lin [20], this chapter assumes that the total reduction in the schedule delay cost depends on the sum of each route's contribution to the reduction in the schedule delay cost. That is, if we express the reduction in the schedule delay cost for the ih route as $g(f_{ih})$, the total reduction in the schedule delay cost for connecting passengers is denoted as $g(f_{ih}) + g(f_{jh})$.

This analysis specifies a benefit function. Therefore, we assume that $g(f_{ih}) = \frac{1}{2}\sqrt{f_{ih}}$. This formula includes the assumption that the marginal scheduling effect of direct passengers is greater than that of connecting passengers. Generally, connecting passengers must wait to change flights at a hub airport. Consequently, even when the frequency of flights on only one route increases, the increase in passengers' convenience is small compared with that of direct passengers.[10]

Moreover, connecting passengers might incur a higher travel time cost T by flying through hub city H than they would if they could take a direct flight (see Brueckner [6]; Kawasaki [18]). Herein, this additional cost is assumed to be sufficiently small, such that at least a passenger with $w = W$ travels using the airline.

From the above discussion, each passenger's utility function is expressed as follows:

$$U_{ij} = \begin{cases} w + \sqrt{f_{ij}} - p_{ij} & \text{if traveling directly} \\ w + \frac{1}{2}\left(\sqrt{f_{ih}} + \sqrt{f_{jh}}\right) - T - p_{ij} & \text{if traveling via hub city } h. \end{cases} \tag{8.1}$$

Without loss of generality, we assume that utility equals zero for passengers not using the airline.

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[7] There exist similar characteristics in Berechman and Shy [4] and Shy [29].

[8] Although the Brueckner-type utility function [6] has a microfoundation, it is unnecessarily complex for analyzing the model. On the contrary, the Kawasaki-type function [18] is simple. Hence, because the characteristics of the Brueckner-type utility function are similar to those of the Kawasaki-type utility function, we can maintain generality through this analysis.

[9] Even if we use a linear benefit function and a quadratic cost function, we obtain the same result.

[10] Generally, it is more reasonable to assume that a connecting passenger's utility depends on the minimum of the square roots of the spoke frequencies. However, this formulation poses many complex problems for analysis. In fact, Flores-Fillol [14] also uses an average-type utility function.

8.4 Deviation of Each Outcome

By using the above model, this section derives each outcome when the monopolistic carrier adopts the hub–spoke (point-to-point) network.

First, we derive each demand function. Because we assume that a passenger whose utility becomes over zero uses airline services, the demand function for direct airline services is

$$q_{ij}^{d} = n_{ij}\left(W + \sqrt{f_{ij}} - p_{ij}\right), \tag{8.2}$$

and the demand function for connecting airline services is

$$q_{ij}^{h} = n_{ij}\left(W + \frac{1}{2}\left(\sqrt{f_{ih}} + \sqrt{f_{jh}}\right) - T - p_{ij}\right). \tag{8.3}$$

Here, n_{ij} denotes the density of w in city pair ij, while $n_{AB} = n_{BC} = \beta$ and $n_{AC} = 1$.

First, we derive the profit when the monopolistic carrier adopts a hub–spoke network with hub city h. The profit function is as follows:

$$\begin{aligned}\pi_h = {} & n_{ih}\left(W + \sqrt{f_{ih}} - p_{ih}\right)p_{ih} + n_{jh}(W + \sqrt{f_{jh}} - p_{jh})p_{jh} \\ & + n_{ij}\left(W + \frac{1}{2}\left(\sqrt{f_{ih}} + \sqrt{f_{jh}}\right) - T - p_{ij}\right)p_{ij} - (f_{ih} + f_{jh})K. \end{aligned} \tag{8.4}$$

By solving the above profit maximization problem for each airfare and flight frequency, we obtain the following airfares and flight frequencies:

$$p_{ih} = \frac{(8KW - n_{ij}T)(4K - n_{jh})}{\Delta}, \tag{8.5}$$

$$p_{jh} = \frac{(8KW - n_{ij}T)(4K - n_{ih})}{\Delta}, \tag{8.6}$$

$$p_{ij} = \frac{-4K(n_{ih} + n_{jh})(W - 2T) + 32K^2(W - T) - 2n_{ih}n_{jh}T}{\Delta}, \tag{8.7}$$

$$f_{ih} = \left(\frac{8KW(2n_{ih} + n_{ij}) + n_{ih}W(n_{ij} + 4n_{jh}) + n_{ih}n_{jh}(W - 2T) + 8n_{ij}KT}{\Delta}\right)^2, \tag{8.8}$$

$$f_{jh} = \left(\frac{-(n_{ih}n_{jh} + n_{ih}(n_{ij} + 4n_{jh}))W + 8K(2Wn_{jh} + n_{ij}(W - T)) + 2n_{ih}n_{ij}T}{\Delta}\right). \tag{8.9}$$

Here,

$$\Delta \equiv 64K^2 + n_{ih}n_{jh} - 8K(2n_{ih} + n_{ij} + 2n_{jh}) + n_{ih}(n_{ij} + n_{jh}). \tag{8.10}$$

By using the outcomes from Eqs. (8.5) to (8.9), we obtain the following quantity:

$$q_{ih} = \frac{n_{ih}(4K - n_{jh})(8KW - n_{ij}T)}{\Delta}, \tag{8.11}$$

$$q_{jh} = \frac{n_{jh}(4K - n_{ih})(8KW - n_{ij}T)}{\Delta}, \tag{8.12}$$

$$q_{ij} = \frac{2n_{ij}(-2K(n_{ih} + n_{jh})(W - 2T) + 16K^2(W - T) - n_{ih}n_{jh}T)}{\Delta}. \tag{8.13}$$

To satisfy the positive demand of connecting passengers, we assume

$$T \leq \frac{2KW(8K - n_{ih} - n_{jh})}{(4K - n_{ih})(4K - n_{jh})}. \tag{8.14}$$

As a result, the maximized profit when the monopolistic carrier adopts the hub–spoke network with hub h is

$$\begin{aligned}\pi_h^* = \{&2K(-n_{ij}n_{jh} + 8K(n_{ih} + n_{ij} + n_{jh}) - n_{ih}(n_{ij} + 4n_{jh}))W^2 \\ &+4Kn_{ij}(-8K + n_{ih} + n_{jh})WT + (4K - n_{ih})n_{ij}(4K - n_{jh})T^2\}/\Delta.\end{aligned} \tag{8.15}$$

Here, π_h^* represents the maximized profit when the hub–spoke network with hub h is adopted.

In the following, we derive the profit when the monopolistic carrier adopts a point-to-point network. The profit function is as follows:

$$\begin{aligned}\pi_p = &\beta(W + \sqrt{f_{AB}} - p_{AB})p_{AB} + \beta(W + \sqrt{f_{BC}} - p_{BC})p_{BC} \\ &+(W + f_{AC} - p_{AC})p_{AC} - (f_{AB} + f_{BC} + f_{AC})K.\end{aligned} \tag{8.16}$$

By solving the above profit maximization problem for each airfare and flight frequency, we obtain the following airfares and flight frequencies:

$$p_{AB} = p_{AC} = \frac{2KW}{4K - \beta}, \tag{8.17}$$

$$p_{BC} = \frac{2KW}{4K - 1}, \tag{8.18}$$

$$f_{AB} = f_{AC} = \left(\frac{W\beta}{4K - \beta}\right)^2, \tag{8.19}$$

$$f_{BC} = \left(\frac{W}{4K - 1}\right)^2. \tag{8.20}$$

By using the outcomes from Eqs. (8.17) to (8.20), we obtain the following quantity:

$$q_{AB} = q_{AC} = \frac{2KW\beta}{4K - \beta} \tag{8.21}$$

$$q_{BC} = \frac{2KW}{4K - 1}. \tag{8.22}$$

As a result, the maximized profit when the monopolistic carrier adopts the point-to-point network is

$$\pi_p^* = \frac{KW^2\{\beta(3 - 8K) - 4K\}}{(\beta - 4K)(4K - 1)}. \tag{8.23}$$

Here, π_p^* represents the maximized profit when the point-to-point network is adopted.

8.5 Comparison of Each Outcome

In this section, we compare each outcome for the hub–spoke network with hub h case with the point-to-point network case.

8.5.1 Comparison of Flight Frequency

In this subsection, we compare flight frequency for the hub–spoke network with hub h with point-to-point network cases. The following Lemma 8.1 shows the comparison result.

Lemma 8.1. *The flight frequency of the hub–spoke network is always larger than that of the point-to-point network.*

This Lemma 8.1 is straightforward. As shown in Brueckner [6], by adopting the hub–spoke network, the monopolistic carrier can aggregate the passengers from two markets onto one route. Consequently, the marginal revenue on its route increases, raising the flight frequency of its route. Additionally, as also shown in Brueckner [6], we verify that flight frequency increases after deregulation because hub–spoke networks are adopted by carriers.

Although it is natural to compare flight frequency when city A is a hub with that when city B is a hub, we omit this comparison because the operating route when city A is the hub is different from that when city B is the hub.[11]

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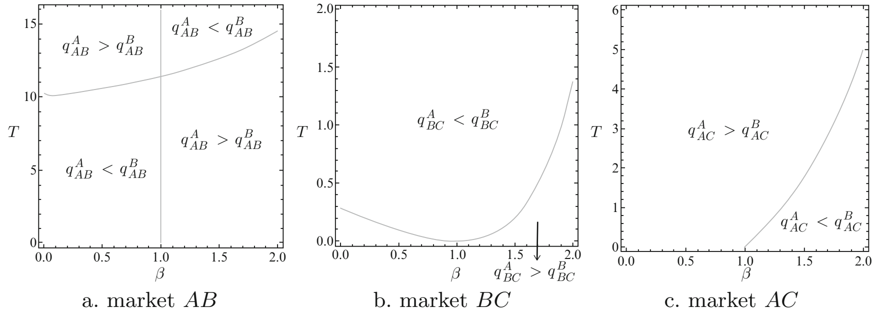
[11] In other words, it is almost meaningless to compare the flight frequencies of the different routes.



a. market AB b. market BC c. market AC

Fig. 8.1 Comparison result of number of passengers

8.5.2 Comparison of Demand

In the following, we compare each market's number of passengers using airline services for the hub–spoke network with hub h with the point-to-point network. First, we compare market demand when a hub–spoke network and a point-to-point network is adopted, obtaining the following Lemma 8.2.

Lemma 8.2. *In markets ih and jh, the number of passengers using airline services when the hub–spoke network is adopted is always larger than that when the point-to-point network is adopted. In market ij, if T is small (large), this number when the hub–spoke network is adopted is larger (smaller) than that when the point-to-point network is adopted.*

As shown in Lemma 8.1, when the monopolistic carrier adopts the hub–spoke network, flight frequency on one route increases, which increases the scheduling effect for passengers. Therefore, when a carrier adopts a hub–spoke network, the number of passengers in markets *ih* and *jh* increases. On the contrary, with regard to the passengers in market *ij*, although flight frequency increases, which increases a passenger's scheduling effect, he/she incurs an additional travel time cost, which decreases his/her utility. If the additional travel time cost is small, the influence of the larger scheduling effect is greater. Therefore, the number of passengers using airline services increases. However, if the additional travel time cost is large, the influence of the larger scheduling effect becomes smaller. Consequently, the number of passengers decreases.

Finally, we compare the number of passengers in each market when city A is the hub with that when city B is the hub.[12] In Fig. 8.1, we assume $W = 10$ and $K = 1$. Additionally, we express the number of passengers in market ij when city h is the hub as q^h_{ij}.

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[12] Here, the number of passengers when city A is the hub and that when city C is the hub is the same. Consequently, we omit the case that city C is the hub.

From Fig. 8.1, we obtain the following Lemma 8.3.

Lemma 8.3. *Comparing the number of passengers using airline services in each market,*

(1) *In market AB, given that* $\beta \leq 1$, *when* $T \geq (<) T_A$, q^A_{AB} *is larger (smaller) than* q^B_{AB}; *given that* $\beta > 1$, *when* $T \geq (<) T_A$, q^B_{AB} *is larger (smaller) than* q^A_{AB};
(2) *In market BC, when* $T \geq (<) T_B$, q^B_{BC} *is larger (smaller) than* q^A_{BC};
(3) *In market AC, when* $T \geq (<) T_C$, q^A_{AC} *is larger (smaller) than* q^B_{AC}.

Here,

$$T_A \equiv \frac{80(\beta(5+\beta) - 8(2+3\beta)K + 64K^2) + 16KW(-7+2\beta)(-1+4K)}{\beta(19-3\beta) + 16(-1+(-5+\beta)\beta)K + 64K^2}, \tag{8.24}$$

$$T_B \equiv \frac{80(\beta(5+\beta) - 8(2+3\beta)K + 64K^2) - 8KW(-7+2\beta)(1+\beta-8K)}{\beta(-23+9\beta) + 8(12+(7-4\beta)\beta)K + 128(-3+\beta)K^2}, \tag{8.25}$$

$$T_C \equiv \frac{-40(\beta(5+\beta) - 8(2+3\beta)K + 64K^2) + 8KW(-7+2\beta)(\beta-4K)}{\beta(-20+3(-2+\beta)\beta) + 4(16+(27-8\beta)\beta)K + 64(-4+\beta)K^2}. \tag{8.26}$$

First, we consider the comparison result of market *AB*. The number of passengers in market *AB* is influenced by flight frequency on route *AB*. When city *A* becomes the hub, flight frequency on route *AB* depends on markets *AB* and *BC*. When city *B* becomes the hub, flight frequency depends on markets *AB* and *AC*. Here, it is noteworthy that the density of passengers in market *AC* is 1, while that of passengers in market *BC* is β. Now, consider the extreme case that the additional travel time cost *T* is zero. First, we assume that β is smaller than 1. Then, because the density of passengers in market *AC* is larger than that in market *BC*, total potential demand on route *AB* is larger when city *B* is the hub than when city *A* is the hub. Here, it is noteworthy that a larger total potential demand brings about larger marginal revenues per flight. Consequently, flight frequency on route *AB* is larger when city *B* is the hub than when city *A* is the hub. As a result, because the scheduling effect when city *B* is the hub is larger than when city *A* is the hub, q^B_{AB} is larger than q^A_{AB}. This result holds even when *T* is small. Given this situation, as *T* sufficiently increases, the utility of connecting passengers largely decreases, resulting in a fall in the number of connecting passengers. Here, when the density of connecting passengers is large, marginal revenue largely decreases and thus flight frequency largely decreases. Consequently, flight frequency when city *A* is the hub becomes larger than that when city *B* is the hub because the influence of the decrease in connecting passengers reduces. As a result, q^A_{AB} becomes larger than q^B_{AB} throughout the scheduling effect.

Contrarily, if we assume that β is larger than 1, the reverse characteristic appears. That is, if T is small (large), an increase in connecting passengers brings more (fewer) number of passengers on route AB, which increases marginal revenues and thus flight frequency. Consequently, q_{AB}^{A} becomes larger (smaller) than q_{AB}^{B} throughout the larger scheduling effect.

In the following, we consider the comparison result of market BC. First, suppose that β is smaller than 1. First, we consider the extreme case, that is, $T = 0$. Then, if city A is the hub, flight frequency on route AB becomes very small and flight frequency on route AC is large, which influences demand in market BC. On the contrary, if city B is the hub, flight frequency on route BC becomes small. Here, in the case that city A is the hub, because flight frequency on route AC is large, the scheduling effect of the passengers in market BC is larger than that in the case that city B is the hub. Consequently, q_{BC}^{A} is larger than q_{BC}^{B}. Given this interpretation, as T increases, it is apparent that the number of connecting passengers decreases. Consequently, when T is large, q_{BC}^{B} becomes larger than q_{BC}^{A}. Suppose that β is larger than 1. Here, we first consider the extreme case $T = 0$. If city A is the hub, flight frequency on route AB becomes very large and that on route AC becomes somewhat large. If city B is the hub, flight frequency on route BC becomes large. Here, in the case that city A is the hub, because flight frequency on route AB is very large, the scheduling effect of the passengers in market BC is larger than that in the case that city B is the hub. Consequently, q_{BC}^{A} is larger than q_{BC}^{B}. Given this interpretation, as T increases, it is apparent that the number of connecting passengers decreases. Consequently, when T is large, q_{BC}^{B} becomes larger than q_{BC}^{A}.

Finally, we consider the comparison result of market AC. Suppose that $T = 0$. When city A is the hub, flight frequency on route AC becomes somewhat large (small) for small (large) β. When city B is the hub, flight frequency on both routes AB and BC, which influences demand for market AC, becomes small (large) for small (large) β. Consequently, for small β, the case that city A is the hub has a larger scheduling effect for passengers than the case that city B is the hub. As a result, q_{AC}^{A} is larger than q_{AC}^{B}. Contrarily, for large β, the case that city B is the hub has a larger scheduling effect for passengers than the case that city A is the hub. As a result, q_{AC}^{B} is larger than q_{AC}^{A}. Given this result, as T increases, if β is small, the result above still holds because the increase in T decreases the number of connecting passengers; if β is large, q_{AC}^{B} is larger (smaller) than q_{AC}^{A} for small (large) T.

8.6 Profit-Maximizing Network Formation and Hub Location

This section analyzes which network is favorable in the monopolistic airline market by comparing each profit. Here, because the profit when the airline adopts the hub–spoke network with hub A and that when it adopts the hub–spoke network with hub C is the same, we assume that in this situation the hub–spoke network with hub

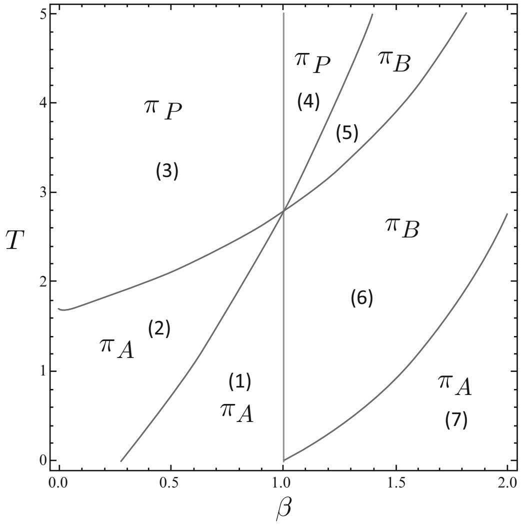


Fig. 8.2 Decision on the choice of network formation and hub city

Table 8.1 The meaning of each range in Fig. 8.2

Range	Comparison of profit	Airline network	City to minimize the potential number of connecting passengers
(1)	$\pi_A > \pi_B, \pi_A > \pi_p, \pi_B > \pi_p$	Hub–spoke with hub *A*	City *A*
(2)	$\pi_A > \pi_B, \pi_A > \pi_p, \pi_B < \pi_p$	Hub–spoke with hub *A*	City *A*
(3)	$\pi_A > \pi_B, \pi_A < \pi_p, \pi_B < \pi_p$	Point-to-point	City *A*
(4)	$\pi_A < \pi_B, \pi_A > \pi_p, \pi_B < \pi_p$	Point-to-point	City *A*
(5)	$\pi_A < \pi_B, \pi_A > \pi_p, \pi_B > \pi_p$	Hub–spoke with hub *B*	City *B*
(6)	$\pi_A < \pi_B, \pi_A > \pi_p, \pi_B > \pi_p$	Hub–spoke with hub *B*	City *B*
(7)	$\pi_A > \pi_B, \pi_A > \pi_p, \pi_B > \pi_p$	Hub–spoke with hub *A*	City *B*

A is adopted. Hereafter, we compare each profit. However, as the calculations are complex, we perform a simulation analysis. In the following, we assume $W = 10$ and $K = 1$ without loss of generality. Figure 8.2 illustrates the comparison results, and Table 8.1 expresses the meaning of each range.

First, Fig. 8.2 and Table 8.1 show that the monopolistic airline adopts the point-to-point network when the additional travel time cost T is large. This characteristic corresponds with Brueckner [6] and Kawasaki [18].

The benefit of adopting the hub–spoke network is to strengthen the scheduling effect and thus to set high airfares. On the contrary, because connecting passengers incur an additional travel time cost (which shifts the demand function downwards), airfares become low, which is a disadvantage of adopting the hub–spoke network. When the additional travel time cost is very large, the utility of connecting passengers largely decreases. Therefore, to let connecting passengers use airline services, the airfare for connecting passengers should become very low. Nonetheless, demand for connecting services also decreases. As a result, although the profits from the other two markets that can use direct services increase throughout the scheduling effect compared with the point-to-point network, total airline profit decreases. Therefore, although the monopolistic carrier cannot obtain a large scheduling effect, the point-to-point network is adopted in order not to lose revenues from connecting passengers.

On the contrary, when the additional travel time cost is small, by adopting the hub–spoke network potential demand in each market increases through the larger scheduling effect, which can increase the airfare in each market. Consequently, the monopolistic carrier adopts the hub–spoke network. Summarizing the above discussion, we obtain Theorem 8.4.

Theorem 8.4. *When the additional travel time cost is large (small), the monopolistic carrier chooses the point-to-point (hub–spoke) network.*

Theorem 8.4 corresponds with various previous studies. According to previous studies, a hub–spoke network has both advantages and disadvantages. If the advantages (i.e., scheduling effect or network effect) are larger (smaller) than the disadvantages (i.e., additional travel time cost), the carrier chooses the hub–spoke (point-to-point) network.

In the following, we discuss which airport becomes a hub. As shown in Table 8.1, in ranges (1), (2), (5), and (6), the hub airport is chosen to minimize the potential number of connecting passengers. On the contrary, in range (7), although city A becomes the hub airport, the city minimizing the potential number of connecting passengers is city B. In other words, in range (7), the hub city is not chosen to minimize the potential number of connecting passengers. This finding shows that the results obtained in previous studies of the hub location problem (i.e., that the hub city is chosen to minimize the potential number of connecting passengers) do not always hold. Indeed, these studies have one important limitation, namely they omit the scheduling effect.

As mentioned earlier, connecting passengers face a decrease in utility by incurring an additional travel time cost. As a result, demand for connecting services becomes small, which causes airfares to fall. If its density (i.e., the potential number of passengers) is large, the monopolistic carrier loses the opportunity to obtain more revenues by letting its passengers use direct services. According to previous studies, because only the disadvantage mentioned above is considered, the monopolistic carrier chooses the hub airport that minimizes the potential number of connecting passengers. However, introducing the scheduling effect allows us to argue that the results of previous studies do not always hold. When demand for one route (not the entire market) increases, the monopolistic carrier increases the flight frequency on that route, which increases the utility of passengers using it. When the density of connecting passengers is large, demand for both routes increases, which raises flight frequency on both routes.

As flight frequency on each route increases, demand for direct services on each route also increases. Furthermore, each airfare increases, and so does the profit of the airline. Consequently, the strategy to minimize the potential number of connecting passengers has a trade-off. This chapter argues that when β (i.e., the density of

BC passengers) is sufficiently large, the advantage of the scheduling effect is larger than the disadvantage of the additional traveling cost. Therefore, the hub airport is not chosen to minimize the potential number of connecting passengers. Contrarily, when β is not sufficiently large, its disadvantage is larger than its advantage; hence, the hub city is chosen to minimize the potential number of connecting services.

Summarizing the above, we obtain Theorem 8.5.

Theorem 8.5. *The monopolistic carrier does not always choose the hub city to minimize the potential number of connecting passengers.*

Next, we discuss the influence of K (i.e., the fixed cost per flight). In the above discussion, we assumed that $K = 1$. When K increases, how do the results obtained here change? As K increases, the monopolistic carrier decreases flight frequency, which reduces the scheduling effect. Therefore, as K increases, the range within which the hub–spoke network is adopted narrows. At the same time, even when the hub–spoke network is adopted, the range within which the potential number of connecting passengers is minimized is also narrow.

8.7 Social Welfare

This section analyzes the socially preferable network formation and socially preferable hub location. Social welfare (W) is defined as the sum of passengers' utility and the carrier's profit. That is,

$$W = \beta U_{AB} + \beta U_{BC} + U_{AC} + \pi_\ell. \tag{8.27}$$

Here, if the hub–spoke network with hub h is adopted, $\pi_\ell = \pi_h$, whereas if the point-to-point network is adopted, $\pi_\ell = \pi_p$. Social welfare when the monopolistic carrier adopts the hub–spoke network with hub city h is expressed as W_h and that when the monopolistic carrier adopts the point-to-point network is expressed as W_p. Because of the complexity of this welfare, we omit the detailed values here.

In the following, we compare social welfare in each case through a simulation analysis. The parameter is the same that used in the previous section. Figure 8.3 shows the result. Here, it is assumed that if social welfare when city A and that when city C is the same, city A is selected as the socially preferable hub. Here, we mainly address the socially preferable hub location. As a result, we obtain Theorem 8.6.

Theorem 8.6. *The socially preferable hub location does not always minimize the potential number of connecting passengers.*

Previous studies using OR have argued that the hub airport should be decided in order to minimize connecting passengers and thus reduce social costs. However, this chapter demonstrates that this argument does not always hold. In other words, when the density of *AB* and *AC* passengers is sufficiently large, it is not socially preferable to minimize the potential number of connecting passengers. The mechanism is

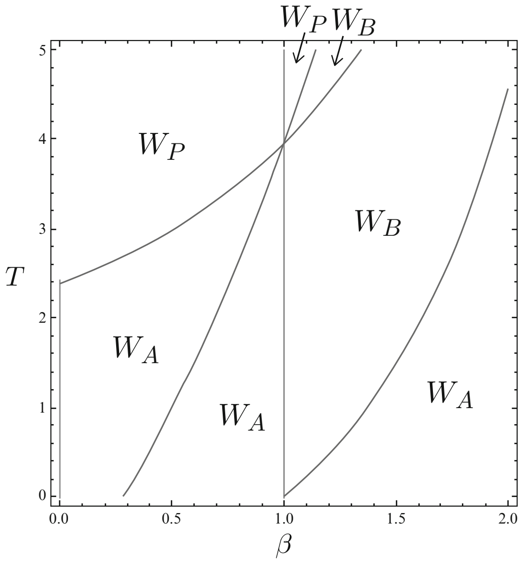


Fig. 8.3 Socially preferable airline network

presented as follows. By increasing the density of connecting passengers on one route, flight frequency increases on that route, which increases passenger utility. Hence, a large scheduling effect arises, which increases not only the number of passengers using airline services but also the utility of those passengers. Although these passengers incur an additional travel time cost, the larger scheduling effect becomes larger than this cost. Consequently, when the density of *AB* and *BC* passengers is sufficiently large, social welfare increases by adopting the hub airport with aim of not minimizing the potential number of connecting passengers.

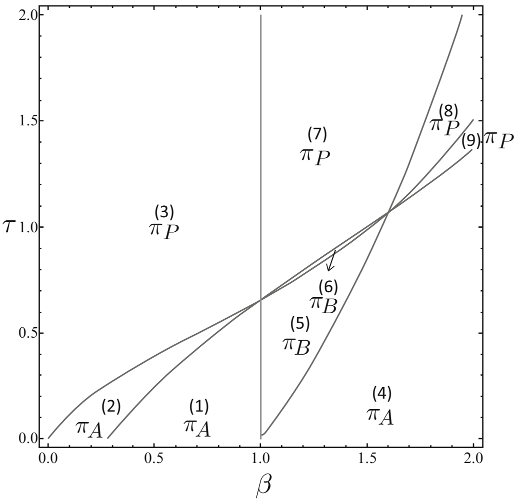
Here, as K increases, the range within which the potential number of connecting passengers is minimized narrows. As mentioned earlier, when K increases, flight frequency decreases, which strengthens the disadvantage of incurring an additional travel time cost. Therefore, it becomes socially preferable to minimize the potential number of connecting passengers.

8.8 Extension

In Sect. 8.6, we assumed that the per-seat cost is zero. Then, if we introduce a positive cost, does the same characteristic appear? Here, we introduce the per-seat cost following Brueckner [6] and re-analyze the airline network formation and hub location problems. Because we mainly address the per-seat cost, it is assumed for simplicity that $T = 0$.

We denote the per-seat cost as τ. The monopolistic carrier uses aircraft which size is s and flies between each city pair f_{ij} times. Here, the load factor is assumed

Fig. 8.4 Airline network formation and hub location



to be 100 %. Then, the total number of passengers on one route (Q_{ij}) equals $s \times f_{ij}$. Because we assume that the per-seat cost is τ, total cost becomes $\tau \times s \times f_{ij}$, which equals τQ_{ij}. Consequently, the operating cost per flight is $f_{ij}K + \tau Q_{ij}$.

Instead of showing the detailed profit in each case and discussing the mathematical comparison, we simply show the simulation result in Fig. 8.4.

First, by comparing π_A with π_B, in ranges (1), (2), (3), (4), (8), and (9), π_A is larger than π_B. In ranges (5), (6), and (7), π_B is larger than π_A. Second, by comparing π_A with π_P, in ranges (1), (2), (4), (5), and (9), π_A is larger than π_P. In ranges (3), (6), (7), and (8), π_P is larger than π_A. Finally, by comparing π_B with π_P, in ranges (1), (4), (5), and (6), π_B is larger than π_P. In ranges (2), (3), (7), (8), and (9), π_P is larger than π_B. Consequently, in ranges (1), (2), and (4), the hub–spoke network with hub *A* is adopted; in ranges (5) and (6), the hub–spoke network with hub *B* is adopted; and in ranges (3), (7), (8), and (9), the point-to-point network is adopted.

When introducing the per-seat cost, total operating costs increase. In particular, when the monopolistic carrier adopts the hub–spoke network, connecting passengers use airline services twice, thereby doubling the per-seat cost for those passengers. If the per-seat cost is small, an increase in the scheduling effect is larger than the increase in total operating costs. Therefore, the monopolistic carrier adopts the hub–spoke network. Furthermore, it chooses the hub airport in order not to minimize the potential number of connecting passengers. However, as the per-seat cost increases, the incentive to minimize the number of passengers strengthens. At the same time, the incentive to adopt the point-to-point network also strengthens. Therefore, the range within which the hub–spoke network with city *A* is adopted narrows as τ increases until it finally disappears.

Although we omit the additional travel time cost, we can easily expect that when this is sufficiently small, the same result obtained here holds; however, when the additional travel time cost becomes large, the monopolistic carrier always chooses the point-to-point network.

8.9 Implications

Previous studies of the hub location problem have focused on developing an algorithm to minimize the number of connecting passengers. However, as discussed herein, the airline hub is not always chosen to minimize this number (e.g., Changi International Airport). In this case, Singapore is a small country and the potential number of passengers traveling there is not always large compared with other countries. However, Changi International Airport is still a well-known hub airport in Asia because, as shown in this chapter, total demand for one particular route can rise by increasing the number of connecting passengers, which increases the flight frequencies of airlines. When flight frequency increases, passengers enjoy more convenience by using its route. Therefore, attracting connecting passengers is crucial. Changi International Airport has devised various ways in which to attract connecting passengers. For example, the departure and arrivals gate is the same, while various services (games, theater, shop, hotel, etc.) are provided to entertain connecting passengers. These services add to the successful reputation of Changi International Airport as a hub airport.

In Japan, various ways to become a hub airport have been discussed. However, these discussions mainly address how to entice more passenger visits to Japan. In other words, they consider how to increase the number of direct passengers. However, as shown in this chapter as well as the example of Changi International Airport, attracting more passengers is not always important for a hub airport. Rather, it is more important for connecting passengers to use Japanese airports as a hub. To attract more connecting passengers, increasing airline routes and flight frequencies are important considerations. Furthermore, improving airport services may be necessary.

8.10 Concluding Remarks

This chapter addressed the airline network formation and hub location problems simultaneously by introducing the scheduling effect. With regard to the hub location problem, previous studies using OR have not always addressed the real-life problem. In this chapter, by introducing the scheduling effect, we explained that the airline hub is not always constructed to minimize the potential number of connecting passengers, which adds to the literature in this regard. On the contrary, with regard to airline network formation, this chapter demonstrated that when the additional travel time cost is small (large), the hub–spoke (point-to-point) network is formed, a finding that corresponds with those of previous studies. Additionally, this chapter demonstrated that the socially preferable hub airport is not always one that aims to minimize its potential number of connecting passengers. Furthermore, we found that the same result is obtained when the per-seat cost is small; however, when this cost is large, the point-to-point network is always adopted. Furthermore, based on this chapter's results, we provided policy implications for Japanese airports. To become a hub airport in Asia like Changi International Airport, not only increasing direct passengers but also increasing connecting passengers is important.

Finally, we mention the limitations of this chapter. First, this chapter omitted airport pricing. Recently, Teraji and Morimoto [30] analyzed this important problem for competitive airports. However, future research must introduce an airport pricing strategy and consider the hub location problem. Second, this chapter assumed a monopolistic airline market. However, the actual airline market is highly competitive, implying that how airline competition influences hub location in the real world is unclear. Third, this chapter did not consider congestion, a problem from which hub airports often suffer. If a hub airport's congestion were introduced, what would be the effect on network formation? Additionally, which airports would become hubs, including socially preferable ones? We leave this important and interesting problem to future research.

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