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On the effects of airport capacity expansion under responsive airlines and elastic passenger demand

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Abstract

This paper investigates the effect of airport expansion on air traffic and its implications on airport congestion, airline competition and the social welfare, considering different airline market structures (i.e., perfect substitutes market or imperfect substitutes market) and airport administrative regimes (i.e., zero-profit, profit-maximizing, and welfare-maximizing). We develop an analytical tri-level model to examine the air traffic equilibrium in the airport-airline-passenger system, the effect of airport capacity expansion on the traffic equilibrium, and the decisions of different stakeholders, i.e., airport's decision on flight charge in the first level, airlines' decisions on flight volume and airfare in the second level, and the passenger choice equilibrium in the third level. The analysis in this paper suggests that (i) airport capacity expansion may induce the airline market to over schedule flights and lead to a more congested airport (i.e., capacity paradox); (ii) with a given airport charge, the capacity paradox is more likely to occur in airline market with fewer competitive airlines; (iii) given the same airport capacity and traffic, capacity paradox is more likely to occur under a welfare-maximizing airport operator (compared to zero-profit and profit-maximizing); (iv) airlines with market power will internalize a portion of airport congestion based on their market share, while a leader airline with the knowledge of the follower's response will scale up/down their airfare in order to maximize its profit; (v) under different market structures, capacity expansion always increases the aggregate traffic volume when the airport charge is fixed.

Keywords: Airport expansion, Air traffic congestion, Airlines competition, Sequential game, Welfare effects

1. Introduction

In recent decades, with the increasing volumes of passengers and flights, air traffic congestion has become increasingly severe in aviation systems worldwide. In year 2019, about 46.4% of flights in Europe experienced departure delay[1], and 19% of flights in the United States experienced an arrival delay larger than 15 minutes. The estimated economic impact induced by flight delays worldwide were about $60 billion a year (Gopalakrishnan & Balakrishnan, 2021). Many studies have proposed solutions to relieve congestion from the demand side, e.g., congestion pricing (e.g., Brueckner, 2002; Zhang & Zhang, 2006; Czerny & Zhang, 2011), slot auction (e.g., Le et al., 2004; Fukui, 2010). These solutions can help relieve congestion, but only to a certain extent due to the capacity constraint of the supply side. An airport's capacity is primarily determined by its number of runways. It is difficult to schedule more flights than the maximum slots available beyond the designed runway capacity, owing to strict safety requirements and operation standards (Odoni & De Neufville, 2003). In this context, many airports decide to expand their capacity to relieve congestion and meet the soaring demand in the future. Hong Kong International Airport (HKIA), for example, has its third runway under construction. The maximum capacity of the existing two-runway system in

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[1] These facts are based on data from the Eurocontrol website (https://www.eurocontrol.int/sites/default/files/2020-04/eurocontrol-coda-digest-annual-report-2019.pdf)

HKIA is about 420 thousand flights a year. There will be a gap of about 182 thousand flights if the capacity remains constrained by 2030[2]. However, airport expansion is also criticized for the huge labor and capital investment and long gestation period. Winston (1991) has commented that the high cost and long lead-times associated with expansion projects suggest that society will be faced with a difficult and expensive catch-up task if it commits itself to reducing air traffic congestion or boosting regional economy by building the new runway. It is important and necessary to carefully examine the effects of airport expansion, considering multiple stakeholders such as the airport, airlines, and passengers.

Extensive studies have been carried out to examine the macroeconomic impact of airport expansion in terms of the employment or productivity growth (e.g., Brueckner, 2003; Sellner & Nagl, 2010; Gibbons & Wu, 2017; Fu et al., 2021a) and agglomeration effects (e.g., Graham, 2007; Graham & Van Dender, 2011). As Zhang & Graham (2020) mentioned, the potential stimulating effect of an expanded airport on local economy is the major argument of proponents, and they concluded that both in developing and developed economies, the causality from air transport to economic growth is applicable. This conclusion is also supported by a series of empirical studies. For example, Fu et al. (2021b) investigated the impacts of airport activities using real data in New Zealand's airport system and suggested that the aviation activities positively affect regional economies. Brueckner (2003) has estimated the potential employment growth at the Chicago area to be above 5% (almost 200,000 jobs) for 50% increase in air traffic, given the proposed doubling flight capacity.

However, little attention is paid to the impacts of airport expansion from the microeconomic perspective. There is a growing body of microeconomic analysis in the air transport literature, for instance, airport pricing (e.g., Zhang & Zhang, 1997; Fu et al., 2006; Zhang et al., 2010; Yang & Zhang, 2011; Czerny & Zhang, 2014; Yang & Fu, 2015; Wan et al., 2015; Kidokoro et al., 2016), airport-airline structure (e.g., Francis et al., 2004; Oum & Fu, 2009; Fu et al., 2011; Xiao et al., 2016), air-rail competition and cooperation (e.g., Yang & Zhang, 2012; Jiang & Zhang, 2014; Takebayashi, 2015, 2016; Xia & Zhang, 2016; Jiang et al., 2017; Wang et al., 2018; Xia et al., 2019; Takebayashi, 2021; Li et al., 2022). Pertaining to airport expansion and capacity choice, Zhang & Zhang (2003, 2006, 2010) have carried out a series of studies analyzing airport's capacity and pricing choices in different airport administrative regimes. Xiao et al. (2013) analyzed the effects of demand uncertainty on airport capacity choices. Takebayashi (2011) examined the effect of airport's capacity on airlines' behavior. Xiao et al. (2016) investigated the effects of airport-airline vertical arrangements on airport capacity choices. Xiao et al. (2017) modeled airport capacity choice when incorporating the responses of oligopolistic airlines and demand uncertainty. Lin (2019) investigated the pricing and capacity investment for a congested airport with asymmetric airline market. However, effects of airport expansion on system performance and downstream markets (i.e., airline and passenger markets) in a tri-level airport-airline-passenger system have not been systematically analyzed and are not fully clear.

The airport expansion can have substantial impacts on the downstream markets (for both airlines and passengers), as a number of adjustments on the operation procedure of passenger and cargo services, air traffic management, aircraft handling and so forth are expected to respond to the airport expansion, and passengers will respond to the aforementioned changes when making travel choices. Fageda & Fernández-Villadangos (2009) reviewed the relationship between airport capacity and airline competition. Their results suggested that the removal of airport capacity constraints does make airline more competitive, but only at large airports that are not hubs of network carriers. Dray (2020) reviewed the actual expansion impacts on aircraft size, flight frequency, number of carriers and destinations with empirical data.

The effect of capacity expansion on congestion is non-trivial and worth investigating. Intuitively, airport capacity expansion relieves the capacity constraint to some extent and is expected to reduce the air traffic congestion. Nevertheless, the reality does not always run as expected. In road transport literature, researchers have identified different capacity paradoxes, in the sense that adding capacity to the road network or transit service network produces counterproductive results if the traffic inducing/diverting effect outweighs the direct benefits of capacity expansion (Duranton & Turner, 2011; Graham et al., 2014). According to Zhang et al. (2014, 2016), the effect of road expansion on a bimodal system depends on not only the fare decision, but also how the transit operator changes the service frequency in response to the road expansion and how travelers choose their travel modes (i.e., car or transit). Operators with different economic objectives generally will react differently to road expansion, which can lead to diverse outcomes.

[2]These facts come from the Legislative Council of Hong Kong Special Administrative Region of the People's Republic of China (https://www.legco.gov.hk/yr10-11/chinese/panels/edev/papers/edev0610cb1-2364-1-c.pdf)

Analogously, capacity expansion at a congested airport can have substantial impact on the existing market conditions in the aviation system. The effect of airport expansion should be systemically examined given that we may have different market structures for airlines, different flight frequency and airfare decisions, and different passenger choice equilibrium (e.g., whether to choose the airport in concern to travel or not, and which airline).

This paper examines the effects of airport expansion in the airport-airline-passenger system and focuses on the following main questions: (i) how airlines will respond to the airport expansion in different market structures; (ii) under what conditions the capacity expansion improves the system performance, and under what conditions the capacity paradox (a larger capacity yields a more congested airport) might occur; (iii) what the impact on user benefits of airport expansion will be. In particular, under the airport capacity expansion with a given airport charge (first-level decisions in the tri-level model), we first investigate the airlines' best responses (second-level in the tri-level model) and passengers' travel choice equilibrium (airline choice and elastic demand equilibrium, i.e., the third-level in the tri-level model). Then, we further consider under the airport capacity expansion how airport may adjust its airport charge in different airport administrative regimes (the first-level in the tri-level model), and analyze airlines' and passengers' responses. Specifically, we examine: (i) an airport that may be operated in alternative administrative regimes (i.e., zero-profit, profit-maximizing, and welfare-maximizing), where airport's flight charge can be optimized in response to the airport capacity expansion; (ii) three typical market structures for the airlines: competitive, monopoly and Cournot oligopolistic and two different market settings where the airlines are either perfect or imperfect substitutes. Different scenarios considered in this paper are summarized in Table 1.

Table 1 Different scenarios considered in this paper

Airport administrative regimes	Airline market structures	
Zero-profit / Profit-maximizing / Welfare-maximizing	Perfect substitutes market	Perfectly competitive airline
		Cournot airline
		Monopoly airline
		A Stackelberg leader with a Cournot follower
	Imperfect substitutes market	Nash equilibrium
		Stackelberg-competitive fringe

The rest of this paper is organized as follows. Section 2 presents the basic model formulation in terms of cost, demand, and profit. Section 3 investigates the airlines' decisions and the resulting demand equilibrium in response to the airport capacity expansion under a given airport flight charge. In Section 4, we consider the airport will optimize its flight charge given the airport capacity expansion in three different airport administrative regimes, and examine how these together affect airlines' decisions and passenger choices. Section 5 provides numerical studies. Section 6 concludes and summarizes the main managerial insights from this paper.

2. Model formulation

We consider a tri-level airport-airline-passenger system as shown in Figure 1, which follows that from Brueckner (2002), Zhang & Zhang (2003, 2006), and Brueckner & Van Dender (2008). In the first-level, this paper considers capacity and operation decisions of an airport where congestion exists. In the second-level, we consider that the airport is served by m carriers. In the third-level, passengers can choose different airlines or another travel alternative (elastic demand). Table 2 summarizes the main notations used in this paper. In the following, we present the formulations from the third level to the first level in the tri-level model (i.e., passengers, airlines and airport) sequentially.

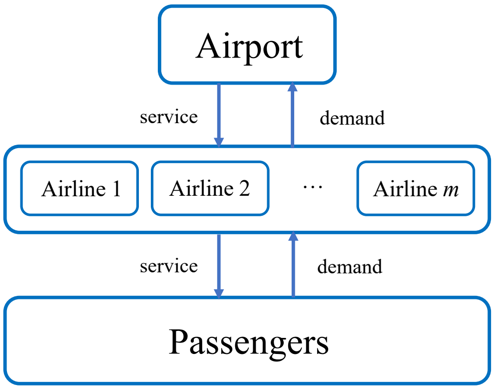

Fig. 1. Airport-airline-passenger system structure

Table 2 List of major notations

t	congestion delay per flight	k	airport capacity
q_i	passenger demand for airline i	ρ	airport charge per passenger
q	total passenger demand for all airlines ($q = \sum_i q_i$)	r	airport concession profit per passenger
p_i	full price of travel with airline i	c_k	airport's unit cost of maintaining capacity
τ_i	airfare per passenger charged by airline i	c_q	airport's unit cost of handling flight
s	number of seats per flight	π_i	profit of airline i
m	number of airlines	Π	profit of airport
c_f	airlines' fixed cost of a flight	SW	social welfare
c_g	airlines' variable cost of a flight due to congestion delay		

(Air traffic congestion) We model the average congestion delay per flight, which is a second-order differentiable function of flight traffic volume and capacity:

$$t = t(q, k), \tag{1}$$

where t is the average congestion delay per flight, k is the maximum runway and terminal capacity of handling flights and q is the total flight traffic volume. Following Zhang & Zhang (2003, 2006, 2010), we consider that the congestion delay is increasing and convex with respect to the traffic volume q, and decreasing and convex with respect to capacity k, i.e., $t'_q = \partial t/\partial q > 0$, $t'_k = \partial t/\partial k < 0$, $t''_{qq} = \partial^2 t/\partial q^2 \geqslant 0$, $t''_{qk} = \partial^2 t/\partial q \partial k \leqslant 0$.

(Passenger demand) Passengers decide whether to travel through the airport in concern and which airline to take based on the full travel cost/price. The full price of traveling by airline i is

$$p_i = \tau_i + t(q, k), i = 1...m. \tag{2}$$

The full price consists of two terms: the first term is the airfare of airline i, and the second term is the congestion cost. Passengers' value of time is normalized to one.

When airlines are perfect substitutes for users, the full price is identical among all used airlines at equilibrium, denoted by p. The total passenger demand in the form of number of flights is a function of the full price: $q = q(p)$, and the demand function is downward sloping (i.e., $q' < 0$).

When different airlines are imperfect substitutes for users, the demand for airline i is function of a series of full prices $q_i = q_i(p_i, p_{-i})$, which depends on not only the price of this particular airline, but also those of all the alternatives, such that $\partial q_i/\partial p_i < 0$, $\partial q_i/\partial p_{-i} \geqslant 0$. If the substitutes are perfectly independent goods, $\partial q_i/\partial p_{-i} = 0$.

Eq. (1), Eq. (2) and the above demand function together define the elastic demand equilibrium (demand is in the form of number of flights).

(Direct effect of capacity expansion on congestion) The equilibrium traffic volume q varies with the airport capacity k. The total direct effect of capacity expansion on congestion at the elastic demand equilibrium is as follows:

$$\frac{dt}{dk} = t'_q \cdot \frac{\partial q}{\partial k} + t'_k. \tag{3}$$

If the congestion reduction due to marginal capacity expansion (t'_k) can cover the congestion caused by additional traffic volume attracted by expansion ($t'_q \cdot \frac{\partial q}{\partial k}$), i.e., $-t'_k < t'_q \cdot \partial q/\partial k$, the expansion will relieve congestion. Otherwise, the expansion will aggravate congestion, which is a "counterproductive" outcome (hereinafter referred to as "capacity paradox" in the paper).

(Airlines' profit) Airline's profit is equal to the ticket revenue from passengers minus the airport charges and the operation costs associated with flight volume and congestion delay. The profit of airline i is as follows:

$$\pi_i = \tau_i sq_i - \rho sq_i - [c_f + c_g t(q,k)]q_i. \tag{4}$$

We consider that on average the aircraft has s seats, which are fully loaded. Then, the number of passengers carried by flight q_i is sq_i for any airline i, and the total number of passengers handled by all airlines is sq. The terms in the square bracket represent an airline's cost of operating a flight, in which c_f is the fixed cost, and $c_g t(q,k)$ represent the extra cost brought by air traffic congestion. Note that later on while we consider different market regimes for airlines, the profit formulation of the airline follows the same formula in Eq. (4).

(Airport's profit) The profit of the airport is equal to the charge/revenue on passengers and airlines minus the maintenance cost related to airport capacity and the operation cost related to handling flights, i.e.,

$$\Pi = (\rho + r)sq - (c_k k + c_q q). \tag{5}$$

where c_k is the maintenance cost per airport capacity and c_q is the unit operation cost of handling flights, and the total operation cost of the airport is $(c_k k + c_q q)$. The airport charges ρ on airlines per passenger and derives r from concession business from each passenger.

(Social welfare) The social welfare in the tri-level airport-airline-passenger system is given as follows:

$$SW = \sum_i \left\{ \int_0^{sq_i} p_i(\epsilon, q_{-i})d\epsilon - p_i \cdot sq_i + (\tau_i - \rho)sq_i - [c_f + c_g t(q,k)]q_i \right\} + (\rho + r)sq - (c_k k + c_q q). \tag{6}$$

where social welfare is the sum of consumer surplus $\sum_i \left\{\int_0^{sq_i} p_i(\epsilon, q_{-i})d\epsilon - p_i \cdot sq_i\right\}$, producer surplus that includes the sum of airlines' profit $\sum_i \left\{(\tau_i - \rho)sq_i - [c_f + c_g t(q,k)]q_i\right\}$ and airport's profit $(\rho + r)sq - (c_k k + c_q q)$.

3. Airline market equilibrium and responses to airport expansion

We consider that airlines choose their flight volumes (and service prices) to maximize their profits under different types of airline market structures given the airport charge and capacity. In this section, we derive the pricing and capacity strategies of airlines, and also investigate their responses to airport capacity expansion under a given airport flight charge. Given the airport capacity expansion, how an airport may optimize its flight charge, and how airlines and passengers will respond to these will be further examined in Section 4.

3.1. Perfect substitutes market

In this subsection, we consider a perfect substitutes market for airlines. All airlines provide indifferent services, which means that all airlines are indifferent to passengers. The full prices/costs for all used airlines are identical at equilibrium, which is denoted by p. Moreover, we examine four market structures, i.e., perfectly competitive airlines, Cournot airlines, monopoly airline, and a Stackelberg leader with a Cournot follower. The first three are symmetric markets. The last one is a leader-follower market. In a symmetric market, all airlines make their decisions simultaneously while no one takes a leading role. In a leader-follower market, one airline leads and the other follows.

3.1.1. Perfectly competitive airlines

First, we consider perfectly competitive airlines. Each airline produces an output (flight traffic volume) of q_i $(i = 1, ..., m)$, and the total flight traffic volume of the airline market is $q = \sum_i q_i$. The full price of travel can be written as the inverse demand function $p = p(q)$ (demand is a function of cost/price). Since $p = \tau + t(q, k)$, the airline charge on each passenger (i.e., airfare) can be written as $\tau = p(q) - t(q, k)$. Substituting the airfare into airline's profit function Eq. (4), the profit of airline i is as follows:

$$\pi_i = [p(q) - t(q, k) - \rho]\, sq_i - \left[c_f + c_g t(q, k)\right] q_i. \tag{7}$$

In a perfectly competitive market, the profit margin of the airlines is zero ($\pi_i = 0$). We then can derive the airfare:

$$\tau = p(q) - t(q, k) = \underbrace{\rho}_{\text{airport charge per seat}} + \underbrace{\frac{c_f + c_g t}{s}}_{\text{airline's operation cost per seat}} . \tag{8}$$

Eq. (8) says that under a competitive airline market, the airfare equals the sum of airport charge and airline's operation cost per seat. It is noteworthy that airport congestion externality is not internalized by the airline.

We now investigate how the demand q responds to a marginal change in airport's decisions through differentiating $\pi_i = 0$ with respect to the airport capacity k and airport charge ρ, where we have

$$\frac{\partial q}{\partial k} = \frac{(1 + c_g/s)t'_k}{p' - (1 + c_g/s)t'_q} > 0, \tag{9a}$$

$$\frac{\partial q}{\partial \rho} = \frac{1}{p' - (1 + c_g/s)t'_q} < 0. \tag{9b}$$

We also investigate how airport capacity decision influence the airport congestion. By substituting Eq. (9a) into Eq. (3) we have

$$\frac{\mathrm{d}t}{\mathrm{d}k} = \frac{t'_k p'}{p' - (1 + c_g/s)t'_q} < 0. \tag{10}$$

According to Eqs. (9a), (9b), and (10), we have Proposition 3.1.

Proposition 3.1. *In a perfect substitutes market with perfectly competitive airlines, a marginal increase of airport capacity will increase flight traffic volume (q) and reduce average air traffic congestion delay (t).*

Proof. According to Eqs. (1) and (2), we have $t'_q > 0$, $t'_k < 0$, and $p' < 0$. Therefore, $(1 + c_g/s)t'_k < 0$ and $p' - (1 + c_g/s)t'_q < 0$. It is thus evident from Eqs. (9a), (9b), and (10) that $\partial q/\partial k > 0$, $\partial q/\partial \rho < 0$, and $\mathrm{d}t/\mathrm{d}k < 0$. This completes the proof. □

Proposition 3.1 states that the perfectly competitive market (for airlines) will respond to the airport expansion positively, i.e., airline will schedule more flights when the airport decides to expand, but to a certain extent where the capacity paradox (expanding airport capacity leads to more congestion) will not occur ($\mathrm{d}t/\mathrm{d}k < 0$).

3.1.2. Cournot airlines

We now consider that airlines have market power and compete (Cournot competition) under given airport capacity k and charges ρ, where each airline in the market maximizes its own profit by choosing its optimal demand level q_i.

We can derive the first-order and second-order derivatives $\partial\pi_i/\partial q_i$ and $\partial^2\pi_i/\partial q_i^2$ based on the airline profit formulation when taking the demand quantities of other airlines q_{-i} as given, i.e.,

$$\frac{\partial \pi_i}{\partial q_i} = [sp' - (s + c_g)t'_q]q_i + [sp - (s + c_g)t - s\rho - c_f], \tag{11}$$

$$\frac{\partial^2 \pi_i}{\partial q_i^2} = [sp'' - (s + c_g)t''_{qq}]q_i + 2[sp' - (s + c_g)t'_q]. \tag{12}$$

The interior Cournot equilibrium is characterized by letting $\partial \pi_i / \partial q_i = 0$, where the second-order condition $\partial^2 \pi_i / \partial q_i^2 < 0$ ensures the sufficiency of the first-order optimality condition and the uniqueness of the equilibrium. Based on $\partial \pi_i / \partial q_i = 0$, we can derive the optimal quantity chosen by airline i

$$q_i = \frac{p - \rho - c_f/s - (1 + c_g/s)t}{(1 + c_g/s)t'_q - p'}, \tag{13}$$

and the airfare of airline i

$$\tau_i = \underbrace{\rho}_{\text{airport charge per seat}} + \underbrace{\frac{c_f + c_g t}{s}}_{\text{airline's operation cost per seat}} + \underbrace{(1 + \frac{c_g}{s})t'_q}_{\text{marginal congestion cost per seat due to one flight}} \cdot \underbrace{q_i}_{\text{airline } i\text{'s traffic volume}} + \underbrace{(-p'q_i)}_{\text{markup}} . \tag{14}$$

By comparing Eq. (8) and Eq. (14), it can be seen that Cournot airlines charge passenger a higher airfare than perfectly competitive airlines. In particular, Cournot airlines charge besides the airport charge ρ and operation cost $(c_f + c_g t)/s$, the marginal congestion delay cost $(1 + c_g/s)t'_q q_i$ (the Cournot airline internalizes the congestion externality related to its own traffic) and a markup of $(-p'q_i)$ that is proportional to its market share.

Following the classic models of quantity competition (e.g., Tirole, 1988), we further assume that airlines in the market are strategic substitutes (Bulow et al., 1985), i.e., the marginal profit of one carrier will decline when other carriers' output rise. Differentiating Eq. (11) with respect to q_{-i} yields

$$\frac{\partial^2 \pi_i}{\partial q_i \partial q_{-i}} = [sp'' - (s + c_g)t''_{qq}]q_i + [sp' - (s + c_g)t'_q]. \tag{15}$$

For airlines in the market to be strategic substitutes, we have $\partial^2 \pi_i / \partial q_i \partial q_{-i} < 0$.

We now discuss the airline market's response to airport decisions. Differentiating Eq. (13) with respect to airport capacity k and airport charge ρ yields

$$\frac{\partial q}{\partial k} = \frac{(1 + c_g/s)(q t''_{qk} + m t'_k)}{q[p'' - (1 + c_g/s)t''_{qq}] + (m + 1)[p' - (1 + c_g/s)t'_q]} > 0, \tag{16a}$$

$$\frac{\partial q}{\partial \rho} = \frac{m}{q[p'' - (1 + c_g/s)t''_{qq}] + (m + 1)[p' - (1 + c_g/s)t'_q]} < 0. \tag{16b}$$

We further investigate the effect of airport expansion on congestion. Substituting Eq. (16a) into Eq. (3) yields

$$\frac{\mathrm{d}t}{\mathrm{d}k} = \frac{t'_k \left\{ q\left[p'' - (1 + c_g/s)t''_{qq}\right] + (m + 1)p' - (1 + c_g/s)t'_q + (1 + c_g/s)t'_q q \cdot t''_{qk}/t'_k \right\}}{q\left[p'' - (1 + c_g/s)t''_{qq}\right] + (m + 1)\left[p' - (1 + c_g/s)t'_q\right]}. \tag{17}$$

According to Eqs. (16a), (16b), and (17), we have Proposition 3.2.

Proposition 3.2. *In a perfect substitutes market with Cournot airlines, following the marginal increase of airport capacity (k)*

(i) flight traffic volume (q) will increase.

(ii) if $\begin{cases} \left(1+\dfrac{c_g}{s}\right)\left(t''_{qq}-\dfrac{t'_q}{t'_k}t''_{qk}\right) > p'' + \dfrac{1}{q}\left[(m+1)p' - \left(1+\dfrac{c_g}{s}\right)t'_q\right] \\ \left(1+\dfrac{c_g}{s}\right)\left(t''_{qq}-\dfrac{t'_q}{t'_k}t''_{qk}\right) < p'' + \dfrac{1}{q}\left[(m+1)p' - \left(1+\dfrac{c_g}{s}\right)t'_q\right] \end{cases}$ *then* *average congestion delay (t) will decrease,* *average congestion delay (t) will increase.*

Proof. Given $t'_q > 0$, $t'_k < 0$, $t''_{qq} \geqslant 0$ and $t''_{qk} \leqslant 0$, the numerator of Eq. (16a) is negative. The denominator of Eq. (16a) will be negative under the "strategic substitutes" assumption, i.e., $\partial^2\pi_i/\partial q_i \partial q_{-i} < 0$. Therefore, we have $\partial q/\partial k > 0$, which implies that flight traffic volume will increase following the marginal airport capacity increase. The denominator of Eq. (17) is the same as Eq. (16a), which is negative. Thus, the sign of $\mathrm{d}t/\mathrm{d}k$ is up to the numerator. When $(1 + c_g/s)(t''_{qq} - t'_q/t'_k \cdot t''_{qk}) < p'' + 1/q \cdot [(m+1)p' - (1 + c_g/s)t'_q]$, the numerator of Eq. (17) is negative, thus $\mathrm{d}t/\mathrm{d}k > 0$ and capacity paradox occurs, and vice versa. This completes the proof. □

Proposition 3.2 implies that when the airport charge is fixed, airlines in Cournot model will schedule more flights following a marginal increase of airport capacity, which is consistent with the analysis in Zhang & Zhang (2006). Proposition 3.2 also provides the condition for the occurrence of capacity paradox in Cournot model, i.e., $(1 + c_g/s)(t''_{qq} - t'_q/t'_k \cdot t''_{qk}) < p'' + 1/q \cdot [(m+1)p' - (1 + c_g/s)t'_q]$. It is noted that the shape of demand curve and congestion curve are critical to the occurrence of capacity paradox. When the demand is more sensitive to the price or when the airport congestion is more sensitive to flight traffic volume than capacity (i.e., t'_q is relatively large and t'_k is relatively small), capacity paradox is more likely to occur. In addition, when there are more airlines in the Cournot market (i.e., $m \to \infty$), Eq. (17) will approach Eq. (10) in perfectly competitive market, where the capacity paradox will not occur.

3.1.3. Monopoly airline

In this subsection, we consider that the airport is dominated by a monopoly airline ($m = 1$) that maximizes its profit. We can derive the first-order derivative $\partial\pi/\partial q$ and second-order derivative $\partial^2\pi/\partial q^2$ from differentiating airline profit π with respect to traffic volume q as follows:

$$\frac{\partial\pi}{\partial q} = [sp' - (s + c_g)t'_q]q + [sp - (s + c_g)t - s\rho - c_f], \tag{18}$$

$$\frac{\partial^2\pi}{\partial q^2} = [sp'' - (s + c_g)t''_{qq}]q + 2[sp' - (s + c_g)t'_q]. \tag{19}$$

The interior monopoly solution is characterized by letting $\partial\pi/\partial q = 0$, where the second-order condition $\partial^2\pi/\partial q^2 < 0$ will ensure sufficiency of the first-order optimality condition and the uniqueness of the equilibrium. We then can derive the quantity chosen by the monopoly airline, i.e.,

$$q = \frac{p - \rho - c_f/s - (1 + c_g/s)t}{(1 + c_g/s)t'_q - p'}, \tag{20}$$

and the airfare:

$$\tau = \underbrace{\rho}_{\substack{\text{airport charge per}\\ \text{seat}}} + \underbrace{\frac{c_f + c_g t}{s}}_{\substack{\text{airline's operation}\\ \text{cost per seat}}} + \underbrace{(1 + \frac{c_g}{s})t'_q}_{\substack{\text{marginal congestion}\\ \text{cost per seat due to}\\ \text{one flight}}} \cdot \underbrace{q}_{\substack{\text{total traffic}\\ \text{volume}}} + \underbrace{(-p'q)}_{\text{markup}} . \tag{21}$$

Eq. (21) means that a monopoly airline imposes on passengers the airport charge ρ, the operation cost $(c_f + c_g t)/s$, the marginal congestion delay cost $(1 + c_g/s)t'_q q$ (the monopoly airline fully internalizes the congestion externality of all traffic), and the monopoly markup of $(-p'q)$ (the monopoly markup is expected to be larger than the airline-specific markup in the Cournot model, where the market share affects the size of the markup).

We now turn to investigate the airline market's response to airport decisions. Differentiating Eq. (20) with respect to airport capacity k and airport charge ρ yields

$$\frac{\partial q}{\partial k} = \frac{(1 + c_g/s)(t'_k + q t''_{qk})}{q[p'' - (1 + c_g/s)t''_{qq}] + 2[p' - (1 + c_g/s)t'_q]} > 0, \tag{22a}$$

$$\frac{\partial q}{\partial \rho} = \frac{1}{q[p'' - (1 + c_g/s)t''_{qq}] + 2[p' - (1 + c_g/s)t'_q]} < 0. \tag{22b}$$

The marginal congestion time can be derived by substituting Eq. (22a) into Eq. (3).

$$\frac{\mathrm{d}t}{\mathrm{d}k} = \frac{t'_k \left\{ q[p'' - (1 + c_g/s)t''_{qq}] + 2p' - (1 + c_g/s)t'_q + (1 + c_g/s)t'_q q \cdot t''_{qk}/t'_k \right\}}{q\left[p'' - (1 + c_g/s)t''_{qq}\right] + 2\left[p' - (1 + c_g/s)t'_q\right]}, \tag{23}$$

One can verify that the monopoly model is equivalent to the Cournot model with only one airline (i.e., $m = 1$). The results of Cournot model in Proposition 3.2 holds for the monopoly airline by letting $m = 1$, and the condition for capacity paradox to occur in a monopoly model is given by $(1 + c_g/s)(t''_{qq} - t'_q/t'_k \cdot t''_{qk}) < p'' + 1/q \cdot [2p' - (1 + c_g/s)t'_q]$. By comparing conditions (for occurrence of capacity paradox) in Cournot model and monopoly model, one can see that given the same traffic volume q and capacity k, the capacity paradox is more likely to occur in the airport with a monopoly airline. This is consistent with the results under Cournot airlines model.

3.1.4. A Stackelberg leader with a Cournot follower

In this subsection, we consider that there are two different airlines competing in a leader-follower market ($m = 2$), i.e., Stackelberg model. One airline leads and the other follows. The Stackelberg leader is indicated by subscript 'ℓ' and the Cournot follower is indicated by subscript 'f'. Airline ℓ makes its decision first and is aware of Airline f's response. Airline f then chooses q_f while taking q_ℓ as given.

Based on Airline f's profit π_f, we can derive the first-order and second-order derivatives, i.e., $\partial\pi_f/\partial q_f$ and $\partial^2\pi_f/\partial q_f^2$ as below:

$$\frac{\partial \pi_f}{\partial q_f} = \left[sp' - \left(s + c_g\right)t'_q\right]q_f + \left[sp - \left(s + c_g\right)t - s\rho - c_f\right], \tag{24}$$

$$\frac{\partial^2 \pi_f}{\partial q_f^2} = [sp'' - (s + c_g)t''_{qq}]q_f + 2[sp' - (s + c_g)t'_q]. \tag{25}$$

An interior equilibrium is characterized by $\partial\pi_f/\partial q_f = 0$, and $\partial^2\pi_f/\partial q_f^2 < 0$ ensures the sufficiency of the first-order optimality condition and the uniqueness of the equilibrium. Based on the first-order condition $\partial\pi_f/\partial q_f = 0$, we can derive the optimal traffic quantity chosen by Airline f:

$$q_f = \frac{p - \rho - c_f/s - (1 + c_g/s)t}{(1 + c_g/s)t'_q - p'}, \tag{26}$$

and the corresponding airfare chosen by Airline f:

$$\tau_f = \underbrace{\rho}_{\text{airport charge per seat}} + \underbrace{\frac{c_f + c_g t}{s}}_{\text{airline's operation cost per seat}} + \underbrace{\left(1 + \frac{c_g}{s}\right)t'_q}_{\text{marginal congestion cost per seat due to one flight}} \cdot \underbrace{q_f}_{\text{Airline } f\text{'s traffic volume}} + \underbrace{(-p' q_f)}_{\text{markup}} . \tag{27}$$

As can be seen in Eq. (27), the terms in the follower airline's airfare are similar to those in the Cournot model.

We further investigate how the optimal q_f in Eq. (26) vary against a marginal change in q_ℓ. Differentiating Eq. (26) with respect to q_ℓ yields

$$\frac{\partial q_f}{\partial q_\ell} = -\frac{[p'' - (1 + c_g/s)t''_{qq}]q_f + [p' - (1 + c_g/s)t'_q]}{[p'' - (1 + c_g/s)t''_{qq}]q_f + 2[p' - (1 + c_g/s)t'_q]}. \tag{28}$$

Given the second-order condition satisfying $\partial^2\pi_f/\partial q_f^2 < 0$, one can verify that the denominator in Eq. (28) is negative. Thus, the sign of Eq. (28) is up to its numerator. We can derive that when $p'' < (1 + c_g/s)t''_{qq}$ (which is true when the demand curve is concave or p'' is small) we have $\partial q_f/\partial q_\ell \in (-1, -1/2)$, which implies that the marginal increase of Airline ℓ's output will decrease Airline f's output and increase the total output of airline market. This is also consistent with the "strategic substitutes" assumption (Bulow et al., 1985). In the following part of Section 3.1.4, to ease the presentation, we let $\lambda \equiv \partial q_f/\partial q_\ell$, where $\lambda \in (-1, -1/2)$.

We now investigate the leader Airline ℓ's optimal decision. Airline ℓ chooses the flight volume to maximize its profit when taking into account Airline f's response. By incorporating Airline f's decision into Airline ℓ's profit function, we can derive the first-order derivative $\partial\pi_\ell/\partial q_\ell$ and second-order derivative $\partial^2\pi_\ell/\partial q_\ell^2$ as follows:

$$\frac{\partial \pi_\ell}{\partial q_\ell} = \left[sp' - \left(s + c_g\right)t'_q\right]q_\ell\,(1+\lambda) + \left[sp - \left(s + c_g\right)t - s\rho - c_f\right], \tag{29}$$

$$\frac{\partial^2 \pi_\ell}{\partial q_\ell^2} = [sp'' - (s + c_g)t''_{qq}]q_\ell(1+\lambda)^2 + [sp' - (s + c_g)t'_q](1+\lambda)\Big(2 + q_\ell\frac{\partial \lambda}{\partial q}\Big). \tag{30}$$

Similarly, an interior equilibrium is characterized by $\partial\pi_\ell/\partial q_\ell = 0$, where $\partial^2\pi_\ell/\partial q_\ell^2 < 0$ ensures that the first-order optimality condition is sufficient and the equilibrium is unique. Rewriting $\partial\pi_\ell/\partial q_\ell = 0$ derives the optimal flight traffic volume q_ℓ and airfare τ_ℓ chosen by Airline ℓ, i.e.,

$$q_\ell = \frac{\rho + c_f/s + (1 + c_g/s)t - p}{(1+\lambda)[p' - (1 + c_g/s)t'_q]}. \tag{31}$$

$$\tau_\ell = \underbrace{\rho}_{\text{airport charge per seat}} + \underbrace{\frac{c_f + c_g t}{s}}_{\text{airline's operation cost per seat}} + [\underbrace{(1 + \frac{c_g}{s})t'_q}_{\text{marginal congestion cost per seat due to one flight}} \cdot \underbrace{q_\ell}_{\text{Airline } \ell\text{'s traffic volume}} + \underbrace{(-p'q_\ell)}_{\text{markup}}] \cdot \underbrace{(1+\lambda)}_{\text{scale down coefficient}}, \tag{32}$$

where $\lambda = \partial q_f/\partial q_\ell$ and $\lambda \in (-1, -1/2)$. The leader airline's airfare in Eq. (32) is different from while comparable to the follower's airfare and the airfare in the Cournot model. In particular, the first two terms (covers the airport charge and operation cost) of the airfare in Eq. (32) are similar to those of the follower. In the third and fourth terms (related to the marginal congestion cost and markup), the formula $q_\ell(1 + \lambda)$ reflects that the leader airline is able to incorporate the follower's response (i.e., λ) in its optimal decision. Moreover, when $\lambda = \partial q_f/\partial q_\ell \in (-1, -1/2)$, $0 < 1 + \lambda < 0.5$, by foreseeing the competition from the follower airline, the leader airline will scale down the terms related to the marginal congestion cost and markup in the airfare when compared to the airfare formula in the Cournot model. Furthermore, the leader airline will scale down the marginal congestion cost and markup to the level that equals that of the follower airline (one can verify that the traffic volumes of Airline f and Airline ℓ (i.e., Eqs. (26) and (31)) satisfy $q_f = q_\ell(1 + \lambda)$). The above can help the leader airline to gain a larger market share in order to maximize its profit. Also note that as $q_f = q_\ell(1 + \lambda)$ and $\lambda < -0.5$, one can derive that leader-follower market produces more traffic volume than symmetric market (i.e., Cournot airlines with $m = 2$).

We further investigate airline market's response to airport decisions. By differentiating Eq. (31) with respect to airport capacity k and airport charge ρ we can derive that

$$\frac{\partial q}{\partial k}=\frac{(1+c_g/s)[(1+\lambda)q_\ell t''_{qk}+t'_k]-[p'-(1+c_g/s)t'_q]\frac{\mathrm{d}\lambda}{\mathrm{d}k}q_\ell}{\left[p''-(1+c_g/s)t''_{qq}\right](1+\lambda)q_\ell+2\left[p'-(1+c_g/s)t'_q\right]}>0, \tag{33a}$$

$$\frac{\partial q}{\partial \rho}=\frac{1-\left[p'-(1+c_g/s)t'_q\right]\frac{\mathrm{d}\lambda}{\mathrm{d}\rho}q_\ell}{\left[p''-(1+c_g/s)t''_{qq}\right](1+\lambda)q_\ell+2\left[p'-(1+c_g/s)t'_q\right]}<0. \tag{33b}$$

We then can substitute Eq. (33a) into Eq. (3), which yields

$$\frac{\mathrm{d}t}{\mathrm{d}k}=\frac{t'_k\left\{(1+c_g/s)t'_q\cdot[1+(1+\lambda)q_\ell\cdot t''_{qk}/t'_k]-[p'-(1+c_g/s)t'_q]\frac{\mathrm{d}\lambda}{\mathrm{d}k}q_\ell\cdot t'_q/t'_k\right\}}{\left[p''-(1+c_g/s)t''_{qq}\right](1+\lambda)q_\ell+2\left[p'-(1+c_g/s)t'_q\right]}+t'_k. \tag{34}$$

According to Eqs. (33a), (33b), and (34), we have Proposition 3.3.

Proposition 3.3. *In a perfect substitutes market with a Stackelberg leader and a Cournot follower, following the marginal increase of airport capacity (k)*

(i) flight traffic volume (q) will increase;

(ii) if
$$\begin{cases}\left(1+\frac{c_g}{s}\right)\left(t''_{qq}-\frac{t'_q}{t'_k}t''_{qk}\right)>p''+\frac{1}{(1+\lambda)q_\ell}\left\{2p'-\left(1+\frac{c_g}{s}\right)t'_q-\frac{t'_q}{t'_k}\left[p'-\left(1+\frac{c_g}{s}\right)t'_q\right]q_\ell\frac{\mathrm{d}\lambda}{\mathrm{d}k}\right\}\\ \left(1+\frac{c_g}{s}\right)\left(t''_{qq}-\frac{t'_q}{t'_k}t''_{qk}\right)<p''+\frac{1}{(1+\lambda)q_\ell}\left\{2p'-\left(1+\frac{c_g}{s}\right)t'_q-\frac{t'_q}{t'_k}\left[p'-\left(1+\frac{c_g}{s}\right)t'_q\right]q_\ell\frac{\mathrm{d}\lambda}{\mathrm{d}k}\right\}\end{cases}$$
then
average congestion delay (t) will decrease,
average congestion delay (t) will increase.

Proof. Eq. (33a) can be further simplified as

$$\frac{\partial q}{\partial k}=\frac{(1+c_g/s)[(1+\lambda)q_\ell t''_{qk}+t'_k]-[p'-(1+c_g/s)t'_q]\cdot d\lambda/dk}{\left[p''-(1+c_g/s)t''_{qq}\right](1+\lambda)q_\ell+\left[p'-(1+c_g/s)t'_q\right](2+q_\ell\cdot d\lambda/dq)}. \tag{35}$$

One can verify that the denominator of Eq. (35) is negative under $\partial^2\pi_\ell/\partial q_\ell^2<0$. Then, differentiating Eq.(28) with respect to capacity k yields

$$\frac{\mathrm{d}\lambda}{\mathrm{d}k}=\frac{\partial q}{\partial k}\frac{[p''-(1+c_g/s)t''_{qq}](3\lambda+1)-p'''q_f(1+\lambda)}{[p''-(1+c_g/s)t''_{qq}]q_f+2[p'-(1+c_g/s)t'_q]}+\frac{(1+c_g/s)t''_{qk}(1+2\lambda)}{[p''-(1+c_g/s)t''_{qq}]q_f+2[p'-(1+c_g/s)t'_q]}. \tag{36}$$

Given $p'<0$, $t'_q>0$, $t'_k<0$, $t''_{qq}\geqslant 0$, $t''_{qk}\leqslant 0$, $\lambda\in(-1,-1/2)$ and based on Eq. (36), we can derive that $d\lambda/dk<0$. It can be further verified that the numerator of Eq. (35) will also be negative. Therefore, we have $\partial q/\partial k>0$, which implies that traffic volume will increase with respect to the capacity expansion. It also can be readily verfied that the denominator of Eq. (34) is negative. Thus the sign of $\mathrm{d}t/\mathrm{d}k$ is up to the numerator of Eq. (34). When $(1+c_g/s)(t''_{qq}-t''_{qk}\cdot t'_q/t'_k)<p''+1/(1+\lambda)q_\ell\cdot\{2p'-(1+c_g/s)t'_q-t'_q/t'_k\cdot[p'-(1+c_g/s)t'_q]q_\ell\,\mathrm{d}\lambda/\mathrm{d}k\}$, the numerator of Eq. (34) is negative, thus we have $\mathrm{d}t/\mathrm{d}k>0$, i.e., capacity paradox occurs, and vice versa. This completes the proof. □

Proposition 3.3 states that the leader-follower market with a Stackelberg leader and a Cournot follower will schedule more flights following a marginal increase of airport capacity. Proposition 3.3 also indicates that the capacity paradox is more likely to occur when $\mathrm{d}\lambda/\mathrm{d}k$ is negative (the follower is more sensitive to the leader's output in response to the airport capacity expansion). In this case, the leader is able to capture most of the market share and the market becomes closer to a monopoly market.

3.2. Imperfect substitutes market

There are differentiated services in the aviation system, e.g., the flag carrier versus the low-cost carrier, which are imperfect substitutes for consumers. In this subsection we consider an imperfect substitutes market, where airlines target differentiated markets. We assume that there are two airlines in the imperfect substitutes market (Airline 1 and Airline 2). The demand for airline i ($i = 1, 2$) depends on not only the price of this particular airline, but also the alternative, such that $q_1 = q_1(p_1, p_2)$. The inverse functions characterize the corresponding full prices under given flow pattern are denoted as $p_1 = p_1(q_1, q_2)$, $p_2 = p_2(q_2, q_1)$, where $p'_{i(i)} = \partial p_i/\partial q_i < 0$, $p'_{i(-i)} = \partial p_i/\partial q_{-i} > 0$ ($i, -i \in \{1, 2\}$ and $i \neq -i$). We consider that the full price traveling by airline i is more sensitive to its own traffic volume (when compared to the other airline's traffic volume), i.e., $|p'_{i(i)}| > |p'_{i(-i)}|$ and $|p'_{i(i)}| > |p'_{-i(i)}|$. Note that the derivatives $p'_{i(i)}$ and $p'_{i(-i)}$ under an imperfect substitutes market is related to both q_i and q_{-i}, which are different from those in a perfect substitutes market. Under the imperfect substitutes consideration, we examine two different markets settings, i.e., Nash equilibrium and a Stackelberg leader with competitive fringe.

3.2.1. Nash equilibrium

We consider two airlines that are denoted as airline i and airline $-i$, where $i, -i \in \{1, 2\}$ and $i \neq -i$. Based on the airline's profit formulation in Section 2, we can derive the following first-order and second-order derivatives for airline i when taking the demand of the other airline q_{-i} as given:

$$\frac{\partial \pi_i}{\partial q_i} = \left[sp'_{i(i)} - \left(s + c_g\right) t'_q \right] q_i + \left[sp_i - \left(s + c_g\right) t - s\rho - c_f \right], \tag{37}$$

$$\frac{\partial^2 \pi_i}{\partial q_i^2} = \left[sp''_{i(ii)} - (s + c_g) t''_{qq} \right] q_i + 2 \left[sp'_{i(i)} - (s + c_g) t'_q \right]. \tag{38}$$

Similarly, an interior optimum is defined by letting $\partial \pi_i/\partial q_i = 0$, while $\partial^2 \pi_i/\partial q_i^2 < 0$ ensures sufficiency of the first-order optimality condition and the uniqueness of the equilibrium. We then can derive Airline i's optimal traffic volume:

$$q_i = \frac{p_i - (1 + c_g/s)t - \rho - c_f/s}{(1 + c_g/s)t'_q - p'_{i(i)}}, \tag{39}$$

and Airline i's airfare

$$\tau_i = \underbrace{\rho}_{\text{airport charge per seat}} + \underbrace{\frac{c_f + c_g t}{s}}_{\text{airline's operation cost per seat}} + \underbrace{(1 + \frac{c_g}{s})t'_q}_{\text{marginal congestion cost per seat due to one flight}} \cdot \underbrace{q_i}_{\text{airline } i\text{'s traffic volume}} + \underbrace{[-p'_{i(i)} q_i]}_{\text{markup}}. \tag{40}$$

The airfare in Eq. (40) is similar to those in the Cournot model when the two airlines are perfect substitutes, which cover airport charge, airline operation cost, marginal congestion cost, and markup. Note that $p'_{i(i)}$ in the markup term depends on both airlines i's own flight traffic volume q_i and the substitute's traffic volume q_{-i}, which is different from the perfect substitutes model.

We also consider that airlines in the imperfect substitutes market are strategic substitutes (Bulow et al., 1985), i.e., the marginal profit of one carrier will decline when other carriers' output rise. For airlines i and airline $-i$ to be strategic substitutes, similar to the perfect substitutes market, we have $\partial^2 \pi_i/\partial q_i \partial q_{-i} < 0$. We then investigate the airline market's response to the marginal change of airport decisions. Differentiating Eq. (39) with respect to capacity k and airport charge ρ yields

$$\frac{\partial q}{\partial k} = \frac{(1 + c_g/s)(t''_{qk} q_2 + t'_k)(\pi''_{1(11)} - \pi''_{1(12)}) + (1 + c_g/s)(t''_{qk} q_1 + t'_k)(\pi''_{2(22)} - \pi''_{2(21)})}{\pi''_{1(11)}\pi''_{2(22)} - \pi''_{1(12)}\pi''_{2(21)}} > 0, \tag{41a}$$

$$\frac{\partial q}{\partial \rho} = \frac{(\pi''_{1(11)} - \pi''_{1(12)}) + (\pi''_{2(22)} - \pi''_{2(21)})}{\pi''_{1(11)}\pi''_{2(22)} - \pi''_{1(12)}\pi''_{2(21)}} < 0. \tag{41b}$$

where

$$\pi''_{1(11)} = \frac{\partial^2 \pi_1}{\partial q_1^2} = [p''_{1(11)} - (1 + c_g/s)t''_{qq}]q_1 + 2[p'_{1(1)} - (1 + c_g/s)t'_q] < 0;$$

$$\pi''_{2(22)} = \frac{\partial^2 \pi_2}{\partial q_2^2} = [p''_{2(22)} - (1 + c_g/s)t''_{qq}]q_2 + 2[p'_{2(2)} - (1 + c_g/s)t'_q] < 0;$$

$$\pi''_{1(12)} = \frac{\partial^2 \pi_1}{\partial q_1 \partial q_2} = [p''_{1(12)} - (1 + c_g/s)t''_{qq}]q_1 + [p'_{1(2)} - (1 + c_g/s)t'_q] < 0;$$

$$\pi''_{2(21)} = \frac{\partial^2 \pi_2}{\partial q_2 \partial q_1} = [p''_{2(21)} - (1 + c_g/s)t''_{qq}]q_2 + [p'_{2(1)} - (1 + c_g/s)t'_q] < 0.$$

According to Eq. (41a), we have Proposition 3.4.

Proposition 3.4. *In an imperfect substitutes market with duopoly airlines, following a marginal increase of airport capacity (k), flight traffic volume (q) will increase.*

Proof. Given $\pi''_{i(ii)} < 0$ and $\pi''_{i(i,-i)} < 0$ ($i = 1,2, -i = 1,2, i \neq -i$), the denominator of Eq. (41a) is positive when $|\pi''_{i(ii)}| < |\pi''_{i(i,-i)}|$, and is negative when $|\pi''_{i(ii)}| > |\pi''_{i(i,-i)}|$. Given $t''_{qk} \leqslant 0$ and $t'_k < 0$, the numerator of Eq. (41a) is positive when $|\pi''_{i(ii)}| < |\pi''_{i(i,-i)}|$, and is negative when $|\pi''_{i(ii)}| > |\pi''_{i(i,-i)}|$. By combining these two conditions, one can verify that $\partial q/\partial k$ will always be positive. This completes the proof. □

According to the second-order condition and "strategic substitutes" assumption made before, we have $\pi''_{i(ii)} < 0$ and $\pi''_{i(i,-i)} < 0$, where $i, -i \in \{1,2\}$ and $i \neq -i$. Eqs. (41a) and (41b) indicate that the capacity expansion will stimulate the airline market to schedule more flights and the increasing airport charge will decrease flight traffic volume.

We then investigate the influence of airport expansion on congestion. Substituting Eq. (41a) into Eq. (3) yields

$$\frac{\mathrm{d}t}{\mathrm{d}k} = \frac{t'_k \left\{(1 + c_g/s)t'_q[(1 + q_1 t''_{qk}/t'_k)(\pi''_{2(22)} - \pi''_{2(21)}) + (1 + q_2 t''_{qk}/t'_k)(\pi''_{1(11)} - \pi''_{1(12)})] + \pi''_{1(11)}\pi''_{2(22)} - \pi''_{1(12)}\pi''_{2(21)}\right\}}{\pi''_{1(11)}\pi''_{2(22)} - \pi''_{1(12)}\pi''_{2(21)}}. \tag{42}$$

Eq. (42) implies that the effect of capacity expansion on congestion is related to the characteristics of demand curves $q_i = q_i(p_i, p_{-i})$ and congestion function $t = t(q,k)$. To get some further understanding on $\mathrm{d}t/\mathrm{d}k$ in Eq. (42), in the following analysis we consider a linear demand function.

Remark 1. *Consider a linear demand function* $p_i = p_0 - \alpha q_i + \beta q_{-i}$, *where* $i, -i \in \{1,2\}$ *and* $\alpha > \beta > 0$. *Eq.* (42) *then can be converted into*

$$\frac{\mathrm{d}t}{\mathrm{d}k} = \frac{t'_k[(1 + c_g/s)q(t'_q \cdot t''_{qk}/t'_k - t''_{qq}) - 2\alpha + \beta - (1 + c_g/s)t'_q]}{-(1 + c_g/s)t''_{qq}q + 2[-\alpha - (1 + c_g/s)t'_q] + [\beta - (1 + c_g/s)t'_q]}. \tag{43}$$

For capacity paradox to occur, $\mathrm{d}t/\mathrm{d}k > 0$ *in Eq.* (43)*, or equivalently,* $(1 + c_g/s)(t''_{qq} - t'_q/t'_k \cdot t''_{qk}) < 1/q \cdot [\beta - 2\alpha + (1 + c_g/s)t'_q]$.

For the occurrence of the capacity paradox in Cournot model under two airlines in the market ($m = 2$) and a linear demand function ($p = p_0 - \gamma q, \gamma > 0$), the condition can be written as follows: $(1 + c_g/s)(t''_{qq} - t'_q/t'_k \cdot t''_{qk}) < 1/q \cdot [-3\gamma - (1 + c_g/s)t'_q]$. By comparing the two conditions for occurrence of capacity paradox under imperfect substitutes and perfect substitutes markets with two competing airlines, it can be seen that if airport capacity k and total traffic volume q are identical in the two markets, the capacity paradox is more likely to occur in an imperfect substitutes market given that $\beta - 2\alpha > -3\gamma$ (considering in the demand functions $\gamma \approx \alpha > \beta > 0$, we should have

$\beta - 2\alpha > -3\gamma$). This is consistent with earlier results that the flatter the demand curve is, the more likely the capacity paradox to occur. Note that in a perfect substitutes market, the term -3γ associated with the total traffic volume q in the Cournot model now is replaced by the term -2α associated with the airline's own output q_i plus the term β associated with the substitute's output q_{-i}.

3.2.2. A Stackelberg leader with competitive fringe

Now suppose the airline market has a Stackelberg leader (who is aware of follower's response to its decisions) and a competitive fringe (which consists of smaller airlines that have no market power). Denote the Stackelberg leader as Airline ℓ, and summing up all airlines in competitive fringe as Airline f. Similar to Subsection 3.1.4, we first investigate Airline f's decision. Competitive fringe implies a zero-profit margin, we then can derive Airline f's choice of flight quantity and airfare as follows:

$$q_f = \arg\left\{p_f(q_f, q_\ell) - t - \rho - \frac{c_f + c_g t}{s} = 0\right\}. \tag{44}$$

$$\tau_f = \underbrace{\rho}_{\text{airport charge per seat}} + \underbrace{\frac{c_f + c_g t}{s}}_{\text{airline's operation cost per seat}}. \tag{45}$$

Similar to the perfectly competitive model (also zero-profit), Airline f's airfare covers the airport charge ρ and operation cost $(c_g + c_g t)/s$. Airport congestion externality is not internalized by Airline f.

We further investigate how the follower airline's output q_f will vary against a marginal change of leader airline's output q_ℓ:

$$\frac{\partial q_f}{\partial q_\ell} = -\frac{(1 + c_g/s)t'_q - p'_{f(\ell)}}{(1 + c_g/s)t'_q - p'_{f(f)}}. \tag{46}$$

Given the "strategic substitutes" assumption (Bulow et al., 1985) and $p'_{f(f)} < p'_{f(\ell)}$, we have $\partial q_f/\partial q_\ell \in (-1, 0)$, which implies that a marginal increase of Airline ℓ's flight output will reduce Airline f's output and increase the total output of the airline market. Again, we let $\lambda = \partial q_f/\partial q_\ell$, where $\lambda \in (-1, 0)$ and $1 + \lambda \in (0, 1)$. In addition, it is noted that if $p'_{f(f)} = p'_{f(\ell)}$, i.e., in a perfect substitutes market, the reaction function will be a constant ($\lambda \to -1$). The total traffic volume in the market will be constant as the marginal increase in q_ℓ will yield an equivalent decrease in q_f.

We now investigate Airline ℓ's optimal decision. Airline ℓ chooses the the flight volume to maximize its profit with Airline f's response taken into consideration. By incorporating Airline f's decision into Airline ℓ's profit function, we can derive the first-order derivative $\partial\pi_\ell/\partial q_\ell$ and second-order derivative $\partial^2\pi_\ell/\partial q_\ell^2$ as follows:

$$\frac{\partial \pi_\ell}{\partial q_\ell} = \left[sp'_{\ell(\ell)} + sp'_{\ell(f)}\lambda - (s + c_g)t'_q(1 + \lambda)\right]q_\ell + sp_\ell - (s + c_g)t - \rho s - c_f. \tag{47}$$

$$\begin{aligned}\frac{\partial^2 \pi_\ell}{\partial q_\ell^2} = &\left[sp''_{\ell(\ell\ell)} + s\lambda p''_{\ell(\ell f)} + s\lambda p''_{\ell(f\ell)} + s\lambda^2 p''_{\ell(ff)} - (s + c_g)(1 + \lambda)^2 t''_{qq}\right]q_\ell \\ &+ 2\left[sp'_{\ell(\ell)} - (s + c_g)t'_q\right] + \left(2\lambda + q_\ell \cdot \frac{\partial\lambda}{\partial q_\ell}\right)\left[sp'_{\ell(f)} - (s + c_g)t'_q\right].\end{aligned} \tag{48}$$

An interior equilibrium is characterized by $\partial\pi_\ell/\partial q_\ell = 0$, where $\partial^2\pi_\ell/\partial q_\ell^2 < 0$ ensures that the first-order optimality condition is sufficient and the equilibrium is unique. Rewriting $\partial\pi_\ell/\partial q_\ell = 0$ derives the optimal flight traffic volume q_ℓ and airfare τ_ℓ chosen by Airline ℓ, i.e.,

$$q_\ell = \frac{p_\ell - \rho - c_f/s - (1 + c_g/s)t}{[(1 + c_g/s)t'_q - p'_{\ell(\ell)}] + \lambda[(1 + c_g/s)t'_q - p'_{\ell(f)}]}, \tag{49}$$

$$\tau_\ell = \underbrace{\rho}_{\text{airport charge per seat}} + \underbrace{\frac{c_f + c_g t}{s}}_{\text{airline's operation cost per seat}} + \underbrace{(1+\frac{c_g}{s})t'_q}_{\text{marginal congestion cost per seat due to one flight}} \cdot \underbrace{q_\ell}_{\text{Airline } \ell\text{'s traffic volume}} \cdot \underbrace{(1+\lambda)}_{\text{scale down coefficient}} \underbrace{-[p'_{\ell(\ell)} + p'_{\ell(f)}\lambda]q_\ell}_{\text{markup}}, \tag{50}$$

where $\lambda = \partial q_f / \partial q_\ell$, $\lambda \in (-1, 0)$ and $1 + \lambda \in (0, 1)$. Airline ℓ's airfare in Eq. (50) consists of similar components as the airfares under the Cournot model and leader-follower model in a perfect substitutes market, and Nash equilibrium model under an imperfect substitutes market, i.e., airport charge, operation cost, marginal congestion cost and markup term. Similar to the Stackelberg leader in a perfect substitutes market, in the airfare in Eq. (50), the first two terms (covers the airport charge and operation cost) are identical to those of the follower. In the third term (related to the marginal congestion cost) and the fourth term (the markup), the formula $q_\ell(1+\lambda)$ and the formula $\{-[p'_{\ell(\ell)} + p'_{\ell(f)}\lambda]q_\ell\}$, respectively, reflect that the leader airline is able to incorporate the follower's response (i.e., λ) in its optimal decision. $0 < 1 + \lambda < 1$ indicates that by foreseeing the competition from the follower airline, the leader airline will scale down the term related to the marginal congestion cost in the airfare when compared to the airfare formula at the Nash equilibrium. $\{-[p'_{\ell(\ell)} + p'_{\ell(f)}\lambda]q_\ell\}$ indicates that the the leader airline will scale up the term related to the markup (a larger market power) when compared to the airfare formula at the Nash equilibrium.

It is noted that the response of follower to leader's choice (i.e., λ) is expected to be more sensitive in the market with a leader airline and a Cournot follower (where $\lambda \in (-1, -0.5)$) than in the market with a leader airline and competitive fringe (where $\lambda \in (-1, 0)$).

It is also noteworthy that a leader airline with competitive fringe in a perfect substitutes market will scale down the marginal congestion cost and markup terms in the airfare to zero (just like a fully competitive market discussed earlier), which is different from a leader airline with competitive fringe in an imperfect substitutes market discussed here. That is because, in an imperfect substitutes market, the follower cannot fully cover the decrease of leader's market share (i.e., $\lambda \in (-1, 0)$), thus the leader is able to earn more profit by increasing its airfare (when compared to a fully competitive market).

We then investigate the airline market's response to a marginal change of airport decisions. Differentiating Eq. (49) with respect to capacity k and airport charge ρ yields

$$\frac{\partial q}{\partial k} = \frac{(1+c_g/s)[t''_{qk}(1+\lambda)q_\ell + t'_k] - [p'_{\ell(f)} - (1+c_g/s)t'_q]q_\ell \frac{\mathrm{d}\lambda}{\mathrm{d}k}}{[\delta - (1+c_g/s)t''_{qq}](1+\lambda)q_\ell + \frac{2}{1+\lambda}[p'_{\ell(\ell)} - (1+c_g/s)t'_q] + \frac{2\lambda}{1+\lambda}[p'_{\ell(f)} - (1+c_g/s)t'_q]} > 0, \tag{51a}$$

$$\frac{\partial q}{\partial \rho} = \frac{1 - [p'_{\ell(f)} - (1+c_g/s)t'_q]q_\ell \frac{\mathrm{d}\lambda}{\mathrm{d}\rho}}{[\delta - (1+c_g/s)t''_{qq}](1+\lambda)q_\ell + \frac{2}{1+\lambda}[p'_{\ell(\ell)} - (1+c_g/s)t'_q] + \frac{2\lambda}{1+\lambda}[p'_{\ell(f)} - (1+c_g/s)t'_q]} < 0, \tag{51b}$$

where $\delta = [p''_{\ell(\ell\ell)} + p''_{\ell(\ell f)}\lambda + p''_{\ell(f\ell)}\lambda + p''_{\ell(ff)}\lambda^2]/(1+\lambda)^2$. According to Eq. (41a), we have Proposition 3.5.

Proposition 3.5. *In an imperfect substitutes market with a Stackelberg leader and a competitive fringe, following the marginal increase of airport capacity (k), flight traffic volume (q) will increase.*

Proof. Eq. (33a) can be further simplified into

$$\frac{\partial q}{\partial k} = \frac{(1+c_g/s)[(1+\lambda)q_\ell t''_{qk} + t'_k] - [p'_{\ell(f)} - (1+c_g/s)t'_q] \cdot \frac{\partial \lambda}{\partial k}}{[\delta - (1+c_g/s)t''_{qq}](1+\lambda)q_\ell + \frac{2}{1+\lambda}[p'_{\ell(\ell)} - (1+c_g/s)t'_q] + (\frac{2\lambda}{1+\lambda} + \frac{\partial \lambda}{\partial q_\ell}q_\ell)[p'_{\ell(f)} - (1+c_g/s)t'_q]}. \tag{52}$$

The denominator of Eq. (52) is recognized as negative by the second-order condition $\partial^2 \pi_\ell / \partial q_\ell^2 < 0$. Then, differentiating Eq. (46) with respect to capacity k yields

$$\frac{\mathrm{d}\lambda}{\mathrm{d}k} = \frac{\partial q_\ell}{\partial k} \frac{p''_{f(ff)}\lambda^2 + p''_{f(f\ell)}\lambda + p''_{f(\ell f)}\lambda + p''_{f(\ell\ell)} - (1+c_g/s)t''_{qq}(1+\lambda)^2}{(1+c_g/s)t'_q - p'_{f(f)}} + \frac{(1+\lambda)(1+c_g/s)t''_{qk}}{(1+c_g/s)t'_q - p'_{f(f)}}. \tag{53}$$

Given $p'_{f(f)} < 0$, $t'_q > 0$, $t'_k < 0$, $t''_{qq} \geqslant 0$, $t''_{qk} \leqslant 0$, $\lambda \in (-1, 0)$, and Eq. (53), we have $\partial\lambda/\partial k < 0$. However, we have $p'_{f(f)} < p'_{\ell(f)}$, thus the numerator of Eq. (35) is negative. Therefore, we have $\partial q/\partial k > 0$, which implies that traffic volume will increase with the capacity expansion. □

We also investigate how airport capacity decisions influence the airport congestion. Substituting Eq. (51a) into Eq. (3) yields

$$\frac{dt}{dk} = \frac{t'_k\left\{(1 + c_g/s)t'_q[1 + (1 + \lambda)q_\ell \cdot t''_{qk}/t'_k] - [p'_{\ell(f)} - (1 + c_g/s)t'_q]q_\ell \frac{\mathrm{d}\lambda}{\mathrm{d}k} \cdot t'_q/t'_k\right\}}{[\delta - (1 + c_g/s)t''_{qq}](1 + \lambda)q_\ell + \frac{2}{1+\lambda}[p'_{\ell(\ell)} - (1 + c_g/s)t'_q] + \frac{2\lambda}{1+\lambda}[p'_{\ell(f)} - (1 + c_g/s)t'_q]} + t'_k. \tag{54}$$

Eq. (54) indicates that the effect of capacity expansion on congestion is related to the shape of the demand function and congestion function. However, it is not straightforward to identify the sign of $\mathrm{d}t/\mathrm{d}k$. In the analysis below, we further discuss the effects of capacity expansion based on a linear demand function.

Remark 2. *Consider a linear demand function $p_i = p_0 - \alpha q_i + \beta q_{-i}$, where $i, -i \in \{\ell, f\}, i \neq -i$, and $\alpha > \beta > 0$. Eq.* (42) *can be written as follows:*

$$\frac{dt}{dk} = \frac{t'_k\left\{(1 + c_g/s)(1 + \lambda)q_\ell(t''_{qk} \cdot t'_q/t'_k - t''_{qq}) - \frac{2}{1+\lambda}\alpha + \frac{2\lambda}{1+\lambda}\beta - (1 + c_g/s)t'_q - [\beta - (1 + c_g/s)t'_q]q_\ell \frac{\mathrm{d}\lambda}{\mathrm{d}k} \cdot t'_q/t'_k\right\}}{-(1 + c_g/s)t''_{qq}(1 + \lambda)q_\ell + \frac{2}{1+\lambda}[-\alpha - (1 + c_g/s)t'_q] + \frac{2\lambda}{1+\lambda}[\beta - (1 + c_g/s)t'_q]}. \tag{55}$$

For the capacity paradox to occur, $\mathrm{d}t/\mathrm{d}k > 0$ *in Eq.* (55)*, or equivalently,* $(1 + c_g/s)(t''_{qk} \cdot t'_q/t'_k - t''_{qq}) < 1/(1 + \lambda)q_\ell \left\{-2\alpha/(1 + \lambda) + 2\lambda\beta/(1 + \lambda) - (1 + c_g/s)t'_q - [\beta - (1 + c_g/s)t'_q]q_\ell \frac{\mathrm{d}\lambda}{\mathrm{d}k} \cdot t'_q/t'_k\right\}$.

By comparing the above condition with that under Nash equilibrium, it can be seen that given the same airport capacity k and traffic volume q, capacity paradox will be more likely to occur in the leader-follower market (i.e., a more relaxed condition), when $\mathrm{d}\lambda/\mathrm{d}k$ is negative. This finding is consistent with that in a perfect substitutes market.

To summarize, in this section, we investigate airline responses to airport decisions (airport capacity and airport charge) while incorporating elastic passenger demand and choice equilibrium. After analyzing six different airlines markets in perfect substitutes and imperfect substitutes settings, we find that airline market will schedule more flights given a marginal increase of airport capacity and will schedule less flights given a marginal increase of airport charge. We also investigate the conditions for capacity paradox (airport capacity expansion leads to a larger congestion delay) to occur under a given airport charge. In particular, the capacity paradox is more likely to occur in the market with fewer competitive airlines (e.g., capacity paradox will not occur in perfectly competitive market while it is more likely to occur in monopoly market). Moroever, in the Stackelberg model, when the leader's market share increases with the capacity expansion, i.e., the leader captures most of the market share, the capacity paradox will also be more likely to occur.

4. Impact of airport expansion under different airport administrative regimes and responsive airlines

Given the airport capacity expansion, this section examines how the airport may optimize its flight charge accordingly in order to achieve its objective (three administrative regimes: zero-profit, profit-maximization, welfare-maximization). This section also further examines how the airport capacity expansion and the optimized airport flight charge might jointly affect airlines' optimal decisions and passenger choices in the airport-airline-passenger system.

We first consider the optimal airport charge ρ under a given airport capacity k, where airline market's response $\partial q/\partial\rho$ is incorporated. Then, we consider the airport makes a marginal capacity expansion and investigate the effects on system performances and user benefits. Note that for simplicity (as we are dealing with a tri-level model), for the airline market, we now only consider the perfectly competitive market, where airlines' responses to airport decisions have been investigated in Section 3.1.1. Other airline markets will be investigated numerically in Section 5.

4.1. Zero-profit airport

We first consider a public airport that maintains break even. In a zero-profit airport, given the airport capacity, the optimal airport charge can be written as follows (to satisfy the zero-profit constraint):

$$\rho = \underbrace{\frac{c_k k}{sq}}_{\substack{\text{airport capacity}\\\text{maintenance cost per}\\\text{seat}}} + \underbrace{\frac{c_q}{s}}_{\substack{\text{airport flight handling}\\\text{cost per seat}}} - \underbrace{r}_{\substack{\text{concession profit}\\\text{per seat}}} . \tag{56}$$

Note that the zero-profit airport flight charge might not be unique. For example, the airport may charge high and serve fewer passengers (save cost) or it can charge low and serve more passengers (more operation cost). We consider the charge policy that brings a higher social welfare (it often corresponds to the lower charge).

We investigate how the airport charge ρ and traffic volume q will change against the capacity expansion. Differentiating Eq. (56) (locally) with respect to capacity k yields

$$\frac{\mathrm{d}\rho}{\mathrm{d}k} = \frac{c_k[p' - (1 + c_g/s)t'_q] - [(\rho + r)s - c_q](1 + c_g/s)t'_k}{q[sp' - (s + c_g)t'_q] + [(\rho + r)s - c_q]}, \tag{57}$$

$$\frac{\mathrm{d}q}{\mathrm{d}k} = \frac{\partial q}{\partial \rho} \cdot \frac{\mathrm{d}\rho}{\mathrm{d}k} + \frac{\partial q}{\partial k} = \frac{c_k + q \cdot (s + c_g)t'_k}{q \cdot [sp' - (s + c_g)t'_q] + [(\rho + r)s - c_q]}. \tag{58}$$

We also investigate the effect of capacity expansion on congestion. Substituting Eq. (58) into Eq. (3) yields

$$\frac{\mathrm{d}t}{\mathrm{d}k} = \frac{c_k t'_q + q \cdot sp' t'_k + [(\rho + r)s - c_q]t'_k}{q \cdot [sp' - (s + c_g)t'_q] + (\rho + r)s - c_q}. \tag{59}$$

According to Eqs. (58) and (59), we have Proposition 4.1.

Proposition 4.1. *In a zero-profit airport with a perfectly competitive airline market, following a marginal increase of airport capacity (k),*

$$\text{(i) if} \begin{cases} q \in (0, q_{m1}) \cup (q_{M1}, +\infty) \\ q \in (q_{m1}, q_{M1}) \end{cases} \text{then} \quad \begin{matrix} \text{flight traffic volume } (q) \text{ will increase,} \\ \text{flight traffic volume } (q) \text{ will decrease.} \end{matrix}$$

$$\text{(ii) if} \begin{cases} q \in (0, q_{m2}) \cup (q_{M2}, +\infty) \\ q \in (q_{m2}, q_{M2}) \end{cases} \text{then} \quad \begin{matrix} \text{average congestion delay } (t) \text{ will decrease,} \\ \text{average congestion delay } (t) \text{ will increase.} \end{matrix}$$

where $q_{m1} = \min\{q_{nq}, q_d\}$, $q_{M1} = \max\{q_{nq}, q_d\}$, $q_{m2} = \max\{0, \min\{q_{nt}, q_d\}\}$, $q_{M2} = \max\{q_{nt}, q_d\}$, *and* $q_{nq} = \frac{c_k}{-(s+c_g)t'_k}$, $q_{nt} = \frac{[(\rho+r)s-c_q]t'_k + c_k t'_q}{-sp't'_k}$, $q_d = \frac{(\rho+r)s-c_q}{(s+c_g)t'_q - sp'}$.

Based on Eqs. (58) and (59), one can verify the signs of $\mathrm{d}q/\mathrm{d}k$ and $\mathrm{d}t/\mathrm{d}k$ and the results in Proposition 4.1. The details are omitted. Proposition 4.1 indicates that under a zero-profit public airport operator, a perfectly competitive airline market may schedule less flights following the capacity expansion. This situation ($\mathrm{d}q/\mathrm{d}k < 0$) occurs when the airport increases the airport charge too much (to cover its cost) that offsets the stimulating effect of capacity expansion on traffic volume. It is noteworthy that the incentive for the airport to increase the charge is related to the demand and supply conditions. In particular, when the traffic volume is inelastic to capacity, i.e., $e^q_k \equiv (\partial q/\partial k)(k/q) \in (0, 1)$, we have $q_{nt} < q_d < q_{nq}$. We can derive that $\mathrm{d}q/\mathrm{d}k < 0$ holds when $q \in (q_d, q_{nq})$, and $\mathrm{d}t/\mathrm{d}k > 0$ holds when $q \in (q_{nt}, q_d)$. In contrast, when the traffic volume is elastic to capacity, i.e., $e^q_k > 1$, we have $q_{nq} < q_d < q_{nt}$. We can derive that $\mathrm{d}q/\mathrm{d}k < 0$ holds when $q \in (q_{nq}, q_d)$, and $\mathrm{d}t/\mathrm{d}k > 0$ holds when $q \in (q_d, q_{nt})$.

We then investigate how will the capacity expansion influence social welfare. Differentiating Eq. (6) with respect to capacity k yields

$$\frac{\mathrm{d}SW}{\mathrm{d}k} = \frac{[(p-t-\rho)s-(c_f+c_g)t-qsp'][c_k+q\cdot(s+c_g)t'_k]}{q\cdot[sp'-(s+c_g)t'_q]+(\rho+r)s-c_q}. \tag{60}$$

According to Eq. (60), we have Proposition 4.2.

Proposition 4.2. *In a zero-profit airport with a perfectly competitive airline market, following a marginal increase of airport capacity,*

$$\text{if} \begin{cases} q\in(0,q_{m1})\cup(q_{M1},+\infty) \\ q\in(q_{m1},q_{M1}) \end{cases} \text{then} \quad \begin{matrix} \textit{social welfare (SW) will increase,} \\ \textit{social welfare (SW) will decrease.} \end{matrix}$$

where $q_{m1}=\min\{\frac{-c_k}{(s+c_g)t'_k},\frac{(\rho+r)s-c_q}{(s+c_g)t'_q-sp'}\}$ *and* $q_{M1}=\max\{\frac{-c_k}{(s+c_g)t'_k},\frac{(\rho+r)s-c_q}{(s+c_g)t'_q-sp'}\}$.

Proposition 4.2 can be readily verified based on the given ranges of q and Eq. (60). The details are omitted. Proposition 4.2 states that the change of social welfare is consistent with the change of traffic volume, when flight traffic volume increases, social welfare will also increase. This is because neither the zero-profit airport nor the perfectly competitive airlines earn a profit, thus the social welfare only consists of consumer surplus. The increase of traffic volume will enlarge the consumer surplus and increase the social welfare, and vice versa.

4.2. Profit-maximizing airport

In this subsection, we consider a private airport that aims to maximize its profit, where the airport can adjusts its airport flight charge in response to the capacity expansion. We can derive the first-order and second-order derivatives $\partial\Pi/\partial\rho$ and $\partial^2\Pi/\partial\rho^2$ based on the airport profit formulation when taking the airport capacity as given, i.e.,

$$\frac{\partial\Pi}{\partial\rho} = sq+[(\rho+r)s-c_q]\frac{\partial q}{\partial\rho}, \tag{61}$$

$$\frac{\partial^2\Pi}{\partial\rho^2} = 2s\frac{\partial q}{\partial\rho}+[(\rho+r)s-c_q]\frac{\partial^2 q}{\partial\rho^2}. \tag{62}$$

An interior equilibrium is characterized by the first-order by letting $\partial\Pi/\partial\rho=0$, where the second-order condition $\partial^2\Pi/\partial\rho^2<0$ ensures the sufficiency of the first-order optimality condition and the uniqueness of the equilibrium. Based on the first-order condition, we can derive the optimal airport charge as follows:

$$\rho = \frac{c_q}{s}-r-\frac{q}{\partial q/\partial\rho} = \underbrace{\frac{c_q}{s}}_{\text{flight handling cost per seat}} + \underbrace{(1+\frac{c_g}{s})t'_q}_{\text{marginal congestion cost per seat due to one more flight}} \cdot \underbrace{q}_{\text{total traffic volume}} + \underbrace{(-p'q)}_{\text{markup}} - \underbrace{r}_{\text{concession profit per seat}}. \tag{63}$$

The optimal airport charge of a profit-maximizing airport with a perfectly competitive airline market shown in Eq. (63) says that the optimal airport charge consists of the flight handling cost c_q/s, the marginal congestion delay cost of all traffic in the market $(1+c_g/s)t'_q q$ and a markup term $(-p'q)$. This is consistent with the findings of Zhang & Zhang (2006).

We further investigate the effects of capacity expansion on airport charge and airline market's total output. Differentiating Eq. (63) with respect to capacity k yields

$$\frac{\mathrm{d}\rho}{\mathrm{d}k} = -\left(1+\frac{c_g}{s}\right)t'_k+\frac{(1+c_g/s)(t''_{qk}q+t'_k)[p'-(1+c_g/s)t'_q]}{q[p''-(1+c_g/s)t''_{qq}]+2[p'-(1+c_g/s)t'_q]}, \tag{64}$$

$$\frac{\mathrm{d}q}{\mathrm{d}k} = \frac{(1+c_g/s)(t''_{qk}q+t'_k)}{q[p''-(1+c_g/s)t''_{qq}]+2[p'-(1+c_g/s)t'_q]}. \tag{65}$$

We then substituting Eq. (65) into Eq. (3), which yields

$$\frac{\mathrm{d}t}{\mathrm{d}k} = \frac{t'_k\left\{(1 + c_g/s)q(t'_q/t'_k \cdot t''_{qk} + t''_{qq}) + 2p' - (1 + c_g/s)t'_q + qsp''\right\}}{q[p'' - (1 + c_g/s)t''_{qq}] + 2[p' - (1 + c_g/s)t'_q]}. \tag{66}$$

By comparing Eqs. (65) and (66) and Eqs. (22a) and (23), it can be seen that the effects of airport capacity expansion under a profit-maximizing airport with a perfectly competitive airline market are similar to that under a monopoly airline with given airport charge in Section 3. While no airport congestion externality is internalized by the airlines in a perfectly competitive market, a profit-maximizing airport has the market power and will pass the airport congestion externality to the airlines through the airport flight charge.

We then investigate how will capacity expansion influence airport profit and social welfare. Differentiating Eq. (5) and Eq. (6) with respect to the capacity k, respectively, yield

$$\frac{\mathrm{d}\Pi}{\mathrm{d}k} = -q \cdot (s + c_g)t'_k - c_k \tag{67}$$

$$\frac{\mathrm{d}SW}{\mathrm{d}k} = -sp'q\frac{\mathrm{d}q}{\mathrm{d}k} - q \cdot (s + c_g)t'_k - c_k \tag{68}$$

According to Eqs. (67) and (68), we have Proposition 4.3.

Proposition 4.3. *Under a profit-maximizing airport with a perfectly competitive airline market, following a marginal increase of airport capacity (k),*

$$\text{(i) if} \begin{cases} c_k < -q \cdot (s + c_g)t'_k \\ c_k > -q \cdot (s + c_g)t'_k \end{cases} \text{then} \quad \begin{array}{l} \text{airport profit } (\Pi) \text{ will increase,} \\ \text{airport profit } (\Pi) \text{ will decrease.} \end{array}$$

$$\text{(ii) if} \begin{cases} c_k < -q \cdot (s + c_g)t'_k - sp'q\dfrac{\mathrm{d}q}{\mathrm{d}k} \\ c_k > -q \cdot (s + c_g)t'_k - sp'q\dfrac{\mathrm{d}q}{\mathrm{d}k} \end{cases} \text{then} \quad \begin{array}{l} \text{social welfare } (SW) \text{ will increase,} \\ \text{social welfare } (SW) \text{ will decrease.} \end{array}$$

Proof. The results in Proposition 4.3 are immediate from Eqs. (67) and (68). □

Proposition 4.3 states that airport profit may decrease given a capacity expansion even if the airport aims to maximize its profit. When the marginal benefit of additional capacity $-q(s + c_g)t'_k$ cannot cover the marginal cost c_k, the airport profit will decrease. We have similar observations for social welfare, i.e., it can go down when the marginal cost is larger than the marginal benefit (associated with a marginal airport capacity expansion). It is also noted that social welfare may increase when the airport profit decreases. This is because, the increase of consumer surplus due to the increasing traffic volume covers the decrease of airport profit, and then the social welfare increases. Following the above results, we also observe that the airport capacity that maximizes social welfare is often larger than the optimal capacity chosen by a profit-maximizing airport.

4.3. Welfare-maximizing airport

In this subsection, we consider a public airport that maximizes the social welfare (by adjusting the airport charge under a given airport capacity). The social welfare formulation is given by Eq. (6), which includes consumer and producer surplus. In a perfectly competitive airline market, airfare τ_i and full price p_i for each airline i are identical and are denoted by τ and p. Based on the social welfare formulation, we can derive the first-order and second-order derivatives, i.e., $\partial SW/\partial\rho$ and $\partial^2 SW/\partial\rho^2$ as below:

$$\frac{\partial SW}{\partial\rho} = [s\tau - (s + c_g)t'_q q - (c_f + c_g t) + rs - c_q]\frac{\partial q}{\partial\rho}, \tag{69}$$

$$\frac{\partial^2 SW}{\partial \rho^2} = [sp' - (s + c_g)(t''_{qq} q + 2t'_q)](\frac{\partial q}{\partial \rho})^2 + [s\tau - (s + c_g)t'_q q - (c_f + c_g t) + rs - c_q]\frac{\partial^2 q}{\partial \rho^2}. \tag{70}$$

An interior equilibrium is characterized by $\partial SW/\partial\rho = 0$, and $\partial^2 SW/\partial\rho^2 < 0$ ensures the sufficiency of first-order optimality condition and the uniqueness of the equilibrium. It is noted that the second-order condition always holds. Based on the first-order condition $\partial SW/\partial\rho = 0$, we can derive the optimal airport charge as follows:

$$\rho = \arg\{s\tau - (s + c_g)t'_q q - (c_f + c_g t) + rs - c_q = 0\}. \tag{71}$$

Eq. (71) states that under the optimal airport charge of a welfare-maximizing airport the airfare paid by passenger will be equal to the marginal social cost. Substituting the airfare of a perfectly competitive airline market in Eq. (8) into Eq. (71) yields

$$\rho = \underbrace{\frac{c_q}{s}}_{\substack{\text{flight handling cost}\\ \text{per seat}}} + \underbrace{(1 + \frac{c_g}{s})t'_q}_{\substack{\text{marginal congestion}\\ \text{cost per seat due to}\\ \text{one more flight}}} \cdot \underbrace{q}_{\substack{\text{total traffic}\\ \text{volume}}} - \underbrace{r}_{\substack{\text{concession}\\ \text{profit per seat}}} . \tag{72}$$

The optimal airport charge shown in Eq. (72) is different while comparable to the airport charge of profit-maximizing airport. In particular, the first, second and last terms regarding the flight handling cost c_q/s, congestion internalization $(1 + c_g/s)t'_q \cdot q$ and concession profit r are identical to those of airport charge in Eq. (63), while welfare-maximizing airport omits the markup term $(-p'q)$. Thus, by comparing Eq. (72) and Eq. (63), it is noted that a welfare-maximizing airport tends to charge less than a profit-maximizing airport.

We then investigate the effects of airport expansion on airport charge and airline market's total output. Differentiating Eq. (72) with respect to capacity k yields

$$\frac{\mathrm{d}\rho}{\mathrm{d}k} = -\left(1 + \frac{c_g}{s}\right)t'_k + \frac{(1 + c_g/s)(t''_{qk} q + t'_k)[p' - (1 + c_g/s)t'_q]}{p' - 2(1 + c_g/s)t'_q - (1 + c_g/s)t''_{qq}}, \tag{73}$$

$$\frac{\mathrm{d}q}{\mathrm{d}k} = \frac{(1 + c_g/s)(t''_{qk} q + t'_k)}{p' - 2(1 + c_g/s)t'_q - (1 + c_g/s)t''_{qq} q}. \tag{74}$$

Then, substituting Eq. (74) into Eq. (3) yields

$$\frac{\mathrm{d}t}{\mathrm{d}k} = \frac{t'_k\left\{(1 + c_g/s) \cdot q(t''_{qk} t'_q/t'_k - t''_{qq}) + [p' - (1 + c_g/s)t'_q]\right\}}{p' - 2(1 + c_g/s)t'_q - (1 + c_g/s)t''_{qq} q}. \tag{75}$$

According to Eqs. (74) and (75), we have Proposition 4.4.

Proposition 4.4. *In a welfare-maximizing airport with a perfectly competitive airline market, following a marginal increase of airport capacity (k),*

(i) flight traffic volume (q) will increase.

(ii) if $\begin{cases} \left(1 + \frac{c_g}{s}\right)\left(t''_{qq} - \frac{t'_q}{t'_k} t''_{qk}\right) > \frac{1}{q}\left[p' - \left(1 + \frac{c_g}{s}\right)t'_q\right] \\ \left(1 + \frac{c_g}{s}\right)\left(t''_{qq} - \frac{t'_q}{t'_k} t''_{qk}\right) < \frac{1}{q}\left[p' - \left(1 + \frac{c_g}{s}\right)t'_q\right] \end{cases}$ *then* *average congestion delay (t) will decrease,*
average congestion delay (t) will increase.

Proof. Given $p' < 0$, $t'_q > 0$, $t'_k < 0$, $t''_{qk} \leqslant 0$, and $t''_{qq} \geqslant 0$, both the numerator and denominator of Eq. (74) are negative. Therefore, we have $\partial q/\partial k > 0$, which implies that flight traffic volume will increase following the marginal capacity increase. The denominator of Eq. (75) is the same as Eq. (75), which is negative. Thus, the sign of $\mathrm{d}t/\mathrm{d}k$ is up to the numerator. When $(1 + c_g/s)(t''_{qq} - t'_q/t'_k \cdot t''_{qk}) < 1/q \cdot [p' - (1 + c_g/s)t'_q]$, the numerator of Eq. (75) is negative, thus $\mathrm{d}t/\mathrm{d}k > 0$ and capacity paradox occurs, and vice versa. This completes the proof. □

Proposition 4.4 states that a perfectly competitive airline market under a welfare-maximizing airport will schedule more flights following the marginal increase of airport capacity. Proposition 4.4 also gives the condition for capacity paradox to occur, i.e., $(1 + c_g/s)(t''_{qq} - t''_{qk} \cdot t'_q/t'_k) < 1/q[p' - (1 + c_g/s)t'_q]$. By comparing the conditions for capacity paradox to occur under a profit-maximizing airport and a welfare-maximizing airport, one can observe that given the same capacity k and same traffic volume q, capacity paradox is more likely to occur under a welfare-maximizing airport.

We further investigate the influence of capacity expansion on airport's profit and social welfare. Differentiating Eq. (5) and Eq. (6) with respect to capacity k respectively yield:

$$\frac{\mathrm{d}\Pi}{\mathrm{d}k} = sp'q \cdot \frac{\mathrm{d}q}{\mathrm{d}k} - (s + c_g)t'_k \cdot q - c_k, \tag{76}$$

$$\frac{\mathrm{d}SW}{\mathrm{d}k} = -q \cdot (s + c_g)t'_k - c_k. \tag{77}$$

According to Eqs. (76) and (77), we have Proposition 4.5.

Proposition 4.5. *Under a welfare-maximizing airport with a perfectly competitive airline market, following a marginal increase of airport capacity (k),*

(i) if $\begin{cases} c_k < sp'q\dfrac{\mathrm{d}q}{\mathrm{d}k} - q \cdot (s + c_g)t'_k \\ c_k > sp'q\dfrac{\mathrm{d}q}{\mathrm{d}k} - q \cdot (s + c_g)t'_k \end{cases}$ *then* *airport profit (Π) will increase, airport profit (Π) will decrease.*

(ii) if $\begin{cases} c_k < -q \cdot (s + c_g)t'_k \\ c_k > -q \cdot (s + c_g)t'_k \end{cases}$ *then* *social welfare (SW) will increase, social welfare (SW) will decrease.*

Proposition 4.5 can be readily verified based on Eqs. (76) and (77). The details are omitted. Proposition 4.5 states that the social welfare under a welfare-maximizing airport will decrease with the airport capacity expansion when the marginal cost of additional unit of capacity is larger than the marginal benefit. Similarly, the marginal airport expansion may also decrease the airport profit. However, it is noted that the optimal airport capacity that maximizes the profit is often smaller than the optimal capacity chosen by a welfare-maximizing airport. By further comparing Eq. (67), Eq. (76), Eq. (68), and Eq. (77), under the same traffic volume q, one can observe that additional capacity under a welfare-maximizing airport will bring less airport profit and social welfare than those under a profit-maximizing airport.

5. Numerical studies

We now conduct numerical studies to further explore and illustrate the quantitative effects of airport expansion. The basic function forms and base-case parameter values are summarized in Table 3. The results are based on the base-case function and parameter settings if not further specified.

Parameter values of airport and airlines are chosen with reference to data from Hong Kong International Airport (HKIA) and IATA. As estimated in HKIA 2030 Outlook, the maximum capacity for the two-runway system in HKIA is about 440 thousand flights a year. According to HKIA Annual Report 2018/19, HKIA hosts about 75.1 million passengers and 429 thousand flights in 2018/19 in total. Airport charge earned HKIA 5,255 million HK$ and concession business earned 7,145 million HK$ (including advertising revenue). Total cost was about 10,150 million HK$ (including amortization and depreciation). Thus, we can have a rough estimation about the value of airport concession profit per passenger r, airport's unit cost of maintaining capacity c_k and airport's unit cost of handling flight c_q. According

Table 3 Basic functional forms and parameter values

	Functional forms	Parameter values
Congestion time	$t(q,k) = q^{w_1}/k + w_2 q$	$w_1 = 2$ $w_2 = 0.1$
Inverse demand function	$p(q) = c_{p0} - c_{p1} q$ $p_i(q_i) = c_{p0} - c_{pii} q_i - c_{pij} q_j$[1]	$c_{p0} = 3000$ HK\$ $c_{p1} = 0.15$ HK\$ $c_{pii} = 0.15$ HK\$ $c_{pij} = 0.1$ HK\$
Airlines profit	$\pi_i = (\tau_i - \rho) s q_i - [c_f + c_g t(q,k)] q_i$	$s = 150$ $c_f = 11000$ HK\$ $c_g = 1600$ HK\$
Airport profit	$\Pi = (\rho + r) s q - (c_k k + c_q q)$	$r = 70$ HK\$ $c_k = 10400$ HK\$ $c_q = 12200$ HK\$

[1] This function is used when airlines are imperfect substitutes.

to the 2018/19 Annual Report of major airlines operated in HKIA, we have the rough estimation about airlines fixed cost per flight c_f, variable cost due to congestion c_g and seat per flight s. Other parameter values are assumed.

We first investigate downstream market's responses against the airport flight charge and capacity. Figure 2 shows the flight traffic volume of downstream market with different combination of airport capacity and airport charge. We consider the capacity varies from 10 flights per day to 500 flights per day, and the airport charge varies from 10 HK$ per seat to 500 HK$ per flight. Generally, airport expansion will yield more traffic volume and increasing airport charge will reduce traffic volume. Moreover, capacity paradox may occur, but does not occur under perfectly competitive airlines in a perfect substitutes market and under Stackelberg leader-competitive fringe in an imperfect substitutes market. In addition, regarding traffic volume, perfectly competitive airlines yield the largest traffic volume, while monopoly provides the least flights in a perfect substitutes market. A leader-follower market yields a higher traffic volume in both the perfect substitutes market and the imperfect substitutes market (in Figure 2(b), when compared to two airlines competing in a Cournot market ($m = 2$)).

We now further take airport's administrative regimes into consideration, where airport will adjust its flight charge following any capacity expansion. Figures 3, 4, and 5 show the system responses to airport expansion with different airline market structures in zero-profit regime, profit-maximizing regime, and welfare-maximizing regime, respectively. We find that in zero-profit regime, the market equilibrium is not unique. Airport has different choices: higher airport charge with lower traffic volume, or lower airport charge with higher traffic volume. Both choices allow the airport to maintain break even but the low charge choice will yield a higher social welfare. In Figures 3(a2) and (b2), one can observe that the capacity paradox occurs when the airport chooses the high airport charge. The high charge discourages passengers from traveling by this airport. In this circumstance, any decrease in the traveling cost may attract huge traffic volume and yield a more congested airport. Figure 4(a1) shows that the profit-maximizing airport serves less traffic volume than the welfare-maximizing airport and the zero-profit airport (with a higher traffic volume).

It is also noteworthy that capacity paradox occurs under a profit-maximizing airport, regardless of the airline market structure. Figure 5(a1) shows that in a perfect substitutes market, the airline market structures have limited influence on the total traffic volume under a welfare-maximizing airport. It is different in the imperfect substitutes market. Figure 5(b1) shows that the downstream market responses will influence the total traffic volume in an imperfect substitutes market. Airport will adjust its airport charge to attract demand in order to achieve its objective, which implies that the airport charge may be negative and become a subsidy to airlines in order to increase the traffic volume. Capacity paradox also occurs in a welfare-maximizing airport, regardless of the airline market structure. Figure 5(a4) shows that airport loses money under a monopoly airline market when compared to other market structures. This is because, the monopoly airline provides less traffic volume and instead the airport has to offer more subsidy.

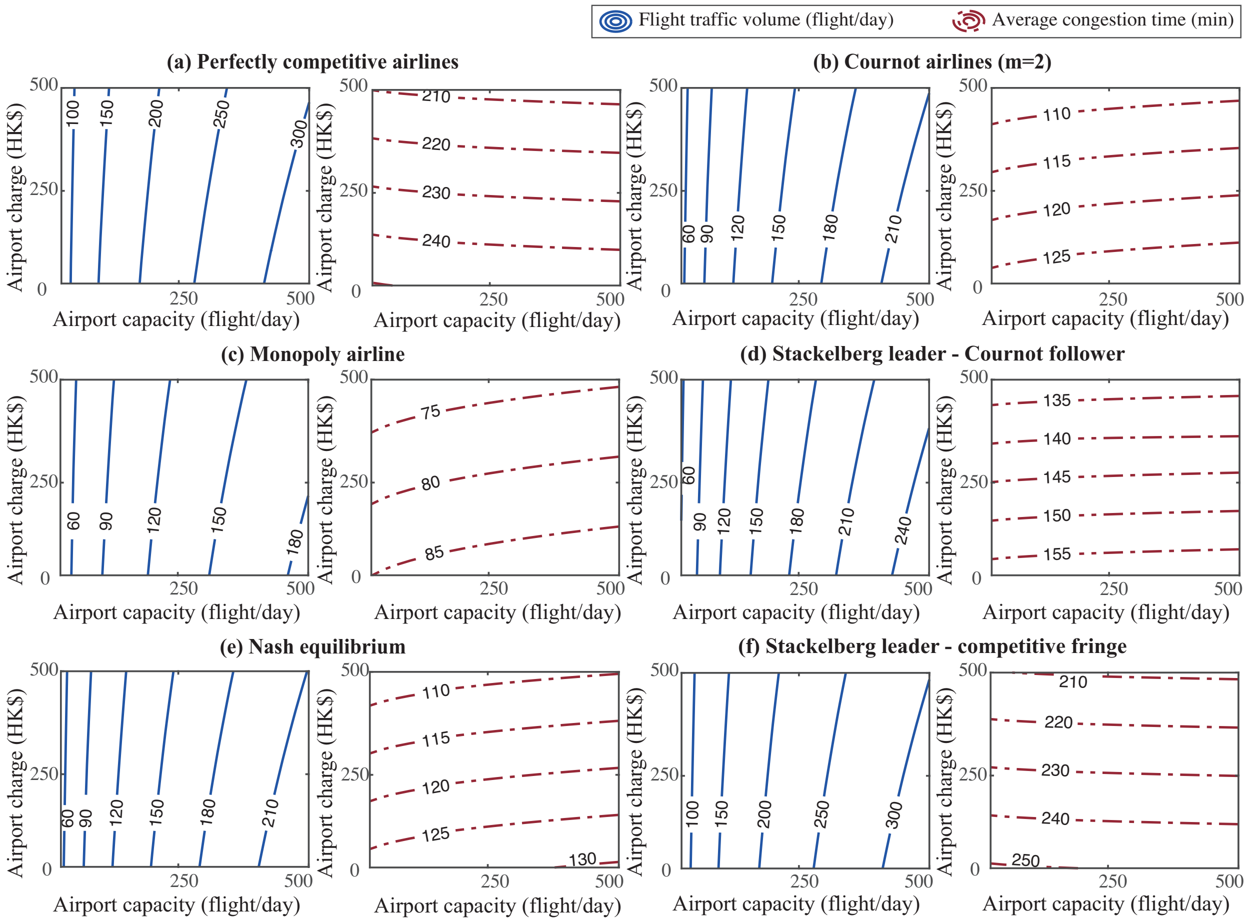

Fig. 2. Traffic volume and congestion delay under different airport charges and capacities

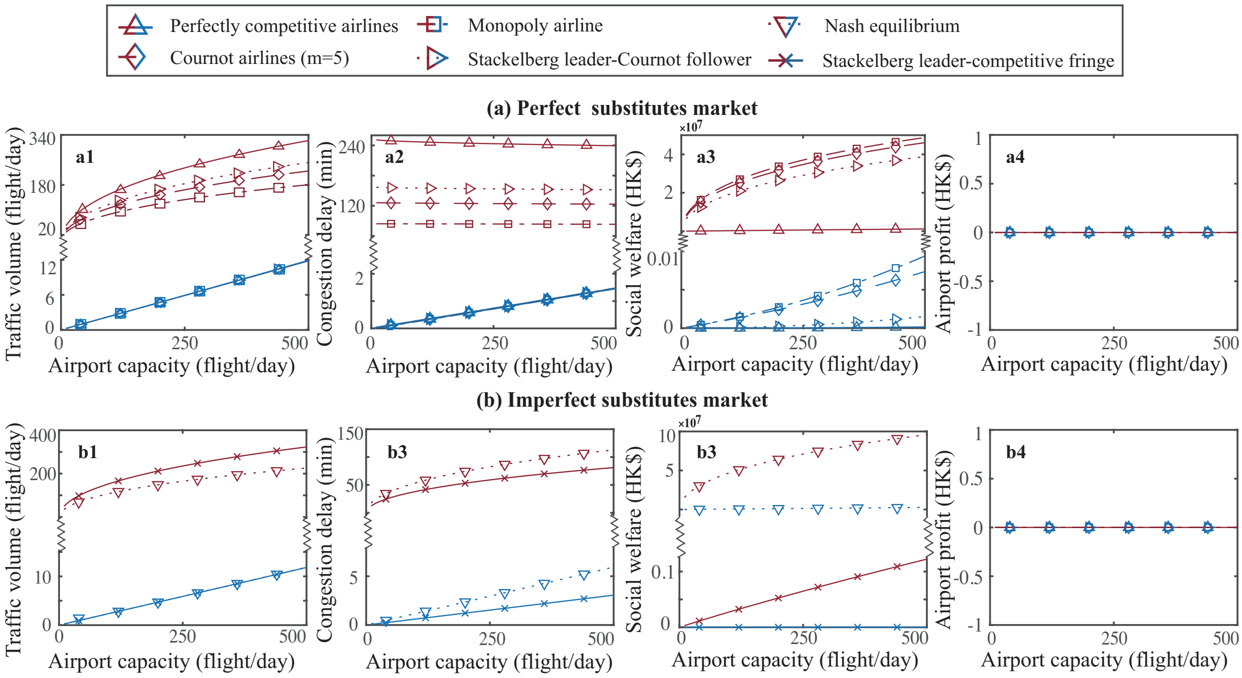

Fig. 3. Effects of the airport capacity expansion in the zero-profit administrative regime (red and blue indicate the solutions with higher and lower traffic volumes, respectively)

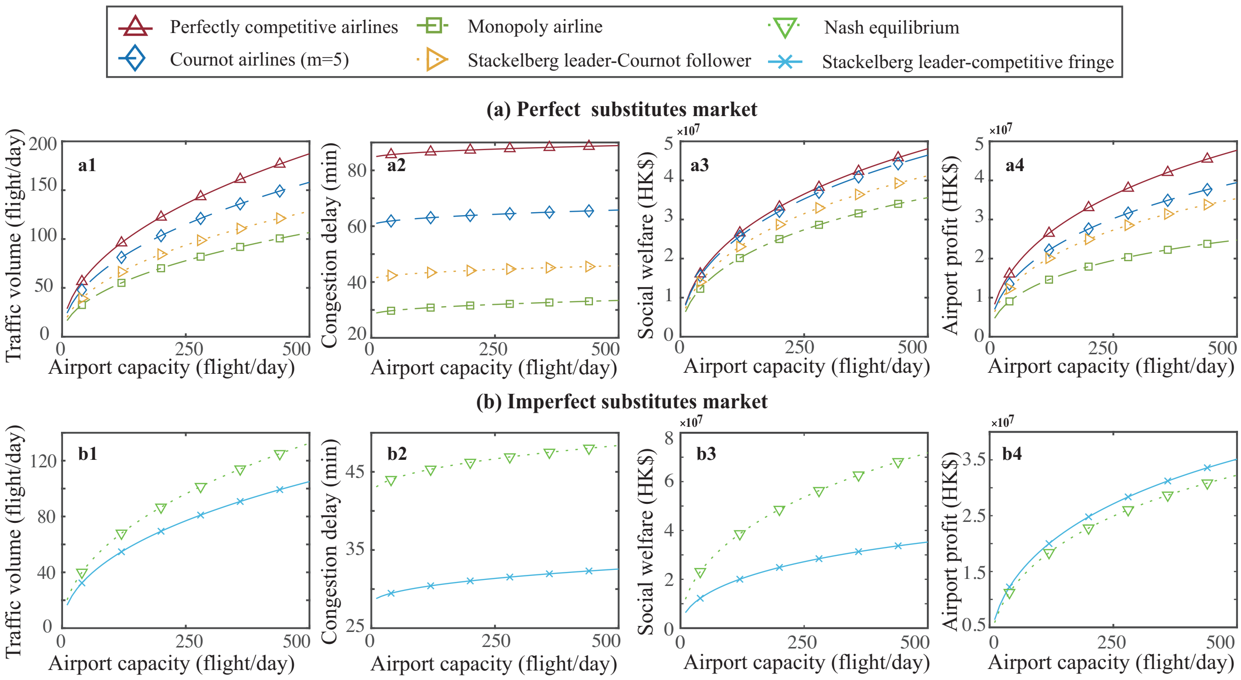

Fig. 4. Effects of the airport capacity expansion in the profit-maximizing administrative regime

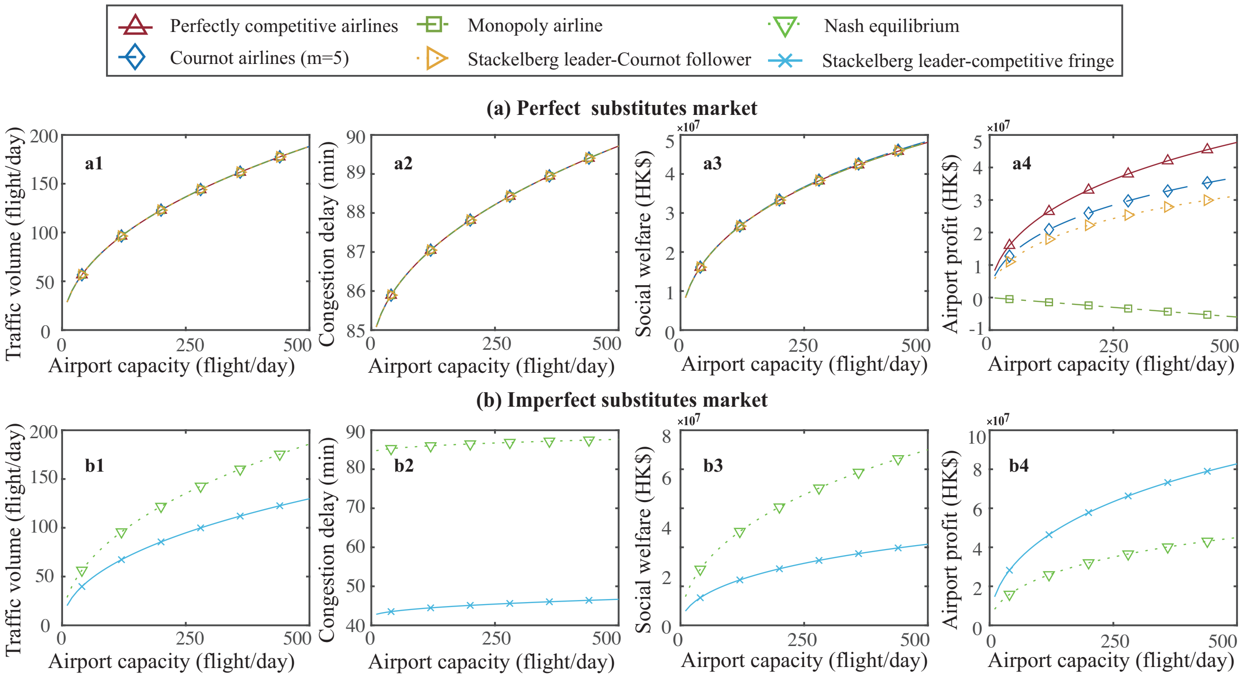

Fig. 5. Effects of the airport capacity expansion in the welfare-maximizing administrative regime

6. Conclusion

In this paper, a tri-level game-theoretical model is developed to examine the air traffic equilibrium in the airport-airlines-passenger system, the decisions of different stakeholders (airport, airlines, and passenger choices), and the effects of airport capacity expansion on the traffic equilibrium and a series of system efficiency metrics. In the airport-airlines-passenger system, airport can have alternative administrative regimes and airlines might be operated in different market structures. In this context, we examine different stakeholders' decisions and the implications on airport congestion, airline competition, and the social welfare.

The first part of the analysis considers a given airport flight charge and examines the impacts of the airport capacity expansion. Several results are summarized here. First, capacity paradox is more likely to occur in market with less competition. For example, in symmetric airline market, the less airlines in market (i.e., less m), the more likely for capacity paradox to occur. Also, in leader-follower market, when the leader captures most of the market share, capacity paradox is more likely to occur. Second, the congestion internalization in different airline market is different. A perfectly competitive airline market will not internalize any congestion, while in Cournot market airline will internalize the congestion proportional to its market share. In a perfect substitutes airline market, the leader will scale down its airfare regarding airport congestion externality to the same level as the follower. However, in an imperfect substitutes market, the leader will charge more than the follower. Third, after examining different market structures, it is found that capacity expansion will stimulate airlines to schedule more flights. Fourth, the shapes of demand curve and congestion curve are critical to the occurrence of capacity paradox. If the congestion delay is more sensitive to the traffic volume than the capacity (i.e., t'_q is large while $|t'_k|$ is small) and traffic volume is very sensitive to price ($|p''|$ and $|p'|$ are small), the capacity paradox is more likely to occur. It is noteworthy that the capacity paradox does not imply that the economic contribution of the airport expansion has not increased. Although the airport can be more congested after the expansion, it does accommodate more demand, which means more economic interactions overall.

The second part of the analysis considers three alternative airport administration regimes where the airport will adjust its flight charge accordingly after the airport capacity expansion. Several major findings are summarized below. First, in the zero-profit regime, the airport's break-even decision is not unique (a higher charge with less traffic and a lower charge with more traffic). In particular, the lower charge will bring more traffic volume and higher social welfare. A profit-maximizing airport brings the lowest traffic volume, as it charges the highest airport charge. Under a welfare-maximizing airport, the traffic volume is not influenced by the airline market structure in perfect substitutes market. The airport will adjust its charge to ensure that the airfare paid by the passenger equals to the marginal social cost, which means that airport may offer a subsidy to the airlines when they need to receive more than the marginal social cost.

This study can be extended in several ways. First, this paper consider one airport and elastic passenger demand. It is of our interest to explicitly model the competitive and/or complementary relationships among multiple airports in a multi-airport region such as the Guangdong-Hong Kong-Macao Greater Bay Area. Second, this study focuses on tractable models to generate strategical level insights for the airport-airline-passenger system, while future studies may examine planning or operation level problems for such systems.

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