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Assessment of countermeasures against the abuse of market power and capacity deficiency of privatized airports

A Dissertation
Submitted to the Department of Transdisciplinary Science and Engineering
in Partial Fulfilment of the Requirements of the Degree of
Doctor of Philosophy

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Abstract

Airports are seeking structural changes, such as privatization, to meet and satisfy the increasing demand. On the one hand, there are open issues on whether privatization can stimulate the capacity investment which is the ultimate countermeasure against capacity shortage. On the other hand, privatization raises the concern regarding the abuse of market power. Based on the background, the objectives of the thesis are, first, assessing the plausibility of the introduction of terminal competition as an alternative countermeasure against the abuse of market power; second, figuring out the relationship between privatization and the investment decisions from some new perspectives.

We first investigate the effect of terminal competition on the pricing and social surplus. We define several business models to characterize the organizational structures of the airport before and after the introduction of terminal competition. Comparing the equilibrium outcomes in each business model, we find that, in most cases, having competing terminals can neither lower the prices nor enhance the social surplus if the operation of the terminal and airfield facilities are not completely separated in the existing business model, whether or not airlines have the freedom to change base terminal in response to the prices. The complementarity between the airfield and terminal service, which is originally internalized by the joint operation, will become a negative effect that cannot be offset even by a strong degree of substitution between terminals, if the two services are provided respectively by independent operators. In contrast, if the operation of the two sections has been completely separated in the existing business model, or the airfield operator can be strictly regulated, having competing terminals can result in a higher social surplus, as it will not increase the negative complementary effect. Instead, it creates a duopoly of substitute goods that can offset the complementary effect.

Second, we analyze the bi-projects investment problem at an airport. Adopting a real-option model, we obtain the optimal rule of the timings for the investment in capacity expansion project and the investment in cost reduction project. We also estimate the loss due to the suboptimal investment. Numerical results suggest that the decision-maker who places a higher premium on social surplus always tends to invest earlier in both projects. Other factors that stimulate an earlier investment include a lower cross-price effect, a

greater total number of airlines, a higher drift, and a lower volatility in demand. The optimal scales of projects are more sensitive to the change in drift and volatility rather than the change in other factors. When the composition of the objective function changes, the pattern of the change in optimal timing differs by project. The loss due to NPV-based investment is much greater than that caused by the adoption of the deterministic model, and its change with the change in the composition of the objective function can have a mountain-shaped pattern, where the minimum can be reached when specific conditions are met.

Third, we investigate the relationship between the privatization decisions and the investment decisions of an airport, and the effect of various factors on the relationship. We consider two scenarios differing in the availability of governmental subsidiary to the investment. We find that the optimal capacity volume does not necessarily decline as the private share increases, if the governmental subsidiary is available. If the governmental subsidiary is unavailable, three clear-cut regions of the investment decisions with regard to the private share can be observed: If the private share is low, no expansion will be carried out; if the private share is moderate, a gap-filling expansion will be carried out; if the private share is high, the expansion will not only fill the current capacity gap, but also leave some vacant capacity preparing for the future demand growth. Maximum aggregated social surplus can be achieved by privatizing a certain share which is just consistent with the value of one of the two breakpoints that connect two adjacent regions, while which breakpoint can maximize the aggregated social surplus depends on the timing of the privatization.

Some findings of this thesis might have policy implications. The results regarding the effect of terminal competition indicate that it cannot work as an alternative to the regular regulation to restrain the abuse of market power, and a respective privatization of airport facilities should be avoided. The results of the bi-project investment problem suggest that the regulatory adjustment of the timings, which aims to enhance social surplus, should be enacted in different rule for different type of project. The results regarding the effect of airport privatization on the capacity expansion imply that the optimal share to privatize in terms of aggregated social surplus can change as the timing for privatization change, and there is a trade-off between the social surplus within the airport and the spill-over social benefit (capacity) in the case of an early privatization.

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Chapter 1 Introduction

1.1 Background

In the past decades, air transport market has seen significant development, which is mainly driven by the rapid growth in the demand for air transport. To maintain such prosperity, two salient issues, namely how to *meet* the growing demand in terms of capacity, and how to *satisfy* the demand in terms of service, are therefore necessary to be addressed. Various development, which partially help address these issues, has taken place in the airline industry in a fairly early stage, thanks to the trend of airline deregulation. Meanwhile, as a participant in the upstream of the supply chain, airport also need to take corresponding actions. Otherwise, the airport industry would become the bottleneck of the expected improvement in supply, since airport's capacity forms the upper bound of supply for air transport, and the quality and price of the service provided by an airport have a direct and immense implication on the service of downstream suppliers.

Facing the increasingly complexity of the market brought by the growing demand and the radical change in the airline industry, public authorities or governments who has operated airports for a longtime gradually find it difficult to address these issues in the traditional way. Many of them thus began to operate their airports in a more commercialized approach, and some even sought a partial or full privatization of airports. Rikhy et al. (2014) summarized that governments privatize airports aiming for developing traffic demand or meeting such demand; financing large-scale airport infrastructure; and bringing efficiency to the design and operations. Indeed, some of these aims can be achieved through commercialization and privatization in many cases. For instance, empirical evidences show that airports with majority private share outperform those with dominant public share in terms of efficiency (Oum et al., 2006; Oum et al., 2008).

However, regarding some aspects of the government's motivation for these structural changes, it is still ambiguous whether the expected effects can be achieved. For instance, there are opposing views on the effect of privatization on the infrastructure investment (Graham, 2020). Numerous studies have tried to figure out the relationship between privatization and infrastructure investment from various perspective, while there are still some aspects needing further investigation. For instance, most studies only focus on the volume choice of capacity expansion, and did not consider the timing for the investment. Investment in airport infrastructure can be a huge project, and has a long-term impact, so it is essential to address the timing issue to avoid the loss caused by the untimely investment. Further, for some airports, non-aeronautical business has already become the most significant revenue source; many airports also welcome the adoption of new technology to enhance efficiency and reduce cost. A holistic view on the infrastructure investments, not only the investment in capacity expansion, but also the investment in the non-aeronautical facilities and the efficiency-enhancing project, is also necessary.

On the other hand, the structural changes more or less make the airport's operation more profit-oriented, thus raising a concern that airport might abuse its substantial market power to provide service with higher price (Graham, 2011). Airports are traditionally defined as natural monopolies, whereas the concern of the abuse of market power seldom appear at that time, as they are treated as public utilities. In recent years, although the natural monopoly aspect of airport has been eroded for many reasons, such as the diseconomies of scale, and a fiercer inter-airport competition (e.g., Gillen et al., 2001; Tretheway, 2001; Kamp et al., 2005), many airports are still monopolies or quasi-monopolies for various reasons. For instance, an airport with a catchment area which never overlap with that of other airports would seldom face competition on departing and arriving passengers. Moreover, if not competent to be an international hub, it would not need to consider how to attract transiting passengers. Clearly, such an airport wields substantial market power. If it is operated in a profit-oriented way as a result of commercialization or privatization, the concern might come true. Traditional countermeasure against this problem is to impose regulation, which has been substantially discussed in the previous studies. However, regulation can be costly and controversial in some cases, so it is worthy to figure out whether there any effective alternative to regulation. An introduction of intra-airport terminal competition, namely a separate privatization of airport, attracts some attention, while its effect has not been fully investigated.

1.2 Research Objectives

This thesis thus aims to take a closer look at some aspects of the effects of the structural change (Fig 1.1). We focus on *privatization*, which is the most radical structural change. As mentioned, privatized airports can have some new concerns (high charge) calling for countermeasures, and privatization can affect the implementation of the countermeasures against the old concerns (capacity deficiency). Therefore, we first assess the plausibility of airport terminal competition as a countermeasure against the abuse of market power of private airport. We then aim to investigate how the "privatized extent" of an airport affect its decision-makings regarding infrastructure investment, the ultimate countermeasure against capacity shortage. To break down, the objectives to be achieved are as follows:

(1) To figure out the effect of intra-airport terminal competition on price and social surplus. Multiple business models characterizing potential organizational structures of the airport before and after the introduction of terminal competition are considered and compared, and several special cases are investigated **(Chapter 3).**

(2) To figure out the optimal investment rule for a sequential investment in two types of projects, namely capacity expansion and cost reduction. To analyze the effect of airport's ownership, the structure of downstream market, and demand uncertainty on the timings and scales of the bi-project investment. We also investigate how these factors affect the loss due to a suboptimal investment **(Chapter 4).**

(3) To investigate how the ownership structure of the airport affect its capacity expansion behavior, considering two cases differing in the availability of the governmental subsidiary for the expansion **(Chapter 5).**

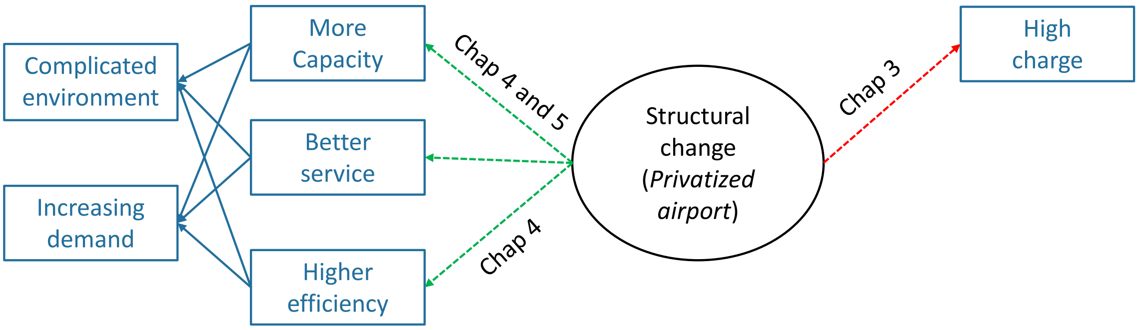


Fig 1.1 Linkage between the chapters

1.3 Scope and Limitations

This thesis focuses on one single airport. We do not consider the interaction with regard to the countermeasures between multiple airports within a metropolitan area or a network in our discussions, otherwise the complexity of modelling might escalate. Nevertheless, further consideration of multiple airports can be an interesting topic for future research.

This study mainly focuses on "private airport" instead of "privatization" itself as a process. In Chapter 3 and Chapter 4, we treat "privatization" as a status-quo, and investigate the countermeasures against high charge and capacity shortage. Therefore, we do not discuss the reasonableness and feasibility of the privatization.

This thesis mainly employs analytical modeling approach to the analyze of the research questions. Most of the results are derived analytically, while in some cases numerical computations are resorted to for the comparison among these results. The advantage of analytical modeling is that solutions can be derived in closed forms without predefining values for parameters in most cases. Hence, the results can be general without being subject to a specific context. Although sometimes it might be difficult to have comparative statics for the results or even closed-form final solutions, the friendly properties (e.g., concavity) of the objective functions enable a quicker and more accurate calculation rather than the optimization of complicated objective function through heuristic algorithm. On the other hand, functions adopted in analytical model usually have simple forms (i.e., demand functions are always linear). Reality is somewhat sacrificed for the sake of tractability. An analytical modelling without explicitly defining the form of functions, which can further enhance the generality of results, proves to be a meaningful attempt in future work.

The study in Chapter 3 can be regarded as a normative study where we discuss the plausibility of the introduction of terminal competition. On the other hand, the studies in Chapter 4 and 5 are generally descriptive. Our main focus is "if A changes, how will B change?" Its result can provide some references to the trade-off for the decision-making, yet it might be difficult to claim that "the policy maker should …", as we did not take into account all the aspects of the motivation which needs to be considered comprehensively in policy making.

Other notable limitations include:

a. In the study of terminal competition (Chap. 3), we do not consider its effect on investment.
b. In the study of bi-project investment (Chap. 4), we assume that the decision-maker can choose the scales of the projects discretely, whereas the volume of each scale is exogenously determined, instead of being optimized by investor.
c. In the studies of airport investment (Chap. 4 and 5), lead times of projects are not considered.
d. In the studies of airport investment (Chap. 4 and 5), hypothetical values are set for parameters in the numerical calculation sections, due to the lack of real-world data.

1.4 Outline

Chapter 1 briefly explains the motivations behind the study. Objectives, contributions, and limitations of the study are then stated.

Chapter 2 presents the impact of the structural change, showing the problems, introducing the countermeasures, and reviewing the previous studies.

Chapter 3 investigates the effect of the introduction of terminal competition on price and social surplus. In the basic model, we consider two cases varying the freedom of airlines to change their base terminal. Under each case, we compare six scenarios, each of which corresponds to one potential organizational structure of the airport before or after the introduction of competing terminals, to figure out whether terminal competition can reduce price and improve social surplus, and how should terminal competition be induced. We then extend the study to see the effect of terminal competition in four special cases, where terminals have different allocative efficiency, airlines participate in upstream market, terminal compete on both price and service level, and terminals are regulated.

Chapter 4 studies a case that airport has the option to carry out two types of investment, namely capacity expansion and cost reduction. We adopt a real option approach to the modelling of investment decision; the investor can choose the timing and scale for investments respectively to maximize its expected payoff. Considering the inter-relationship between the two projects, we derive the optimal rule for the sequential investment. We investigate the effect of airport's ownership, the structure of downstream market, and demand uncertainty on the timings and scales of the investments. We also estimate the loss due to suboptimal investment and how it is affected by various factors.

Chapter 5 investigates the relationship between the privatization decisions and capacity expansion decisions of an airport. In a real option approach, we analyze the effect of time and the share to sell of privatization on the optimal timing and volume for the capacity expansion, and the aggregated social surplus.

Chapter 6 summarizes the results and findings of this study, and propose the future scope.

1.5 Contributions

We would like to illustrate the contributions of the study chapter by chapter as follows:

Chapter 3: This study sheds light on the important yet unanswered question of whether the introduction of terminal competition can restrain the abuse of market power by a monopoly airport and lead to lower prices and higher social surplus, in various potential business models, considering the participations of airlines in the upstream and the properties of operators. This study can also help support relevant decision-making, as current empirical evidence is insufficient, and related discussions are always mixed with political issues and conflicts of interest.

Chapter 4: We investigate the bi-project investment problem at an airport in a real option approach, which has not been addressed in the previous studies, to the best of our knowledge. The downstream market is explicitly modeled, which enables us to examine the effects of its features on the investment decisions. We formally prove the inter-relationship between the two types of projects. Based on the inter-relationship, we correct the optimal rule for the sequential investment proposed by the previous studies.

Chapter 5: By investigating the relationship between the privatization decisions and the investment decisions, and analyzing how these decisions affect the long-term social surplus, we provide some references for the decision-makers who need to balance various objectives when planning the privatization. We find that the effect of ownership on the investment decision might not be as simple as suggested by the previous studies.

Chapter 2 Literature review

2.1 The impacts of airport privatization

In the airport industry, the private sector involvement has become an important trend for several years. As per ACI (2018), 51% of the top 100 busiest airports more or less have private participation, representing 41% of all passengers around the world. Privatization has brought various impacts, and the most discussed is the impact on efficiency. Graham (2020) has extensively reviewed the relevant studies on this issue. In summary, most studies find that privatization at least would not cause an efficiency decline. Moreover, in terms of the effect of mixed ownership, Oum et al. (2006), Oum et al. (2008) and Adler Adler and Liebert (2014) reach a common conclusion that airport with a minority private share is most inefficient. The impacts on service quality and non-aeronautical business are also important points to be investigated, but there lack convincing studies. Regarding the impact on price, it is obvious that the privatized airport is very likely to levy a higher charge than the public airport, constituting the reason why regulation on privatized airport with great market power is essential. However, is there any effective alternative? We will introduce one potential alternative in Section 2.2 and 2.3, and investigated its effectiveness in Chapter 3. Regarding infrastructure investment, the impact might still be ambiguous, as presented by the opposing views. ACI (2018) claims that '… privatization has been shown to be a successful means by which to fund infrastructure development. Indeed, ACI World estimates that airports with private sector participation indeed invested 14% more in CAPEX measured as compared to their public counterparts and 12% more than the global average in the last five years'. By contrast, IATA (2018) contends that '… we could not see any gains in efficiency or levels of investment'. The contradictory opinions and the lack of clarity of the effect necessitate further investigation of the issue. Chapter 4 and 5 investigate the relationship between privatization and investment from new perspectives to supplement those put forward by previous studies. In prior to the study, the current situation of capacity deficiency is introduced in Section 2.4, and relevant studies in Section 2.5.

2.2 Intra-airport terminal competition

2.2.1 The abuse of market power by the airport

Market power, which generally refers to the ability of a firm to charge a price above marginal cost and earn a positive profit, is wielded by a monopoly hardly facing competition (Perloff, 2014). In terms of an airport, the monopolistic status, namely the lack of competition, may come about for two types of reasons: locational reasons and natural monopoly reasons (Forsyth et al., 2010). The locational reasons say that there are various geographical and political barriers for multiple airports to coexist adjacently in one region to compete with each other. Besides, some airports are not situated in a favorable location for the establishment of a hub, making the emergence of hub competition unrealistic. The natural monopoly reasons argue that the entry of new competitor will be precluded, as the colossal sunk cost and the economies of scale form a huge barrier. Many markets are indeed showing these characteristics, so the airports thereof are regarded as monopolies with market powers. Nevertheless, monopoly does not necessarily result in the abuse of market power, if the airport is not profit-oriented[1]. In earlier decades, given a lower aviation demand and a more conservative regulatory regime, the monopolistic characteristic of the airport ought to be much stronger than how it is now. Yet the concern regarding the abuse of market power were seldom raised at that time, for airports were under public sectors which would not place a high premium on profit. However, the trend of airport commercialization and privatization makes airports more profit-oriented, and thus more inclined to abuse market power. Although the monopolistic characteristics of the airports are becoming weaker thanks to factors, such as the growing demand and the emergence of LCC, it cannot outweigh the increasing extent of the abuse of market power in many circumstances. The abuse of market power often results in a high charge that harms the social benefit. Several empirical studies investigate the abuse of market power occurred in recent years, for example, Bel and Fageda (2010) find that private airports not regulated charge higher prices than public or regulated airports.

[1] Non-profit-oriented airport may also levy high charges, but this is mainly due to the inaction on reducing cost rather than the abuse of market power.

2.2.2 Countermeasures

It is literally plain that there are two ways to tackle the problem regarding the abuse of market power: to reduce the extent of the abuse, or to eliminate market power as much as possible. The former refers to the restriction on the pricing right of the airport, namely a regulation, while the latter is to weaken the extent of monopoly of the airport, namely an introduction of competition.

Various regulations are widely employed to counter the high charges levied by airport; they can be generally categorized into three types (Graham and Morrell, 2017):

<u>Rate of return (ROR) or cost-based regulation</u>: Under this type of regulation, airport is permitted to cover its cost and gain some profit by levying the charge. In other words, it defines an upper bound for the rate of return on the asset base. Besides preventing the abuse of market power, ROR regulation can also work to encourage the capital investment, for the larger the whole pie, the larger the airport can get, given a fixed share. However, a big difficulty regarding its implementation is the determination of the assets that should be included in the asset base. In addition, a costly scrutiny on financial date is necessary to prevent cost inefficiency and overinvestment. Airports where this type of regulation is adopted include Amsterdam, Athens, etc.

<u>Incentive or price-cap regulation:</u> Under this type of regulation, a price-cap is determined based on the formula CPI – X + Y where CPI stands for the consumer price index, X the efficiency gain target and Y the external cost. Since any efficiency gains that the airport can make in excess of the required X will directly benefit the airport, this regulation can encourage the operator to enhance efficiency. The cost of scrutiny for it is also significantly lower than that of ROR regulation. However, this regulation might undermine the operator's incentive to carry out long-term investment, since it focused on short-term operational efficiency gain within each price control period. Airports where this type of regulation is adopted include Vienna, Heathrow, etc.

<u>Price monitoring or light-handed regulation:</u> This type of regulation will be imposed on the airport only when the abuse of market power has been affirmed. The market power of the airport is constrained by the threat of regulation, rather than actual regulation. It is considered as a more proportionate approach for dealing with the modern day, more

competitive, airport industry, due to its compatibility and flexibility (ACI Europe, 2014). The main challenge for its implementation would be the establishment of the appropriate trigger criteria. Airports where this type of regulation is adopted include Sydney, Auckland, etc.

There are three common concerns whatever the type of regulation is. First, a dearth of a common method for the assessment of market power makes it difficult to judge whether a regulation is necessary for an airport (Bilotkach and Mueller, 2012). Second, while most regulations focus on pricing and efficiency, the establishment of service standards or appropriate quality-monitoring systems are often overlooked. Third, heavy regulation that implicates government intervention might lead to strong protests from stakeholders, which can evolve into time-consuming litigation (e.g., Aer Rianta v. Commission for Aviation Regulation [CAR] in Ireland, 2002).

As a market-based anti-monopoly alternative to regulation, the introduction of competition could be politically less controversial. The so-called 'new view on airport regulation' (Gillen et al., 2001; Tretheway, 2001) argues that airports are no longer natural monopolies and that more competition would be preferable to traditional regulation. ACI Europe (1999) identified six different forms of competition or 'perceptions of competition' between airports:

1. Competition to attract new services.
2. Competition between airports with overlapping hinterlands.
3. Competition for a role as a hub airport and for transfer traffic between hubs.
4. Competition between airports within urban areas.
5. Competition for the provision of services at airports.
6. Competition between airport terminals.

The first form refers to the situation that airports with remaining capacity compete with each other to attract airlines to involve them into their airway networks. However, in this case, rather than airports themselves, the demand levels behind the airports play a more important role in the airlines' decision-makings. The second form and the fourth form can be actually combined together under the current context that new means of transport such as HSR has greatly improved passengers' accessibility to the airport. This kind of competition can take place between a primary airport and a secondary airport which has seen strong development contributed by LCCs (e.g., Brussels and Charleroi, see Barbot (2006)), or between two main airports with different functions (e.g., Narita and Haneda). The competition between Incheon and Narita for China-U.S. transit traffic exactly exemplifies the third form. The last two are not competition between airports, but between service providers within one airport.

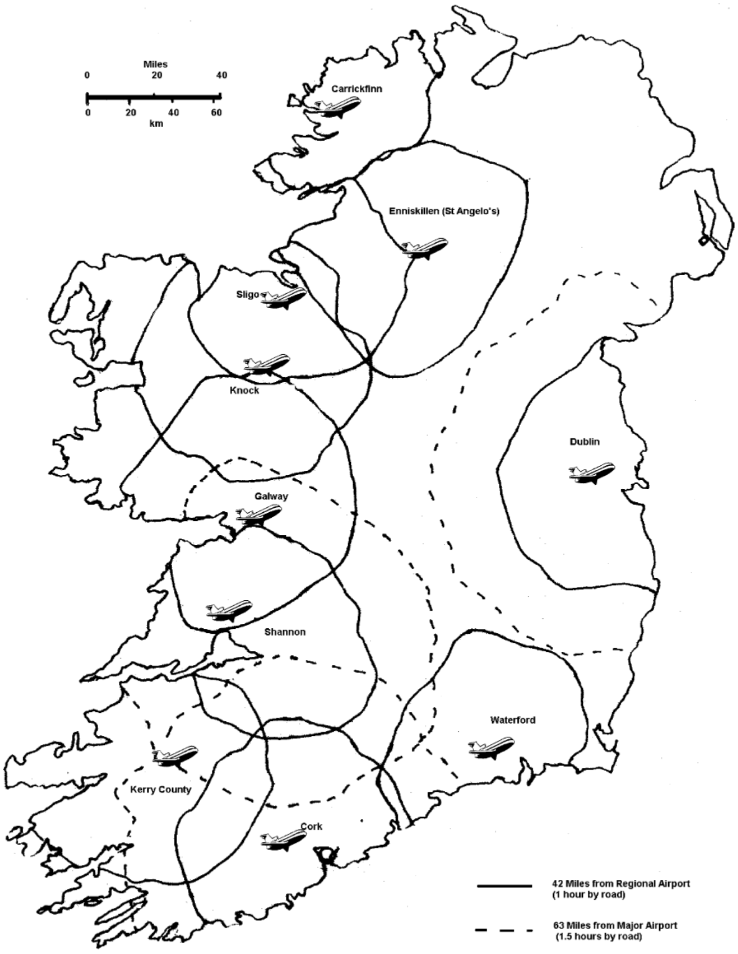


Fig 2.1 Catchment areas of airports in Ireland

However, some of the above-mentioned forms can be unrealistic for some airports. In terms of hub competition, a good geographical location proves to be an important advantage, yet many airports do not have such merit. In some overcentralized countries, there lacks the conditions for the competition between airports with overlapping hinterland. A typical example is Dublin airport in Ireland. From Fig 2.1, we can see that the catchment area of Dublin Airport does not overlap with that of other Irish airports.

This, together with the huge edge in the frequency of flight and the number of routes over other Irish airports, making Dublin Airport hardly face any domestic challenge. In addition, a deliberate introduction of a competing airport (e.g., construction of a new airport) could be fraught with many obstacles such as proper funding and land-use restrictions. Hence, for airports located in remote areas with an independent hinterland, a compromised approach, introduction of intra-airport competition (e.g., competition between terminals) is conceived, as a terminal is somewhat easier than an entire airport to duplicate (Kuchinke and Sickmann, 2005).

2.2.3 Terminal competition: History and current status

Terminals within an airport can compete on price and service quality (Graham, 2018). Price generally refers to the passenger service facility fee. Terminals compete for passengers via airlines, as “terminal service” is one of the inputs for the airline’s production of “air travel service”. Given a cheap and high-quality input, the airlines are able to produce cheap and high-quality output to attract consumers.

There are few industry examples of terminal competition (See Table 2.1). In Canada, Terminal 3 at Toronto Airport was once taken over by a private consortium in 1987 to provide new investment, and was permitted to levy higher fees for cost recovery (Juan, 1996). However, the practice did not last long as the terminal was brought back to non-profit authority along with new policy development in 1996. Similar cases can be observed at Birmingham Airport, Brussels Airport, and Ninoy Aquino International Airport (Manila), where terminals were at one point operated separately through build-operate-transfer (BOT) contracts but eventually all returned to centralized operation (Graham, 2018). At some airports (e.g., New York JFK, Munich, Riga), leader airlines run terminals, ostensibly creating terminal competition, but in fact merely creating competition among the leader airlines.

Table 2.1 Examples of airport terminal competition

Country	Airport/Terminal	Form	Period
Canada	Terminal 3, Toronto	BOT	1991 - 1996
U.K.	Eurohub, Birmingham	BOT	1989 ~ ? (terminated)
Philippines	Intl. terminal, Manila	BOT	1999 - 2005
U.S.	JFK (New York)	Vertical integration	Ongoing
Australia	Domestic terminals, several airports	Vertical integration	Ongoing

In the United Kingdom and Ireland, issues regarding terminal competition had been seriously considered, and were brought into discussions several times. In a decision document issued by the Department for Transport (2009), the UK government proposed that for airports with substantial market power, the regulatory framework should not preclude the possibility of separating the operation and development of terminals. Whilst the proposal was advocated by airlines such as British Airways, it was opposed mainly by airports for reasons such as difficulties in coordination and lack of evidence on inter-terminal competition. Finally, the government simply reiterated that the new regulatory regime should not prohibit the development and operation of competing terminals. There was no further progress as it was not convinced that the risks and shortcomings would outweigh the potential benefits, such as reducing regulatory costs and improving the passenger experience. In Ireland, the introduction of terminal competition at Dublin Airport has been put on the agenda previously. Strong conflicts of interest among stakeholders and ministerial turnover eventually led to the shelving of the plan, although the expert panel "was favourably [sic] disposed to the idea of an independent terminal on operational and technical feasibility grounds" (Irish Department of Transport, 2003; Reynolds-Feighan, 2010). To summarize, no consensus has been reached so far, since no stakeholder can give opinions persuasive enough to convince their opponents. The door is not completely closed, though, as the Department for Transport still insists that "…the new regulatory framework will not preclude the development of inter-terminal competition…" even after the unbundling of airports operator BAA (Department for Transport, p.69, 2013).

2.3 Relevant studies regarding terminal competition

Few studies examine intra-airport terminal competition. McLay and Reynolds-Feighan (2006) elaborate on the incentives, processes, and potential implications of terminal competition, taking the Irish case as an example. Dublin Airport, the gateway of Ireland, wields significant market power due to its indispensability and independent catchment area. The entry of a new competitor seems unrealistic because potential developers of new airports would face substantial regulatory obstacles. Regulatory efforts to restrain the incumbent monopolist resulted in strong protest; thus, the introduction of terminal competition was proposed as an alternative. The authors raise several issues that need further consideration in terms of terminal competition. They suggest that the net welfare effect of introducing terminal competition will depend upon the aggregate of individual effects on each type of efficiency. They also note that airport service as a whole is a bundle of terminal service and airfield service, and attention should be paid to this characteristic when deciding on a business model. Finally, they touch upon the investment implications of terminal competition. However, they do not further analyze the impacts of various business models on competing terminals to see whether they can work to improve social welfare; they only suggest that "it may be unreasonable to expect competition between airport terminals to deliver unambiguous welfare improvements if it is not accompanied by changes to the structure of the incumbents business" (p. 199). In a subsequent study, Reynolds-Feighan (2010) reviews the development of terminal competition in Dublin Airport, which went nowhere. Although he concludes that the Irish case is now added to the shortlist of examples cited by monopoly airport operators claiming that terminal competition is unworkable, the key questions of whether competing terminals can really restrict the abuse of market power of airports and improve social welfare remain unclear.

Issues regarding competition among rival facilities are widely investigated due to their significance in transportation studies (i.e., De Borger and Van Dender, 2006; Basso and Zhang, 2007; Barbot, 2009; Zhang et al., 2010; Saeed and Larsen, 2010; Matsumura and Matsushima, 2012; D'Alfonso and Nastasi, 2012; Benoot et al., 2013; Xiao et al., 2013; Teraji and Morimoto, 2014; Noruzoliaee et al., 2015). We categorize these studies into three general types. The first type investigates the impact of duopolistic competition between rival facilities. The competition is purely "substitutive" and the downstream market is assumed to be under perfect competition, but there are multiple decisions to make, so the impact is not self-evident. For example, De Borger and Van Dender (2006) study the duopolistic interaction between congestible facilities that supply perfect substitutes and make sequential decisions on capacities and prices, and compare the results to monopoly and first-best outcomes. They find that the service level provided under a monopoly is the same as that in the social optimum while surpassing that provided under a duopoly. Other similar studies include Noruzoliaee et al. (2015), which considers competitive airports with different objectives, and Randrianarisoa and Zhang (2019), which considers competing ports under uncertainty. The second type of study relaxes the perfect competition assumption of the first type by modelling downstream market, while the upstream market is still oligopoly of substitute goods. For example, Basso and Zhang (2007) extends De Borger and Van Dender (2006) by further considering the vertical structure of the market and suggest that the conclusion of De Borger and Van Dender (2006) will hold only if the downstream market is perfectly competitive. Benoot et al. (2013) extends Basso and Zhang (2007) by specifically characterizing intercontinental airport regulators. Barbot (2009) analyses the incentives for vertical collusion between one airport and one airline that compete with another airport and another airline and finds that the incentives exist when airports and airlines have different market sizes. Zhang et al. (2010) study the effect of the duopolistic competition of airports on their revenue sharing with airlines and finds that competition results in a higher degree of vertical cooperation between an airport and its home carriers and improves social welfare. Other similar studies include D'Alfonso and Nastasi (2012), which extends Barbot (2009) by involving other types of vertical agreement besides vertical collusion, and Saraswati and Hanaoka (2014), which extends Zhang et al. (2010) by considering a network with hub and spokes. The third type considers competing facilities with complementarity. For example, Wan et al. (2016) investigate the strategic investment decisions of local governments on regional landside accessibility in the context of seaport competition where complementarity exists between the inland and port regions, and discusses the conditions under which the social-optimal grand coalition can be achieved; However, the decision makers regarding the investment in accessibility are all social-surplus maximizer, which is different from our problem. Teraji and Morimoto (2014) address the question of how airport competition affects the carriers' network choice where complementarity originates from connecting routes.

In summary, we can find that, (a), in many studies, facilities that compete with each others are pure substitutes and downstream carriers do not have market power (first type); (b), some studies model vertical structure and the complementarity between upstream and downstream can be strengthened through considering vertical arrangement, while the upstream market is still an oligopoly of pure substitute goods (second type); (c), in studies where complementarity and substitute coexist in upstream markets, downstream markets are not (or are only roughly) modeled (third type). To answer the question of our study, A model that involves the coexistence of complementarity and substitutes in upstream markets and a relatively comprehensive modeling of downstream markets is needed. We can hardly refer to the conclusion of previous studies directly. For instance, despite the similarity to terminal competition, airport competition is basically between substitute goods. Passengers only need to choose one airport among the competitors and buy the airline service therein. However, the service at an airport consists of the service at terminals and the service at airfield facilities. One can choose a terminal service (equivalently an airline service thereof) if multiple terminals exist, while the purchase of the single (bundle of) airfield service is compulsory, regardless of the terminal choice. This feature makes the intra-airport competition different from that between airports and therefore a new model is necessary.

2.4 Capacity shortage at airports

The air transport market has seen unprecedented demand growth in recent years. The International Air Transport Association suggests that air passenger numbers could double to 8 billion per year in 2039. By region, Asia Pacific is predicted to see the strongest annual growth rate of 5%, while the lowest number is 2.2% for North America and Europe.

Although COVID-19 is having a profound impact on near-term demand, strong recovery can be expected in the next few years.

It is questionable whether the existing capacity and the capacity planned to be increased can meet the rapid growth of air traffic. In Europe, although a 16% increase in airport capacity has been planned (As of 2018), it is reckoned not adequate to meet the demand. In the optimistic scenario, it is estimated that 360 million passengers, that is, 16% of the demand, will not be accommodated in 2040, given that no additional expansion plan will be carried out. Even in a fairly conservative estimation, the capacity gap in 2040 will reach to 8%. In the optimistic scenario, almost all countries in Europe will more or less encounter capacity deficiency. Even in the conservative scenario, countries such as Turkey and Britain are unlikely to be free of capacity concerns. The capacity gap, as a result, might cause the total delay to increase from 12.3 minutes to 20.1 minutes on average, per flight. There were 6 airports at a level of congestion that 80% or more of the capacity are occupied for at least 6 consecutive hours in 2016, while such congested, 'Heathrow-like' airports will reach a number of 16 by 2040 in the conservative scenario, or even 28 in the optimistic scenario (Eurocontrol, 2018).

Gelhausen et al. (2019) adopt the Capacity Utilization Index (CUI), namely the ratio of the average hour traffic volume to the 5% peak hour traffic volume, to calculate the capacity utilization at airports worldwide. As per their yardstick that airports with CUI values higher than 0.65 are those suffering significant congestion problem[2], significantly congested airports already cover about 35% of the total global flights. Furthermore, their global analysis shows that 35 airports are more or less constrained in terms of capacity in 2016. These "constrained" airports are the primary airports of the global network; they handled a traffic volume of 13.3 million aircraft movements, corresponding to a share of nearly 19% of the global traffic in 2016. Finally, they estimate that there will be a substantial shortage of capacity in 2040, with almost 256 million passengers cannot be served due to capacity constraints. The problem might be especially severe in Asia, with Delhi Indira Gandhi, Mumbai Chhatrapati Shivaji and Jakarta Soekarno-Hatta ranked as the top three constrained airports, due to the strong growth in demand.

[2] If the corresponding 5% peak hour volumes reach the near-capacity values.

Consequently, as Alexandre de Juniac, Director General and CEO of IATA said in 2018, “we are in a capacity crisis. And we don't see the required airport infrastructure investment to solve it”[3]. There are indeed various ways to mitigate the capacity crisis, such as the development of a more efficient air traffic control system, or the adoption of a more reasonable slot allocation. However, capacity expansion proves to be the most direct and effective countermeasure from a long-term perspective. It can be a construction of a new runway, a new terminal, or even a new airport. As per Gelhausen et al. (2019), the number of runways at airports of the global network has increased by 7.9% from 2008 to 2016. In Asia, the increasing rate is outstandingly high reaching 23.1%. More capacity expansion projects has been planned and will be started henceforward. Table 2.2 lists some representative examples across the globe.

Table 2.2 Examples of investments in capacity expansion at airports

Airport	**Country**	**Major infrastructures**	**Expected to be completed in**
Cape Town	South Africa	Runway	2023
Chongqing	China	Runway & terminal	2024
Hong Kong	China	Runway	2024
Melbourne	Australia	Runway	2025
Denver	U.S.	Terminal	2025
Narita	Japan	Runway	2029
Vienna	Austria	Runway	?
Hanoi	Vietnam	Runway & terminal	?

2.5 Studies on airport capacity expansion

In general, quantitative studies on airport capacity construction/expansion can be categorized into two major types. One major type of studies aims to develop new methodologies for the decision-makings on the capacity expansion. Equivalently, they try to devise new decision-making techniques. For instance, Smit (2003) developed a

[3] https://www.france24.com/en/20180604-global-airport-capacity-crisis-amid-passenger-boom-iata

discrete-time binomial analysis under a combined real option and game theory framework, of which the modularity enables the consideration of many strategic features. Jorge and de Rus (2004) developed a cost–benefit analysis approach which does not entail much data and time for the investment in airport infrastructure. Their emphasis is placed in the consistency across projects in deciding whether a given project is a good or bad investment, rather than on the accuracy of project return estimates. Sun and Schonfeld (2015) proposed an "Out-Approximation" method which can enhance the efficiency of the optimization for the airport capacity expansion model.

Another major type focuses on the effects of various factors on the decision-makings regarding the capacity expansion using existing methods, to which most studies belong. We can further subdivide this major type into two types: the orthodox approach and the real option approach, based on if the opportunity cost, or the option is taken into account.

<u>The orthodox approach</u>: Studies belonging to this type generally ignore the optimal timing of the expansion. Instead, they mainly focus on the optimal volume of the capacity. Zhang and Zhang (2011) investigated the effects of the airport's objective and the form of regulation on the capacity investment decisions. They found that profit-maximizing airports and regulated social surplus-maximizing airports tend to over-invest in aeronautical capacity. One limitation of their study is that they did not consider the case that the airport has a mixed objective, neither pure profit nor pure social surplus. Xiao et al. (2012) considered the mixed objective in token of the public-private ownership. Although the subject is seaport, their model can also be compatible with airports thanks to the similarity between them. This kind of single-airport investment problem has been extended in various directions: Zhang and Zhang (2006) examined how can airlines' behavior of self-internalization affect the investment decision; Lin and Zhang (2017) considered a hub-spoke network and the scheduling of airlines to investigate the effect of different charging form on the capacity expansion decision; Kidokoro et al. (2016) included the investment in non-aeronautical infrastructure. However, these above-mentioned studies did not address the demand uncertainty which can be non-negligible in many cases in the air transport industry. Xiao et al. (2013) studied on the airport's capacity choice addressing the demand uncertainty by a uniform distribution. Xiao et al. (2016) further enlarged their previous scope by investigating the effect of airport-airline

vertical structure on the capacity choice. Several studies also investigated the capacity expansion problem of two competing airports. For instance, Basso (2008) examined the effect of airport deregulation on the capacity investment of two congestible airports; Noruzoliaee et al. (2015) studied the capacity and pricing choice of two congestible airports in a multi-airport metropolitan region, under transition from a pure public, centralized airport system to partial or full privatization. However, most of these studies did not address the demand uncertainty as well.

The real option approach: Studies belonging to this type always explicitly address the issue of timing, continuously or discretely. For example, Xiao et al. (2017) modelled the real option by supposing that the airport has another opportunity to expand its capacity at some time in the future, on the reserved land purchased before. Balliauw and Onghena (2020) investigated the effect of various factors on the optimal timing and volume of capacity expansion at a profit-oriented airport. Balliauw et al. (2019) can be regarded as an enhanced version of the former, with facility rivalry addressed through a game theory modelling, although the subject was seaport. Zheng et al. (2020) studied the timing decision of airlines' investments in exclusive airport facilities in the presence of demand ambiguity and competition.

However, despite the great number of the relevant literatures, there still lacks studies that focus on the relationship between privatization and investment considering timing by a real option approach. Real option approach greatly underlines the opportunity cost of investment, which is not addressed by the traditional cost-benefit analysis. If an irreversible investment is carried out, the cost incurred can hardly be redeemed. When the uncertainty of the market is high, its natural that the investor tends to wait more to see how will the price or the demand changes, in order to avoid the loss caused by a potential negative shock. Therefore, it is more reasonable for the investor to invest only when the NPV exceeds the cost by some degree, as suggested by the real option approach. The project at an airport, such as capacity expansion, is always costly and lumpy, and the air travel demand can be very vulnerable to catastrophes, making the opportunity cost non-negligible. Thus, adopting real option approach to model the decision-making regarding the investment in airport projects can be more reasonable. In Chapter 4 and Chapter 5, we investigate the investment behavior of private airport employing real option approach.

Chapter 3 Effects of airport terminal competition: A vertical structure approach

3.1 Introduction

As mentioned in Section 2.1, the introduction of intra-airport terminal competition is conceived as a potential alternative to the regular countermeasures, such as regulation and the introduction of airport competition, against the abuse of market power by monopolist airport. In the United Kingdom and Ireland, regarding issues had been intensively discussed for several times, yet no consensus has been reached mainly due to conflict of interest and other political factors. Nevertheless, the belief that terminal competition can work to restrain the abuse of market power was seldom doubted; the British document highlights that the target airports for the introduction of terminal competition are those with such power.

However, it is far from certain that an airport with competing terminals will levy lower charges. Since the services of different terminals are substitutes, whereas terminal services and runway services are complementary, splitting the operation of an airport by introducing terminal competition will not only create a substitutive duopoly between terminals but also create at least one complementary duopoly between terminal and airfield facilities. Economic theory suggests that compared to monopoly, a substitutive duopoly can reduce prices, while a complementary duopoly will raise prices, giving rise to an interesting question as to which effect will dominate the other when they coexist. This is one of the most crucial issues with respect to terminal competition, and no academic study has hitherto investigated it.

Thus, to bridge this research gap, this study aims to investigate the impact of terminal competition on pricing and social surplus under different business models. We adopt an analytical model with a vertical structure and three market participants including an airfield and two terminals in the oligopolistic upstream market. Competition among airlines, interactions between downstream and upstream markets, and competition between terminals are formulated, and the airport’s equilibrium prices are solved. We compare and analyze the results of six different business models in two cases differing in airlines' freedom to change terminals. We further investigate four extended cases addressing terminals with different allocative efficiency level, airlines' participation in the upstream market, multi-dimensional competition, and regulated terminals.

Contrary to the common belief, we find that the introduction of terminal competition cannot restrict the abuse of market power by a profit-oriented airport. In other words, the price of the service provided by the airport with competing terminals can be higher, causing a loss in the social surplus. This is because the existence of the airfield facilities, which is complementary to the terminals. If we introduce terminal competition, not only the substitutive duopoly, but also at least one complementary duopoly will be created. When these two types of duopoly coexist, the price reducing effect of the former will be dominated by the price increasing effect of the latter, resulting in the negative outcomes.

The contribution of the present paper is twofold. From the perspective of modelling, we study a differentiated Bertrand model of substitute and complementary goods with a vertical structure. We investigate the effect of firm number and the product combination of each firm on prices and social surplus. This issue is seldom addressed in previous studies. Practically, this study sheds light on the important yet unanswered question of whether the introduction of terminal competition can restrain the abuse of market power by a monopoly airport, or is it better to privatize an airport's facilities separately compared with the all-in-one privatization. This study can also help support relevant decision-making, as current empirical evidence is insufficient, and related discussions are always mixed with political issues and conflicts of interest.

3.2 The basic model

3.2.1 Description of the problem

<u>Stakeholders</u>: We focus on one section of the entire supply chain of the air transport industry. In the upstream, we focus on one single airport. Inside the airport, there are three "facility group" denoted as *airfield, terminal A,* and *terminal B.* Airfield refers to the facilities which are prepared for the movement of aircrafts (e.g., runway, taxiway). Terminal A or B does not necessarily refer to one terminal; instead, it can be a group of several terminals. We assume that each "facility group" cannot be divided and operated

by multiple operators. In the downstream, there are $N = n_A + n_B$ airlines, with n_A at terminal A, and n_B at terminal B. We ignore the entry and exit of airlines.

<u>Decision-making process</u>: In the upstream, each "facility group" has an action which is the price to levy. For airfield, the action is *landing charge* T per flight*;* for terminal, the action is *terminal fee* w per passenger. The three actions (prices) are determined in a Bertrand fashion[4]. Landing charge is levied to all airlines, while terminal fee is levied to the passengers of the corresponding terminal. In the downstream, N airlines choose their quantities (passenger) in a Cournot fashion to maximize their respective profits respectively, given the decisions of the upstream[5]. The relation between the upstream and downstream will be modelled as a Stackelberg game, where the upstream acts at first (stage I), and then the downstream follows (stage II) (Fig 3.1).

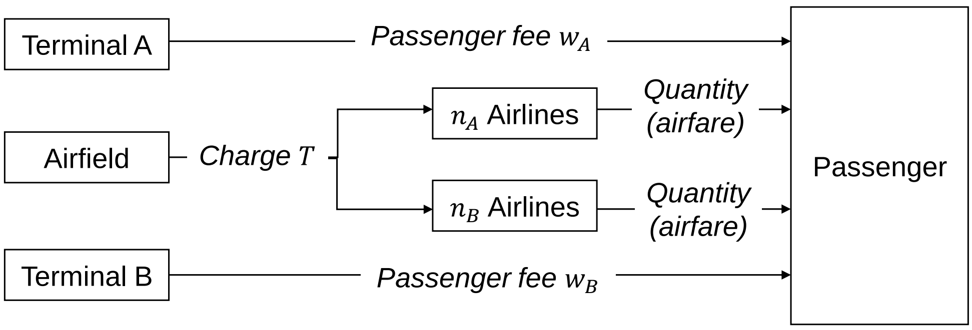


Fig 3.1 Decision making process

<u>Cases</u>: In the basic analysis, we consider two cases. In case 1, we assume that the allocation of airlines at the terminals is fixed. In case 2, we assume that the allocation of airlines can be influenced by the price. Airlines have the freedom to choose their base terminals according to the terminal fee. In each case, we consider six *Business Models* to reflect various situations before and after the introduction of terminal competition (Fig

[4] If we assume a Cournot model in the upstream market, (i.e., terminals compete on outputs [quantities of passengers]), one terminal will be driven out of market in some cases (i.e., Model II introduced in following part). Thus, to ensure that all Models investigated are at least feasible, we adopt a Bertrand model in upstream market. In fact, there are hardly any study regarding airport competition assuming a Cournot model to the best of our knowledge.

[5] Brander and Zhang (1990) and Oum et al. (1993) find that Cournot model seems much more consistent with the empirical data of U.S. airline market. Many recent studies also assume Cournot behaviour among airlines under imperfect competition (e.g., Czerny and Zhang, 2011; Gillen and Mantin, 2014; Xiao et al., 2017; Zheng et al., 2020).

3.2). The description of each Model is as follows:

Business Model I (Centralized operation): A single profit-maximizing operator operates all facilities including the airfield and both Terminals A and B in the airport. It may correspond to an airport which is privatized in an all-in-one approach. Such privatization can have various motivations, such as enhancing efficiency, or simply producing financial gain (Graham, 2011). This Model serves as a yardstick which enables us to investigate whether a "separate privatization" has the function of a regulation, leading to a better outcome.

Business Model II (One independent terminal): Operator 1 operates the airfield and one terminal (e.g., Terminal A) while the remaining terminal (e.g., Terminal B) is operated by operator 2. All operators aim to maximize profit[6]. Historically, the cases of Toronto airport and Manila airport might be similar to Model II, while none of them lasted long. Currently, there are no such evidence, to the best of our knowledge (Graham, 2018). Nevertheless, this Model represents a highly likely form of terminal competition and it addresses the issue of runway service allocation where the incumbent who operates one terminal and airfield facilities jointly can "bully" the independent terminal operator by over-biding runway access.

Business Model III (All independent): There are three operators. Each operates one facility independently. All operators aim to maximize profit. We investigate this Model to see whether it can serve as a possible method to tackle the runway service allocation problem as the integrated terminal-airfield operation of the incumbent is partitioned as well.

Business Model IV (Independent airfield): Operator 1 operates two terminals while operator 2 operates the airfield. All operators aim to maximize profit. This Model can show the effect of a pure complementary duopoly.

Business Model V (Regulated airfield): Operator 1 operates two terminals, while operator 2 operates the airfield. Operator 2 follows the Ramsey pricing, which maximizes social surplus subject to a non-negative profit constraint, while operator 1 aims to

[6] The question whether Terminal B will be driven out of the market in this Business Model is discussed in Appendix A.

maximize profit. This Model is a variant of Model IV with complementarity neutralized.

Business Model VI (Regulated airfield, competing terminals): Operators 1 and 2 operate Terminals A and B, respectively, while operator 3 operates the airfield. Operator 3 follows the Ramsey pricing, which maximizes social surplus subject to a non-negative profit constraint, whereas operators 1 and 2 aim to maximize profit. This Model can be regarded as another method to resolve the runway access allocation problem by imposing a price-cap on the price of runway access.

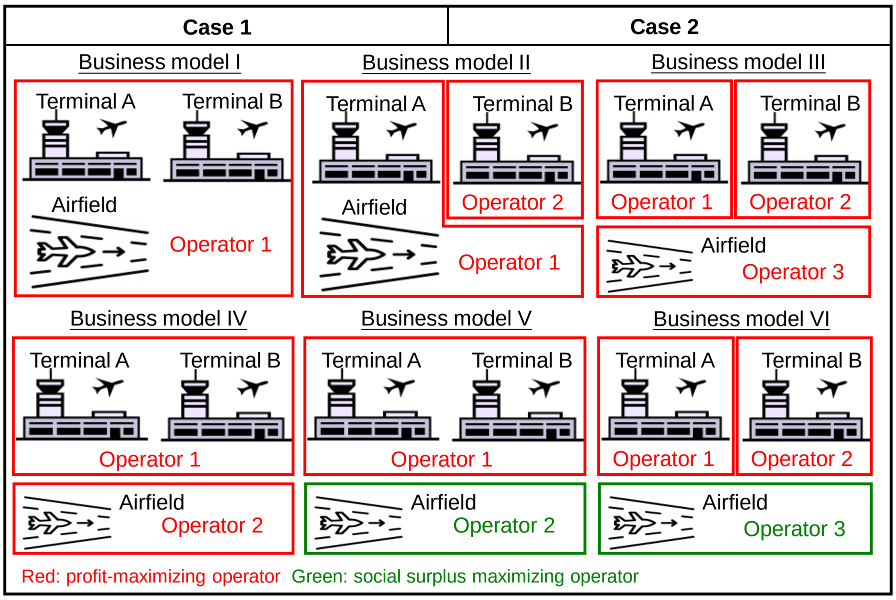


Fig 3.2 Illustration of business models

The action set of each player (operator) in each Model depends on the facility groups it operates. Fig 3.3 shows a more concrete demonstration of the decision-making process taking Business Model II as an example. The effect of terminal competition thus can be figured out by comparing the equilibrium outcome of each Business Model[7].

[7] We only focus the payoff, profit or social surplus, in one period, not in a dynamic approach. We can see that some of the ranking of price and social surplus in each Business Model will not change, given any parameters including that reflects the demand dynamics, so the ranking of one-period social surplus and the ranking of aggregated net social surplus will be same. Therefore, a one-period consideration might not be implausible.

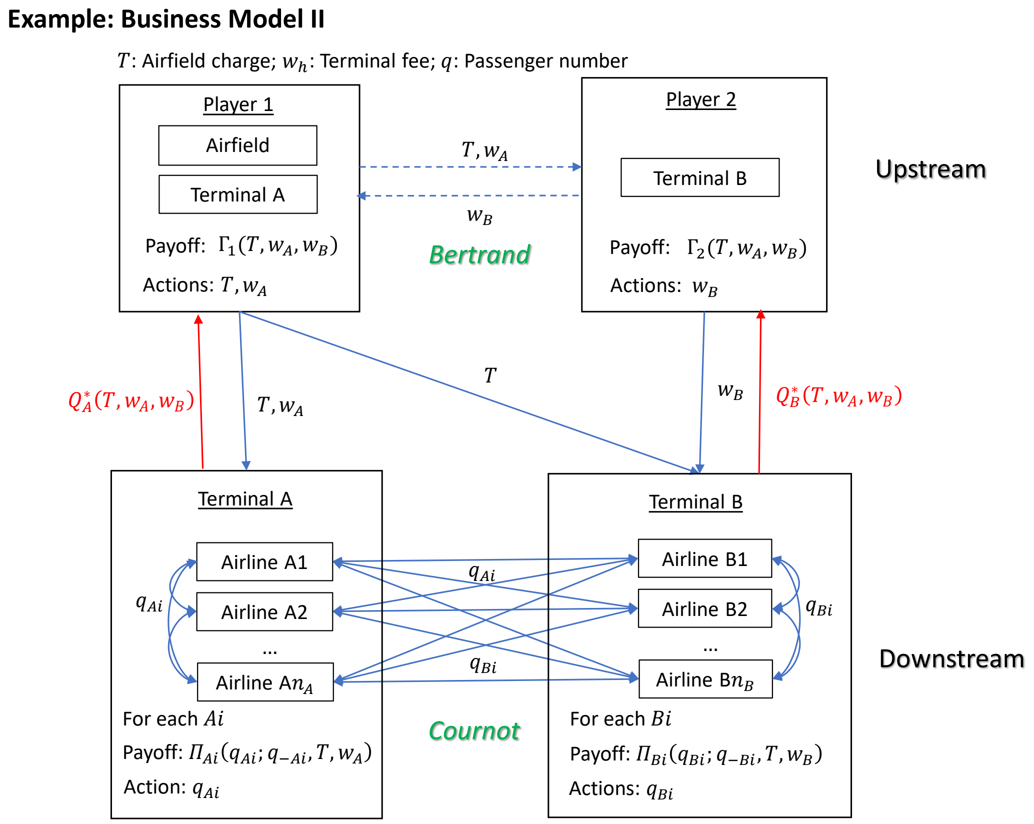


Fig 3.3 A detailed illustration of the model's framework

We also consider some special cases. They are either uncommon in the real world, or difficult to be investigated for all six business models in the basic analysis section. Therefore, studies on them are relegated to the extension section. Extension 1 considers a case that the unit cost or unit non-aeronautical profit of each terminal is different. Although such case might well exist in the reality, it is difficult to deal with all six Models here, so we only investigate Model I and II in this section. Extension 2 considers a case that airline(s) participate in the upstream by operating or holding share of the terminal(s). Although such situation can be observed in some countries such as U.S. and Australia, as a practice it is far from common. Extension 3 considers a case that the terminals can compete not only on price, but also on service level. As is with the case of Extension 1, it is difficult to treat all six Models, so we only compare Model I, II and III. Extension 4 focus on a case that the airfield is public, while the terminals are not purely social surplus oriented, which corresponds to the potential situation that terminals are to some degree allowed to pursue profit, in terms of a public airport.

The notations of the variables and parameters are shown in Table 3.1

Table 3.1 Notations for Chapter 3

Decision variables	
q_{hi}	Number of passengers of airline i at terminal h
T	Landing charge
w_h	Usage fee of terminal h
v_h (extension 3)	Service level of terminal h
Parameters	
a	Own-price effect
l $(0 \leq l \leq 1)$	Cross-price effect coefficient
s	Aircraft capacity * load factor
c	Unit cost per flight for airline
γ	Unit cost per flight for airfield facility
n_h	Number of airlines at terminal h
r_h	Difference between unit non-aeronautical profit and unit cost per passenger at terminal h
α	Delay cost for passenger
β	Delay cost for airline
k	Airport capacity
σ (extension 3)	Unit cost of service provision per passenger
η (extension 3)	Own-price effect in terms of service level
m $(0 \leq m \leq 1)$ (extension 3)	Cross-price effect coefficient in terms of service level

3.2.2 Objective functions

We use a quadratic utility function to represent consumer's utility with differentiated goods as (e.g., Vives, 1999)[8]:

[8] All "utility" presented in this thesis refers to the cardinal utility.

$$U = Q_A + Q_B - \frac{1}{2}(aQ_A^2 + 2alQ_AQ_B + aQ_B^2) \quad (3.1)$$

where $Q_h = \sum_{i=1}^{n_h} q_{hi}$, $h \in \{A, B\}$. q_{hi} denotes the number of passengers of airline i at Terminal h. a denotes own price effect, and l denotes cross-price effect or degree of substitution between airlines at different terminals and the product differentiation of terminal services. $a > 0$, and l can be any value within the interval $[0,1]$. $l = 1$ means that the two terminals and their airlines are perfect substitutes, while $l = 0$ indicates that services provided by airlines at different terminals are independent (e.g., a domestic terminal and an international terminal). If $0 < l < 1$, airlines and services at different terminals are somewhat substitutable. We assume that airlines in the same terminal are perfect substitutes. Thus, the cross-price effect among them is also denoted by a in the basic cases. Maximizing utility, we have the following demand function:

$$\rho_h = p_h + w_h + \alpha\delta = \frac{\partial U}{\partial q_{hi}} = 1 - a(Q_h + lQ_{-h}) \quad (3.2)$$

where δ=F/k, $F = F_A + F_B$, $F_h = \sum_{i=1}^{n_h} f_{hi}$, f=q/s, $h = A, B$, and $-h$ labels the terminal besides h. ρ denotes the total cost that a passenger faces including airfare p from the airline, passenger fee w from the terminal, and time cost $\alpha\delta$, where α is the time-value parameter, and δ denotes the congestion delay at the runway. k denotes the capacity of airfield facilities. f_{hi} denotes the number of flights of airline i at Terminal h. s denotes the product of average aircraft capacity and load factor. For simplicity, we assume that the s is identical for all airlines[9]. Besides, we do not consider the congestion cost at the terminals

Some may argue that it is unnecessary to include the congestion cost in the demand function, since the passengers have to use the airport in many cases; they have no other choices even if the congestion therein is very severe. This setting can be justified as follows. Due to the report of IATA, the air travel demand elasticity is estimated to be -0.6 at supra-national level in 2007[10]. Although the value implies that the air travel demand is relatively inelastic, we cannot assert that the price has no effect on the decision-makings

[9] For airlines with similar business model, this assumption is not far away from some real cases. For example, the s values of U.S.'s legacy airlines in 2019 is 160 for American, 165 for Delta, and 167 for United (Source: http://web.mit.edu/airlinedata/www/default.html).

[10] https://www.travelready.org/PDF%20Files/Travel%20-%20IATA%20-%20Air%20Travel%20Demand.pdf

of the passengers. As an economic man, which is implicitly assumed in the modelling, the passenger will consider the total price of the travel including the monetary cost and time cost, so the congestion delay cost can have an effect on her decision-making whatever the extent is. If the effect is weak, we can express it by a small time value parameter α, and doing so would not affect our analytical results, but it might not be appropriate to completely exclude it.

The profits of airlines in each terminal are formulated as:

$$\Pi_{hi} = p_h q_{hi} - f_{hi}(c + T + \beta\delta) \qquad \forall\, h, i \tag{3.3}$$

where c denotes the unit cost per flight for the airline, T denotes the charge for runway service from the airfield facilities, and β denotes the time cost of the congestion delay for airlines[11].

The profit functions of airfield and terminal operators are:

$$\Gamma_R = F(T - \gamma) \tag{3.4}$$

$$\Gamma_h = Q_h(w_h + r_h) \qquad \forall\, h \tag{3.5}$$

Where R labels airfield, γ denotes the marginal cost per flight for the airfield facilities, r_h denotes the difference between unit commercial profit and marginal cost per passenger for Terminal h. For simplicity, we assume $r_A = r_B = r$ in the basic case and leave the analysis for asymmetric r_h to Section 4.1. The objective functions of operators are formulated as:

$$\Gamma_j = x\Gamma_R + y\Gamma_A + z\Gamma_B \tag{3.6}$$

$\{x, y, z\}$ have different values depending on the Business Model and operator j. For example, in Model II, $\{x, y, z\} = \{1,1,0\}$ when $j = 1$, and $\{x, y, z\} = \{0,0,1\}$ when $j = 2$. Readers can learn the values of $\{x, y, z\}$ in different cases from Fig. 2. Social surplus is

[11] If we ignore the complicated problem of fleet rotation and allocation in the whole network of an airline, and assume each route to be independent, then the maximization of the airline's gross profit is equivalent to the profit maximization for each route. In this case, our setting can be partially justified by assuming the charge of airport in the other end of each route is exogenous and fixed (e.g., cost-covering charge). Under such assumption, the charge in other airports can be regarded just as a part of the airline's cost which will not change as the airline's decision changes.

defined as the difference between utility and total cost:

$$S = (s - \alpha\delta s - c - \beta\delta - \gamma)F - \frac{1}{2}as^2\big((F_A)^2 + (F_B)^2\big) - als^2F_AF_B + \sum_{h=A,B} r_h sF_h \qquad (3.7)$$

Note that in Model V and VI, $\Gamma_R = S$ in Eqn. (3.6) with non-negative profit constraint. Moreover, to simplify the following analysis, we assume that $s > \max\{\frac{c+\gamma}{1+r}, \frac{c-\gamma}{1-r}\}$ and $(\alpha s + \beta) < aks^2$. Backward induction is employed to solve the problem, and details are shown in Appendix B1.

Flight of airline i at terminal h and total output under subgame perfect equilibrium can be then derived as:

$$f_{hi}^*(T_h, T_{-h}) = \frac{k^2\big(C_1(n_{-h}+1)(T_h + c - s) - C_2 n_{-h}(T_{-h} + c - s)\big)}{C_2^2 n_h n_{-h} - C_1^2(n_h+1)(n_{-h}+1)} \qquad (3.8)$$

$$Q^*(T_A, T_B) = \frac{(C_1 - C_2)k^2 s n_A n_B\big(T_A + T_B + 2(c-s)\big) + C_1 k^2\, s\big(n_A(T_A + c - s) + n_B(T_B + c - s)\big)}{C_2^2 n_A n_B - C_1^2(n_A+1)(n_B+1)} \qquad (3.9)$$

Where $T_h = T + sw_h$ denotes the *total price* that a flight of airline at terminal h bears. This integrated variable will be frequently used in the subsequent analysis for convenience. $C_1 = k(s(aks + \alpha) + \beta)$ and $C_2 = k(s(alks + \alpha) + \beta)$; thus $C_1 \geq C_2$. The effects of prices on outputs can be summarized as follows:

Lemma 3.1 If airlines cannot change the base terminal, and the number of airlines in each terminal is fixed, then

$$\frac{\partial f_{hi}^*}{\partial T_h} < 0, \frac{\partial f_{hi}^*}{\partial T_{-h}} > 0;\ \ \frac{\partial Q^*}{\partial T_A} < 0, \frac{\partial Q^*}{\partial T_B} < 0$$

The proof is presented in Appendix B2. The effects are quite intuitive in that the output (the number of flights) decreases as the price of the airline's own terminal increases, while the output increases with the price of the rival terminal due to the relation of substitutes, and the total output always decreases as the prices increase.

3.2.3 Case 1: airlines cannot change terminal

FOCs of the airfield and facilities in each business model are shown in Appendix B1. By solving these FOCs, we have the equilibrium airfield charge and terminal fees in each

Business Model, as shown in Appendix C1. Combining them by $T_h = T + sw_h$, we derive the equilibrium total prices in each Business Model as summarized in Table 3.2.

Comparing total prices in each business model and denoting the equilibrium value in each Business Model by a superscript of its label (i.e., T_A^I denotes equilibrium total price of Terminal A in Model I), we have:

Table 3.2 Equilibrium total prices of each business model in Case 1

Business Model	T_A	T_B
First-best	$[n_A(2k(s-c)(\beta+\alpha s)-(C_1+C_2)(rs-\gamma))-C_1((r+1)s-c-\gamma)]/n_A(C_1+C_2+2k(\beta+\alpha s))$	$[n_B(2k(s-c)(\beta+\alpha s)-(C_1+C_2)(rs-\gamma))-C_1((r+1)s-c-\gamma)]/n_B(C_1+C_2+2k(\beta+\alpha s))$
I	$\frac{1}{2}((1-r)s-c+\gamma)$	$\frac{1}{2}((1-r)s-c+\gamma)$
II	$\frac{1}{2}((1-r)s-c+\gamma)$	$[c(C_2n_A-4C_1(n_A+1))+C_2n_A(-(-\gamma+rs+s))-2C_1(n_A+1)((r-2)s-\gamma)]/6C_1(n_A+1)$
III	$[-2C_1^3(n_A+1)(n_B+1)(n_A(2n_B+1)+n_B)(2c-\gamma+(r-2)s)+C_2C_1^2(n_A+1)n_B(n_A(2n_B(4c-\gamma+(r-4)s)+7c-3\gamma+3rs-7s)+n_B(c+\gamma-(r+1)s))+2C_2^2C_1n_An_B(n_A(n_B(c-\gamma+(r-1)s)+c-s)+n_B(rs-\gamma))+2C_2^3n_A^2n_B^2(s-c)]/[2(3C_1^3(n_A+1)(n_B+1)(n_A(2n_B+1)+n_B)-5C_2C_1^2n_A(n_A+1)n_B(n_B+1)-C_2^2C_1n_An_B(n_A(2n_B+1)+n_B)+C_2^3n_A^2n_B^2)]$	$[-2C_1^3(n_A+1)(n_B+1)(n_A(2n_B+1)+n_B)(2c-\gamma+(r-2)s)+C_2C_1^2n_A(n_B+1)(n_A(2n_B(4c-\gamma+(r-4)s)+c+\gamma-(r+1)s)+n_B(7c-3\gamma+3rs-7s))+2C_2^2C_1n_An_B(n_A(n_B(c-\gamma+(r-1)s)-\gamma+rs)+n_B(c-s))+2C_2^3n_A^2n_B^2(s-c)]/[2(3C_1^3(n_A+1)(n_B+1)(n_A(2n_B+1)+n_B)-5C_2C_1^2n_A(n_A+1)n_B(n_B+1)-C_2^2C_1n_An_B(n_A(2n_B+1)+n_B)+C_2^3n_A^2n_B^2)]$
IV	$\frac{1}{3}((2-r)s-2c+\gamma)$	$\frac{1}{3}((2-r)s-2c+\gamma)$
V	$\frac{1}{2}((1-r)s-c+\gamma)$	$\frac{1}{2}((1-r)s-c+\gamma)$
VI	$[2C_1^2(n_A+1)(n_B+1)((r-1)s-c-\gamma)+C_2C_1(n_A+1)n_B(c+\gamma-(r+1)s)+C_2^2n_An_B(c+\gamma-s)]/[4C_1^2(n_A+1)(n_B+1)-C_2^2n_An_B]+\gamma$	$[2C_1^2(n_A+1)(n_B+1)((1-r)s-c-\gamma)+C_2C_1n_A(n_B+1)(c+\gamma-(r+1)s)+C_2^2n_An_B(c+\gamma-s)]/[4C_1^2(n_A+1)(n_B+1)-C_2^2n_An_B]+\gamma$

Proposition 3.1 If airlines cannot change the base terminal, and the number of airlines in each terminal is fixed, then

(i) $T_A^{IV} > T_A^{III} > T_A^{II} = T_A^{I} = T_A^{V} > T_A^{VI}$; $T_B^{IV} > T_B^{III} > T_B^{II} > T_B^{I} = T_B^{V} > T_B^{VI}$

(ii) $\frac{\partial w_A^{II}}{\partial n_A} < 0$, $\frac{\partial w_B^{II}}{\partial n_A} < 0$, $\frac{\partial T^{II}}{\partial n_A} > 0$; $\frac{\partial T_B^{II}}{\partial n_A} < 0$, $\frac{\partial T_B^{II}}{\partial n_B} = \frac{\partial T_A^{II}}{\partial n_B} = \frac{\partial T_A^{II}}{\partial n_A} = 0$;

(iii) $\frac{\partial T_A^{II}}{\partial l} = 0$; $\frac{\partial T_B^{II}}{\partial l} < 0$; $\frac{\partial T_A^{III}}{\partial l} < 0$; $\frac{\partial T_B^{III}}{\partial l} < 0$

(iv) $Q^{VI} > Q^{I} = Q^{V} > Q^{II} > Q^{III} > Q^{IV}$

Proof: See Appendix C2.

From Proposition 3.1, we find that inducing inter-terminal competition or splitting terminals from the centralized operation leads to higher prices. When one of the two terminals is operated independently (Business Model II), the integrated operator, which operates one terminal and the airfield facilities, can intentionally set a fairly high charge T^{II} for runway service, making the reaction functions of both operators move inward toward the origin. Due to the effect of uninternalized complementarity with airfield, the independent operator (Terminal B) cannot have its reaction function moving as much as that of the integrated operator. The integrated operator thus gains a price advantage over its opponent: the equilibrium terminal fee of Terminal A (w_A^{II}) becomes much lower than that of Terminal B (w_B^{II}) (see Appendix C1). This supports the concern raised by McLay and Reynolds-Feighan (2006) that "it may be attractive for the runway/incumbent terminal business to 'over-bid' for runway access, and to effectively subsidize its terminal operations from the inflated proceeds of the sale of runway access." The prerogative to charge the runway service works as a strong tool for the integrated operator to place its competitor at a disadvantage, and also helps the integrated operator maintain profitability despite its low terminal fee. As a result, the total price using Terminal A, T_A^{II}, remains at the same level compared with the centralized case (Business Model I), whereas the total price using Terminal B, T_B^{II}, increases. Further, as the number of airlines n_A goes greater, Terminal A would gain greater superiority over Terminal B in the competition. In such a situation, Terminal B has to lower its terminal fee w_B^{II} to maintain market share. To counter, operator 1 raises the airfield charge, on the one hand, to offset Terminal B's low fee. It then lowers its own terminal fee w_A^{II}, on the other hand, to keep the total price of Terminal A unchanged. Nevertheless, a greater airline number at Terminal A will reduce the difference between the total price of Terminal B and A, as $\frac{\partial T_B^{II}}{\partial n_A} < 0$ and $\frac{\partial T_A^{II}}{\partial n_A} = 0$. Interestingly, the number of airlines n_B at the independent terminal will not affect the prices of both terminals. Consequently, although an increase in the number of airlines might lead to a rise in substitutability between the two terminals, which can lead to lower prices, the impact of substitutes can never outweigh that of complementarity between the terminal and airfield to lower prices. Moreover, a higher cross-effect parameter l will cause a universal shrinkage of downstream demand, driving down prices.

When both terminals are split and operated by independent operators (Business Model III), both T_A and T_B go higher as additional uninternalized complementarity emerges, Higher l can lower the prices; however, the prices will always be higher than that in the centralized and partially separated operation (Business Models I and II). When the airfield is operated independently while the two terminals are operated jointly (Business Model IV), the prices become highest, since all that remains is the uninternalized complementarity, and the competition of substitute goods is completely neutralized in the upstream market.

When the ability for the airfield to use the "tool of complementarity" is restricted, or a price-cap is equivalently imposed on airfield service, as suggested by McLay and Reynolds-Feighan (2006) (Business Models V and VI), even without terminal competition, the prices will not be high. Thus, T_A^V and T_B^V are at the same level with T_A^I and T_B^I, and the introduction of terminal competition in this situation would lead to lowest prices (T_A^{VI} and T_B^{VI}) among all business models. Finally, we find that the introduction of inter-terminal competition generally lowers the total output Q, which declines as the prices increase.

To summarize, if the operation of the terminal service section is completely separated from that of the runway service section in the existing business model, or the pricing of airfield operator is strictly regulated, having competing terminals can lower the prices and increase the total output (e.g., from Business Model IV to III, from Business Model V to VI), since the complementarity has already been fully "externalized" or neutralized in these cases, so the separation of terminal operation will not further aggravate the negative effect of complementarity. Otherwise, the introduction of terminal competition would only increase the prices and lower the total output (e.g., from Business Model I to II or III). These results are generally in line with that of De Borger and De Bruyne (2011) regarding the integration of firms that produce complementary good; they study the effect of the vertical integration of port terminal operators and hinterland transport firms on government's policy. They show that vertical integrations make government levy higher port access charges, since lower price can be achieved through the elimination of double marginalization so correction by government is no longer necessary. This is in line with our result in terms of the integration of firms producing complementary goods. While their modeling assumes balanced and symmetric vertical interactions, our result show that biased and asymmetric internalization of complementarity can also lead to lower price under some conditions (from Model III to II). Regarding the social surplus with optimal prices in each Business Model, we have:

Proposition 3.2 If airlines cannot change the base terminal and the number of airlines in each terminal is fixed, then

$S^I = S^V > S^{II}; S^I > S^{IV}$

Proof: See Appendix C3.

For the social surpluses of other business models, as it is arduous to compare them analytically, we resort to numerical examples. We change airline number n_A and n_B in each terminal and the cross-effect l, and fix other parameters. Parameters are set based on the realistic data as much as possible, and the sources are as follows. In The United State, the average CASM (Cost per Available Seat Mile) of airlines is USD 0.126 in 2019. Dividing this by the average load factor (0.84), we can get the cost per passenger mile as USD 0.15. Multiplying it by the average stage length (1166 miles), we have the marginal cost per passenger as USD 175. Multiplying the average seat number 179 by the load factor, we have the average passenger number per flight as 150. Finally, multiplying the average passenger number by marginal cost per passenger, we obtain the average marginal cost per flight as USD 26319. All data above are collected from the airline data project,[12] and the unit of monetary values is the US dollar in 2019. For passengers, the time value of delay is USD 37.6/hour in 2007 US dollars (NEXTOR, 2010). The average delay cost of US airlines is estimated to be USD 391 per flight per hour in 2007 US dollars (Ferguson et al., 2013). Regarding the airport's cost and revenue, Martín and Voltes-Dorta (2011) make a careful estimation based on the data of 161 airports worldwide between 1991 and 2008. Their results show that the average marginal cost is USD 5.33 per domestic passenger and USD 6.19 per international passenger, respectively, in 2008 US dollars. The average marginal cost per flight in the Asia-Pacific region is about USD 450. The average unit commercial profit is USD 3.49 per passenger. The unit of all monetary values mentioned above is converted to US dollars in 2019 and scaled by dividing the actual value of maximum willingness-to-pay which is normalized to 1 in the demand function. We choose 2000 for the maximum willingness-to-pay, and 0.15 for the own-price effect (Basso and Zhang, 2008). Finally, the parameters for numerical examples are determined, as shown in Table 3.3.

Table 3.3 Values of parameters for numerical examples

a	c	α	β	γ	r	k	s
7.5×10^{-5}	12.5	2.25×10^{-2}	0.24	0.275	-1.25×10^{-3}	120	150

Fig. 3.4 shows the results of $S^{II} - S^{III}$. Under the pre-set parameters, S^{II} is always higher than S^{III}. The reason might be that, compared with Business model II, an additional complementary duopoly emerges between terminal and airfield while the substitutive duopoly between terminals is kept unchanged in Business model III. Loss in social surplus occurs as the complementarity can no longer be internalized by a single operator. Further, we can find that $S^{II} - S^{III}$ increases with n_A, yet decreases as l increases; the greater the n_A, the stronger the complementary effect, thus the greater the surplus loss when complementarity are not internalized. The greater the cross-effect l, the smaller the universal downstream demand, thus smaller the output difference between II and III, leading to a smaller difference between S^{II} and S^{III}. Other comparison results are shown in Appendix C4. Consequently, $S^{VI} > S^{V} = S^{I} > S^{II} > S^{III} > S^{IV}$, which follows the pattern that the lower the prices, the higher the social surplus. Having competing terminals

[12] <http://web.mit.edu/airlinedata/www/default.html>

can enhance social surplus if the terminal service and runway service sectors are operated separately in the existing business model (e.g., from IV to III, from V to VI). Otherwise, the introduction of terminal competition would have a negative effect on social surplus (e.g., from I to II and from II to III).

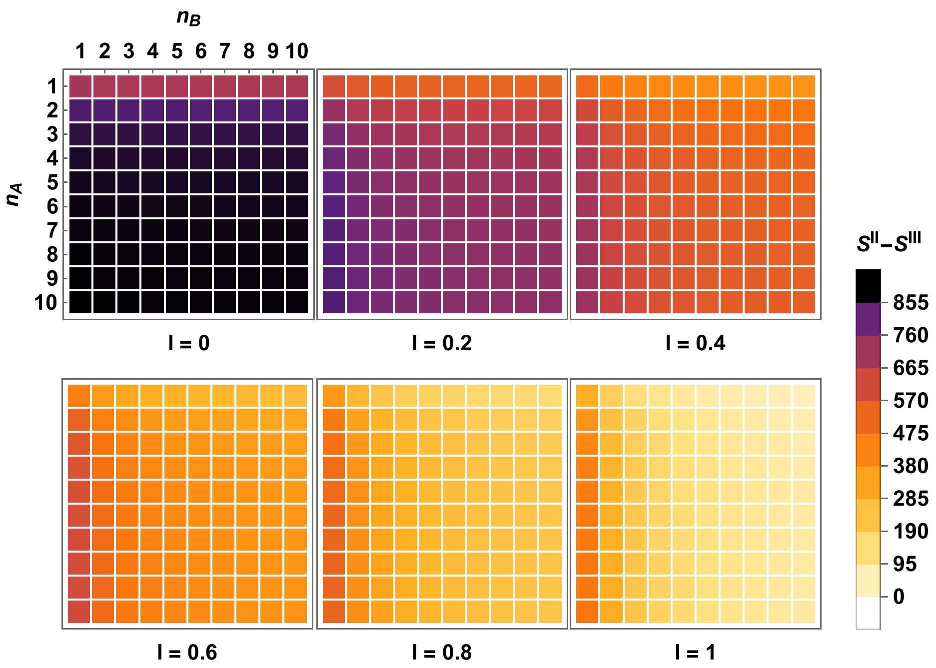


Fig 3.4 Numerical results of $S^{II} - S^{III}$

In addition, we try an alternative modelling by relaxing the assumption that airlines in same terminal are perfect substitutes. Results are relegated to Appendix D. The ranking of Business Models in terms of social surplus will not change by relaxing this assumption. What changes is the extent of the difference in pricing and social surplus between different Business Models.

3.2.4 Case 2: airlines can change terminal

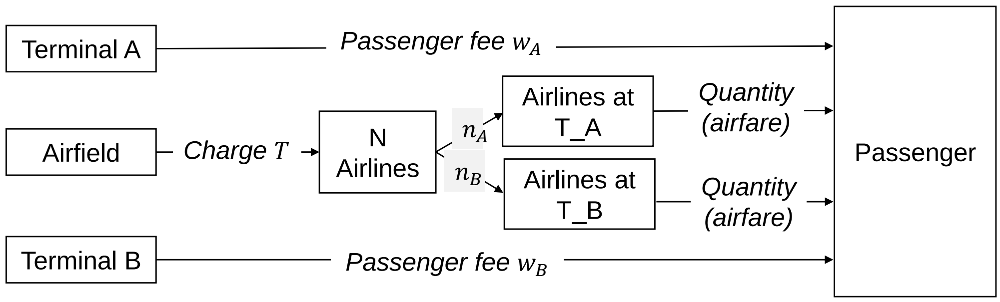


Fig 3.5 Illustration of the air transport market in Case 2

Table 3.4 Optimal total prices of each Business Model in Case 2

Business Model	$\boldsymbol{T_A}$	$\boldsymbol{T_B}$
First-best	$\frac{C_1((N+2)\gamma - s((N+2)r+2)+2c) - 2Nk(c-s)(\beta+\alpha s) + NC_2(\gamma - rs)}{N(C_1+C_2+2k(\beta+\alpha s))}$	
I	$\frac{1}{2}(s - rs - c + \gamma)$	
II	$\frac{1}{2}(s - rs - c + \gamma)$	$\frac{C_1(s(4N-2Nr-3r+3)+(2N+3)\gamma-(4N+3)c)-NC_2((r+1)s-c-\gamma)}{6(N+1)C_1}$
III	$\frac{C_1((1-N(r-2)-r)s-(2N+1)c+(N+1)\gamma)-NC_2(s-c)}{(3N+2)C_1-NC_2}$	
IV	$\frac{1}{3}((2-r)s-2c+\gamma)$	
V	$\frac{1}{2}(s - rs - c + \gamma)$	
VI	$\frac{C_1(N((1-r)s-c+\gamma)+\gamma-rs)-NC_2(s-c)}{(2N+1)C_1-NC_2}$	

In Case 2, an airline can move to the terminal where it can make the highest profit; thus, the number of airlines at each terminal can change according to the prices. The freedom of changing terminal further increases the degree of substitution between the two terminals, allowing us to examine whether the effect of complementarity can be dominated, and lower prices can be realized through the introduction of terminal competition. The interactions among market participants can be modeled as a three-stage game: The airfield and terminals set prices first, then airlines choose their base terminals; finally, airlines compete in Cournot fashion (Fig 3.5). To induce backward, we start from the second stage. The optimal profits of each airline are as follows:

$$\Pi_{hi}^{*}(T, w_h, w_{-h}) = \frac{C_1 k^2 \big(C_1(n_{-h}+1)(s(w_h-1)+T)+c(C_1 n_{-h}-C_2 n_{-h}+C_1)-C_2 n_{-h}(s(w_{-h}-1)+T)\big)^2}{\big(C_2^2 n_h n_{-h}-C_1^2(n_h+1)(n_{-h}+1)\big)^2} \quad (3.10)$$

By simply observing the form of the airlines' optimal profit function, we can see that obtaining the precise number of airlines at each terminal in equilibrium appears to be difficult. Thus, we make several assumptions to simplify the problem:

Assumptions for Case 2: (1) Airlines believe that, in each terminal, the profit of each airline decreases as the number of airlines increases; (2) the cost for changing terminals is ignored (e.g., airlines have long-term considerations); (3) the number of airlines is treated as continuous.

Then, the equilibrium allocation of airlines can be achieved when $\Pi_{hi}^{*} = \Pi_{-hi}^{*}$. By solving this equation, we can derive the equilibrium numbers as:

$$n_B^{*} = \frac{N\big(C_1(s(w_B-1)+T) - C_2(s(w_A-1)+T) + c(C_1-C_2)\big) + C_1 s(w_B - w_A)}{(C_1-C_2)(s(w_A+w_B-2)+2c+2T)} \quad (3.11)$$

$$n_A^{*} = N - n_B^{*} \quad (3.12)$$

Substituting the equilibrium numbers into outputs, we derive the equilibrium flights and total output as functions of the total prices:

$$f_{hi}^{*} = \frac{k^2(2s-2c-T_h-T_{-h})}{(N+2)C_1 + NC_2} \quad (3.13)$$

$$Q^{*} = \frac{k^2\,\mathrm{s}(n_A+n_B)\,(2s-2c-T_A-T_B)}{(N+2)C_1 + NC_2} \quad (3.14)$$

We can then summarize the effects of prices on the flight of each airline and total output as:

Lemma 3.2 If airlines can change the base terminal and the number of airlines in each terminal is obtained according to *Assumptions for Case 2*, we have

$\frac{\partial f_{hi}^{*}}{\partial T_h} = \frac{\partial f_{hi}^{*}}{\partial T_{-h}} < 0; \frac{\partial Q^{*}}{\partial T_A} = \frac{\partial Q^{*}}{\partial T_B} < 0.$

An increase (decrease) in the price of any terminal will result in a flight declining (increasing) for all airlines at both terminals. A lower price in Terminal h not only increases the flights of airlines therein, but also attracts newcomers from Terminal $-h$. The share increasing effect of a declining number of airlines at Terminal $-h$ outweighs the flight decreasing effect of a relatively high price compared with Terminal h. Substituting the subgame equilibrium output and airline numbers into the objective functions and solving the FOCs in Table A1, we can derive the optimal prices as shown in Table 3.4. Under these optimal prices, the curves of airlines' profits generally conform to (1) of *Assumptions for Case 2* (see Appendix E1). Comparing these prices, we can summarize:

Proposition 3.3 If airlines can change the base terminal, and the number of airlines in each terminal is obtained according to *Assumptions for Case 2,* we have

(i) $T_A^{IV} > T_A^{III} > T_A^{II} = T_A^{I} = T_A^{V} > T_A^{VI}$; $T_B^{IV} > T_B^{III} > T_B^{II} > T_B^{I} = T_B^{V} > T_B^{VI}$

(ii) $Q^{IV} < Q^{III} < Q^{II} < Q^{I} = Q^{V} < Q^{VI}$

Proposition 3.3 can be proved in the same approach as that of Proposition 3.1, so we omit the discussion here. The results are the same as in Case 1. A greater degree of substitution between terminals cannot offset the effect of uninternalized complementarity, so having competing terminals can lower the prices and increase total output only when "complementary duopoly" already exists in the existing business model (e.g., from IV to III, from V to VI). Comparison of the social surplus in each business model leads to the following finding:

Proposition 3.4 If airlines can change the base terminal and the number of airlines in each terminal is obtained according to *Assumptions for Case 2,* we have

$S^{II} < S^{I} < S^{VI}$; $S^{IV} < S^{III} < S^{I} = S^{V}$

Proof: See Appendix E2.

The comparison between S^{II} and S^{III} is investigated by numerical example (see Appendix E3). As a result, the social surplus in Case 2 ranks as $S^{VI} > S^{V} = S^{I} > S^{II} > S^{III} > S^{IV}$, which is the same as that in Case 1. The increasing degree of substitute contributed by airlines' freedom to change the base terminal cannot make the Business Model with competing terminals better-off.

3.3 Extensions

3.3.1 Asymmetric terminals

In this case, we consider terminals with different marginal costs and non-aeronautical profitability. We only investigate Business Models I and II as Business Model II is most likely to occur in reality, and the tractability of the model under other business models in extended cases is questionable. The two Business Models are re-labeled as Model HI and HII in this case. By solving the FOCs shown in Table 3.1, we have the optimal prices as follows:

$$w_A^{HII} = \frac{C_1(n_A+1)(s(1-3r_A-2r_B)-\gamma) - C_2 n_A(sr_A-\gamma+s) - c(C_1n_A - C_2n_A + C_1)}{6C_1 s(n_A+1)} \quad (3.15)$$

$$w_B^{HII} = \frac{C_1(n_A+1)(s-2sr_B-\gamma) - C_2 n_A(sr_A-\gamma+s) - c(C_1n_A - C_2n_A + C_1)}{3C_1 s(n_A+1)} \quad (3.16)$$

$$T^{HII} = \frac{C_2n_A(s-\gamma+sr_A) + 2C_1(1+n_A)(s+2\gamma+sr_B) - c\big(C_2n_A + 2C_1(1+n_A)\big)}{6C_1(1+n_A)} \quad (3.17)$$

$$T_A^{HI} = T_A^{HII} = \frac{1}{2}(s-c+\gamma-sr_A) \quad (3.18)$$

$$T_B^{HI} = \frac{1}{2}(s-c+\gamma-sr_B) \quad (3.19)$$

$$T_B^{HII} = \frac{2C_1(n_A+1)(s(2-r_B)+\gamma) - C_2n_A(sr_A-\gamma+s) + c\big(C_2n_A - 4C_1(n_A+1)\big)}{6C_1(n_A+1)} \quad (3.20)$$

Comparing these prices, we can derive the condition that $T_B^{HII} < T_B^{HI}$ (i.e., the condition that Business Model HII can result in lower prices compared with Model HI, as T_A^{HII} always equals T_A^{HI}). The condition is $r_B < A + Br_A$, where

$A = -\frac{(C_1n_A+C_1-C_2n_A)(s-c-\gamma)}{C_1 s(n_A+1)} < 0; B = \frac{C_2n_A}{C_1(n_A+1)} < 1.$

The equation $r_B = A + Br_A$ intersects with the line $r_B = r_A$ at $(\frac{c+\gamma-s}{s}, \frac{c+\gamma-s}{s})$. The case that r_A or r_B is lower than $\frac{c+\gamma-s}{s}$, where the profitability of terminal cannot be ensured, is excluded form the discussion. We find that T_B^{HII} can be lower than T_B^{HI} if r_A is greater than r_B, and the difference is above a certain degree. The intuition behind the findings is that, when r_A is much greater than r_B, the integrated operator, who operates the airfield and Terminal A, can lower its price much further than the independent operator who operates Terminal B thanks to the "cost advantage", so it does not need to set a runway charge as high as that in Model II to obtain the price advantage additionally (note that $\frac{\partial T^{HII}}{\partial r_A} < \frac{\partial T^{HII}}{\partial r_B}$). As a consequence, the total price using Terminal B in Model HII will be lower than in Model HI, though still higher than T_A^{HII}.

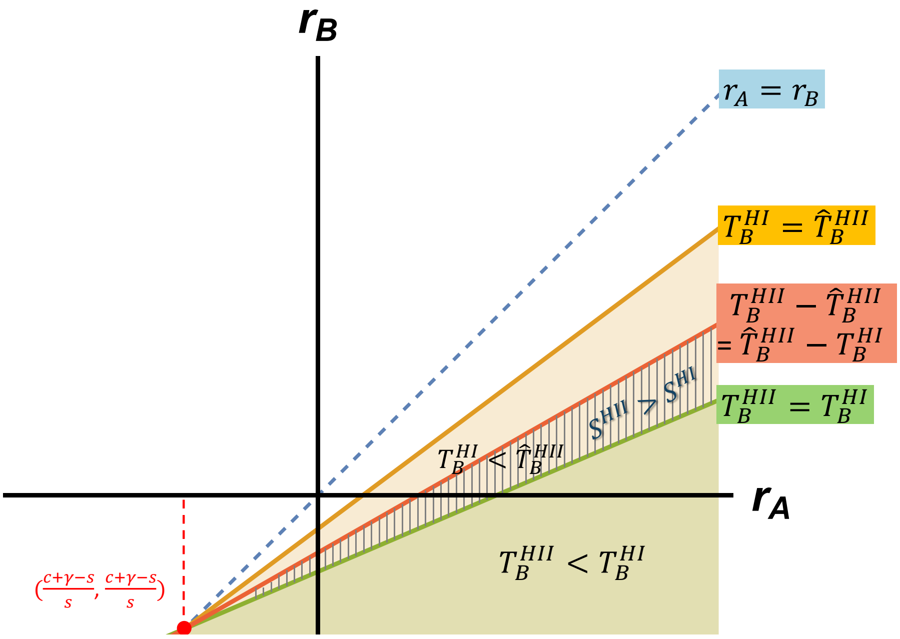


Fig 3.6 Visualization of price and social surplus comparison

However, lower prices do not necessarily enhance social surplus. Since $T_A^{HI} = T_A^{HII}$, to have $S^{HII} > S^{HI}$, $|T_B^{HII} - \hat{T}_B^{HII}| < |T_B^{HI} - \hat{T}_B^{HII}|$ should be satisfied, where $\hat{T}_B^{HII}$ is the stationary point of function $S(T_A = T_A^{HI} = T_A^{HII})$. To identify the area of $\boldsymbol{r}$ that satisfies the condition, we further derive lines $T_B^{HII} - \hat{T}_B^{HII} = \hat{T}_B^{HII} - T_B^{HI}$ and $T_B^{HI} = \hat{T}_B^{HII}$. Interestingly, these two lines and $T_B^{HII} = T_B^{HI}$ and $r_B = r_A$ all intersect at $(\frac{c+\gamma-s}{s}, \frac{c+\gamma-s}{s})$, and by comparing their intercept (see Appendix F1) at r_B axis, we can draw a graph as shown in Fig 3.6. From the graph, it is not difficult to find that $S^{HII} > S^{HI}$ can occur only when both $\boldsymbol{r}$ are in the hatched area. The lower price T_B^{HII} only proves to be a result of underpricing. Since the social optimal prices are low prices which are balanced between the two terminals regarding airline numbers, to get closer to such prices rather than T_A^{HI} and T_B^{HI}, an appropriate difference between r_A and r_B should be ensured in Model HII; otherwise, the prices will be either too high or biased. The above analysis can be verified by a numerical example shown in Appendix F2. The numerical example demonstrates that even in the case where $S^{HII} > S^{HI}$, the difference is quite limited. To summarize, the conditions under which the introduction of terminal competition can enhance social surplus are quite stringent, and the improvement is modest even if the conditions can be satisfied. Finally, we summarize these finding as follows:

Proposition 3.5 If terminals have different non-aeronautical profitability and unit costs, to have $T_B^{HII} < T_B^{HI}$, $r_B < A + Br_A$, where $A < 0$ and $B < 1$, should be satisfied. $S^{HII} > S^{HI}$ can be true if $\varepsilon^-(n_A, n_B) < r_A - r_B < \varepsilon^+(n_A, n_B)$ where $\varepsilon^-(n_A, n_B)$ and $\varepsilon^+(n_A, n_B)$ are positive.

3.3.2 Airline in the upstream market

In recent years, airports and airlines have begun to have cooperative interactions with each other frequently to gain competitive advantage, given an increasingly commercialized air transport market (D'Alfonso and Nastasi, 2014). Various forms of vertical arrangement can be observed around the world (Fu et al., 2011; Fu and Yang, 2017). In the context of this study, we roughly categorize vertical arrangement into two types based on whether the ownership or operation of key airport facilities which provide indispensable services to multiple consumers (airlines) are shared with airlines. An arrangement belongs to Type I if yes and Type II if no. Type I vertical arrangements mainly include airlines' control of and investment in airport facilities (e.g., Terminal 2 of Munich Airport), long-term usage contract (e.g., Melbourne Airport and Virgin Blue), airport-airline consortium (e.g., New York JFK Airport), and common ownership (e.g., Changi Airport). Type II vertical arrangements mainly include signatory airline agreement (e.g., Seattle-Tacoma International Airport), revenue sharing (e.g., Tampa International Airport), information sharing and joint marketing, and incentive programs. Since Type I might create intra-airport competition via the participation of dominant airline in upstream, which is highly relevant to this study, we further investigate this issue by introducing and analyzing several new potential Business Models with the vertical arrangement.

We first characterize the cases that airlines directly and fully operate terminals, which can correspond to the long-term lease in Australia or some BOT contracts (Forsyth, 2008; Starkie, 2008). In Business Model DI, Terminal B is operated independently by an airline while Terminal A and airfield facility is operated jointly by a profit-maximizing operator. In Model DII, Terminal B is operated independently by an airline while Terminal A and airfield facilities are operated by two operators separately. In Model DIII, two terminals are operated by two dominant airlines separately, while a profit-maximizing operator operates airfield facilities. In Model DIV and DV, public operators operate airfield facilities. The difference is that terminals are operated by an airline and a profit-maximizing operator, respectively, in the former Model; in the latter Model, terminals are operated by two airlines, respectively. The modelling approach is similar to that of Barbot (2011): in the upstream market, airfield operator, terminal operator and/or terminal operating airlines first decide airfield charge T, terminal fee $\boldsymbol{w}$, and the quantities of terminal operating airlines f_D. Given these prices and judging the remaining demand, airlines in the downstream market compete in a Cournot fashion to clear the market. Next, we characterize the case that terminal is operated by a join venture of an airline and a terminal operator as Model DVI, which bear some similarity with the vertical merger case illustrated in Barbot (2011). In this model, the airline has a share θ of Terminal B and can acquire a corresponding part of its profit, However, the terminal is operated by the terminal operator. Airfield and terminal operators decide prices, then the shareholder airline chooses the quantity, and, finally, other airlines compete on quantities. Fig 3.7 provides an intuitive illustration of these Business Models.

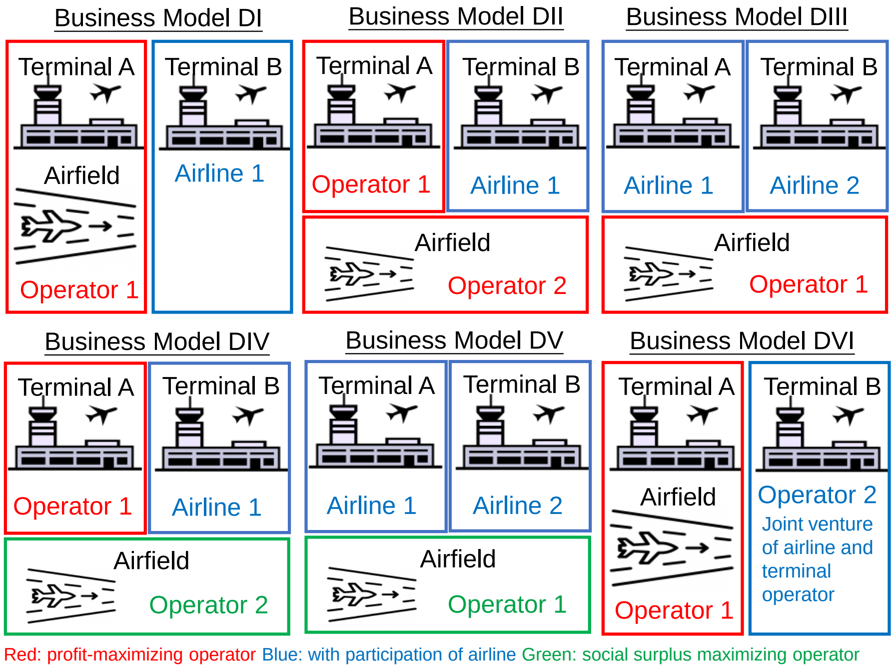


Fig 3.7 Illustration of Business Models with airlines in upstream

The demonstration of the tedious solving process, merely a similar variant of that in the basic modeling, and the lengthy equilibrium solutions are omitted. Note that in the modeling of Barbot (2011), if the leader airline has the pricing right of the terminal, all other airlines will be driven out of the market. In our modeling, this can be avoided by removing the terminal fee from the total price that the passengers of the terminal operating airline are facing or, equivalently, by allowing airfare differentiation between upstream airline and downstream airlines in the same terminal. By doing so, the total quantity of the downstream airlines in that terminal (Terminal B) becomes $\frac{k^2s^2r(n_B-1)}{2C_1}$ in Business Model DI, DII, DIII, DIV, and DV. Thus, as long as $r > 0$, they will get a market share. In Model DVI, the share parameter should satisfy $0 \leq \theta \leq \frac{C_1^2(n_A+1)(2n_B-1)-2C_2^2n_A(n_B-1)}{C_1^2(n_A+1)(2n_B+1)-2C_2^2n_A(n_B-1)}$ to ensure a market share of downstream airlines.

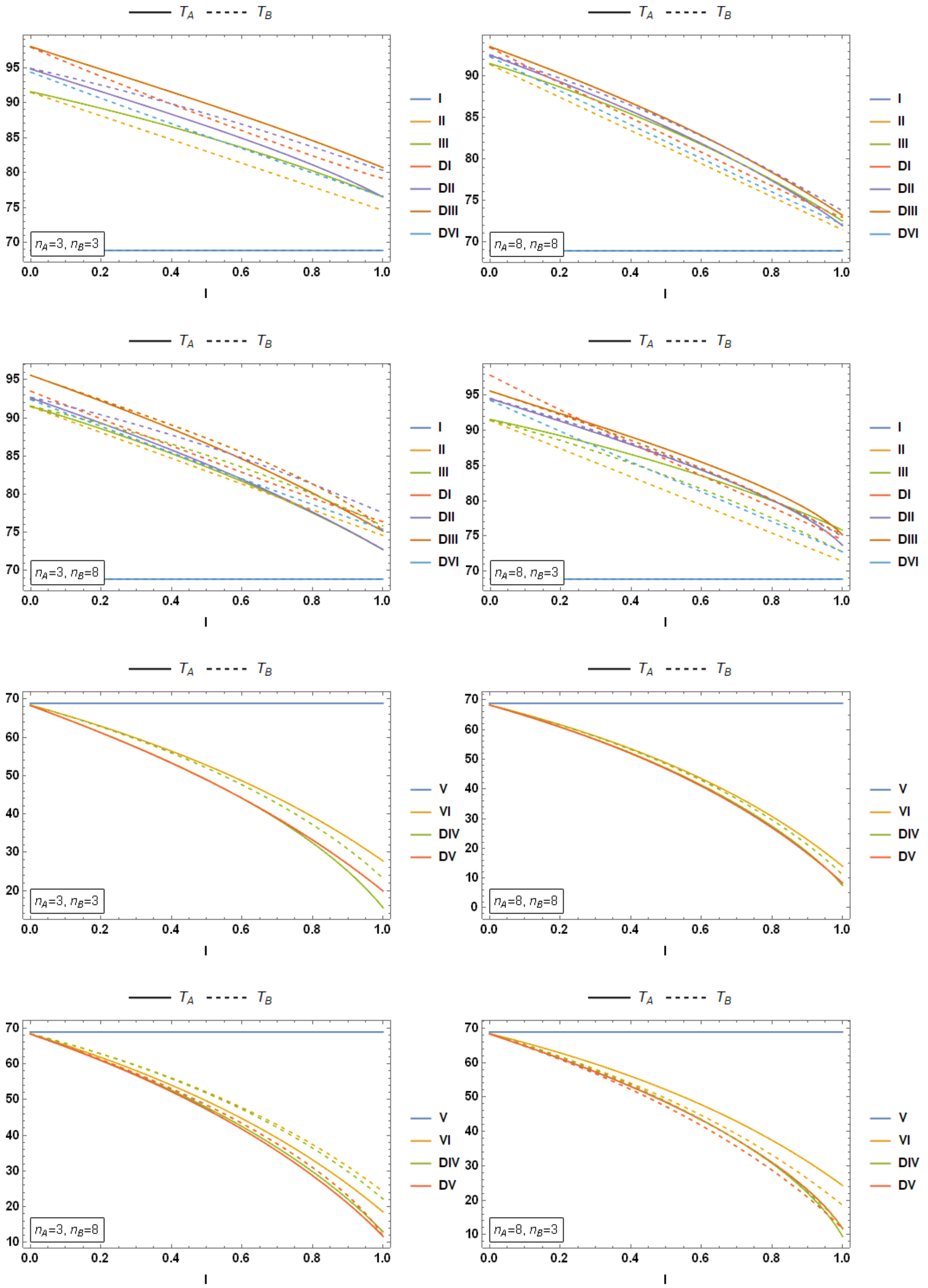


Fig 3.8 Comparison of equilibrium total prices in each Model

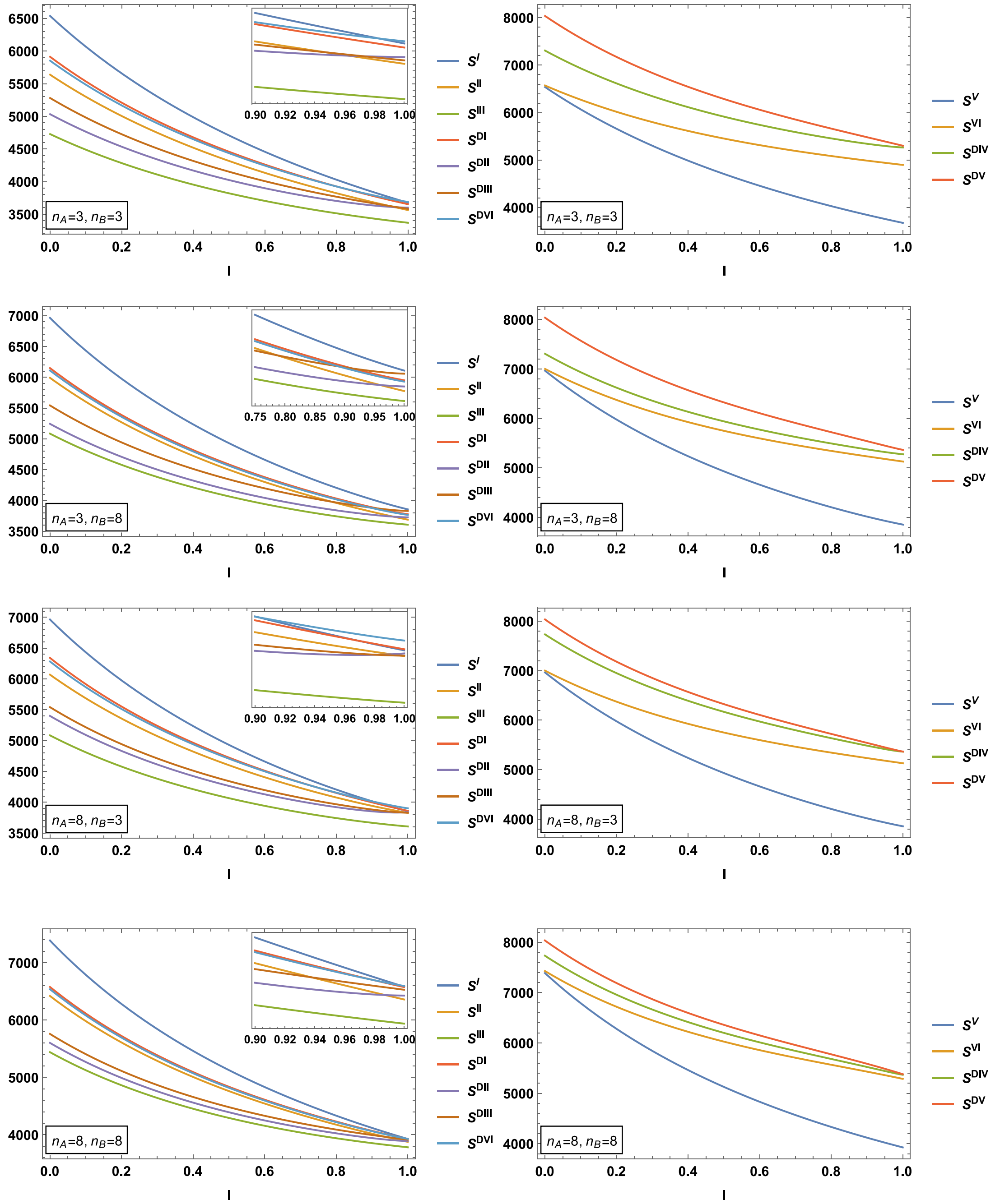


Fig 3.9 Comparison of the social surplus of each Model

Numerical examples of equilibrium prices and social surplus are shown in Fig 3.8 and 3.9, respectively. Same values are defined for parameters except that r is changed to 1/4000. From the plots of prices, we can observe that total prices of Business Models with airline(s) in the upstream market (DI, DII, DIII, DVI) are generally higher than that of the ordinary Models (I, II, III), when a private operator operates the airfield facilities, and vice versa (V and VI versus DIV and DV). The latter indicates that airlines' participation in terminal operations originally has a price-reducing effect due to a smaller share of follower airlines whose passengers are the only payers of terminal fees and the less intense competition in the downstream market (number of airlines are $n_h - 1$). However, when the airfield operator is private, the effect of uninternalized complementary will greatly raise the prices, especially the charge for airfield facilities. Since the potential demand can be greater due to the partial elimination of double marginalization when an airline operates terminal, the effect of complementarity works more prominently than in ordinary Models, thereby causing the reverse results.

However, the high prices do not necessarily lead to a decline in social surplus when the airfield operator is private. Comparing the Models with similar configuration (II and DI; III and DII, DIII), we can find that Models with upstream airlines outperform their counterparts in social surplus ($S^{DI} > S^{II}$; $S^{DII} > S^{III}; S^{DIII} > S^{III}$). The intuition behind the result is that the high prices in Models with upstream airlines are merely imposed on follower airlines and their passengers fully, while the terminal operating airline(s) only bears the airfield charge. The decline in the quantities of follower airlines is offset by the increase in the quantities in the terminal operating airline(s), as compared to the ordinary Models. Therefore, the social surplus does not go down with high prices. Together, the increase in total quantities and airfield charge generates a higher profit of airfield operator. It is contrary to the findings of Kaselimi et al. (2011), where vertical integration only means a "virtual exit" of the dedicated terminal, which cannot exploit the price advantage to expand market share as done by the terminal operating airline in their study. In the case that a public operator operates airfield facilities, it is straightforward that lower prices lead to higher social surplus. Thus, we have $S^{DIV} > S^{VI}$ and $S^{DV} > S^{VI}$.

Consequently, we can summarize the results as follows. If a private operator operates the airfield facilities (i.e., the effect of uninternalized complementarity exists), almost no Business Models with the upstream airline can work as an alternative introduction of terminal competition to improve social surplus. Only in extremely limited case (e.g., when the cross-effect or the degree of substitute l is very large) can Model DVI yield higher social surplus than the integrated operation, Model I, thanks to the joint effect of the shift from pure Cournot to Cournot-Stackelberg model (Daughety, 1990), less double-marginalization, a stronger increase in quantity from monopoly due to higher degree of substitution, and a weaker effect of complementarity. Nonetheless, in Models II and III, if the independent terminal(s) are operated by airline(s), the social surplus can be improved despite a rise in price. On the other hand, if the airfield facilities are public while terminals are privatized, having airlines to operate the terminals can always lower the prices and enhance social surplus. The more the terminals operated by airlines, the stronger the positive effect, which is consistent with the finding of D'Alfonso and Nastasi (2012). Finally, we must restate that these Business Models with the upstream airline(s) are meaningful only when r (the difference between unit non-aeronautical profit and the marginal cost of terminal) is positive.

3.3.3 Terminal competition on both price and service level

In this section, we try an alternative modeling where terminal operators can determine their service levels. In this case, product differentiation between terminals is characterized by service level instead of the cross-effect parameter l, which is now used to address the degree of substitution among all airlines regardless of which terminal they are situated. The inverse demand function is defined as follows:

$$p_{hi} = 1 - aq_{hi} - al(Q - q_{hi}) - w_h - \alpha\left(\frac{Q}{k}\right) + \eta v_h - \eta m v_{-h} \tag{3.21}$$

Where v_h denotes the service level of terminal h, η denotes the passengers' valuing of the service, or own service level effect, and m denotes the degree of substitute between the service of different terminal ($0 \leq m \leq 1$). This type of demand function is widely adopted in the literature (e.g., Boyaci and Ray, 2003; Wang et al., 2017).

Accordingly, the profit function of Terminal h becomes

$$\Gamma_h(w_h, v_h) = (w_h + r - v_h\sigma) * Q_h^*(\boldsymbol{w}, T, \boldsymbol{v}) \tag{3.22}$$

where σ denotes the unit cost of service provision. Adopting backward induction, we can obtain the equilibrium prices and service levels of terminals in Business Model I, II and III as:

$$T_A^I = T_A^{II} = T_A^{III} = \frac{\sigma(s-c) + \eta(1-m)(rs-\gamma)}{\eta(m-1) + \sigma} \tag{3.23}$$

$$T_B^I = T_B^{II} = T_B^{III} = \frac{\sigma(s-c) + \eta(1-m)(rs-\gamma)}{\eta(m-1) + \sigma} \tag{3.24}$$

$$v_A^I = v_A^{II} = v_A^{III} = \frac{s(r+1) - c - \gamma}{s(\eta(m-1) + \sigma)} \tag{3.25}$$

$$v_B^I = v_B^{II} = v_B^{III} = \frac{s(r+1) - c - \gamma}{s(\eta(m-1) + \sigma)} \tag{3.26}$$

Interestingly, when competing both on price and service level, the two terminals will make identical decisions regardless of being bundled with airfield facilities or operated independently. With the same equilibrium decisions, the social surplus of these three Business Models will also be identical. These results are partially consistent with the findings of Basso and Zhang (2007) that duopolists will offer same service quality as the monopolist if price and service level are determined simultaneously. The difference is that Basso and Zhang (2007) find that price set by duopolists will be lower, while the price remains the same in our results. A possible explanation is that the price-increasing effect of uninternalized complementary can only be partially offset by multi-dimensional competition between substitute products. Thus, the price will not be as high as those in the pure price competition; however, it cannot go further lower to the level of substitute duopoly. These findings indicate that the introduction of terminal competition might not be worse-off in terms of social surplus as long as terminals can decide their service levels in addition to prices, while no improvement can be achieved both in social surplus and service level.

3.3.4 Regulated terminals

This section considers Business Models where the airfield operator aims to maximize social surplus by marginal-cost pricing, while the objective functions of terminals are a mixture of profit and social surplus. That is, the airfield operation is strictly regulated, whereas terminals can retain profitability to some extent. Terminals, in this case, may correspond to those under some kind of price-cap regulation, or those with mixed public-private ownership. Two new business models are labeled respectively as Model $\bar{V}$, where two terminals are jointly operated, and Model $\overline{VI}$, where two terminals are separately operated by two independent operators, with a mixed objective of profit and social surplus.

Since the public airfield operator will always levy a cost recovery charge $T^{\overline{V}} = T^{\overline{VI}} = \gamma$, we only need to focus on the equilibrium pricing of terminals. In Model $\overline{V}$, the joint objective function of the terminal operator is formulated as follows:

$$\Gamma^{\overline{V}} = (1-\mu) * (\Gamma_A + \Gamma_B) + \mu * S \tag{3.27}$$

where μ denotes the share of social surplus in the objective with $0 \leq \mu \leq 1$. The Lagrange function is

$$L^{\overline{V}} = \Gamma^{\overline{V}} + \lambda(\Gamma_A + \Gamma_B) \tag{3.28}$$

The KKT conditions are

$$\frac{\partial L^{\overline{V}}}{\partial w_A} = 0;\ \frac{\partial L^{\overline{V}}}{\partial w_B} = 0;\ \frac{\partial L^{\overline{V}}}{\partial \lambda} \geq 0;\ \lambda \geq 0;\ \lambda \frac{\partial L^{\overline{V}}}{\partial \lambda} = 0 \tag{3.29}$$

Solving them, we have two cases as follows: if $\lambda^* > 0, \boldsymbol{w}^{\overline{V}} = \bar{\boldsymbol{w}}^{\overline{V}}$, which is the solution of $\frac{\partial L^{\overline{V}}}{\partial w_A} = 0,\ \frac{\partial L^{\overline{V}}}{\partial w_B} = 0$; otherwise, $\boldsymbol{w}^{\overline{V}} = \widehat{\boldsymbol{w}}^{\overline{V}}$, which is the solution of $\frac{\partial \Gamma^{\overline{V}}}{\partial w_A} = 0, \frac{\partial \Gamma^{\overline{V}}}{\partial w_B} = 0$. Numerical results are obtained, as the problem is intractable analytically.

In Model $\overline{VI}$, the objective function of terminal *h* is formulated as

$$\Gamma_h^{\overline{VI}} = (1-\mu) * \Gamma_h + \mu * S \tag{3.30}$$

The Lagrange function for terminal *h* is

$$L_h^{\overline{VI}} = \Gamma_h^{\overline{VI}} + \lambda_h \Gamma_h \tag{3.31}$$

The KKT conditions are

$$\frac{\partial L_h^{\overline{VI}}}{\partial w_h} = 0;\ \frac{\partial L_h^{\overline{VI}}}{\partial \lambda_h} \geq 0;\ \lambda_h \geq 0; \lambda_h \frac{\partial L_h^{\overline{VI}}}{\partial \lambda_h} = 0 \quad h = A, B \tag{3.32}$$

Solving them, we have four cases as follows:

(i). If $\lambda_A^{**} > 0$ and $\lambda_B^{**} > 0$

$w_A^{\overline{VI}} = w_B^{\overline{VI}} = -r,$

where λ_A^{**} and λ_B^{**} are the solutions of $\frac{\partial L_h^{\overline{VI}}}{\partial w_h} = 0, \frac{\partial L_h^{\overline{VI}}}{\partial \lambda_h} = 0.$

(ii). If $\lambda_A^{**} \leq 0$ or $\lambda_B^{**} \leq 0$, $\lambda_A^* \leq 0$ and $\lambda_B^* \leq 0$,

$w_A^{\overline{VI}} = w_A^{\overline{VI}**}$; $w_B^{\overline{VI}} = w_B^{\overline{VI}**}$.

where λ_h^* is the solution of $\frac{\partial L_h^{\overline{VI}}}{\partial \lambda_h} = 0$, $\frac{\partial L_h^{\overline{VI}}}{\partial w_h} = 0$, $\frac{\partial \Gamma_{-h}^{\overline{VI}}}{\partial w_{-h}} = 0$. $w_h^{\overline{VI}**}$ is the solution of $\frac{\partial \Gamma_h^{\overline{VI}}}{\partial w_h} = 0$.

(iii). If $\lambda_A^{**} \leq 0$ or $\lambda_B^{**} \leq 0$, $\lambda_A^* > 0$ and $w_B^{\overline{VI}*} > -r$,

$w_A^{\overline{VI}} = -r$; $w_B^{\overline{VI}} = w_B^{\overline{VI}*}$.

(iv). If $\lambda_A^{**} \leq 0$ or $\lambda_B^{**} \leq 0$, $\lambda_B^* > 0$ and $w_A^{\overline{VI}*} > -r$,

$w_A^{\overline{VI}} = w_A^{\overline{VI}*}$; $w_B^{\overline{VI}} = -r$,

where $w_h^{\overline{VI}*}$ is the solution of $\frac{\partial \Gamma_h^{\overline{VI}}}{\partial w_h} = 0$, $\frac{\partial L_{-h}^{\overline{VI}}}{\partial \lambda_{-h}} = 0$, $\frac{\partial L_{-h}^{\overline{VI}}}{\partial w_{-h}} = 0$.

The equilibrium solutions are quite lengthy so we omit the demonstration. Hence, using the same parameter values defined in previous section, numerical examples with different μ (the share of social surplus), l (the cross effect between terminals), and n_h (the number of airlines in each terminal) are shown in Fig 3.10. We can find that if the numbers of airlines in both terminals are the same, the social surplus of Model $\bar{V}$ will never exceed that of Model $\overline{VI}$ regardless of the social surplus share μ. The lower the μ, the greater the difference in social surplus. If terminals have different numbers of airlines, when μ is not so high, Model $\overline{VI}$ outperforms $\bar{V}$ in the social surplus and vice versa.

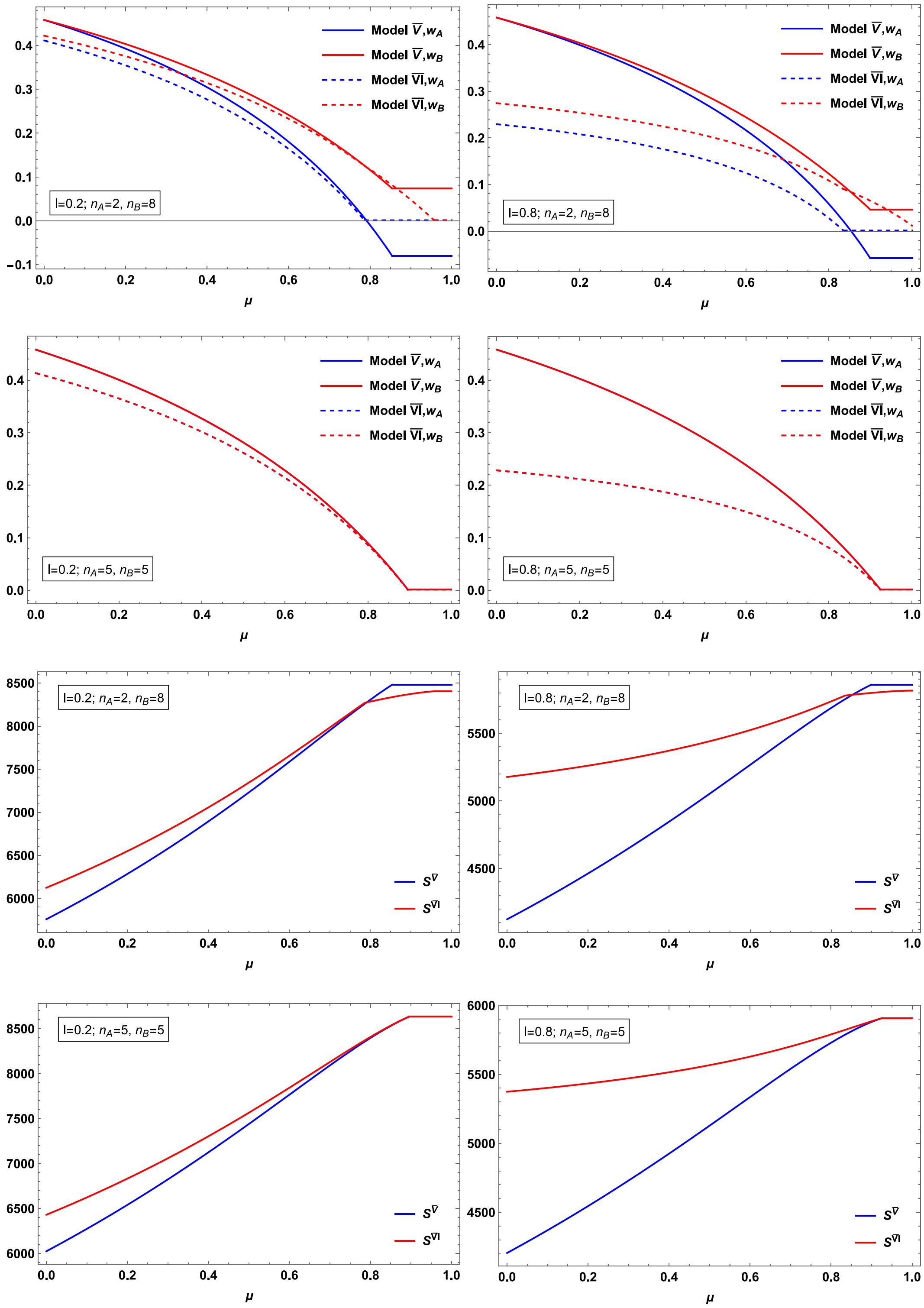


Fig 3.10 Comparison of total prices and the social surplus of each Model

The reason can be found from the comparison of terminal fees. In Model $\overline{V}$ with asymmetric terminals regarding the airline number, when μ is so high that the non-negative profit constraint is bound, the operator can set out a flexible “high-low” or “positive-negative” pricing strategy to balance the quantities of two terminals in pursuit of higher social surplus since the centralized operation allows for cross-subsidization between terminals to ensure non-negative profits of terminals. This cannot be realized in the separated Model $\overline{VI}$ where both operators have to ensure the profit of terminals respectively and a negative terminal fee (equivalently an incentive) therefore seems infeasible. On the other hand, as the comparison between Model V and VI shows, profit-maximizing duopoly of substitutes can always lead to lower prices and higher social surplus than monopoly. Therefore, when μ is low, the positive effect of competing substitutes outweighs the negative effect of separated social surplus maximization, thus resulting in the advantage of Model $\overline{VI}$. These results indicate that when a heavy regulation or a high public share cannot be achieved, the introduction of terminal competition can serve as a means to restrain market power, when the airfield is public. This is also in line with McLay and Reynolds-Feighan (2006) that terminal competition is only a fallback option when regulation is difficult to impose.

3.4. Conclusion

The introduction of inter-terminal competition is viewed as an alternative to regulation to restrain the abuse of market power by airports with specific characteristics. Although the idea has been given much consideration in some countries, it is still far from realized. Discussions about relevant issues are always dominated by conflicts of interest among stakeholders, while in-depth investigations of some critical questions, such as whether terminal competition can truly restrain substantial market power, is lacking. Thus, to bridge this gap and help support decision-making, this study investigates the impact of introducing terminal competition on pricing and social surplus. We solve an analytical model and compare results across several cases.

Our results suggest that, in most cases, having competing terminals can neither lower the prices nor enhance the social surplus if the operation of the terminal and airfield facilities are not completely separated in the existing business model (e.g., the incumbent operator operates both the airfield facilities and terminals), whether or not airlines have the freedom to change base terminal in response to the prices. The complementarity between the airfield and terminal service, which is originally internalized by the joint operation, will become a negative effect that cannot be offset even by a strong degree of substitution between terminals, if the two services are provided respectively by independent operators. When the complementary duopoly and the substitutive duopoly coexist, the price reducing effect of the latter is dominated by the price increasing effect of the former. In contrast, if the operation of the two sections has been completely separated in the existing business model (e.g., one operator operates the terminals while another operates the airfield), or the airfield operator can be strictly regulated, having competing terminals can result in a higher social surplus, as it will not increase the negative complementary effect. Instead, it creates a duopoly of substitute goods that can offset the complementary effect. The runway service allocation problem regarding terminal competition, raised by McLay and Reynolds-Feighan (2006), that the incumbent operating one terminal and airfield facilities jointly can “bully” the independent terminal operator by over-biding runway access, can only be tackled by the imposition of price-cap on the airfield service. Split of the joint operation will cause a further adverse outcome.

If the terminals have different marginal costs and non-aeronautical profitability, stringent conditions must be satisfied to make the business model with competing terminals better-off. However, the improvement in social surplus might be modest. Regarding terminal competition with airlines’ participation in the upstream market, social surplus can be improved only in the case that an airline owns a share of a terminal instead of directly operating it, if the airfield operator is not regulated. If terminals can compete on both price and service level, the introduction of terminal competition will not have any effect on the price, service level, and social surplus. Finally, if airfield operation is strictly regulated while terminals can retain profitability to some extent, competing terminals can be better-off as long as the regulation on terminals is not too heavy.

Overall, our findings indicate that the introduction of terminal competition fails to restrain the abuse of market power by monopoly airport, and improve social surplus in most cases, contrary to common belief. If we further take into account other potential problems of competing terminals, such as the safety concern and loss of economies of scale, we can only say that having competing terminals without any restrictions may not be a reasonable solution. If an airport is to be privatized, all-in-one privatization can lead to better results, and if a new terminal is to be constructed, it should be operated by the incumbent operator. If intra-airport competition between terminals becomes inevitable, a well-designed regulation imposed on operators is necessary to avoid welfare loss, but at the same time, this creates regulatory costs for the operators and the regulator, which is just one of the reasons governments want to find a new approach to replace regulations.

The findings of this study can also be extended to other transport facilities with similar structures. For instance, in terms of the seaport, intra-port terminal competition is not rare in the reality (e.g., Rotterdam, ECT vs APMT), and, apart from the substitutive container handing services provided by terminals, there also has navigation service provided by the port authority which can be complementary with the handling services. Since in most cases the supplier of the complementary good, namely the port authority, is public, part of our findings can be extended to the seaport case that the intra-terminal competition can be better-off as long as the pricing of the complementary good is regulated under certain conditions, which is partially consistent with the conclusion of De Langen and Pallis (2006).

The study has some limitations. First, the impact of introducing terminal competition on long-term infrastructure investment, which is also a very important issue in this context, is not considered. McLay and Reynolds-Feighan (2006) note that the fragmentation of commercial information-gathering across multiple terminals may obscure the evidence of potential demand growth and existing terminal capacity constraints, making decision-making for investment more complex. Further, related to the terminal capacity problem, terminal congestion is also ignored. This issue should be further addressed together with pricing in a future study. Second, we employ Bertrand model to formulate the competition in the upstream market, but its plausibility needs further verification. Third, the diversity of airlines is not fully addressed; in reality, airlines with different market positioning can have different operating objectives and efficiency level (e.g., marginal cost). These limitations offer directions for additional study.

Chapter 4 Expand Capacity or Reduce Cost? An Analysis of the Optimal Timings for Two Types of Projects at an Airport

4.1 Introduction

As mentioned in Section 2.3, many airports in the world are encountering or going to encounter capacity crisis. Whilst there are plenty of measures that can alleviate the disutility caused by capacity shortage temporarily, a capital investment in the airport infrastructure proves to be a "surgical" solution that can tackle the problem for a long term.

On the other hand, airports are embracing innovation, technology adoption, and new services aiming to improve security, operational efficiency, and passenger experience. Among them, improvements in operational efficiency have been paid much attention by both public and private airports. For public airports, higher operational efficiency could mean lower cost, higher financial sustainability, and better social surplus. For private airports, since regulations are always imposed based on efficiency level (for example, incentive regulation or CPI +/- X), higher operational efficiency means higher "free profit." Many examples of airports investing in innovation for efficiency improvement can be observed: a digital twin, which can create a virtual replica of airport assets through real-time data, was built in Amsterdam Airport Schiphol in 2017[13]. The International Data Corporation projects that cost saving up to 25 per cent can be realized through the adoption of a digital twin[14]. Heathrow Airport invested £50 million in facial recognition to greatly improve the efficiency of various checks[15].

In addition to improving operational efficiency, there is another approach that could indirectly "reduce" operational costs: increasing non-aeronautical revenue. Non-aeronautical revenue has become a major component of airports' revenue streams. In some airports, non-aeronautical revenues even exceed aeronautical revenues (for example, Atlanta and Singapore) (Graham, 2018). As the significance of non-aeronautical activities

[13] https://www.esri.com/about/newsroom/arcuser/digital-twin-helps-airport-optimize-operations/

[14] https://www.altran.com/as-content/uploads/sites/7/2019/09/digital-twin-pov-whitepaper_v7.pdf

[15] https://mediacentre.heathrow.com/pressrelease/details/81/Brand-News-22/10209

is unlikely to decline in the future (Flores-Fillol et al., 2018), many airports have proactively conducted projects to renovate existing commercial facilities, or construct new ones, in recent years. For instance, Helsinki Airport opened a new commercial area called "Aukio" in 2019[16]; retail and hospitality expansion of Terminal 2 in Melbourne Airport is expected to be completed in 2022[17]. Although it will be up to the concessionaire to provide the investment for fitting out the facility, it was found that an increase of 1 per cent in the commercial area space led to a 0.2 per cent growth in commercial revenue[18].

Facing two types of investments, capacity expansion and cost reduction (including the expansion of non-aeronautical facilities in the context of this paper), how should airports make decisions that could bring the greatest benefit? Three points need to be addressed carefully. First, decision-makers should have a holistic consideration. Since aeronautical and non-aeronautical services are complementary, and the advantages of lower cost cannot be fully exploited if passenger growth is hindered by capacity shortage, a partial consideration might result in biased investment that fails to bring expected benefits. Second, the timing of each type of investment should be considered. Investment in infrastructure is lumpy, costly, and irreversible. An untimely investment decision might cause substantial losses that cannot be redeemed. Third, demand uncertainty should not be ignored. Aviation demand is generally growing year by year in most markets, but it can be highly vulnerable to some kind of catastrophe (for example, 9/11, the Great Recession, or COVID-19). Decision-makers should carefully estimate the risk caused by demand shock when planning projects in airports. Although numerous studies regarding airport investment can be found, most of them only focus on capacity expansion, and many of them do not consider timing and demand uncertainty. Only few studies consider multiple types of investments in airports. Kidokoro et al. (2016) study the airport's decision on the size choices for both aeronautical and non-aeronautical services employing a general-equilibrium model. However, their analysis is based on deterministic modeling. Sun and Schonfeld (2015) developed an airport capacity expansion model for

[16] https://www.finavia.fi/en/newsroom/2019/helsinki-airports-new-aukio-central-plaza-showcases-finnish-brands-long-haul

[17] https://my.melbourneairport.com/t2-retail-expansion

[18] https://www.moodiedavittreport.com/aci-underlines-role-of-service-quality-on-commercial-revenues/

three types of facilities—airfield, terminal, and cargo—considering demand uncertainty. While they address the timing issue in the simulation, the investment period is partitioned discretely, and the value of the option is not considered. For studies regarding multi-type investments in other areas, Décamps et al. (2006) provide an excellent discussion on the problem of investment in alternative projects with real options, which supersedes the classical theory of Dixit (1993). However, in their settings, two projects are each exclusive in that they are not allowed to coexist, and the investment sequence is predetermined. Truong et al. (2018) study the investment decisions of multiple climate change adaptation projects in the real option approach. However, they do not address the case in which several projects are invested in simultaneously.

To bridge the research gaps, this study aims to investigate the effect of various external factors on the timings and scales of airport investment considering two types of investments, namely capacity expansion and cost reduction. First, we examine the plausibility of modeling airport traffic evolution as a geometric Brownian process. Next, we build an analytical model to present the vertical structure of the market and derive the equilibrium output. Employing a real option approach to the decision-making for investments, we derive an optimal rule for the sequential investment taking into account of the inter-relationship between the projects. We then investigate how the profit-oriented degree, together with the downstream market structure and the dynamics of demand, affect the timing and scale of investments through numerical examples. Finally, we investigate the effects of those factors on the loss incurred when investments are carried out in sub-optimal timings following net present value (NPV) and deterministic rules.

4.2. Uncertainty test

Before modeling, we need to determine the type of stochastic process that is used to address the growing trend and uncertainty of airport traffic. Owing to its friendly mathematical properties, geometric Brownian motion (GBM) is widely used in various areas, including some recent studies regarding investments in transportation infrastructures (for example, Balliauw et al., 2019; Balliauw and Onghena, 2020; Zheng et al., 2020). A standard GBM is formulated as $dx = \alpha x dt + \sigma x dz$, where x denotes the stochastic variable, α and σ denote drift and variance, respectively, and t refers to time.

z is a Wiener process with $dz = \epsilon_t \sqrt{dt}$, where ϵ_t is a standard normal deviate. While demand is assumed to follow GBM in the studies mentioned above, plausibility of such an assumption is seldom examined using realistic data. In this section, we follow the approach of Hamilton (1994) and also Pindyck and Rubinfeld (1998) to perform a Dickey-Fuller test to verify whether it is reasonable to formulate airport traffic as GBM. The process is as follows:

1. Take logarithm of the data. If the data follows GBM, its logarithm will follow Brownian motion.

2. Define the null hypothesis, H_0, as $x_t = \alpha + x_{t-1} + u_t$ with u_t i.i.d. with mean zero. It corresponds to a random walk whose limit is Brownian motion. Define the alternative hypothesis, H_A, as $x_t = \alpha + \beta t + \rho x_{t-1} + u_t$, which corresponds to a first-order autoregressive process.

3. Run regressions. Regression for H_0 and H_A is called restricted and unrestricted regression, respectively. Then, calculate F and t statistics, and refer to the values in the Dickey-Fuller table. F is calculated by $F = (N - k)(ESS_R - ESS_{UR})/qESS_{UR}$, where N is the sample size, k denotes the number of estimated parameters in the unrestricted regression (H_A), and q denotes the number of parameter restrictions. ESS_R and ESS_{UR} denote the sums of squared residuals in the restricted and unrestricted regressions, respectively. The t statistic is calculated by $t = (\hat{\rho} - 1)/\hat{\sigma}_{\hat{\rho}}$, where $\hat{\rho}$ is the estimated ρ and $\hat{\sigma}_{\hat{\rho}}$ denotes the standard errors.

We use the historical traffic data of four airports, as shown in Table 4.1 and Fig. 4.1. Each of the four represents one type of airport. As one of the busiest airports in the world, Heathrow is a typical international hub. While Sydney is also a hub airport with high traffic, its "hubness" is significantly lower than that of Heathrow (Cheung et al., 2020). Bergen, with much lower traffic than the previously mentioned two large airports, is an international airport of medium scale, while Ljubljana is an emerging regional hub with low traffic in the current stage. The test results are shown in Table 4.2. In terms of the F-test, the null hypothesis that the traffic follows a random walk cannot be rejected at the 0.01 level for Heathrow and at the 0.1 level for the other three airports. In terms of the t-test, for all airports, the null hypothesis cannot be rejected at the 0.1 level. These results suggest that it is not unacceptable to describe airport traffic as GBM.

Table 4.1 Basic information of airports selected for the test

Airport	Country	Traffic in 2019
Heathrow	UK	80,884,310
Sydney	Australia	44,428,845
Bergen	Norway	5,964,341
Ljubljana	Slovenia	1,721,355

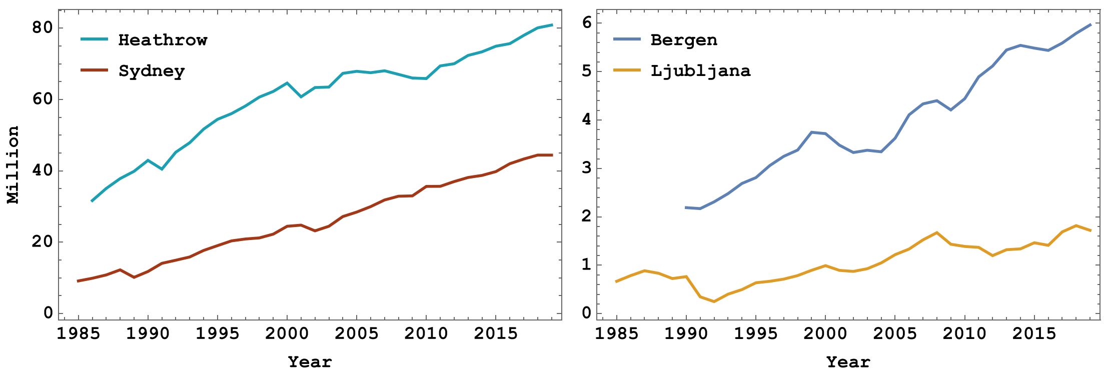


Fig 4.1 Evolutions of traffic at the selected airports

Table 4.2 Results of the Dickey-Fuller test

Airport	Sample size (N)	Dickey-Fuller F	Cannot be rejected at (F)	Dickey-Fuller t	P-value (t)
Heathrow	32	8.71253	1%	-2.9046	0.175582
Sydney	33	3.33851	10%	-2.04189	0.555857
Bergen	28	2.10197	10%	-1.8791	0.637216
Ljubljana	33	2.44653	10%	-2.17775	0.484232

4.3 The model

4.3.1 Description of the problem

Stakeholders: We focus on one section of the air transport supply chain for our discussion. It comprises the upstream market where the one single airport sells airport service to airlines and the downstream market where the airlines sell air service, which is a bundling of airport service and airline service, to passengers. We consider two types of airlines in the downstream: Leader airlines and follower airlines. We ignore the entry and exit of airlines.

Decision-making process: The airport has two types of decisions, investing decision and pricing decision, to make. The investing decision embodies the time and the scale for the investment in each project, and the pricing decision refers to the charge airport levies to the airlines. The investment decision is made in prior to the pricing decision. In the downstream, given the decisions from the upstream, the leader airlines choose their outputs (passenger) at first to maximize their profits respectively. Next, observing the remaining market, the follower airlines decide their outputs. Under such setting, the output of each leader airline will be higher than that of each follower airline, which can reflect the situation that hub airlines always have higher market shares than other airlines at an airport. The multi-stage game is illustrated by Fig 4.2.

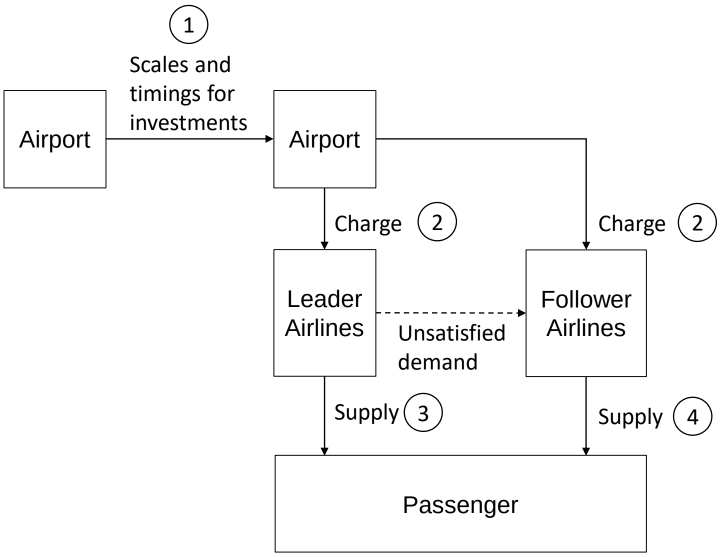


Fig 4.2 Diagram of the multi-stage game (Numbers in the circles indicate the sequence of decision-making)

Table 4.3 Notations for Chapter 4

Decision variables	
q_i	Number of passengers of airline i
w	Airport charge per passenger
Y_C	Optimal timing (demand level) for the investment in cost reduction
c_1	New cost level after the investment in cost reduction
Y_K	Optimal timing (demand level) for the investment in expansion
k_1	New capacity level after the investment in expansion
Parameters	
a	Delay cost parameter
b $(0 \leq b \leq 1)$	Cross-price effect coefficient
X	Maximum willingness to pay of the passenger
Y	Reverse of the own price effect
m	Number of leader airlines
n	Number of follower airlines
I_K	Fixed cost for the investment in capacity expansion
c_K	Unit cost for the investment in capacity expansion
c_C	Unit cost for the investment in cost reduction
c_0	Cost level before the investment
k_0	Capacity level before the investment
θ	Proportion of profit in the airport's objective function
α	Drift
σ	Volatility
r	Discount rate

Several important assumptions are made as follows for the sake of tractability or simplicity:

a. The decision-maker cannot optimize the volumes of the projects. Instead, he or she can select the scales of the projects from several pre-determined discrete levels to maximize the payoff.

b. Lead times of the investments are ignored. Alternatively, this can be explained by the fact that timing refers to the time when the project is expected to be finished, and the cost refers to the aggregated retrospective cost (for example, if the span is three years, the cost stands at $I * e^{3r}$ instead of I) incurred in the entire investment span.

c. Incremental investments are not considered.

Table 4.3 shows the notations of variables and parameters.

4.3.2 Formulation

We adopt backward induction to obtain the optimal decisions for each market participant. A quadratic function is employed to formulate the passengers' utility (for example, Vives, 1999). It is formulated as

$$U = XQ - \frac{1}{2Y}(Q_L^2 + 2bQ_LQ_F + Q_F^2) \tag{4.1}$$

where U denotes utility, X denotes the maximum level of willingness-to-pay of passengers, and $1/Y$ denotes the own-price effect. $Q_L = \sum_{i=1}^{m} q_{Li}$ and $Q_F = \sum_{j=1}^{n} q_{Fj}$ denote the total passenger numbers (quantities) of the leader airlines and follower airlines, respectively. b denotes the cross-price effect with $0 \leq b \leq 1$. $Q = Q_L + Q_F$. Maximizing the utility function, we can derive the inverse demand functions for passengers as

$$\rho_h = p_h + \left(\frac{a}{Y}\right)\delta = \frac{\partial U}{\partial q_h} = X - \left(\frac{1}{Y}\right)Q_h - \left(\frac{b}{Y}\right)Q_{h-} \tag{4.2}$$

where $h = L, F$; p_h denotes the airfare of airline that belongs to type h; w denotes the charge from airport; a denotes the unit delay cost; and $\delta = Q/k$ denotes the delay time, where k is the capacity level. It is clear that both X and Y are external factors that can determine the demand level, and most similar studies let X follow a stochastic process to describe demand uncertainty. In contrast, we set Y as the stochastic variable in this study. Doing so ensures a linear payoff function of the stochastic variable, which greatly simplifies the calculation, as shown in the following section. As examined in Section 3, GBM is not inappropriate to describe airport traffic, so we formulate the evolution of Y

as

$$dY = \alpha Y dt + \sigma Y dz \tag{4.3}$$

where the meanings of the parameters have been explained in Section 3. Some may question that while GBM has been verified to be reasonable for describing airport *traffic*, it is employed here to describe airport *demand*. This doubt can be resolved by obtaining the final output of traffic.

Next, we solve the subgame perfect equilibrium of the downstream market. The profit function of the follower airline i is

$$\pi_{Fi}(q_{Fi}; \boldsymbol{q}_{Fi-}, w, k, Q_L, Y) = [p_{Fi}(q_{Fi}, \boldsymbol{q}_{Fi-},\ k,\ Q_L, Y) - w]q_{Fi} \tag{4.4}$$

where the operational cost was normalized to 0. For simplicity, we assume that airlines do not incur congestion costs following Wan et al. (2015). This can be explained by the fact that the cost is transferred to the passengers. Solving the first-order condition (FOC) of Eq. (4) and imposing symmetry, we have

$$q_{Fi}^{***}\ (w, k,\ Q_L, Y) = \frac{kY(X - w) - (a + bk)Q_L}{(n + 1)(a + k)} \tag{4.5}$$

Substituting Eq. (5) into the profit function of the leader airline and solving the FOC of $\pi_{Li}(q_{Li}; \boldsymbol{q}_{Li-}, w, k, Q_F^*, Y) = [p_{Li}(q_{Li}, \boldsymbol{q}_{Li-},\ k, Q_F^*, Y) - w]q_{Li}$, we have the subgame perfect equilibria of outputs as

$$Q_L^{**}\ (w, k, Y) = C_L Y(X - w) \tag{4.6}$$

$$Q_F^{**}\ (w, k, Y) = C_F Y(X - w) \tag{4.7}$$

where:

$$C_L = \frac{km[a + k(1 + (1 - b)n)]}{(m + 1)\left[k^2\big((1 - b^2)n + 1\big) + a^2 + 2ak\big((1 - b)n + 1\big)\right]} \tag{4.8}$$

$$C_F = \frac{kn}{m + 1}\left[\frac{(1 - b)km}{k^2\big((1 - b^2)n + 1\big) + a^2 + 2ak\big((1 - b)n + 1\big)} + \frac{1}{(n + 1)(a + k)}\right] \tag{4.9}$$

m and n denote the number of leader and follower airlines respectively.

The airport's objective function is formulated as

$$\Gamma(w; k, c, Y) = \theta \Pi(w, k, c, Y) + (1 - \theta)S(w, k, c, Y) \tag{4.10}$$

where:

$$\Pi(w,k,c,Y) = Q^{**}(w-c) \quad (4.11)$$

$$S(w,k,c,Y) = \left(X - c - \left(\frac{a}{Y}\right)\delta(Q^{**},k)\right)Q^{**} - \frac{1}{2Y}\left(Q_L^{**2} + 2bQ_L^{**}Q_F^{**} + Q_F^{**2}\right) \quad (4.12)$$

θ is a coefficient that determines the premium the airport places on profit with $0 \le \theta \le 1$. It can also be interpreted as the amount of private share in the airport's ownership. The higher the θ, the more profit-oriented the airport is. If $\theta = 0$, the airport will never take advantage of its market power; it will maximize the social surplus. c denotes the difference between unit cost and unit non-aeronautical profit per passenger.

We assume that the airport must ensure financial break-even when setting the optimal charge, so a non-negative profit constraint should be attached to Eq. (4.10). From Eq. (4.11), we know that the non-negative profit constraint is equivalent to $w \ge c$, so the Lagrange function becomes

$$L(w,\lambda;k,c,Y) = \Gamma(w;k,c,Y) + \lambda(w-c) \quad (4.13)$$

The Karush-Kuhn-Tucker condition for the problem is $\frac{\partial L}{\partial w} = 0, w \ge c, \lambda \ge 0, \lambda(w-c) = 0$. Solving these conditions, we obtain the optimal charge as

$$w^*(k,c) = \begin{cases} c, & 0 \le \theta < \theta^* \\ \dfrac{k(X-c)(C_F+C_L)}{2C_F\big((bk+2a)(\theta-1)C_L-k\theta\big)+(\theta-1)C_F^2(2a+k)+C_L\big((\theta-1)C_L(2a+k)-2k\theta\big)} + X, & \theta^* \le \theta \le 1 \end{cases} \quad (4.14)$$

Maximum payoff is accordingly derived as

$$\Gamma^*(k,c,Y) = \begin{cases} \dfrac{(\theta-1)Y(X-c)^2\big(2a(C_F+C_L)^2+k\big(2C_F(bC_L-1)+C_F^2+(C_L-2)C_L\big)\big)}{2k}, & 0 \le \theta < \theta^* \\ \dfrac{kY(X-c)^2(C_F+C_L)^2}{4a(1-\theta)(C_F+C_L)^2-2k\theta\big(2C_F(bC_L-1)+C_F^2+(C_L-2)C_L\big)+2k\big(2bC_FC_L+C_F^2+C_L^2\big)}, & \theta^* \le \theta \le 1 \end{cases} \quad (4.15)$$

where $\theta^* = \frac{k(C_F+C_L)}{k\left(2C_F(bC_L-1)+C_F^2+(C_L-2)C_L\right)+2a(C_F+C_L)^2} + 1$. From Eq. (4.14), it is clear that the optimal charge is not a function of Y. The equilibrium output (traffic), derived by substituting the optimal charge into Eq. (4.6) and (4.7), is merely a linear function of Y without an intercept. By Eq. (4.3), it is known that if Y follows GBM, the product of Y and a constant will follow GBM as well. Hence, the equilibrium output follows GBM.

Let the initial levels of capacity and cost be k_0 and c_0, respectively. Improvement in the maximum payoff by expanding capacity from k_0 to k_1 at Y is denoted as

$$R_K Y = \Gamma^*(k_1, c_0, Y) - \Gamma^*(k_0, c_0, Y) \tag{4.16}$$

Improvement in the maximum payoff by reducing cost from c_0 to c_1 at Y is denoted as

$$R_C Y = \Gamma^*(k_0, c_1, Y) - \Gamma^*(k_0, c_0, Y) \tag{4.17}$$

Improvement in the maximum payoff by carrying out two projects simultaneously at Y is denoted as

$$R_A Y = \Gamma^*(k_1, c_1, Y) - \Gamma^*(k_0, c_0, Y) \tag{4.18}$$

We then have:

Lemma 4.1

For any $k_1 > k_0 > 0$ and $c_0 > c_1 > 0$, the improvement in payoff by carrying out two types of projects simultaneously will always be greater than the summation of the two respective improvements in payoffs, namely, $R_A > R_K + R_C$.

Proof: The objective function $\Gamma^*(k, c, Y)$ can be written as a multiplicative function of three one-variable functions, namely, $\Gamma^*(k, c, Y) = \Gamma_K(k) * \Gamma_C(c) * Y$, so we have $R_K + R_C = [\Gamma_K(k_1) - \Gamma_K(k_0)] * \Gamma_C(c_0) + [\Gamma_C(c_1) - \Gamma_C(c_0)] * \Gamma_K(k_0)$

$R_A = \Gamma_K(k_1) * \Gamma_C(c_1) - \Gamma_K(k_0) * \Gamma_C(c_0)$, and

$R_A - (R_K + R_C) = [\Gamma_K(k_1) - \Gamma_K(k_0)] * [\Gamma_C(c_1) - \Gamma_C(c_0)]$.

To complete the proof, it suffices to prove that $\frac{d\Gamma_C(c)}{dc}$ and $\frac{d\Gamma_K(k)}{dk}$ have different signs. It is self-evident that $\frac{d\Gamma_C(c)}{dc} < 0$. We can then prove that $\frac{d\Gamma_K(k)}{dk} > 0$ as follows:

To prove $\frac{d\Gamma_K(k)}{dk} > 0$, it suffices to show $\frac{\partial \Gamma^*(k,c,Y)}{\partial k} > 0$. Following the envelope theorem, we have $\frac{\partial \Gamma^*(k,c,Y)}{\partial k} = \frac{\partial L(w,\lambda;k,c,Y)}{\partial k}\Big|_{w=w^*,\lambda=\lambda^*} = \frac{\partial \Gamma(w;k)}{\partial k}\Big|_{w=w^*}$. Since

$\left.\frac{\partial Q_F(w,k)}{\partial k}\right|_{w=w^*} = (X-w^*)Y\frac{\partial C_F}{\partial k} = \left(\frac{n(X-w^*)Y}{m+1}\right)\left[\frac{2a(1-b)km\big(a+k(n(1-b)+1)\big)}{\big((a+k)^2+(1-b)kn(2a+bk+k)\big)^2} + \frac{a}{(a+k)^2(1+n)}\right] > 0$ and

$\left.\frac{\partial Q_L(w,k)}{\partial k}\right|_{w=w^*} = (X-w^*)Y\frac{\partial C_L}{\partial k} = \left(\frac{am(X-w^*)Y}{m+1}\right)\left[\frac{((a+k)^2+(1-b)k(2a+(3-b)k)n+2(1-b)^2k^2n^2)}{((a+k)^2+(1-b)k(2a+k+bk)n)^2}\right] > 0,$

we have $\left.\frac{\partial \Pi(w,k)}{\partial k}\right|_{w=w^*} = (w^*-c)\left[\left.\frac{\partial Q_F(w,k)}{\partial k}\right|_{w=w^*} + \left.\frac{\partial Q_L(w,k)}{\partial k}\right|_{w=w^*}\right] > 0.$

Since $\left.\frac{\partial S(,;k)}{\partial Q_F}\right|_{w=w^*} = p_F(w^*) - c - \frac{a\big(Q_F(w^*)+Q_L(w^*)\big)}{kY}$, $\left.\frac{\partial S(w,k)}{\partial Q_L}\right|_{w=w^*} = p_L(w^*) - c - \frac{a\big(Q_F(w^*)+Q_L(w^*)\big)}{kY}$, we have

$$\begin{aligned}\left.\frac{\partial S(w,k)}{\partial k}\right|_{w=w^*} &= \left[\frac{\partial S(w,Q_L,Q_F,k)}{\partial Q_F}\frac{\partial Q_F(w,k)}{\partial k} + \frac{\partial S(w,Q_L,Q_F,k)}{\partial Q_L}\frac{\partial Q_L(w,k)}{\partial k}\right.\\ &\quad\left.\left. + \frac{\partial S(w,Q_L,Q_F,k)}{\partial k}\right]\right|_{w=w^*}\\ &= (p_F(w^*)-c)\left.\frac{\partial Q_F(w,k)}{\partial k}\right|_{w=w^*} + (p_L(w^*)-c)\left.\frac{\partial Q_L(w,k)}{\partial k}\right|_{w=w^*}\\ &\quad + \frac{a\big(Q_F(w^*)+Q_L(w^*)\big)^2}{k^2Y} - \left(\frac{\partial(Q_F(w^*)+Q_L(w^*))}{\partial k}\right)\left(\frac{a\big(Q_F(w^*)+Q_L(w^*)\big)}{kY}\right)\end{aligned}$$

The first and the second terms are positive $(p_j(w^*) > w^* \geq c)$. We then need to investigate the sign of the remnant, which is equivalent to the sign of $\frac{C_F+C_L}{k} - \frac{\partial(C_F+C_L)}{\partial k}$. It can be shown that $\frac{C_F+C_L}{k} - \frac{\partial(C_F+C_L)}{\partial k} = \frac{k}{1+m}(C_1 + \frac{C_2}{C_3})$, where

$C_1 = \frac{n}{(n+1)(a+k)^2} > 0,$

$C_2 = m\big[a^2 + 2ak(n(1-b^2)+1) + k^2(2(1-b)n+1)\big((1-b^2)n+1\big)\big] > 0,$

$C_3 = ((a+k)^2 + (1-b)kn(2a+bk+k))^2 > 0.$

Hence, $\frac{C_F+C_L}{k} - \frac{\partial(C_F+C_L)}{\partial k} > 0$, and $\left.\frac{\partial S(w,k)}{\partial k}\right|_{w=w^*} > 0.$

Consequently, we can obtain $\left.\frac{\partial \Gamma(w,k)}{\partial k}\right|_{w=w^*} = (1-\theta)\left.\frac{\partial S(w,k)}{\partial k}\right|_{w=w^*} + \theta\left.\frac{\partial \Pi(w;k)}{\partial k}\right|_{w=w^*} > 0,$ so $\frac{d\Gamma_K(k)}{dk} > 0.$

Therefore, $R_A > R_C + R_K$. ■

We then solve the optimal timing problem in a real option approach. As mentioned in

Chapter 2, real option approach greatly underlines the opportunity cost of investment, which can be colossal in the case of airport. Hence, it might be more appropriate to model the decision-making regarding the investment in airport projects in a real option approach. The optimal timing problem can be formulated as

$$F_{CK}(Y) = \max_{t_{CK}} \left[V_C(Y) + \mathbb{E}\left[e^{-rt_{CK}} \left(V_A(Y_{CK}) - V_C(Y_{CK}) \right) \right] \right] \tag{4.19}$$

$$F_{KC}(Y) = \max_{t_{KC}} \left[V_K(Y) + \mathbb{E}\left[e^{-rt_{KC}} \left(V_A(Y_{KC}) - V_K(Y_{KC}) \right) \right] \right] \tag{4.20}$$

$$F^s(Y) = \max\{F_{CK}(Y), F_{KC}(Y)\} \tag{4.21}$$

$$F(Y) = \max_{t_s} \mathbb{E}[e^{-rt_s} F^s(Y_s)] \tag{4.22}$$

where $F_{xy}(Y)$ denotes the maximum expected value of the entire investment in a sequence that project x is started first at Y and project y will follow subsequently. Similarly, t_{xy} denotes the time to invest in project y, given that project x has been finished and $Y_{xy} = Y(t_{xy})$. Subscripts K and C denote capacity expansion and cost reduction, respectively. $V_z(Y)$ denotes the expected value of project z at Y, and subscript A denotes the case in which two types of projects are started simultaneously. $F(Y)$ denotes the value of the option for the entire investment, which can be carried out in any sequence (KC, CK, or A), given that the investment has not started yet. t_s denotes the time to start the entire project. r denotes discount rate.

The problem can be solved using a backward induction approach (from t_{xy} to t_s). We take the sequence CK as an example to illustrate the solving process. First, we calculate the expected value V_A at Y as

$$V_A(Y) = \mathbb{E}\left[\int_0^\infty R_A Y_t e^{-rt} dt \right] - I_K - I_C = \frac{R_A Y}{r - \alpha} - I_K - I_C \tag{4.23}$$

where I_K and I_C denote the investment cost of project K and C, respectively. Then, we obtain $\mathcal{F}_{CK}(Y) = F_{CK}(Y) + I_C$ by the Bellman function as follows:

$$\mathcal{F}_{CK}(Y) = R_C Y dt + \mathbb{E}[\mathcal{F}_{CK}(Y + dY) e^{-rdt}] \tag{4.24}$$

Expanding Eq. (4.24) by Ito's lemma, we have the following differential equation:

$$\frac{1}{2}\sigma^2 Y^2 \mathcal{F}_{CK}{}''(Y) + \alpha Y \mathcal{F}_{CK}{}'(Y) - r\mathcal{F}_{CK}(Y) + R_C Y = 0 \tag{4.25}$$

Solving Eq. (4.25) and ruling out worthless terms, we have

$$F_{CK}(Y) = \mathcal{F}_{CK}(Y) - I_C = \frac{R_C Y}{r-\alpha} - I_C + B_{CK} Y^{\beta} \tag{4.26}$$

where B_{CK} is a constant that is yet to be determined. $\beta = \sqrt{\left(\frac{1}{2} - \frac{\alpha}{\sigma^2}\right)^2 + \frac{2r}{\sigma^2}} - \frac{\alpha}{\sigma^2} + \frac{1}{2}$.

The optimal timing (demand level) Y_{CK}^* and B_{CK} can be obtained by the following boundary conditions (Dixit and Pindyck, 1994):

$$F_{CK}(Y_{CK}^*) = V_A(Y_{CK}^*) \tag{4.27}$$

$$F'_{CK}(Y_{CK}^*) = V'_A(Y_{CK}^*) \tag{4.28}$$

where Eq. (4.27) is the value-matching condition and Eq. (4.28) is the smooth-pasting condition. Solving them, we have

$$Y_{CK}^* = \frac{\beta I_K (r-\alpha)}{(\beta-1)(R_A - R_C)} \tag{4.29}$$

$$B_{CK} = \left(\frac{\beta-1}{I_K}\right)^{\beta-1} \left(\frac{R_A - R_C}{\beta(r-\alpha)}\right)^{\beta} \tag{4.30}$$

If $F^s(Y) = F_{CK}(Y)$, by a similar approach we can derive the option value $F(Y)$ as

$$F(Y) = B_C Y^{\beta} \tag{4.31}$$

where $B_C = \left(\frac{\beta-1}{I_K}\right)^{\beta-1} \left(\frac{R_A - R_C}{\beta(r-\alpha)}\right)^{\beta} + \left(\frac{\beta-1}{I_C}\right)^{\beta-1} \left(\frac{R_C}{\beta(r-\alpha)}\right)$. The optimal timing (demand level) to start the entire project can thus be obtained as

$$Y_C^* = \frac{\beta I_C (r-\alpha)}{(\beta-1) R_C} \tag{4.32}$$

As a result, we can summarize the value of the investment in sequence CK as

$$\mathcal{V}_{CK}(Y) = \begin{cases} V_A(Y) = \dfrac{R_A Y}{r-\alpha} - I_K - I_C, & Y \geq Y_{CK}^* \\ F_{CK}(Y) = \dfrac{R_C Y}{r-\alpha} - I_C + B_{CK} Y^{\beta}, & Y_C^* \leq Y < Y_{CK}^* \\ F(Y) = B_C Y^{\beta}, & Y < Y_C^* \end{cases} \tag{4.33}$$

Similarly, we derive the optimal timing (demand level) of investment in other sequences (KC, A) as

$$Y_K^* = \frac{\beta I_K(r-\alpha)}{(\beta-1)R_K} \tag{4.34}$$

$$Y_{KC}^* = \frac{\beta I_C(r-\alpha)}{(\beta-1)(R_A-R_K)} \tag{4.35}$$

$$Y_A^* = \frac{\beta(I_K+I_C)(r-\alpha)}{(\beta-1)R_A} \tag{4.36}$$

We then obtain the optimal rule of the investment as:

Proposition 4.1

If and only if $\frac{R_C}{I_C} > \frac{R_A}{I_C+I_K} > \frac{R_K}{I_K}$, it is optimal to invest in cost reduction (C) once Y reaches Y_C^*, and then invest in capacity expansion (K) once Y reaches Y_{CK}^*. If and only if $\frac{R_K}{I_K} > \frac{R_A}{I_C+I_K} > \frac{R_C}{I_C}$, it is optimal to invest in capacity expansion (K) once Y reaches Y_K^*, and then invest in cost reduction (C) once Y reaches Y_{KC}^*. Otherwise, it is optimal to invest in the two projects simultaneously (A) when Y reaches Y_A^*.

Proof: Comparing the optimal timings derived, we have following four cases:

Case 1. $Y_{KC}^* > Y_K^*$ and $Y_{CK}^* > Y_C^*$

In this case, rearranging the inequalities, we have $R_K + R_C > R_A$. Lemma 4.1 has proven that $R_K + R_C > R_A$ is false. By *modus tollens*, $Y_{KC}^* > Y_K^*$ and $Y_{CK}^* > Y_C^*$ are thus false. It is impossible for Case 1 to happen.

Case 2. $Y_{KC}^* > Y_K^*$ and $Y_{CK}^* \leq Y_C^*$(Fig. 4.3a)

In this case, the decision-maker has two alternatives: investing in sequence KC or A. Since it can be proved that $Y_A^* < Y_{KC}^*$ in this case, KC is greater than A in terms of the value of the investment at Y_A^*, namely, $\mathcal{V}_{KC}(Y_A^*) > \mathcal{V}_A(Y_A^*)$. It is self-evident that $\mathcal{V}_{KC}(Y) \geq \mathcal{V}_A(Y)$ for any Y satisfying $Y > Y_A^*$. To prove that $\mathcal{V}_{KC}(Y) > \mathcal{V}_A(Y)$ for any Y satisfying $Y < Y_A^*$, it suffices to show that $B_C > B_A$. If $B_C \leq B_A$, as the slope of $\mathcal{V}_A$ in region $Y < Y_K^*$ will not grow slower than that of $\mathcal{V}_C$, and their starting values and slopes are all zero, $\mathcal{V}_{KC}(Y_K^*)$ will not be greater than $\mathcal{V}_A(Y_K^*)$. Then, as the region changes from $Y < Y_K^*$ to $Y_K^* \leq Y < Y_{KC}^*$, the growing speed of the slope of $\mathcal{V}_{KC}(Y)$ will decline, so

$\mathcal{V}_A(Y) - \mathcal{V}_{KC}(Y)$ will be larger and $\mathcal{V}_A(Y_A^*)$ should definitely be greater than $\mathcal{V}_{KC}(Y_A^*)$. This is false, and so $B_C > B_A$ is true. As a result, $\mathcal{V}_{KC}(Y) \geq \mathcal{V}_A(Y)$ will hold given any positive Y, so the decision-maker will never invest in sequence A. Rearranging the inequalities, we can easily find that $Y_{CK}^* \leq Y_C^*, Y_{KC}^* > Y_K^*$ is necessary and sufficient for $\frac{R_K}{I_K} > \frac{R_A}{I_C+I_K} > \frac{R_C}{I_C}$.

Case 3. $Y_{KC}^* \leq Y_K^*$ and $Y_{CK}^* > Y_C^*$(Fig. 4.3b)

This is symmetrical to Case 2. Using the same method, we find that $Y_{KC}^* \leq Y_K^*, Y_{CK}^* > Y_C^*$ is necessary and sufficient for $\frac{R_C}{I_C} > \frac{R_A}{I_C+I_K} > \frac{R_K}{I_K}$.

Case 4. $Y_{KC}^* \leq Y_K^*$ and $Y_{CK}^* \leq Y_C^*$(Fig. 4.3c)

The only alternative for the decision-maker is to invest in two projects simultaneously. It is straightforward that $Y_{KC}^* \leq Y_K^*, Y_{CK}^* \leq Y_C^*$ is necessary and sufficient for $\frac{R_A}{I_C+I_K} > \frac{R_K}{I_K}, \frac{R_A}{I_C+I_K} > \frac{R_C}{I_C}$. ■

As a result, the optimal rule proves to be very simple: investing in the project with the greatest gain-cost ratio first. The sequence of investments depends on the ranking of the gain-cost ratio. The optimal timing for the investment in each project can be expressed as:

$$Y_K = \begin{cases} Y_{CK}^*, & \dfrac{R_C}{I_C} > \dfrac{R_A}{I_C + I_K} > \dfrac{R_K}{I_K} \\ Y_K^*, & \dfrac{R_K}{I_K} > \dfrac{R_A}{I_C + I_K} > \dfrac{R_C}{I_C} \\ Y_A^*, & \dfrac{R_A}{I_C + I_K} > \dfrac{R_K}{I_K}, \dfrac{R_A}{I_C + I_K} > \dfrac{R_C}{I_C} \end{cases} \tag{4.37}$$

$$Y_C = \begin{cases} Y_C^*, & \dfrac{R_C}{I_C} > \dfrac{R_A}{I_C + I_K} > \dfrac{R_K}{I_K} \\ Y_{KC}^*, & \dfrac{R_K}{I_K} > \dfrac{R_A}{I_C + I_K} > \dfrac{R_C}{I_C} \\ Y_A^*, & \dfrac{R_A}{I_C + I_K} > \dfrac{R_K}{I_K}, \dfrac{R_A}{I_C + I_K} > \dfrac{R_C}{I_C} \end{cases} \tag{4.38}$$

As discussed, under our setting, the output will be a linear function of Y without an intercept. Thus, in practice, we can determine the time to invest just by observing the number of passengers (output) using the airport. For example, let the current daily number of passengers be 10000, and obtain the current value of Y as 10. If the optimal demand level (timing) is derived as 20, the decision-maker should invest as long as the number of passengers reaches 20000. Following Proposition 1, we can write the value of the whole investment as:

$$\mathcal{V}(Y) = \begin{cases} \mathcal{V}_{CK}(Y), & \frac{R_C}{I_C} > \frac{R_A}{I_C+I_K} > \frac{R_K}{I_K} \\ \mathcal{V}_{KC}(Y), & \frac{R_K}{I_K} > \frac{R_A}{I_C+I_K} > \frac{R_C}{I_C} \\ \mathcal{V}_A(Y), & \frac{R_A}{I_C+I_K} > \frac{R_K}{I_K}, \frac{R_A}{I_C+I_K} > \frac{R_C}{I_C} \end{cases} \tag{4.39}$$

The optimal rule will then be applied to the numerical simulations in following sections.

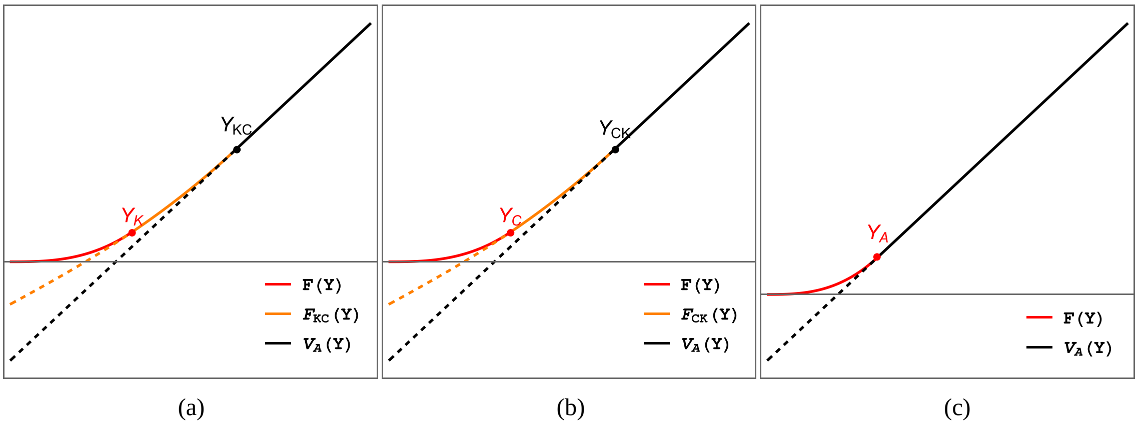


Fig 4.3 Value function $\mathcal{V}$ in each case: (a) $\mathcal{V}_{KC}$, (b) $\mathcal{V}_{CK}$, and (c) $\mathcal{V}_A$

4.4 Numerical examples

4.4.1 Settings

In this section, we present several numerical examples to see the effect of θ (the private share), b (the cross-price effect), m and n (the number of airlines), α (drift), and σ (volatility) on the optimal timings and scales for the investments. For each combination of project scale (for example, *small-scale* project of capacity expansion plus *large-scale* project of cost reduction), we obtain its optimal timing of each type of investment based on the abovementioned rules, and then calculate the value of the investment according to Eq. (4.33). Combination with the highest value is chosen, and the optimal timings thereof are presented as the final results.

Values of parameters that will not change throughout this section, if not specifically mentioned, are set as shown in Table 4.4. The value of X is set based on Basso and Zhang (2008), the marginal operating cost of airport is set based on Martín and Voltes-Dorta (2011), and the cost of the investment in capacity expansion is set based on Sun and Schonfeld (2015). Following Petrakis and Roy (1999), we define the cost of the investment in cost reduction as a convex function with regard to the volume of reduction. Other values are set hypothetically due to the lack of data. The scale of each project has five levels as shown in Table 4.5.

Table 4.4 Values of parameters for the numerical examples

Parameter	**Value**	**Parameter**	**Value**
X	2000	I_C	$c_C * (c_0 - c_1)^2$
a	300	c_K	$2 * 10^5$
b	0.5	f_K	$6.5 * 10^7$
m	2	c_C	$8 * 10^7$
n	2	σ_{year} (annual)	0.1
k_0	10000	α_{year} (annual)	0.04
c_0	8	r_{year} (annual)	0.1
I_K	$f_K + c_K * (k_1 - k_0)$	Y_0 (Starting time)	2

Table 4.5 The scale of each project

	Very small	**Small**	**Medium**	**Large**	**Very large**
Capacity expansion ($\boldsymbol{k_1}$)	12000 (+20%)	14000 (+40%)	16000 (+60%)	18000 (+80%)	20000 (+100%)
Cost reduction ($\boldsymbol{c_1}$)	7.6 (-5%)	7.2 (-10%)	6.8 (-15%)	6.4 (-20%)	6 (-25%)

Note that the payoff will be calculated on a monthly basis, so the monthly drift, volatility and discount rate are obtained by $\alpha = \alpha_{year}/12$, $\sigma = \sqrt{\frac{\sigma_{year}{}^2}{12}}$ and $r = \sqrt[12]{1 + r_{year}} - 1$, respectively.

4.4.2 Comparation of the optimal rules

Before conducting the formal analysis, we would like to compare the optimal rules through a numerical experiment. Truong et al. (2018) gives an optimal rule for the sequential investment in inter-related projects. Their rule prescribes that the decision-maker should select the sequence which yields the maximum value, but they did not consider a case that the optimal timings therein can be just opposed to the selected sequence (in our context, for example, the optimal sequence is CK, while $Y_{CK}^* < Y_C^*$, namely the optimal timing to invest in K is prior to C). Setting the scale of capacity expansion as medium, and the scale of cost reduction very large, numerical experiment shows that the investment following their "optimal" rule will cause some loss in the value compared with ours, although the loss is not significant (Fig 4.4).

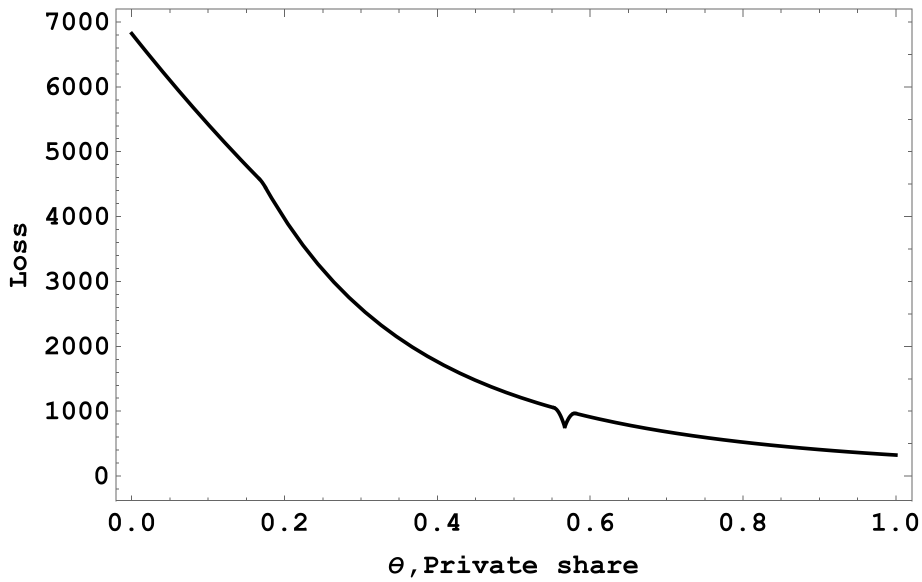


Fig 4.4 Loss due to the optimal rule proposed by Truong et al. (2018)

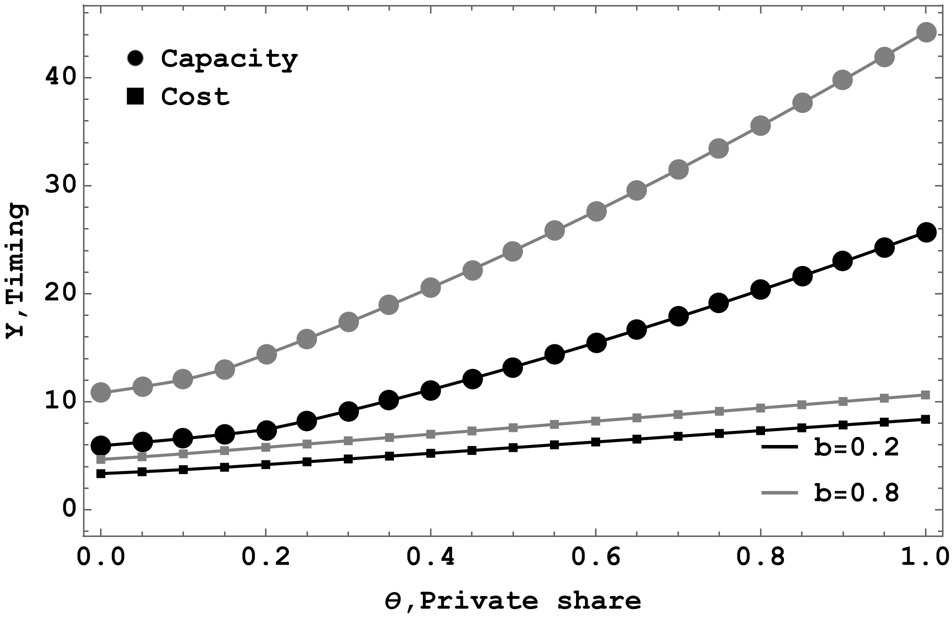


Fig 4.5 Optimal timings (demand level Y) for the investments with different b and different θ

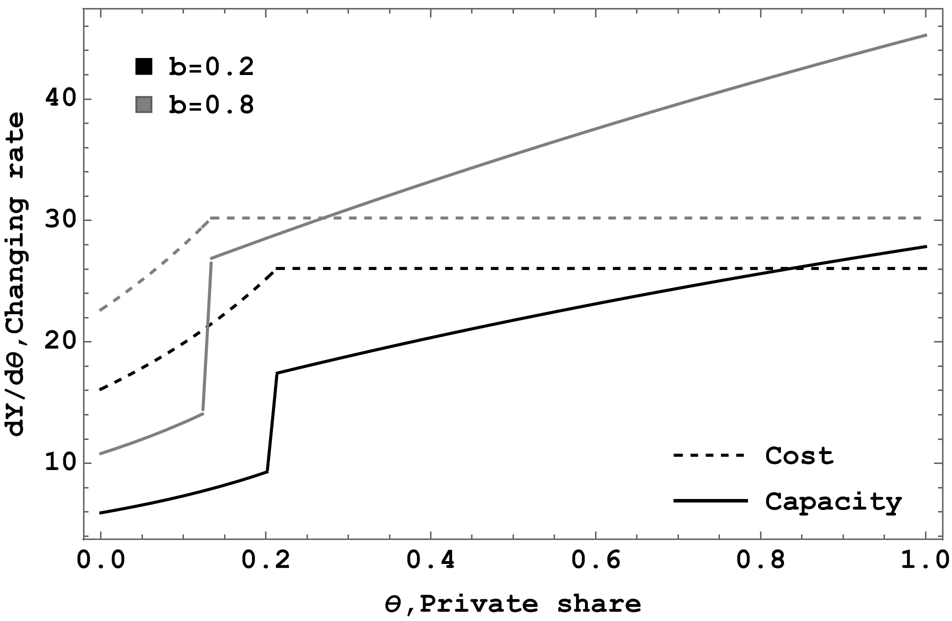


Fig 4.6 Changing rate of optimal timings

4.4.3 Results of the optimal timings

Fig. 4.5 shows how the optimal timings (demand level Y) for the investments change as

b and θ change. First, it is obvious that the optimal timings for the investments in both projects become earlier as the private share goes lower. A social surplus-oriented airport always has stronger inclination to invest earlier than a profit-oriented airport in spite of the type of project. Next, we can see that the higher the b (cross-price effect between leader and follower airlines), the later the optimal timings. A higher b will lead to a lower output of the follower airline, while the leader airline's output is a convex function with regard to b: It increases with b when b is high, and vice versa. Anyway, the total output will always decrease as b goes higher. A lower output leads to a lower payoff, making the demand level (timing) which can justify the investment higher. However, the scale of each project does not change as θ and b change. In current setting, the optimal scale of capacity expansion is *very large*, while the optimal scale of cost reduction is *very small* (see Table 4.5). Given higher θ and b, the decision maker would rather postpone the investment than reduce the scale, and vice-versa.

The priority between the two investments can change as the gain-cost ratio differs. The changing rate of the optimal timings with regard to the change in θ (private share) is an interesting issue to investigate. To make things clearer, we further present the numerical examples that describe $\frac{dY}{d\theta}$ (Fig 4.6). We can observe that in the non-binding region (recall that the charge will be bound to unit cost if private share is too low, see Eq. (4.14)), the timing for cost reduction changes uniformly along with θ, while the timing for capacity expansion seems to be convex with regard to θ. In other words, the changing rate of the optimal timing for capacity expansion will grow faster as θ goes higher. Regarding the optimal timing for cost reduction, the following result can be deduced analytically.

Proposition 4.2

In the region where the non-negative profit constraint is not binding (that is, $\lambda^* = 0$) and two types of investments are not carried out simultaneously, given a fixed scale of project, the optimal timing for the investment in cost reduction changes uniformly as θ changes, namely, $\frac{d^2Y}{d\theta^2} = 0$.

Proof: In the case where the investment in cost reduction is carried out first, R_{CU} can be rewritten as $R_{CU} = Z(\theta, k_0)[(X - c_1)^2 - (X - c_0)^2]$ referring to Eq. (17), where

$Z(\theta,k)=\frac{k(C_F+C_L)^2}{4a(1-\theta)(C_F+C_L)^2-2\theta k\left(2C_F(bC_L-1)+C_F^2+(C_L-2)C_L\right)+2k\left(2bC_FC_L+C_F^2+C_L^2\right)}$ and the subscript U denotes the unbounded region. Hence, $\frac{d^2Y_{CU}^*}{d\theta^2}=\frac{\beta I_C(r-\alpha)}{(\beta-1)[(X-c_1)^2-(X-c_0)^2]}*\frac{d^2(1/Z(\theta,k_0))}{d\theta^2}$. Because $1/Z(\theta,k_0)$ is a linear function of θ, $\frac{d^2(1/Z(\theta,k_0))}{d\theta^2}=0$ and $\frac{d^2Y_{CU}^*}{d\theta^2}=0$. For the case in which the investment in capacity is carried out first, $\frac{d^2Y_{KCU}^*}{d\theta^2}=\frac{\beta I_C(r-\alpha)}{(\beta-1)[(X-c_1)^2-(X-c_0)^2]}*\frac{d^2(1/Z(\theta,k_1))}{d\theta^2}$, so $\frac{d^2Y_{KCU}^*}{d\theta^2}=0$ also holds. ■

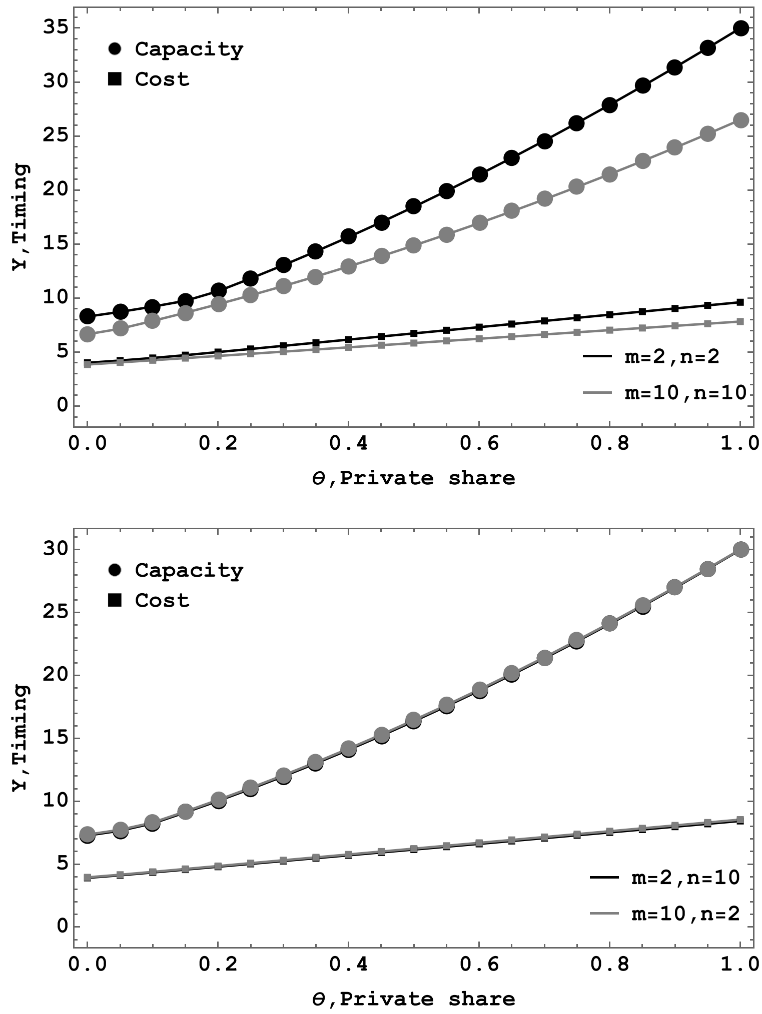


Fig 4.7 Optimal timings (demand level Y) for the investments with different m, n and different θ

Fig 4.7 shows how the optimal timings (demand levels) for the investments change as m (number leader airlines) and n (number follower airlines) change. Results indicate that the larger the total number of airlines, the earlier the optimal timings, while the respective number of leader and follower airlines does not have a significant impact, as long as the total number keeps unchanged. This is not difficult to understand, as the more the number of airlines, the fiercer the competition in the downstream market, and the greater the downstream demand. However, the total downstream demand would not change greatly given the total number of airlines $m + n$ remains unchanged, although the allocation of demand might differ as m and n vary. As with the case changing b, the optimal scale of project is not sensitive to the structure of the downstream.

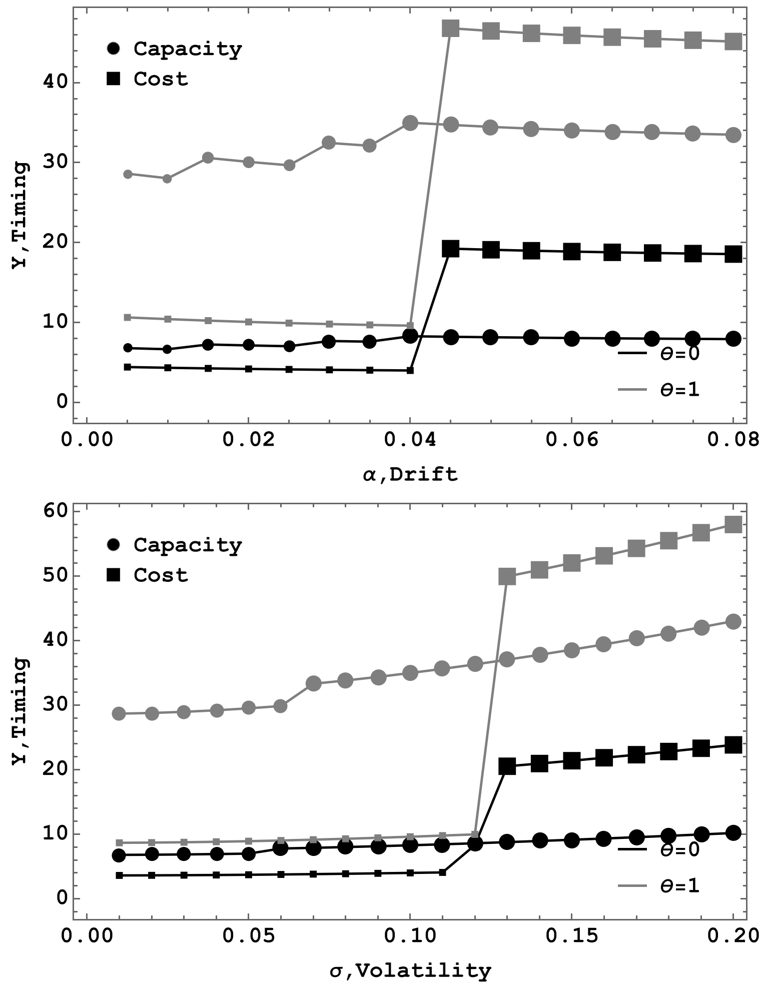


Fig 4.8 Effect of α and σ on the optimal scales and timings (demand level Y) (The size of the marker indicates the scale of project)

Fig 4.8 shows how do α (drift) and σ (volatility) affect the optimal timings and scales. Results indicate that the optimal scale of project increases as α and σ go higher, and an increase in the scale also postpones its investment. The scale of cost reduction jumps from the smallest to the largest scale when α or σ reaches a certain level, while the scale of capacity expansion increases gradually. It is difficult to figure out the actual reason of the difference. However, it might originate from the following two aspects. First, cost reduction and capacity expansion affect the payoff function in different ways. The capacity level k is involved in the subgame equilibrium, while the cost level c only appears in the airport's objective function. Second, the investment cost function is linear in terms of capacity expansion project, while convex in terms of cost reduction project. Anyway, given same project scale, the higher the α, the earlier the investments. This is consistent with the common sense that a sound prospect of the industry could stimulate investment. Similarly, a higher σ results in a later investment. This is because the investor always tends to wait when being uncertain about the prospect so that she can avoid loss if demand goes down and retain the opportunity to invest when demand goes up (Dixit and Pindyck, 1994).

In summary, these results imply that, to restrain the abuse of market power by airports, that is, to improve social surplus, adjustment to the timing for investment might be as important as price regulation. The government can use instruments such as subsidization to align the timings for investments with the social optimum (e.g., Zheng et al., 2020). Depending on the goal of improvement in social surplus to be achieved, the optimal adjustment to the timing for different projects can vary by project and external factors. Generally, projects with lower gain-cost ratios should be brought forward by a longer span than the other projects. While the span to bring forward can be consistent for cost reduction in the non-binding region if the goal $\Delta\theta$ is the same, the span for capacity expansion is always decreasing as θ decreases. For example, in terms of cost reduction, the spans to bring forward can be the same for reducing θ from 0.5 to 0.4, and reducing θ from 0.4 to 0.3. However, to achieve the former, the span to bring forward should be longer than achieving the latter in terms of capacity expansion (see Fig. 4.5). External factors including cross-price effect, number of airlines, drift and volatility also have non-negligible effect on the optimal times and the changing rate thereof as θ changes. The optimal scale is more sensitive to drift and volatility rather than other factors.

4.4.4 Loss due to investments following suboptimal rules

In reality, as there are several obstacles to adopting the real option rule (Zhang and Babovic, 2011), many investments are still planned based on traditional rules such as the net present value (NPV) rule. In this section, we follow the approach of Truong et al. (2018) to estimate the loss incurred due to investment following two suboptimal rules, namely, the NPV rule and the deterministic model. The incentive to perform this estimation is to see the case in which the decision-maker should avoid suboptimal investment as much as possible.

By the NPV rule, the decision-maker ignores the value of the option to invest and the opportunity cost incurred when investment is carried out. He or she will invest immediately as soon as the NPV becomes positive, that is, the expected gain exceeds the total cost. The NPV of a project can be formulated as

$$NPV_i(Y) = \mathbb{E}\left[\int_0^\infty R_i Y e^{-rt} dt\right] - I_i \quad i = K, C, A \tag{4.40}$$

Solving $NPV_i(Y) = 0$ for each sequence, we can derive the optimal timings (for example, $Y_{NC}^* = \frac{I_C}{R_C}\frac{1}{(r-\alpha)}$, $Y_{NCK}^* = \frac{I_K}{R_A - R_C}\frac{1}{(r-\alpha)}$).

The sequencing rule for the investment is the same as in Proposition 4.1. We then obtain the loss due to the NPV rule as

$$Loss_{NCK}(Y) = \begin{cases} \mathcal{V}(Y_{NC}^*) * (Y/Y_{NC}^*)^\beta, & Y < Y_{NC}^* \\ \mathcal{V}(Y) - NPV_C(Y), & Y_{NC}^* \leq Y < Y_{NCK}^* \\ \mathcal{V}(Y) - NPV_A(Y), & Y \geq Y_{NCK}^* \end{cases} \tag{4.41}$$

$$Loss_{NCK}(Y) = \begin{cases} \mathcal{V}(Y_{NK}^*) * (Y/Y_{NK}^*)^\beta, & Y < Y_{NK}^* \\ \mathcal{V}(Y) - NPV_K(Y), & Y_{NK}^* \leq Y < Y_{NKC}^* \\ \mathcal{V}(Y) - NPV_A(Y), & Y \geq Y_{NKC}^* \end{cases} \tag{4.42}$$

$$Loss_{NA}(Y) = \begin{cases} \mathcal{V}(Y_{NA}^*) * (Y/Y_{NA}^*)^\beta, & Y < Y_{NA}^* \\ \mathcal{V}(Y) - NPV_A(Y), & Y \geq Y_{NA}^* \end{cases} \tag{4.43}$$

$$Loss_N(Y) = \begin{cases} Loss_{NCK}(Y), & \frac{R_C}{I_C} > \frac{R_A}{I_C+I_K} > \frac{R_K}{I_K} \\ Loss_{NKC}(Y), & \frac{R_K}{I_K} > \frac{R_A}{I_C+I_K} > \frac{R_C}{I_C} \\ Loss_{NA}(Y), & \frac{R_A}{I_C+I_K} > \frac{R_K}{I_K}, \frac{R_A}{I_C+I_K} > \frac{R_C}{I_C} \end{cases} \tag{4.44}$$

Using a deterministic model, the decision-maker will not consider demand uncertainty, that is, $\sigma = 0$. Investment will be carried out at the time when the NPV of the whole project reaches its maximum. The problem is formulated as

$$DV_j(Y) = \max_{t_i,t_j} \int_{t_i}^{\infty} R_i Y e^{-(r-\alpha)t} dt - e^{-rt_i} I_i + \int_{t_j}^{\infty} (R_A - R_i) Y e^{-(r-\alpha)t} dt - e^{-rt_j} I_j \quad (4.45)$$

The optimal times can then be derived as $t_i^* = \frac{1}{\alpha} \ln \frac{rI_i}{R_i}$ and $t_j^* = \frac{1}{\alpha} \ln \frac{rI_j}{(R_A - R_i)}$, and the optimal demand levels are $Y_{Di} = Y(t_i^*) = \frac{rI_i}{R_i}$ and $Y_{Dij} = Y\left(t_j^*\right) = \frac{rI_j}{(R_A - R_i)}$. The loss due to adopting a deterministic model is

$$Loss_{DCK}(Y) = \begin{cases} \mathcal{V}(Y) - DV_C(Y_{DC}^*)(Y/Y_{DC}^*)^{\beta}, & Y < Y_{DC}^* \\ \mathcal{V}(Y) - DV_C(Y) - DV_{CK}(Y_{DCK}^*)(Y/Y_{DCK}^*)^{\beta}, & Y_{DC}^* \leq Y < Y_{DCK}^* \\ \mathcal{V}(Y) - DV_C(Y) - DV_{CK}(Y), & Y \geq Y_{DCK}^* \end{cases} \quad (4.46)$$

$$Loss_{DKC}(Y) = \begin{cases} \mathcal{V}(Y) - DV_K(Y_{DK}^*)(Y/Y_{DK}^*)^{\beta}, & Y < Y_{DK}^* \\ \mathcal{V}(Y) - DV_K(Y) - DV_{KC}(Y_{DKC}^*)(Y/Y_{DKC}^*)^{\beta}, & Y_{DK}^* \leq Y < Y_{DKC}^* \\ \mathcal{V}(Y) - DV_K(Y) - DV_{KC}(Y), & Y \geq Y_{DKC}^* \end{cases} \quad (4.47)$$

$$Loss_{DA}(Y) = \begin{cases} \mathcal{V}(Y) - DV_A(Y_{DA}^*)(Y/Y_{DA}^*)^{\beta}, & Y < Y_{DA}^* \\ \mathcal{V}(Y) - DV_A(Y), & Y \geq Y_{NA}^* \end{cases} \quad (4.48)$$

$$Loss_D(Y) = \begin{cases} Loss_{DCK}(Y), & \frac{R_C}{I_C} > \frac{R_A}{I_C + I_K} > \frac{R_K}{I_K} \\ Loss_{DKC}(Y), & \frac{R_K}{I_K} > \frac{R_A}{I_C + I_K} > \frac{R_C}{I_C} \\ Loss_{DA}(Y), & \frac{R_A}{I_C + I_K} > \frac{R_K}{I_K}, \frac{R_A}{I_C + I_K} > \frac{R_C}{I_C} \end{cases} \quad (4.49)$$

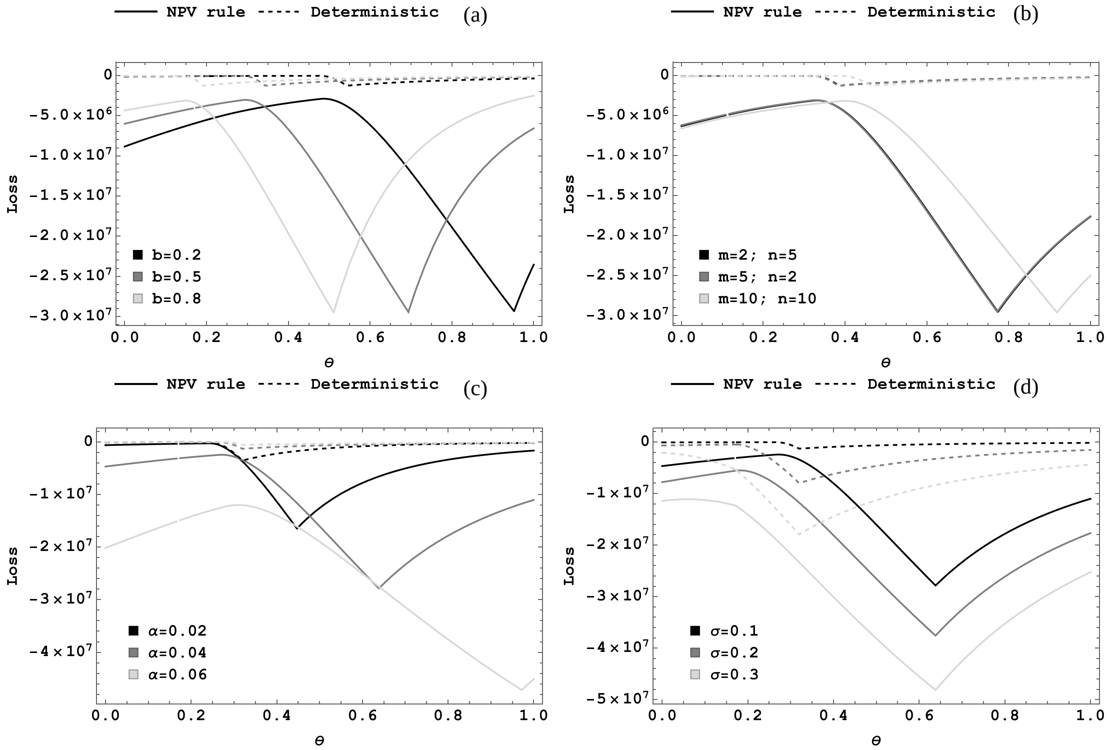


Fig 4.9 Results of the loss due to suboptimal investment (Absolute)

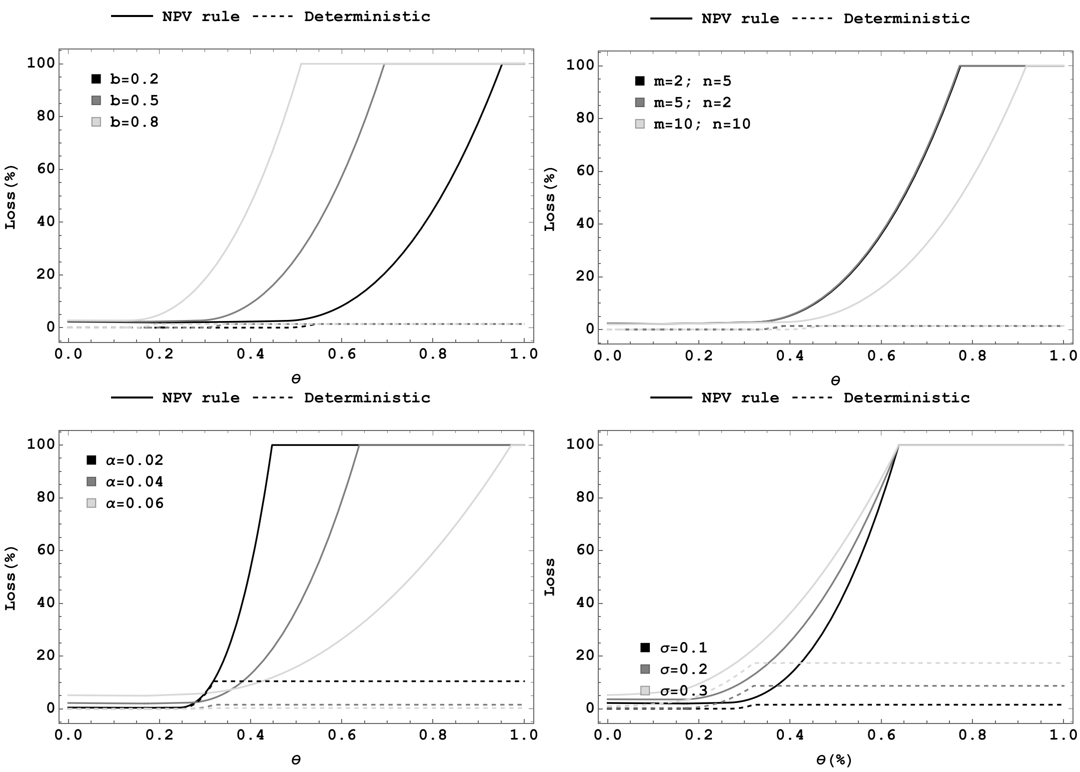


Fig 4.10 Results of the loss due to suboptimal investment (Relative)

Fig 4.9 shows the effects of various factors on the absolute loss due to suboptimal investment. We can find that the loss due to the NPV rule changes significantly as the private share θ varies. Particularly, in some cases, a minimum (a reverse peak) can appear with specific value of θ[19]. Defining the θ that leads to the minimum as $\hat{\theta}$, this can be interpreted as follows. When θ is larger than $\hat{\theta}$, the optimal timing (demand level) to carry out the investment based on the NPV rule would not be reached, and the loss would merely be the discounted expected value of the option in terms of the optimal rule (see Eq. (4.39–4.41) and Truong et al. (2018)). This value increases as θ declines, as the more social surplus-oriented the airport, the earlier it is likely to invest, thus the lesser the loss discounted. In contrast, when θ is smaller than $\hat{\theta}$, the investment based on the NPV rule should have been finished. Its value increases as θ declines, and the growing speed exceeds that of the value in terms of the optimal rule because the latter is merely an option value with the investment not started yet (investment based on the NPV rule always start earlier, see Dixit and Pindyck, 1994). Therefore, when smaller than $\hat{\theta}$, as θ declines, the difference between the two values will decrease. $\hat{\theta}$ can change as the cross-price effect b and the number of airlines m and n change, while the depths of the minima will not change (Fig 4.9a, 4.9b). However, when the drift α changes, both the height and position of the minimum change (Fig 4.9c). The depth of the minimum changes when volatility σ changes, but the position remains unchanged (Fig 4.9d). In contrast, the loss due to the investment adopting the deterministic model is quite modest compared with that caused by the NPV rule, as long as the volatility is not very high. Fig 4.10 shows the relative loss ($\frac{V_{optimal}-V_{suboptimal}}{V_{optimal}}$) due to suboptimal investment. It can be found that the loss is 100% when θ is high. This is because the optimal timing of NPV-based investment will go later as θ increases, and it might exceed the starting time when θ is high enough. In this case, following NPV rule, the decision-maker will invest once the demand level reaches a level that makes the NPV equals to 0, so the value of the investment in this case also 0. By contrast, the optimal timing of the optimal rule will always be later than that of the NPV

[19] To demonstrate such cases, we reset the values of some parameters (the scales of projects are fixed): $k_0 = 2000, k_1 = 3000, c_1 = 6, f_K = 2 * 10^7, c_K = 1 * 10^5, c_C = 2 * 10^7, a = 60$.

rule, so the value must be positive, causing a 100% loss. In summary, these results indicate that investment based on the NPV rule should be avoided, especially when the external factors satisfy certain conditions.

4.5 Conclusion

We study the optimal timings for investment in two types of projects, namely, capacity expansion and cost reduction, at an airport. A real option model considering demand uncertainty is developed, and the values of projects are obtained endogenously through a multi-stage Stackelberg model. We formally prove the inter-relationship of the two projects, and obtain the optimal rule for the investment. The effects of various external factors on the optimal timings for each project are investigated, and the loss due to the investment following suboptimal rules is estimated. We find that the decision-maker who places a higher premium on social surplus always tends to invest earlier in both projects. Other factors that stimulate an earlier investment include a lower cross-price effect, a greater total number of airlines, a higher drift, and a lower volatility in demand. The optimal scales of projects are more sensitive to the change in drift and volatility rather than the change in other factors. When the composition of the objective function changes, the pattern of the change in optimal timing differs by project: for cost reduction, the changing rate does not change with the share of profit in most cases, while the optimal timing is convex with regard to the share for capacity expansion. The loss due to NPV-based investment is much greater than that caused by the adoption of the deterministic model, and its change with the change in the composition of the objective function has a mountain-shaped pattern, where the minimum can be reached when specific conditions are met.

The contribution of this study is two-fold. Theoretically, we improve the optimal rule for a sequential investment in inter-related projects proposed by the previous study (Truong et al., 2018). Practically, the results might provide following implications. First, to improve social surplus, adjustment to the timing for investment might be as important as price regulation. To improve social surplus, the timings of investments in both projects should be brought forward. Second, the adjustment for different types of projects should be distinguished, as their pattern of change in timings is not the same. Third, even when the real option rule is not applicable, NPV-based investment should be avoided in most cases.

This study has several limitations. First, we focus only on the optimal timings and scales for the investment. The volume of each scale is pre-determined instead of being optimized endogenously. Second, we only consider one-time investment in the modeling. Piecewise investment is beyond the scope of this study. Third, the numerical calculations are performed using hypothetical values of parameters because we are unable to collect realistic data from the industry. Real data from industrial practice can make the results more persuasive. Fourth, we only show that the optimal rule derived from a real option approach benefit the airport. Whether other stakeholders can be benefited by the real-option based optimal rule is questionable, which is worthy to be investigated further. Fifth, the demand trend of an airport might not simply follow a single stochastic process. It can be more complicated, especially when some catastrophes occur (e.g., Covid-19). These shortcomings provide directions for future work.

Chapter 5 Effects of airport's privatization decisions on capacity expansion: A real option approach

5.1 Introduction

In the recent decades, airport privatization has become a worldwide trend. Despite the various form, it can be generally categorized into two types based on whether the airport is privatized with a transfer of ownership. The type without ownership transfer includes concession, project finance/BOT, and management contract. The former two are also called public–private partnerships (PPP). With this type of privatization, the government maintains the ownership of the airport, while the operating right is leased to the private investor for a certain period. Another type includes share floatation and trade sale, which results in a permanent transfer of ownership from to the public sector to the shareholders or the consortium that comprises various investors (Graham and Morrell, 2017)[20].

Privatization can have immense impacts on the future of the airport and the public sector. On the one hand, the potential positive impacts are inferred by the objectives for airport privatization. As summarized by Graham (2011), six most significant objectives for privatization are identified as: improving efficiency and performance; providing new investment funds; improving the quality of management and encouraging diversification; improving service quality; producing financial gains for the public sector; lessening the public sector influence. On the other hand, airport privatization might lead to several potential negative impacts such as the loss of social benefit due to the incompatibility of the public and private interests, and the loss of control over the vital national assets. Besides, the impacts on some aspects are not clear yet. For instance, according to the previous practices, privatization did not necessarily lead to the improvement of efficiency (Oum et al., 2006). Therefore, the decision-making regarding privatization is highly associated with the trade-off among these impacts. In order to make good decisions on privatization - in other words, to make reasonable trade-offs, a comprehensive understanding of these impacts is necessary.

[20] In some cases, the transfer of ownership has a period, but the period is always very long compared with that of concession or BOT (e.g., the period for the privatization of Sydney airport is 50+49 year).

Different type of privatization has different emphasis on the above-mentioned objectives, or the positive impacts. For instance, the main incentive for the privatization with an ownership transfer can be a financial gain which can either be directed to other sectors or serve as the funds for new investment, or improving the efficiency. Much academic attention has been paid to these impacts: Oum et al. (2006) investigated the effect of airport ownership form on the productive efficiency, finding that airports owned and managed by a mixed enterprise with a government-owned majority is significantly less efficient than 100% publicly owned and operated airports; this finding was further reinforced by their subsequent study (Oum et al., 2008); Adler and Liebert (2014) investigated similar issues taking into account airport competition, while the previous finding in the ownership's effect on efficiency was hardly invalidated. However, the secondary impacts, which might not be the main incentive for the privatization, are always overlooked. For example, a trade sale privatization might not be designed for the sake of the facilitation of capacity expansion if the proceeds are not directed to the airport, but capacity expansion is not impossible to take place in the future as long as it is in line with the operator's interest. Some examples can be observed in the real world: Liverpool Airport, with 90% of its interest held by private investors, plans to expand runway and terminal in the future decades[21]; Brussels Airport, with 75% of its share held by a private consortium, aims to complete the construction of two new piers by 2040[22]. To comprehend the long-term effect of such kind of privatization, the secondary impacts such as those regarding the capacity expansion needs further investigation. There are some studies on this issue (e.g., Zhang and Zhang (2003)), but the timing of investment and the long-term effect on social surplus were not explicitly discussed.

To bridge the research gaps, this study aims to investigate the effect of airport privatization on the decisions of its subsequent capacity expansion, namely the timing and the volume choice. We consider two scenarios. In Scenario I, while the budget constraint (i.e., profit should not be negative) is addressed in terms of charging, it is not taken into account for the decision-makings regarding capacity expansion. In other words, the governmental subsidiary to the investment is available. In Scenario II, the budget

[21] https://www.liverpoolairport.com/about-ljla/liverpool-john-lennon-airport-master-plan-to-2050
[22] https://www.brusselsairport2040.be/en/vision-2040/48/terminal-and-gate-capacity

constraint is considered in both decision-making phases. In other words, the governmental subsidiary to the investment is unavailable. To achieve the objectives, we adopt a real-option model with demand growth and demand uncertainty considered to optimize the decisions on capacity expansion; a Stackelberg model is employed to address the charging behavior of the airport and the competition among downstream airlines.

5.2 The model

5.2.1 Description of the problem

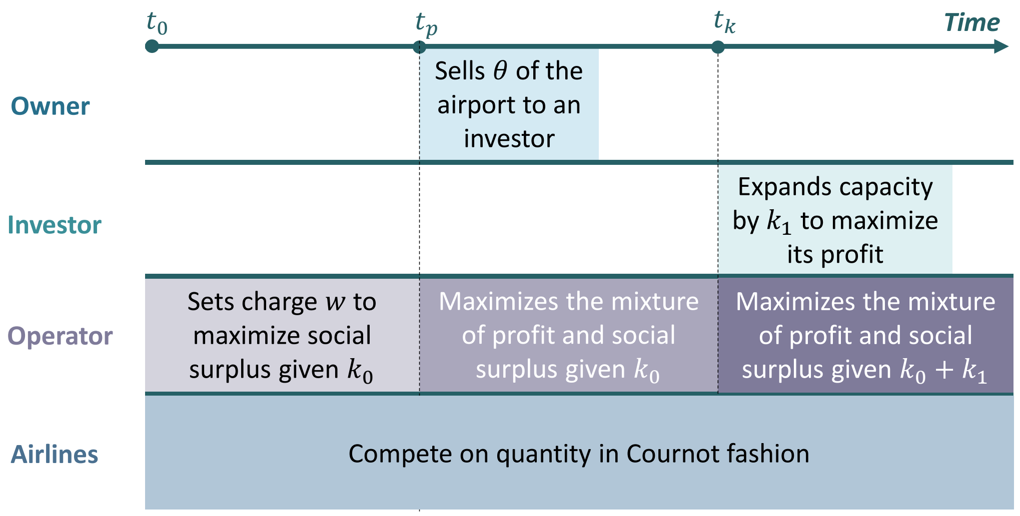


Fig 5.1 The sequence of the events in Scenario II

Stakeholders: We focus on one section of the air transport supply chain for our discussion. In the upstream, there is one single airport owned by the government, or jointly owned by the government and the private investor. The operator is in charge of setting the charge, while the investor is in charge of making capacity expansion decisions for the airport. Depending on the scenario introduced later, the operator and the investor can have same or different objective. In the downstream, there are n symmetric airlines selling air travel service to the passengers. We ignore the entry and exit of airlines.

Scenarios:

- *Scenario I*: We investigate how the ownership structure of an airport affects the timing and volume choice for the capacity expansion. We assume that the governmental subsidiary is available for the investment. In other word, the constraint that the budget used for the investment should only originate from the airport's profit is removed. In this case, since the investment does not necessarily take place after the privatization, we do not consider the effect of the timing of privatization for simplicity. We focus on a privatized airport. The operator and the investor are same.

- *Scenario II*: We assume that the governmental subsidiary is unavailable for the investment, and the proceeds from the privatization will be directed towards other public projects. We further assume that the social surplus-oriented government would not obtain any profit form the operation of the airport, so when the government is the operator of the airport, namely before the privatization, the investment cannot take place. After privatization, with the financing of the private investor, the expansion can be carried out at some time in the future. In this case, the operator and the investor are not same after the privatization. The operator set charge based on the mixed benefit of all shareholders, while the investor makes decisions based on its own profit, as it bears all the cost of the expansion. Under such settings, we investigate how the privatization decision affect the investment decision of the airport and the aggregated social surplus. The timing of investment decision is considered as well as the share to sell.

Decision-making process:

- *Scenario I*: A multi-stage Stackelberg game is modelled to reflect the hierarchical interactions among the market participant: In the first stage, the investor makes decisions regarding capacity expansion by choosing the time and the volume. In the second stage, the operator sets the charge, given the current level of capacity. The objectives of the investor and the operator are same, that is, to maximize the mixture of profit and social surplus depending on the ownership structure. In the third stage, given the charge and the capacity level, airlines in the downstream compete in a Cournot fashion.
- *Scenario II*: The airport is assumed to be fully controlled by the government originally, and the operator sets a charge that maximizes the social surplus subject to the non-negative profit constraint. At time t_p, the public owner sells θ (0 <

$\theta \leq 1$) of the airport's ownership to a private investor[23]. The new operator then sets a new charge that maximize the mixture of profit and social surplus, which reconciles the different objectives of the private and public shareholders. At time t_k, the investor expands the capacity of the airport by k_1, making the airport's capacity $k_1 + k_0$. The operator then adjusts its charge based on the new condition. In the downstream, n airlines compete with each other in a Cournot fashion to maximize their respective profit, given the capacity level and charge. Fig 5.1 presents an intuitive illustration of the whole sequence of the events.

Several assumptions are made as follows for the sake of tractability or simplicity:

a. The proceeds from the privatization will be directed towards other public projects, instead of being directed to airport. In the ICAO (International Civil Aviation Organization)'s document regarding airport privatization, it writes: "In several States, such as in European States, Australia and New Zealand, funds generated through private participation and privatization in the provision of airports are credited to the treasury without any commitment to use them for the development of the aviation industry."[24] Therefore, this assumption can be plausible in some cases.
b. Lead times of the investments are ignored. Alternatively, this can be explained that the timing refers to the time when the project is expected to be finished, and the cost refers to the aggregated retrospective cost (e.g., if the span is 3 year, the cost stands for $I * e^{3r}$ instead of I) incurred in the whole investment span.
c. Incremental investments are not considered. Airport capacity investment is a lumpy project which is unlikely to be carried out twice in a relatively short time span (e.g., Amsterdam Airport's first large-scale expansion took place in 1960s, the second happened in 2000s). The value in the far future when the expansion

[23] It is not implausible that an airport sells part of its ownership to the private investor(s). Generally, it can take place in the case that the government find it difficult to finance the airport without private capital, but it still wants to retain some control of the airport since it can be a strategic infrastructure. In this case, there are two approach. The first is share floatation, which is to issue and trade the share on the stock market. For example, the New Zealand government sold Auckland airport's 52 percent shareholders through an IPO (initial public offering) in 1998. The second is trade sale, which is to sell part of the ownership to a consortium. For example, 60% of Lyon airport's ownership was sold to a consortium in 2016.

[24] http://www.aviationchief.com/uploads/9/2/0/9/92098238/icao_doc_9980_-_manual_on_privatization_of_airports_and_ans_1.pdf

can take place again will be greatly discounted, so we ignore it.

d. The composition of ownership will not change after the capacity expansion[25].

Notations of the decision variables and parameters are shown in Table 5.1

Table 5.1 Notations for Chapter 5

Decision variables	
q_i	Number of passengers of airline i
w	Airport charge per passenger
a_k	Timing (demand level) for the capacity expansion
k_1	Capacity level to expand
Parameters	
a	Maximum willingness to pay
b $(0 \leq b \leq 1)$	Own-price effect
l $(0 \leq l \leq 1)$	Cross-price effect
n	Number of airlines
γ	Unit cost per passenger of airline
c	Unit cost per passenger of airport
k_0	Original capacity level
c_K	Unit cost for the capacity expansion
f_K	Fixed cost for the capacity expansion
a_p	Timing (demand level) for the privatization
θ	Private share
α	Drift
σ	Volatility
r	Discount rate

5.2.2 The optimal charging problem

We use the backward induction to solve the optimal charging problem. We first derive

[25] We cannot find counter examples.

the demand function (Eq. (5.2)) from a quadratic utility function (Eq. (5.1)).

$$U(q_i, q_j) = aQ - \frac{1}{2}\left[b\left(\sum_{i}^{n} q_i^2\right) + 2bl\left(\sum_{i>j} q_i q_j\right)\right] \quad (5.1)$$

$$p_i = a - bq_i - bl(Q - q_i) \quad (5.2)$$

Where q_i denotes the number of passengers of airline i and $Q = \sum_{i=1}^{n} q_i$; p_i denotes the airfare of airline i; a denotes the maximum willingness-to-pay. b and l denote the own price effect and the cross-price effect respectively with $0 \leq l \leq 1$.

The demand uncertainty is described by the Geometric Brownian motion (GBM):

$$da = \alpha a dt + \sigma a dz \quad (5.3)$$

Where α denotes the drift; σ denotes the volatility.

The airlines' Cournot competition problem is formulated as:

$$\max_{q_i} \pi_i = (p_i(q_i; q_{i-}) - \gamma - w)q_i \quad \forall i \quad (5.4)$$

$$\text{s.t. } Q \leq k$$

Where γ denotes the marginal cost of airline; w denotes the charge. The solution is:

$$q_i^{**}(w, k) = \begin{cases} 0, & w \in [a - \gamma, \infty) \\ \dfrac{a - \gamma - w}{b(l(n-1) + 2)}, & w \in (w_b, a - \gamma) \\ \dfrac{k}{n}, & w \in (0, w_b] \end{cases} \quad (5.5)$$

Where $w_b = a - \gamma - \frac{bk(2 + ln - l)}{n}$ is the charge that makes the optimal outputs hit the capacity bound. If the charge is very high, airlines will stop operation to avoid loss (the first row of Eq. (5.5)). If the charge is lower than w_b, airlines' real optimal outputs will exceed the capacity constraint, so they have to choose the suboptimal outputs that fully occupy the capacity loss (the third row of Eq. (5.5)). The real optimum can only be achieved when the charge is neither too high nor to low (the second row of Eq. (5.5)).

The airport operator's optimal charging problem is formulated as:

$$\max_{w} \Lambda(w,k) = \theta\Gamma(w,k) + (1-\theta)S(w,k) \tag{5.6}$$
$$\text{s.t.}\ \ \Gamma(w,k) \geq 0$$

Where θ denotes the private share[26]. $\Gamma(w,k)$, the profit of airport, is formulated as:

$$\Gamma(w,k) = (w-c)Q^{**}(w,k) \tag{5.7}$$

Where c denotes airport's marginal cost. $S(w,k)$, the social surplus, is formulated as:

$$S(w,k) = U\left(q_i^{**}(w,k), q_j^{**}(w,k)\right) - (c+\gamma)Q^{**}(w,k) \tag{5.8}$$

To solve the problem, we first see the case that the capacity constraint is not binding. In this case, substituting the second row of Eq. (5.5) into Eq. (5.6), and solving the KKT conditions $\Gamma(w,k) \geq 0, \lambda \geq 0, \lambda * \Gamma(w,k) = 0, \frac{\partial(\Lambda(w,k)+\lambda*\Gamma(w,k))}{\partial w} = 0$, we have:

$$w_u^* = \begin{cases} c, & \theta \in (0,\bar{\theta}) \\ \dfrac{\theta(a-\gamma)(l(n-1)+3) - a + c(l(n-1)+2) + \gamma}{3\theta + (\theta+1)l(n-1)+1}, & \theta \in [\bar{\theta},1] \end{cases} \tag{5.9}$$

Where $\bar{\theta} = \frac{1}{l(n-1)+3}$, the subscript u refers to being unbound in terms of capacity (abbreviated as "capacity-unbound" hereinafter).

Next, we discuss the two cases with regard to different region of θ respectively. In the "profit-binding" ($\theta \in (0,\bar{\theta})$) case, comparing the maximized payoff and the optimal charge, we have the following four cases: (i), $w_u^* > w_b$ and $\Lambda(w_u^*,k) > \Lambda(w_b,k)$; (ii), $w_u^* > w_b$ and $\Lambda(w_u^*,k) \leq \Lambda(w_b,k)$; (iii), $w_u^* \leq w_b$ and $\Lambda(w_u^*,k) > \Lambda(w_b,k)$; (iv), $w_u^* \leq w_b$ and $\Lambda(w_u^*,k) \leq \Lambda(w_b,k)$. For (i) and (iii), it seems that the optimal choice is to set the charge as w_u^*, since $\Lambda(w_u^*,k)$ is greater. However, this is only available for (i); for (iii), the final outputs will not change as long as the charge is not higher than w_b because of

[26] To justify such setting, we can assume that the board comprises outside directors who focuses on the reconciled total benefit of the firm instead of favoring certain group of shareholders, and the fair public sector will not abuse its voting right (i.e., not veto the fair resolutions proposed by the board). In this case, the board is assumed to make decisions that maximizes the mixed objective coordinated by θ. If the public sector has majority share, although the decision is not expected to maximize its own objective (social surplus), it would not veto the decision otherwise the private investors cannot get any dividend. If the private investors have majority share, the decision will be fairly profit-oriented. The fair public sector certainly would not veto it. On the other hand, although the decision is not purely profit-maximizing, the private shareholders can get expected dividend, since all profit goes to them. Hence, we assume they would not veto as well.

the capacity bound. Similarly, for (ii) and (iv), choosing w_b is only available for (iv); for (ii), the non-negative profit constraint will be violated by doing so. Consequently, in the "profit-binding" region, the optimal charge is the highest one among w_u^* and w_b. For the "profit-unbounded" region, the optimal charge can be derived in a similar way. To organize, we have:

Proposition 5.1

Let $g = c + \gamma$,

(i) If $0 < \theta < \bar{\theta}$, the non-negative profit constraint is binding. In this case, if $a \leq g$, the operation will terminate, the payoff of the expansion decision-maker $R_{11}(a, k)$ is 0 for both Scenario I and II; if $g < a < \frac{bk(l(n-1)+2)}{n} + g$, the optimal charge is $w^* = c$; the payoff of the expansion decision-maker $R_{12}(a, k)$ is $\frac{n(l(n-1)+3)(a-g)^2}{2b(l(n-1)+2)^2}$ for Scenario I, 0 for Scenario II. If $a \geq \frac{bk(l(n-1)+2)}{n} + g$, the optimal charge is $w^* = a - \gamma - \frac{bk(2+ln-l)}{n}$; the payoff of the expansion decision-maker $R_{13}(a, k)$ is $\frac{k(2n(a-g)-bk(3\theta+(\theta+1)l(n-1)+1))}{2n}$ for Scenario I, $k(a - g - \frac{l(n-1)+2}{n})$ for Scenario II.

(ii) If $\bar{\theta} \leq \theta \leq 1$, the constraint is not binding. In this case, if $a \leq g$, the operation will terminate, the payoff of the expansion decision-maker $R_{21}(a, k)$ is 0 for both Scenario I and II; if $g < a < g + \frac{bk(3\theta+(\theta+1)l(n-1)+1)}{n}$, the optimal charge is $w^* = \frac{\theta(a-\gamma)(l(n-1)+3)-a+c(l(n-1)+2)+\gamma}{3\theta+(\theta+1)l(n-1)+1}$, the payoff of the expansion decision-maker $R_{22}(a, k)$ is $\frac{n(a-g)^2}{2b(3\theta+(\theta+1)l(n-1)+1)}$ for Scenario I, $\frac{n(a-g)^2(\theta(l(n-1)+3)-1)}{b(3\theta+(\theta+1)l(n-1)+1)^2}$ for Scenario II; if $a \geq g + \frac{bk(3\theta+(\theta+1)l(n-1)+1)}{n}$, the optimal charge is $w^* = a - \gamma - \frac{bk(2+ln-l)}{n}$; the payoff of the expansion decision-maker $R_{23}(a, k)$ is $\frac{k(2n(a-g)-bk(3\theta+(\theta+1)l(n-1)+1))}{2n}$ for Scenario I, $k(a - g - \frac{l(n-1)+2}{n})$ for Scenario II.

5.2.3 The capacity expansion problem

Following Balliauw and Onghena (2020), we first derive the net value of the airport *from the perspective of the private investor* in each case. Solving the Bellman function $V_{xy}(a,k) = R_{xy}(a,k)dt + \mathbf{E}\left[V_{xy}(a+da,k)e^{-rdt}\right]$ for each $x \in 1,2$ and $y \in 1,2,3$, and removing the meaningless terms, we have:

$$V_1(a,k) = \begin{cases} V_{11}(a,k) = A_{11}(k)a^{\beta_1}, & a \in [0,g] \\ V_{12}(a,k) = B_{11}(k)a^{\beta_1}, & a \in (g, \overline{a_1}(k)) \\ V_{13}(a,k) = C_{12}(k)a^{\beta_2} + \dfrac{akT}{r-\alpha} + \dfrac{T(v_1(k) - gk)}{r}, & a \in [\overline{a_1}(k), \infty) \end{cases} \tag{5.10}$$

$$V_2(a,k) = \begin{cases} V_{21}(a,k) = A_{21}(k)a^{\beta_1}, & a \in [0,g] \\ V_{22}(a,k) = B_{21}(k)a^{\beta_1} + B_{22}(k)a^{\beta_2} + Tv_2\left(\frac{a^2}{-2\alpha+r-\sigma^2} + \frac{2ag}{\alpha-r} + \frac{g^2}{r}\right), & a \in (g, \overline{a_2}(k)) \\ V_{23}(a,k) = C_{22}(k)a^{\beta_2} + \frac{akT}{r-\alpha} + \frac{T(v_1(k)-gk)}{r}, & a \in [\overline{a_2}(k), \infty) \end{cases} \tag{5.11}$$

Where $\beta_1 = \frac{1}{2} - \frac{\alpha}{\sigma^2} + \sqrt{(\frac{1}{2} - \frac{\alpha}{\sigma^2})^2 + \frac{2r}{\sigma^2}}$, $\beta_2 = \frac{1}{2} - \frac{\alpha}{\sigma^2} - \sqrt{(\frac{1}{2} - \frac{\alpha}{\sigma^2})^2 + \frac{2r}{\sigma^2}}$, $v_1(k) = -\frac{k(bk(l(n-1)+1))}{2n}$, $v_2 = \frac{n(\theta(l(n-1)+3)-1)}{b(3\theta+(\theta+1)l(n-1)+1)^2}$. r denotes the discount rate, and T denotes the number of the periods when a remains the same[27]. $\overline{a_1}(k) = \frac{bk(l(n-1)+2)}{n} + g$, $\overline{a_2}(k) = g + \frac{bk(3\theta+(\theta+1)l(n-1)+1)}{n}$.

Unknown parameters $A_{11}(k), B_{11}(k), C_{12}(k), A_{21}(k), B_{21}(k), B_{22}(k), C_{22}(k)$ can be derived via value-matching and smooth-pasting conditions (Dixit and Pindyck, 1994), their lengthy expressions are omitted here.

The gain through carrying out the capacity expansion can thus be expressed as:

$$G_1(a,k_1) = \begin{cases} G_{1a}(a,k_1) = V_{11}(a,k_1+k_0) - V_{11}(a,k_0), & a \in [0,g] \\ G_{1b}(a,k_1) = V_{12}(a,k_1+k_0) - V_{12}(a,k_0), & a \in (g, \overline{a_1}(k_0)) \\ G_{1c}(a,k_1) = V_{12}(a,k_1+k_0) - V_{13}(a,k_0), & a \in [\overline{a_1}(k_0), \overline{a_1}(k_0+k_1)) \\ G_{1d}(a,k_1) = V_{13}(a,k_1+k_0) - V_{13}(a,k_0), & a \in [\overline{a_1}(k_0+k_1), \infty) \end{cases} \tag{5.12}$$

$$G_2(a,k_1) = \begin{cases} G_{2a}(a,k_1) = V_{21}(a,k_1+k_0) - V_{21}(a,k_0), & a \in [0,g] \\ G_{2b}(a,k_1) = V_{22}(a,k_1+k_0) - V_{22}(a,k_0), & a \in (g, \overline{a_2}(k_0)) \\ G_{2c}(a,k_1) = V_{22}(a,k_1+k_0) - V_{23}(a,k_0), & a \in [\overline{a_2}(k_0), \overline{a_2}(k_0+k_1)) \\ G_{2d}(a,k_1) = V_{23}(a,k_1+k_0) - V_{23}(a,k_0), & a \in [\overline{a_2}(k_0+k_1), \infty) \end{cases} \tag{5.13}$$

[27] For example, if α, σ, r denote monthly drift, volatility and discount rate respectively, and the payoff (Eq. (5.6)) is calculated on a daily basis, $T = 30$.

$$G(a, k_1) = \begin{cases} G_1(a, k_1), & \theta \in (0, \bar{\theta}) \\ G_2(a, k_1), & \theta \in [\bar{\theta}, 1] \end{cases} \tag{5.14}$$

Next, we need to maximize the gain by choosing the optimal timing a_k and the optimal volume k_1^* for the expansion. According to Dangl (1999), the problem can be formulated as:

$$F(a) = \max\{\mathrm{e}^{-rdt}\mathbf{E}[F(a) + dF(a)], \max_{k_1}[G(a, k_1) - I(k_1)]\} \tag{5.15}$$

Where $I(k_1)$ denotes the total cost of the expansion. The inner optimization can be solved by the first order condition, and the outer optimization can be solved by the boundary conditions. Consequently, a_k and k_1^* can be obtained by solving the following system of equations:

$$\begin{aligned} G(a_k, k_1^*) - I(k_1^*) &= \left(\frac{a_k}{\beta_1}\right) * \left(\left.\frac{\partial[G(a, k_1) - I(k_1)]}{\partial a}\right|_{a=a_k, k_1=k_1^*}\right) \\ \left.\frac{\partial[G(a, k_1) - I(k_1)]}{\partial k_1}\right|_{a=a_k, k_1=k_1^*} &= 0 \end{aligned} \tag{5.16}$$

As per Hagspiel et al. (2016), under this kind of setting, the investor will never carry out the investment when a is in the regions where it cannot improve its profit, so we only need to focus on $G_{1c}(a, k_1)$, $G_{1d}(a, k_1)$, $G_{2c}(a, k_1)$ and $G_{2d}(a, k_1)$ for Scenario I, and $G_{1d}(a, k_1)$, $G_{2c}(a, k_1)$ and $G_{2d}(a, k_1)$ for Scenario II. It is difficult to derive the precise solutions through solving Eq. (5.16). An approximate algorithm is proposed utilizing the intersection point-finding function of the software Mathematica. The brief procedure is as follows:

Step 1: Set the starting value of a as $a = \bar{a}(k_0)$. Define the values of $\hat{a}$ and Δa.

Step 2: Solve $\frac{\partial[G(a,k_1) - I(k_1)]}{\partial k_1} = 0$ for k_1, and exclude the negative solutions.

Step 3: Check whether the remaining solution k_1^{**} maximizes the objective function. If $\frac{\partial^2(G(a,k_1^{**}) - I(k_1^{**}))}{\partial k_1^2} < 0$, go to Step 4; otherwise, go to Step 5.

Step 4: Check whether k_1^{**} is within the feasible domain; if yes, go to Step 6; otherwise, go to Step 5.

Step 5: Compare the boundary values. Set k_1^{**} to the value which maximizes the objective function.

Step 6: Set $k_1^{**}(a) = k_1^{**}$. Calculate $G(a, k_1^{**}(a)) - I(k_1^{**}(a))$.

Step 7: If $a < \hat{a}$, set $a = a + \Delta a$ and return to Step 1; otherwise, plot $G(a, k_1^{**}(a)) - I(k_1^{**}(a))$ and $\left(\frac{a}{\beta_1}\right) * \left(\frac{\partial[G(a,k_1)-I(k_1)]}{\partial a}\bigg|_{k_1=k_1^{**}(a)}\right)$ with a as the horizontal axis, and find the intersection point which is regarded as a_k.

Step 8: Set $a = a_k$ and return to Step 1. Stop at Step 6 and set $k_1^* = k_1^{**}(a_k)$. Output k_1^* and a_k as the final results.

Following this procedure, we can derive the optimal solutions for $G_{1c}(a, k_1), G_{1d}(a, k_1)$, $G_{2c}(a, k_1)$ and $G_{2d}(a, k_1)$, respectively. Note that we need to compare the optimal value of ${G_c}^*(a, k_1)$ and ${G_d}^*(a, k_1)$ to obtain the final solution for the "profit-unbound" region.

5.2.4 Calculation of aggregated social surplus in Scenario II

We first divide the whole time span into three periods:

- *Period 1* ($t_0 \sim t_p$): Pre-privatization.
- *Period 2* ($t_p \sim t_k$): Post-privatization, pre-expansion.
- *Period 3* ($t_k \sim$): Post-expansion.

For Period 1, there are three possible cases:

- *Case 1.1*: During the whole period, the capacity constraint is binding.
- *Case 1.2*: During the whole period, the capacity constraint is non-binding.
- *Case 1.3*: The capacity is originally non-binding, while it becomes binding at $\widetilde{t_1} \in (t_0, t_p)$ as a result of the demand growth.

The expected social surplus of Period 1 in each case can be formulated as $S_{11} = \mathbb{E}\left[\int_0^{t_p} S_{b1}(a_t)e^{-rt}\,dt\right]$, $S_{12} = \mathbb{E}\left[\int_0^{t_p} S_{u1}(a_t)e^{-rt}\,dt\right]$, and $S_{13} = \mathbb{E}\left[\int_0^{\widetilde{t_1}} S_{b1}(a_t)e^{-rt}\,dt\right] + \mathbb{E}\left[\int_{\widetilde{t_1}}^{t_p} S_{u1}(a_t)e^{-rt}\,dt\right]$, where the subscripts u and b denote non-binding and binding respectively. $S_1(a_p)$ can then be confirmed based on the case.

For Period 2 and 3, there are two possible cases, as the investor will never invest when capacity is not binding:

- *Case 2(3).1*: During the whole period, the capacity constraint is binding.
- *Case 2(3).2*: The capacity is originally non-binding, while it becomes binding at some time.

The social surplus in each case and each period can be calculated in a similar way as done for period 1. Consequently, summing up the results of all periods, we can get the aggregated social surplus as:

$$S(a_p, a_k, k_1^*) = S_1(a_p) + S_2(a_p, a_k) + S_3(a_k, k_1^*) - \mathbb{E}[e^{-rt_k}]I(k_1^*) \tag{5.17}$$

5.3 Numerical examples

The values of the parameters for the numerical computation are set as shown in Table 5.2. These values will not change throughout this section if not specifically mentioned. The marginal operating cost of airline γ is set based on the airline data project[28], and the marginal operating cost of airport c is set based on Martín and Voltes-Dorta (2011). The cost of the investment in capacity expansion is set based on Sun and Schonfeld (2015). Other values are set hypothetically due to the lack of data.

Table 5.2 Values of the parameters for the numerical computation

Parameter	**Value**	**Parameter**	**Value**
a_0	1000	I	$f_K + c_K * k_1$
b	0.25	c_K	$1 * 10^5$
l	0.5	f_K	$6.5 * 10^7$
n	2	α_{year} (annual)	0.01
c	8.5	σ_{year} (annual)	0.05
γ	175	r_{year} (annual)	0.1
k_0	3000	T	30

[28] http://web.mit.edu/airlinedata/www/default.html

5.3.1 Scenario I

Fig 5.2 shows how the private share θ affects the optimal decisions for the capacity expansion. As opposed to the finding of Xiao et al., (2012), our results show that the optimal volume does not monotonically decrease as θ increases. Instead, the change of the optimal volume with regard to θ can have an irregular pattern. The intuition behind the result can be explained as follows. There are two countervailing effects driving the change of the optimal volume with regard to θ. On the one hand, as θ goes higher, the maximum number of passengers will decline ($Q^*(a;\theta) = \frac{n(a-g)}{b(3\theta+(\theta+1)l(n-1)+1)}$ and $\frac{\partial Q^*(a;\theta)}{\partial \theta} < 0$ for any $\theta \in [0,1]$), so the airport can expect to accommodate all potential passengers with a lower volume. On the other hand, when θ is low, even if the capacity is no longer enough at one time, the loss is not significant; however, the loss due to a transfer from the capacity non-binding region to the binding region will grow as θ increases, namely $\frac{(\partial R_{12}(a;\theta) - \partial R_{13}(a;\theta))}{\partial \theta} > 0$ and $\frac{(\partial R_{22}(a;\theta) - \partial R_{23}(a;\theta))}{\partial \theta} > 0$, thus, in order to avoid the loss, or to make the loss insignificant in the current view, the airport tends to increase the volume to postpone the loss as much as possible. The intensity of each effect varies by the value of parameters, making the pattern of the optimal volume different in each case. Moreover, the pattern can change greatly due to the change of region, since the payoff function also changes. The change of the optimal timing a_k[29] basically follows one pattern; as θ increases, it becomes earlier in the charge-binding region, while goes later in the non-binding region.

Regarding the effect of parameters, we can find that a lower cross-price effect l and a higher airline number n do not necessarily lead to a greater capacity volume, but might push forward the expansion greatly. A higher drift α, a higher volatility σ and a lower discount rate r can lead to a greater capacity volume and a later expansion. Generally, factors regarding the airline market (l, m) affect the timing more than the volume, while factors regarding the dynamics of demand (α, σ) and discount factor r have stronger

[29] In fact, a_k should be written as $a(t_k)$. a denotes the demand level (maximum willingness-to-pay) which is a function of time t. t_k is the time when the investment should be carried out, yet with uncertainty it does not have a fixed value, so we use the demand level to denote the "timing" instead of a precise "time".

effect on the volume rather than the timing.

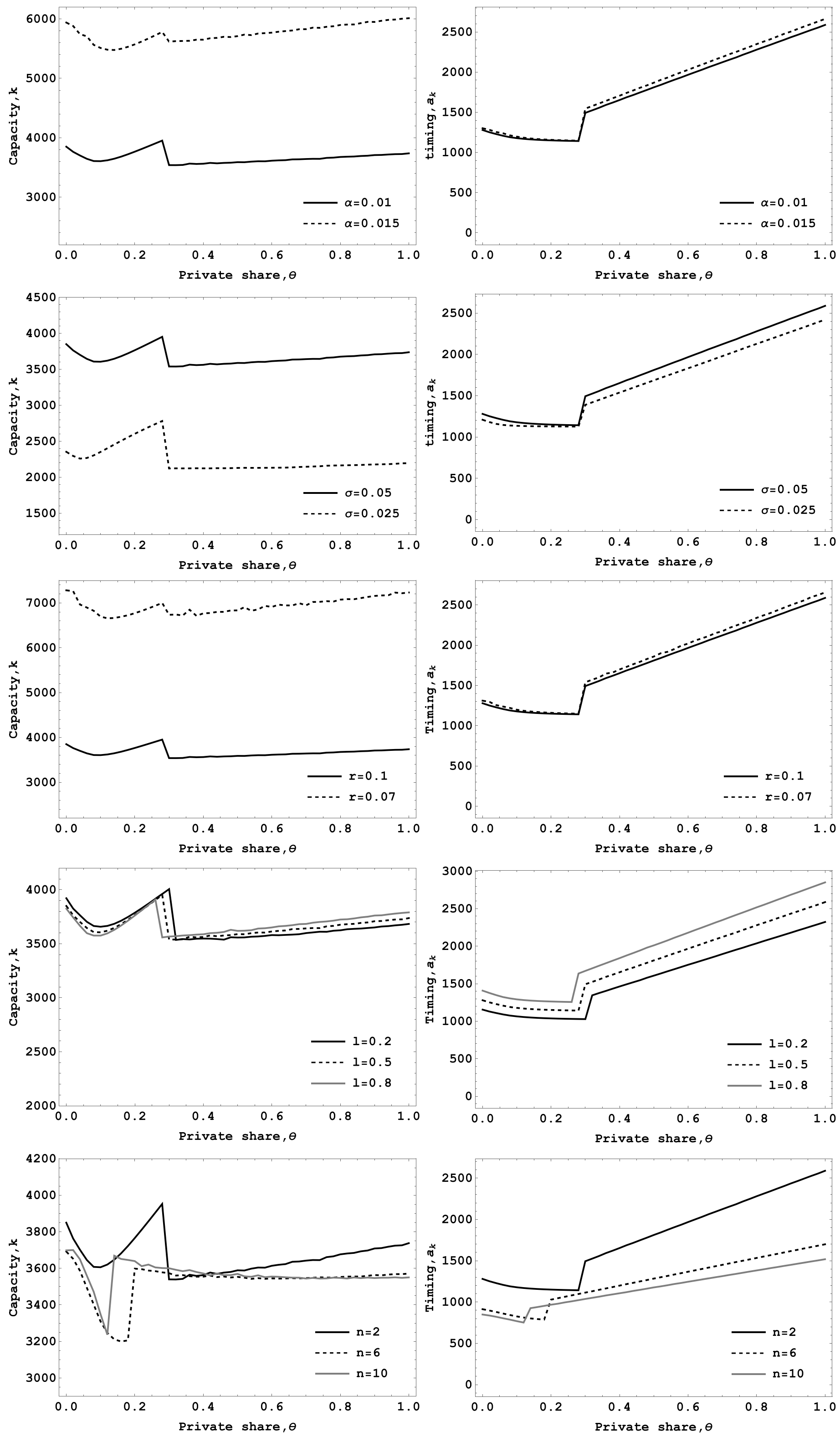


Fig 5.2 Effect of private share θ on the optimal investment decisions

5.3.2 Scenario II

Fig 5.3 shows the effect of the private share θ and the timing (demand level) of privatization a_p on the optimal decisions for the capacity expansion. We can observe three clear-cut regions with regard to the private share. If θ is low, capacity expansion will never be carried out (*no-expansion region*). If θ is moderate, capacity expansion will be carried out at some time in the future, while the volume, which just fill a part of the capacity gap, will not be very great (*gap-filling region*). As θ goes high, a jump of the optimal volume can be observed. When θ has a high value, the capacity expansion will be carried out in a more extensive way; the volume will be much greater than that of the moderate-θ case, and the expansion will take place a little earlier. The high-volume capacity is expanded not only for the gap-filling, but as a preparation for the future demand growth, as it will not be fully occupied after the expansion (*future-preparing region*). In each region, the optimal volume and timing only change slight as θ changes. On the other hand, the timing of the privatization has no effect on the optimal decisions for the expansion as long as it precedes the expansion time.

Fig 5.4 shows the effect of the private share and the time of privatization on the aggregated social surplus. It can be found that if the privatization largely precedes the expansion (i.e., a_p is low), the maximum of the aggregated social surplus can be achieved by a fairly low θ which is just the breakpoint between *no-expansion region* and *gap-filling region*. However, if the expansion does not happen much later than the privatization (i.e., a_p is high), the peak-point of the aggregated social surplus will transfer; it will be the breakpoint between *gap-filling region* and *future-preparing region*, characterized by a fairly high θ. This is because of the trade-off between the social-surplus improving effect of the expansion, and the social-surplus reducing effect of the privatization. When the privatization takes place at a late time, the loss of social surplus due to the privatization is greatly discounted, making its negative effect overweighed by the positive effect of the capacity expansion, so a high-share privatization which can lead to an extensive expansion is favored in this case, and vice-versa.

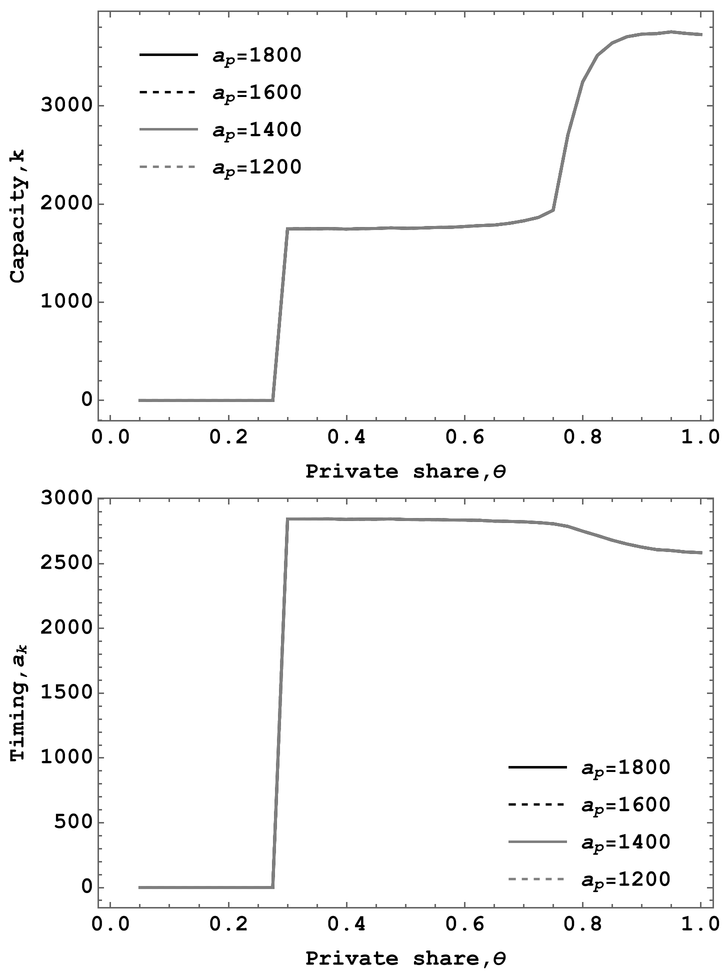


Fig 5.3 The effect of the private share and the time of privatization on the optimal decisions for the capacity expansion

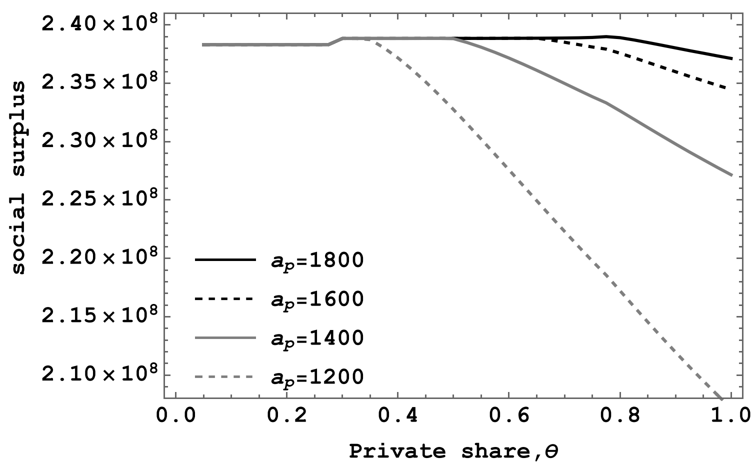


Fig 5.4 The effect of the private share and the time of privatization on the aggregated social surplus

Fig 5.5 shows how volatility σ affect the optimal decisions for the capacity expansion. As expected, the higher the uncertainty, the larger the optimal volume, and the later the expansion. Moreover, it can be observed that the breakpoint between *gap-filling region* and *future-preparing region* moves leftward, that is, moves to a lower θ as σ goes higher, while the breakpoint between *no-expansion region* and *gap-filling region* hardly changes. Fig 5.6 shows the effect of the private share and volatility on the aggregated social surplus given a privatization time a_p, indicating that some other factors can also greatly affect the relation between the private share and the aggregated social surplus. When σ is low, although the period between the privatization and the expansion is shortened compared with other case, the peak point is not the breakpoint between *gap-filling region* and *future-preparing region*. This is because the difference in the volume of expansion between the two regions in this case is fairly low, so the increase of volume realized by the high-share privatization is not enough to offset the social surplus loss it causes.

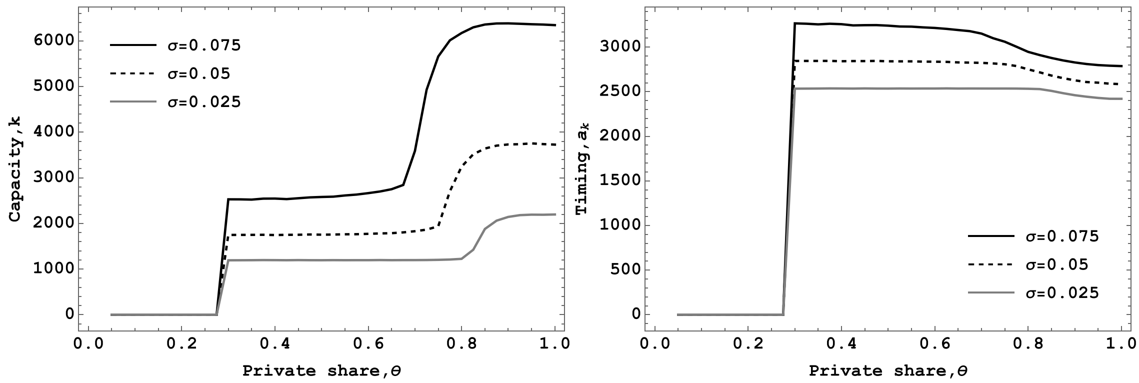


Fig 5.5 The effect of the private share and volatility σ on the optimal decisions for the capacity expansion ($a_p = 1600$)

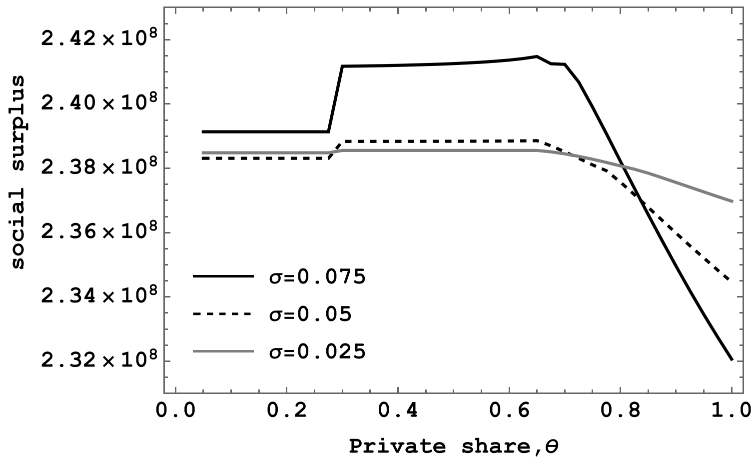


Fig 5.6 The effect of the private share and volatility σ on the aggregated social surplus ($a_p = 1800$)

Fig 5.7 shows the joint effect of the private share and drift α, which is similar as that of volatility: The stronger the growth, the larger the optimal volume, and the later the expansion. Also, the breakpoint between *gap-filling region* and *future-preparing region* moves leftward as α goes higher, while the breakpoint between *no-expansion region* and *gap-filling region* hardly changes. Fig 5.8 shows the joint effect of the private share and discount rate r. A lower r has very similar effects as what a higher α has. Fig 5.9 presents the joint effect of private share and airline number n. Interestingly, a fiercer downstream competition will not necessarily result in an expansion of high volume; instead, the investor would rather choose to push the expansion forward. The change of the breakpoint between *gap-filling region* and *future-preparing region* is not so conspicuous, while an obvious leftward movement of the breakpoint between *no-expansion region* and *gap-filling region* can be observed as n becomes greater. Similar phenomenon can be observed regarding the effect of the cross-price effect l (Fig. 5.10). A low l makes the volume slight smaller, yet the expansion will be greatly pushed forward.

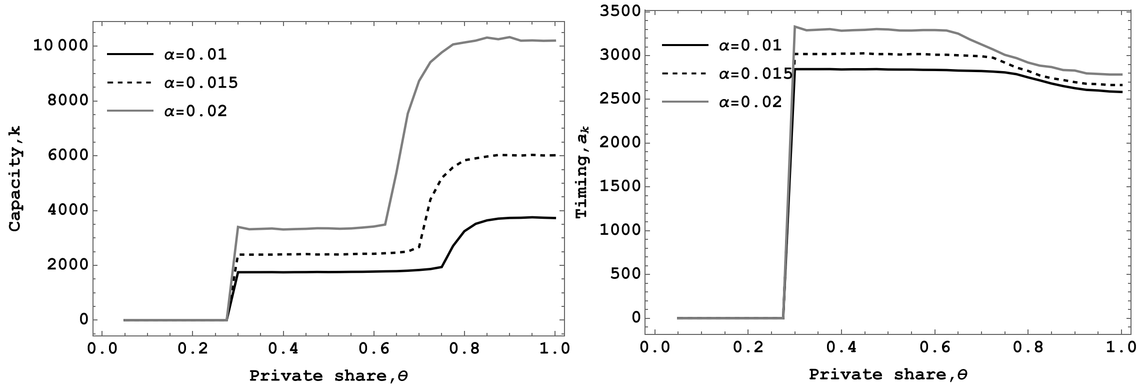


Fig 5.7 The effect of the private share and drift α on the optimal decisions for the capacity expansion ($a_p = 1600$)

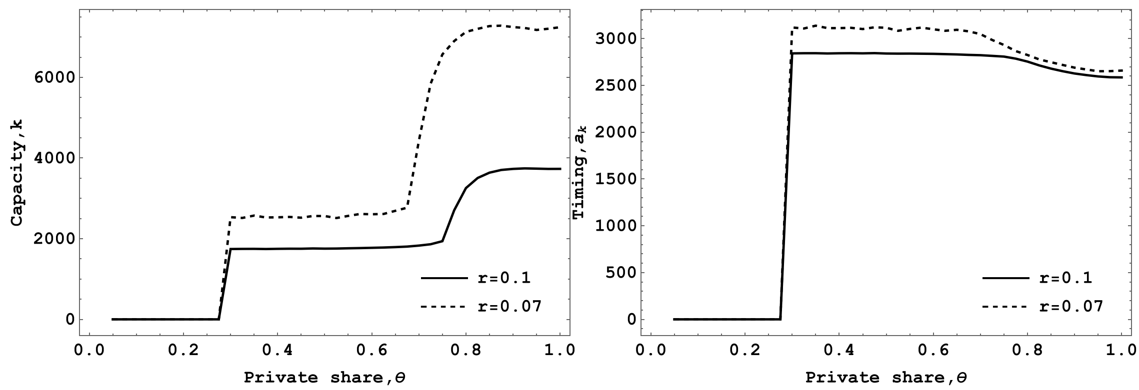


Fig 5.8 The effect of the private share and discount rate r on the optimal decisions for the capacity expansion ($a_p = 1600$)

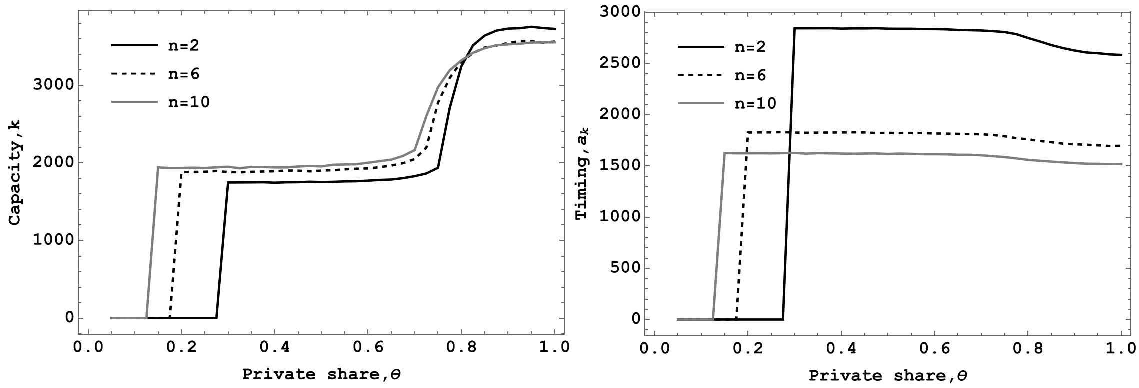


Fig 5.9 The effect of the private share and airline number n on the optimal decisions for the capacity expansion ($a_p = 1200$)

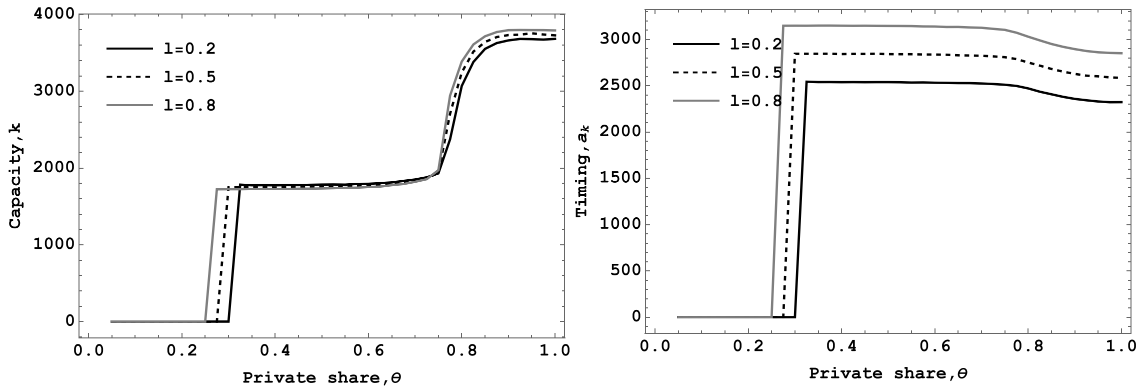


Fig 5.10 The effect of the private share and the cross-price effect l on the optimal decisions for the capacity expansion ($a_p = 1600$)

In summary, there are three regions of the private share in terms of the investor's capacity-expanding behaviour. The volume and the timing vary greatly by region, while the change is modest within each region. Therefore, we can have an optimal value of the private share in terms of the aggregated social surplus, and that value, in many cases, is consistent with one of the breakpoints that link two regions. Which breakpoint maximize the aggregated social surplus depends on a joint effect of the privatization time and some other factors. Moreover, the breakpoints can change given different external factors. The breakpoint between *no-expansion region* and *gap-filling region* is more sensitive to the change of the situation of the downstream airlines, while the breakpoint between *gap-filling region* and *future-preparing region* is more sensitive to the change of the dynamics of demand and the discount rate. These findings can provide some references for the government to determine the privatization time and the private share. For instance, if the degree of product differentiation between the downstream airlines is fairly low (i.e., l is low), and the social-surplus oriented government want to privatization the airport earlier, although a fairly low share might be appropriate, its should not be too low because the breakpoint has been drawn rightward by the low l. However, if the government place higher premium on the capacity rather than the aggregated social surplus (this might happen in the case that the spill-over benefit brought by the increasing passengers is highly valued), a high private share might be better-off, but a very high share (e.g., an utter transfer of the ownership) is unnecessary.

5.4 Conclusion

Privatization of an airport would have immense and long-term impacts on various aspects. A comprehensive understanding of these impacts thus proves to be important for a reasonable decision-making regarding airport privatization. This study investigates the effect of the airport privatization with ownership transfer on the investor's decisions of the capacity expansion and the long-term aggregated social surplus. We consider two scenarios. In Scenario I, while the budget constraint (i.e., profit should not be negative) is addressed in terms of charging, it is not taken into account for the decision-makings regarding capacity expansion. In other words, the governmental subsidiary to the investment is available. In Scenario II, the budget constraint is considered in both decision-making phases. A Stackelberg model is employed to present the optimal pricing behavior of the airport, and the decision-makings on the capacity expansion is modelled in a real option approach. Numerical computation is performed to show the relationship between the privatization decisions and the investment decisions, and the effect of various external factors on that relationship.

The main findings can be concluded as follows. In Scenario I, the optimal volume and timing for the investment do not monotonically increase or decrease with regard to the private share. Their changing patterns are not simple due to two countervailing effects. Generally, the earliest and largest investment can be achieved by a fairly low private share. Factors regarding the airline market affect the timing more than the volume, while factors regarding the dynamics of demand and the discount factor have stronger effect on the volume rather than the timing. In Scenario II, there are three clear-cut regions of the investment decisions with regard to the private share: If the private share is low, no expansion will be carried out; if the private share is moderate, a gap-filling expansion will be carried out; if the private share is high, the expansion will not only fill the current capacity gap, but also leave some vacant capacity preparing for the future demand growth. The maximization of the long-term aggregated social surplus can be achieved by privatizing a certain share which is just consistent with the value of one of the two breakpoints that link two adjacent regions, while which breakpoint can maximize the aggregated social surplus depends on the timing of the privatization. While factors regarding the downstream airlines might have greater effects on the timings rather than the volume of the investment, factors regarding the demand dynamics and the discount rate can have strong effect on both timing and volume. Moreover, the effects on the breakpoint also vary by the type of the factors.

These findings can provide some references for the government to determine the privatization time and the private share. For instance, if governmental subsidiary is available, the earliest and largest expansion can be achieved by a fairly low private share. By contrast, a low private share should be avoided, if governmental subsidiary is unavailable. In this case, there is a trade-off between the social surplus within the airport and the spill-over social benefit (capacity) in terms of an early privatization. A fairly low private share can maximize the aggregated social surplus, while the capacity to be expanded will not be large.

This study has several limitations. First, we merely regard capacity as an “inelastic” upper bound for the output; no congestion cost or disutility will occur as long as the capacity is not fully occupied. This might not be the case in reality. Second, we do not consider the possibility of incremental investment in capacity. However, as a matter of fact, an airport can be expanded for several times. Third, the assumption that the social-surplus oriented government will obtain no profit is fairly strong. When capacity is binding, the government does not necessarily just levy a cost-recovering charge. Fourth, the privatization decisions are exogenous to the private investor. In fact, the private investor is willing to purchase some share only when the privatization proves to be beneficial. A bargaining between the government and the investor for the decisions on the privatization should be modelled. Fifth, regarding the public sector’s objective, we only focus on the social surplus within the airport. As a matter of fact, airport capacity investment can have various externalities, such as the noise problem. Such aspects should be explored further. These limitations provide the directions for the future improvement.

Chapter 6 Conclusion

6.1 Summary and conclusions

In the recent decades, airports are seeking structural changes, such as privatization, to meet and satisfy the increasing demand. On the one hand, there are open issues on whether privatization can stimulate the capacity investment which is the ultimate countermeasure against capacity shortage. On the other hand, privatization raises the concern regarding the abuse of market power. Based on the background, the objectives of the thesis are, first, assessing the plausibility of the introduction of terminal competition as an alternative countermeasure against the abuse of market power; second, figuring out the relationship between privatization and the capacity expansion from some new perspectives. Main findings of this thesis are summarized by chapter as follows:

In **Chapter 2**, we explain why the introduction of intra-airport terminal competition is proposed, presenting the limited practical examples, and showing the remarks of official discussions on it. We then review the studies on competing facilities, clarifying the necessity of a new modelling. Next, we introduce the current status of airport capacity shortage and expansion in the real world. We review the relevant studies, confirming that our study can supplement the existing findings.

Chapter 3 studies the effect of intra-airport terminal competition on the pricing and social surplus. We consider several Business Models characterizing the potential situations before and after the introduction of terminal competition, and address the freedom of airlines to change their base terminals in response to the charges. An analytical model is developed considering the competition of downstream airlines. Comparing the charges and the social surplus in equilibrium in each Business Model, we discuss the effect of terminal competition. We further extend the study by considering four special cases: (i), terminals have different levels of marginal cost and unit non-aeronautical profit; (ii), leader airlines participate in the upstream via directly operating or owing terminals; (iii), terminals not only compete on price, but also compete on service level (quality); (iv), terminals are regulated. We investigate whether an airport with terminal competition can be better-off in these special cases.

We find that, in most cases, having competing terminals can neither lower the prices nor enhance the social surplus if the operation of the terminal and airfield facilities are not completely separated in the existing business model (e.g., the incumbent operator operates both the airfield facilities and terminals), whether or not airlines have the freedom to change base terminal in response to the prices. The complementarity between the airfield and terminal service, which is originally internalized by the joint operation, will become a negative effect that cannot be offset even by a strong degree of substitution between terminals, if the two services are provided respectively by independent operators. In contrast, if the operation of the two sections has been completely separated in the existing business model (e.g., one operator operates the terminals while another operates the airfield), or the airfield operator can be strictly regulated, having competing terminals can result in a higher social surplus, as it will not increase the negative complementary effect. Instead, it creates a duopoly of substitute goods that can offset the complementary effect. Moreover, only few special cases can make the introduction of terminal competition better-off in terms of social surplus.

Our findings indicate that the introduction of terminal competition fails to restrain the abuse of market power by monopoly airport, and improve social surplus in most cases, contrary to common belief. If we further take into account other potential problems of competing terminals, such as the difficulty of coordination and loss of economies of scale, we can only contend that having competing terminals without any restrictions may not be a reasonable solution.

Chapter 4 analyzes the optimal timing problem of investment when the airport faces two types of project, namely capacity expansion and cost reduction. We adopt the Stackelberg model to solve the optimal pricing problem for the airport, and formally prove the inter-relationship between the projects. Then, employing the real option approach, we derive the optimal rule of the timings for the bi-projects investments which improves the rule proposed by the previous study. We also investigate the loss of the investments due to suboptimal rules.

The results of the numerical examples suggest that the decision-maker who places a higher premium on social surplus always tends to invest earlier in both projects. Other factors that stimulate an earlier investment include a lower cross-price effect, a greater total number of airlines, a higher drift, and a lower volatility in demand. The optimal scales of projects are more sensitive to the change in drift and volatility rather than the change in other factors. When the composition of the objective function changes, the pattern of the change in optimal timing differs by project: for cost reduction, the changing rate does not change with the share of profit in most cases, while the optimal timing is convex with regard to the share for capacity expansion. The loss due to NPV-based investment is much greater than that caused by the adoption of the deterministic model, and its change with the change in the composition of the objective function has a mountain-shaped pattern, where the minimum can be reached when specific conditions are met.

Our results imply that, to improve social surplus, the timings of investments in both projects should be brought forward. However, the adjustment for different types of projects should be distinguished, as their pattern of change in timings is not the same. Besides, NPV-based investment should be avoided in most cases even when the real option rule is not applicable.

Chapter 5 investigates the relationship between the privatization decision and the investment decision. We consider two scenarios differing in the availability of governmental subsidiary to the investment. Similar with Chapter 4, we use the Stackelberg model to derive the optimal charge of the airport, and then obtain the optimal timing and volume for the capacity expansion by a real option approach. Numerical computations are performed with different privatization timings and the private shares.

The results suggest that the optimal volume and timing for the investment do not monotonically increase or decrease with regard to the private share. Their changing patterns are not simple due to two countervailing effects, if the governmental subsidiary to the investment is available. If the governmental subsidiary to the investment is unavailable, three clear-cut regions of the investment decisions with regard to the private share can be found: If the private share is low, no expansion will be carried out; if the private share is moderate, a gap-filling expansion will be carried out; if the private share is high, the expansion will not only fill the current capacity gap, but also leave some vacant capacity preparing for the future demand growth. Maximum aggregated social surplus can be achieved by privatizing a certain share which is just consistent with the value of one of the two breakpoints that connect two adjacent regions, while which breakpoint can maximize the aggregated social surplus depends on the timing of the privatization. Whilst factors regarding the downstream airlines might have greater effects on the timings rather than the volume of the investment, factors regarding the demand dynamics can have strong effect on both timing and volume. Moreover, the effects on the breakpoint also vary by the type of the factors.

These findings can provide some references for the government to determine the privatization time and the private share. For instance, if governmental subsidiary is available, the earliest and largest expansion can be achieved by a fairly low private share. By contrast, a low private share should be avoided, if governmental subsidiary is unavailable.

6.2 Future scope

A multitude of aspects of the thesis can be improved. We first point out the common limitations of all studies involved, and then summarize the flaws of each chapter respectively. Those are followed by the recommendations for the future works.

<u>Common limitations</u>

1. All studies in the thesis only focus on one single airport. However, many changes in the recent years, such as the deregulation of airlines and the emergence of LCC, have made inter-airport competition no longer an ignorable factor. Future study can extend the works in this thesis by taking into account multiple airports which can be competing hubs or airport-pair in a metropolitan area.
2. This thesis mainly employs analytical model which, to some degree, ensures the generality of result, due to the lack of realistic data. However, several factors are excluded from the modelling for the sake of tractability. A more comprehensive and explicit modelling using realistic data is expected to examine the robustness of the findings of this thesis.

<u>Respective flaws</u>

Chapter 3

1. We did not consider LCC terminal which should have fairly different features compared with the normal terminal. Future study can address this issue by investigating whether an independently operated LCC terminal should exist in terms of various aspects.
2. We did not address the issues regarding investment. In reality, a new terminal at an airport was constructed through a BOT project in many cases, so the terminal competition might not exist forever. Future study can investigate issues such as the effect of the details of BOT contract on the aggregated social surplus.

Chapter 4

1. Capacity is not treated as a “hard” bound in the setting, meaning that there is no upper bound for the output. A shortcoming of such setting is that a congestion cost will still occur even if the output is well under the capacity, which is not realistic. Analysis using other capacity setting might should be tried.
2. Incremental investment is not considered. In reality, especially the project for cost reduction, can be invested in many times. Future improvement should address this issue.
3. The airport can decide the scale of each project discretely, while the volume of each scale is pre-determined. A “pure” optimization of both timing and volume of the investment is desired.
4. Lack of real data, particularly the data regarding the cost for the investment, renders the results less persuasive. Case studies with real-world data are desired.

Chapter 5

1. The modelling of the privatization decisions is fairly rough. In reality, the privatization contract and the process to reach the agreement can be quite sophisticated. Future study should consider more details of the contract, and address the complex process of bargaining.
2. Several assumptions in the settings are fairly strong, such as the non-profiting assumption for the social surplus-oriented government, as mentioned. These assumptions should be relaxed as much as possible in the future improvement.

3. Comparison of the effects on investment of different forms of privatization can be a meaningful extension for the future study.
4. Regarding the public sector's objective, we only focus on the social surplus within the airport. As a matter of fact, airport capacity investment can have various externalities, such as the noise problem. Such aspects should be explored further.
5. Private share does not necessarily affect the composition of the objective function in this continuous way. For instance, 51% and 49% can be very different in terms of the decision-makings. Future study should seriously address such difference.

Appendices

Appendix A A discussion on Business Model II

The concern that Terminal B will be driven out of the market in Business Model II might be true if the profit function of operators can be written as follows.

$$\Gamma_1 = Q_A * (\tau_1 - c_1) + Q_B * \tau_{12}$$

$$\Gamma_2 = Q_B * (\tau_2 - c_2 - \tau_{12})$$

And the condition $((1/a) - c_1)/((1/a) - c_2) \geq l$ should be satisfied (Arya et al., 2008). Where τ_1, τ_2 are the prices of whole airport service (terminal plus airfield) per passenger set by operator 1 and 2 respectively, τ_{12} is the price of runway access that operator 2 has to purchase in order to produce the final good (airport service). l is the cross-price effect between terminals.

However, a crucial difference should be noticed comparing this with our modeling. In our setting, there are no direct trades between the two upstream operators, all goods are sold to the downstream airlines, albeit an indispensable input (airfield service) for all airlines is only produced by operator 1. In contrast, in the model shown above, the runway access will be sold by operator 1 to 2, indicating a price-discrimination in the homogenous airfield goods due to double marginalization. Moreover, if we assume identical cost, the condition $((1/a) - c_1)/((1/a) - c_2) \geq l$ can only be satisfied when two terminals are perfect substitutes, which merely corresponds to an extreme case in our setting. Consequently, in this study, different from the results of Barbot (2011) and D'Alfonso and Nastasi (2012), operator 2 will not be driven out as long as the competition in the upstream market is in a differentiated Bertrand form (if two operators compete on quantity, operator 2 will indeed be driven out). Findings in Chen (2001) are also in line with this result.

Besides, observing the equilibrium output of Terminal B in Model II, we can find $Q_B^{II} = \frac{k^2 s n_B (C_1 n_A - C_2 n_A + C_1)((r+1)s - \gamma - c)}{3C_1^2 (n_A+1)(n_B+1) - 3C_2^2 n_A n_B} > 0$ as $C_1 \geq C_2$ and $s > \max\{\frac{c+\gamma}{1+r}, \frac{c-\gamma}{1-r}\}$ defined as basic assumption. Operator 2 can still ensure a share and thus will not exit. If operator 1 forces operator 2 to exit by setting a much higher airfield charge $T =$

$\frac{(2C_1(n_A+1)-C_2n_A)((r+1)s-c)+\gamma C_2 n_A}{2C_1(n_A+1)}$ and lowering terminal fee accordingly, its own profit will also sustain a loss of $\Delta=\frac{k^2 n_B(C_1n_A-C_2n_A+C_1)((r+1)s-c-\gamma)((C_1n_A-C_2n_A+C_1)((r+1)s-c-\gamma)+3C_1\lambda s(n_A+1))}{9C_1(n_A+1)(C_1^2(n_A+1)(n_B+1)-C_2^2n_An_B)}>0$, causing a lose-lose outcome.

Appendix B Solving process and proof of Section 3.2

B1. Solving process of the multi-stage games

First order conditions (FOCs) of the subgame equilibrium are:

$$\frac{\partial \Pi_{hi}}{\partial f_{hi}}=s(1-w_h-s(aF_h+alF_{-h})-\alpha\delta)-c-T-\left[s\left(as+\frac{\alpha}{k}\right)+\frac{\beta}{k}\right]f_{hi}-\beta\delta=0 \quad (B.1)$$

Adopting symmetry and solving the system, we have the equilibrium outputs as Eq. (3.8) and (3.9) as functions of total prices, or as functions of airfield charge and terminal fees as:

$$f_{hi}^*(T,w_h,w_{-h})=\frac{k^2\big(C_1(n_{-h}+1)(T+w_hs+c-s)-C_2n_{-h}(T+w_{-h}s+c-s)\big)}{C_2^2n_hn_{-h}-C_1^2(n_h+1)(n_{-h}+1)} \quad (B.2)$$

$$Q^*(T,w_A,w_B)=\frac{(C_1-C_2)k^2n_An_B\big((w_A+w_B)s+2(T+c-s)\big)+C_1\big(\sum_{h=A,B}n_h(T+w_hs+c-s)\big)}{C_2^2n_An_B-C_1^2(n_A+1)(n_B+1)} \quad (B.3)$$

Substituting Eq. (3.8) and (3.9) into the Eq. (3.7), we first check the concavity of social surplus function with respect to the total prices. Second order conditions are derived as follows.

$$|H_1|=\frac{\partial^2 S}{\partial T_A^2}=\frac{k^2n_A^2\big(C_2^2C_1n_B(n_B+2)-C_1^3(n_B+1)^2-k(\alpha s+\beta)(C_1n_B-C_2n_B+C_1)^2\big)}{\left(C_2^2n_An_B-C_1^2(n_A+1)(n_B+1)\right)^2}<0 \quad (B.4)$$

$$|H_2|=\begin{vmatrix}\frac{\partial^2 S}{\partial T_A^2} & \frac{\partial^2 S}{\partial T_A\partial T_B}\\ \frac{\partial^2 S}{\partial T_B\partial T_A} & \frac{\partial^2 S}{\partial T_B^2}\end{vmatrix}=\frac{(C_1-C_2)k^4n_A^2n_B^2\big(C_1+C_2+2k(\beta+\alpha s)\big)}{\left(C_2^2n_An_B-C_1^2(n_A+1)(n_B+1)\right)^2}>0 \quad (B.5)$$

Next, substituting the equilibrium outputs of the downstream subgame into the objective functions of each Business Model respectively, we can obtain the equilibrium prices. Note that for the first-best benchmark and Business Model I, the objective function must be converted into a form with two decision variables, which are the total price T_A and T_B, to ensure the non-singularity of the coefficient matrix of FOCs. While for other Models, objective functions with three decision variables, namely airfield charge T, terminal fees w_A and w_B, can be retained. FOCs of each Models are summarized in Table A.1.

Table A.1 Objective functions and first order conditions of each business model

Models	Objective functions	First order conditions
First-best		$\frac{\partial S}{\partial T_A}=0; \frac{\partial S}{\partial T_B}=0$
I	$j=1,\{x,y,z\}=\{1,1,1\}$	$\frac{\partial \Gamma_1}{\partial T_A}=0; \frac{\partial \Gamma_1}{\partial T_B}=0$
II	$j=1,\{x,y,z\}=\{1,1,0\}$ $j=2,\{x,y,z\}=\{0,0,1\}$	$\frac{\partial \Gamma_1}{\partial T}=0; \frac{\partial \Gamma_1}{\partial w_A}=0; \frac{\partial \Gamma_2}{\partial w_B}=0$
III	$j=1,\{x,y,z\}=\{0,1,0\}$ $j=2,\{x,y,z\}=\{0,0,1\}$ $j=3,\{x,y,z\}=\{1,0,0\}$	$\frac{\partial \Gamma_1}{\partial w_A}=0; \frac{\partial \Gamma_2}{\partial w_B}=0; \frac{\partial \Gamma_3}{\partial T}=0$
IV	$j=1,\{x,y,z\}=\{0,1,1\}$ $j=2,\{x,y,z\}=\{1,0,0\}$	$\frac{\partial \Gamma_1}{\partial w_A}=0; \frac{\partial \Gamma_1}{\partial w_B}=0; \frac{\partial \Gamma_2}{\partial T}=0$
V	$j=1,\{x,y,z\}=\{0,1,1\}$ $j=2,\{x,y,z\}=\{1,0,0\}, \Gamma_R=S+\lambda\Gamma_R$	$\frac{\partial \Gamma_1}{\partial w_A}=0; \frac{\partial \Gamma_1}{\partial w_B}=0; \frac{\partial \Gamma_2}{\partial T}=0;$ $\frac{\partial \Gamma_2}{\partial \lambda}\geq 0; \lambda\geq 0; \frac{\partial \Gamma_2}{\partial \lambda}\lambda=0$
VI	$j=1,\{x,y,z\}=\{0,1,0\}$ $j=2,\{x,y,z\}=\{0,0,1\}$ $j=3,\{x,y,z\}=\{1,0,0\}, \Gamma_R=S+\lambda\Gamma_R$	$\frac{\partial \Gamma_1}{\partial w_A}=0; \frac{\partial \Gamma_2}{\partial w_B}=0; \frac{\partial \Gamma_3}{\partial T}=0;$ $\frac{\partial \Gamma_3}{\partial \lambda}\geq 0; \lambda\geq 0; \frac{\partial \Gamma_3}{\partial \lambda}\lambda=0$

A2. Proof of Lemma 1

$$\frac{\partial f_{hi}^*}{\partial T_h}=-\frac{C_1k^2(n_{-h}+1)}{C_1^2(n_h+1)(n_{-h}+1)-C_2^2n_hn_{-h}}<0 \qquad (B.6)$$

$$\frac{\partial f_{hi}^*}{\partial T_{-h}}=\frac{C_2k^2n_{-h}}{C_1^2(n_h+1)(n_{-h}+1)-C_2^2n_hn_{-h}}>0 \qquad (B.7)$$

$$\frac{\partial Q^*}{\partial T_A} = -\frac{k^2 s n_A\big((C_1 - C_2)n_B + C_1\big)}{C_1^2(n_A+1)(n_B+1) - C_2^2 n_A n_B} < 0 \qquad (B.8)$$

$$\frac{\partial Q^*}{\partial T_B} = -\frac{k^2 s n_B\big((C_1 - C_2)n_A + C_1\big)}{C_1^2(n_A+1)(n_B+1) - C_2^2 n_A n_B} < 0 \qquad (B.9)$$

Since $C_1 \geq C_2 > 0$, these signs can be judged easily.

Appendix C Results and proofs of Section 3.2.3

C1. Equilibrium airfield charge and terminal fees in each Business Model

$$w_A^{II} = \frac{C_1(n_A+1)(s - 5rs - \gamma) - C_2 n_A(s + rs - \gamma) - c(C_1 n_A - C_2 n_A + C_1)}{6C_1 s(n_A+1)} \qquad (C.1)$$

$$w_B^{II} = \frac{C_1(n_A+1)(s - 2rs - \gamma) - C_2 n_A(s + rs - \gamma) - c(C_1 n_A - C_2 n_A + C_1)}{3C_1 s(n_A+1)} \qquad (C.2)$$

$$T^{II} = \frac{(2C_1(n_A+1) + C_2 n_A)\big((r+1)s - c\big) + \gamma(4C_1(n_A+1) - C_2 n_A)}{6C_1(n_A+1)} \qquad (C.3)$$

$w_A^{III} = [2C_1^3(n_A+1)(n_B+1)(n_A(2n_B+1)+n_B)(s-2rs-c-\gamma) + C_2C_1^2(n_A+1)n_B(n_B(n_A(6c+6\gamma+4rs-6s)+c+\gamma-(r+1)s)+5n_A(c+\gamma+(r-1)s)) + C_2^2C_1n_An_B(n_A(4rsn_B+c+\gamma+(r-1)s)-n_B(c+\gamma-3rs-s)) - 2C_2^3n_A^2n_B^2(c+\gamma-s)]/sD_0 \qquad (C.4)$

$w_B^{III} = [(2C_1^3(n_A+1)(n_B+1)(n_A(2n_B+1)+n_B)(s-2rs-c-\gamma) + C_2C_1^2n_A(n_B+1)(n_A(n_B(6c+6\gamma+4rs-6s)+c+\gamma-(r+1)s)+5n_B(c+\gamma+(r-1)s)) + C_2^2C_1n_An_B(n_A(4rsn_B-c-\gamma+3rs+s)+n_B(c+\gamma+(r-1)s)) - 2C_2^3n_A^2n_B^2(c+\gamma-s))]/sD_0 \qquad (C.5)$

$T^{III} = [(2C_1^3(n_A+1)(n_B+1)(n_A(2n_B+1)+n_B)((r+1)s-c+2\gamma) + 2C_2C_1^2n_A(n_A+1)n_B(n_B+1)(c-4\gamma-(r+1)s) + C_2^2C_1n_An_B(n_A(2n_B+1)+n_B)(c-\gamma-(r+1)s) + 2\gamma C_2^3n_A^2n_B^2)]/D_0 \qquad (C.6)$

$$w_A^{IV} = w_B^{IV} = \frac{s - 2rs - c - \gamma}{3s} \qquad (C.7)$$

$$T^{IV} = \frac{1}{3}(s + rs - c + 2\gamma) \qquad (B.8)$$

$$w_A^V = w_B^V = \frac{s - rs - c - \gamma}{2s} \qquad (C.9)$$

$$T^V = \gamma \qquad (C.10)$$

$$w_A^{VI} = \frac{2C_1^2(n_A+1)(n_B+1)(s-rs-c-\gamma) - C_2C_1(n_A+1)n_B\big((r+1)s-c+\gamma\big) - C_2^2n_An_B(s-c-\gamma)}{s\big(4C_1^2(n_A+1)(n_B+1) - C_2^2n_An_B\big)} \qquad (C.11)$$

$$w_B^{VI} = \frac{2C_1^2(n_A+1)(n_B+1)(s-rs-c-\gamma) - C_2C_1n_A(n_B+1)\big((r+1)s-c+\gamma\big) - C_2^2n_An_B(s-c-\gamma)}{s\big(4C_1^2(n_A+1)(n_B+1) - C_2^2n_An_B\big)} \qquad (C.12)$$

$$T^{VI} = \gamma \qquad (C.13)$$

Where $D_0 = 2(3C_1^3(n_A + 1)(n_B + 1)(n_A(2n_B + 1) + n_B) - 5C_2C_1^2n_A(n_A + 1)n_B(n_B + 1) - C_2^2C_1n_An_B(n_A(2n_B + 1) + n_B) + C_2^3n_A^2n_B^2)$

C2. Proof of Proposition 1

For (i), we can confirm that

$$T_A^{III} - T_A^{II} = (C_1n_B - C_2n_B + C_1)(n_A((3C_1^2 - C_1C_2)n_B + C_1^2) + n_A^2((2C_1^2 - C_2C_1 - C_2^2)n_B + C_1^2) + C_1^2n_B)((r + 1)s - c - \gamma)/2D_1 > 0 \qquad (C.14)$$

$$T_A^{IV} - T_A^{III} = [C_2n_B((r + 1)s - c - \gamma)(n_A((7C_1^2 - 4C_1C_2)n_B + C_1^2) + n_A^2((4C_1^2 - 2C_2C_1 - 2C_2^2)n_B + C_1^2 + 2C_2C_1) + 3C_1^2n_B)]/6D_1 > 0 \qquad (C.15)$$

$$T_A^V - T_A^{VI} = \frac{C_2n_B\big(C_2n_A + 2C_1(n_A + 1)\big)\big((r + 1)s - c - \gamma\big)}{8C_1^2(n_A + 1)(n_B + 1) - 2C_2^2n_An_B} > 0 \qquad (C.16)$$

$$T_B^{II} - T_B^I = \frac{\big((C_1 - C_2)n_A + C_1\big)\big((r + 1)s - c - \gamma\big)}{6C_1(n_A + 1)} > 0 \qquad (C.17)$$

$$T_B^{III} - T_B^{II} = \frac{\prod_{h=A,B}[n_h(C_1(n_h+1) - C_2n_h)]\big(C_2n_A + 2C_1(n_A+1)\big)\big((r+1)s-c-\gamma\big)C_2}{6C_1D_1(n_A+1)} > 0 \qquad (C.18)$$

$$T_B^{IV} - T_B^{III} = [C_2n_A((r + 1)s - c - \gamma)(n_A((4C_1^2 - 2C_2C_1 - 2C_2^2)n_B^2 + (7C_1^2 - 4C_1C_2)n_B + 3C_1^2) + (C_1^2 + 2C_2C_1)n_B^2 + C_1^2n_B)]/6D_1 > 0 \qquad (C.19)$$

$$T_B^V - T_B^{VI} = \frac{C_2n_A\big(C_2n_B + 2C_1(n_B + 1)\big)\big((r + 1)s - c - \gamma\big)}{8C_1^2(n_A + 1)(n_B + 1) - 2C_2^2n_An_B} > 0 \qquad (C.20)$$

Where $D_1 = 3C_1^3(n_A + n_B + n_A^2 + n_B^2) + (9C_1^3 - 5C_2C_1^2 - C_2^2C_1)(n_An_B^2 + n_A^2n_B) +$

$(C_1 - C_2)(3C_1 - C_2)(2C_1 + C_2)n_A^2 n_B^2 + (12C_1^3 - 5C_1^2 C_2)n_A n_B > 0.$

Remaining equations/inequations are self-evident.

For (ii), we have

$$\frac{\partial w_A^{II}}{\partial n_A} = -\frac{C_2\big((r+1)s - c - \gamma\big)}{6C_1 s(n_A+1)^2} < 0 \qquad (C.21)$$

$$\frac{\partial w_B^{II}}{\partial n_A} = -\frac{C_2\big((r+1)s - c - \gamma\big)}{3C_1 s(n_A+1)^2} < 0 \qquad (C.22)$$

$$\frac{\partial T^{II}}{\partial n_A} = \frac{C_2\big((r+1)s - c - \gamma\big)}{6C_1 (n_A+1)^2} > 0 \qquad (C.23)$$

$$\frac{\partial T_B^{II}}{\partial n_A} = -\frac{C_2\big((r+1)s - c - \gamma\big)}{6C_1 (n_A+1)^2} < 0 \qquad (C.24)$$

Remaining equations/inequations are self-evident.

For (iii), since $\frac{\partial T_h^M}{\partial l} = \frac{\partial T_h^M}{\partial C_2}\frac{\partial C_2}{\partial l}$ and $\frac{\partial C_2}{\partial l} = ak^2 s^2 > 0$, we only need to investigate the sign of $\frac{\partial T_h^M}{\partial C_2}$ for each case.

$$\frac{\partial T_B^{II}}{\partial C_2} = -\frac{n_A\big((r+1)s - c - \gamma\big)}{6C_1 (n_A+1)} < 0 \qquad (C.25)$$

$$\frac{\partial T_A^{III}}{\partial C_2} = -[C_1(n_A+1)n_B(n_A^3(2(C_1-C_2)(7C_1^2+5C_2C_1-3C_2^2)C_1n_B^2 + 2(-2C_1^2+C_2C_1+C_2^2)^2n_B^3 + (7C_1^4+8C_2C_1^3-9C_2^2C_1^2)n_B + C_1^4 + 4C_2C_1^3) + n_A^2(2(C_1-C_2)(9C_1^2-C_2C_1+C_2^2)C_1n_B^3 + (28C_1^4-24C_2C_1^3+2C_2^2C_1^2)n_B^2 + (11C_1^4-4C_1^3C_2)n_B + C_1^4) + n_A(4C_1^4n_B + (13C_1^4-8C_2C_1^3+C_2^2C_1^2)n_B^3 + (17C_1^4-8C_1^3C_2)n_B^2) + 3C_1^4n_B^3 + 3C_1^4n_B^2)((r+1)s-c-\gamma)]/2D_1^2 < 0 \qquad (C.26)$$

$$\frac{\partial T_B^{III}}{\partial C_2} = -[C_1n_A(n_B+1)(n_A^3(2(C_1-C_2)(9C_1^2-C_2C_1+C_2^2)C_1n_B^2 + 2(-2C_1^2+C_2C_1+C_2^2)^2n_B^3 + (13C_1^4-8C_2C_1^3+C_2^2C_1^2)n_B + 3C_1^4) + n_A^2(2(C_1-C_2)(7C_1^2+5C_2C_1-3C_2^2)C_1n_B^3 + (28C_1^4-24C_2C_1^3+2C_2^2C_1^2)n_B^2 + (17C_1^4-8C_1^3C_2)n_B + 3C_1^4) + n_A(4C_1^4n_B + (7C_1^4+8C_2C_1^3-9C_2^2C_1^2)n_B^3 + (11C_1^4-4C_1^3C_2)n_B^2) + C_1^4n_B^2 + (C_1^4+4C_2C_1^3)n_B^3)((r+1)s-c-\gamma)]/2D_1^2 < 0 \qquad (C.27)$$

Remaining equation is self-evident.

For (iv), recalling Lemma 1 that $\frac{\partial Q^*}{\partial T_A} < 0$ and $\frac{\partial Q^*}{\partial T_B} < 0$, and (i) of Proposition 1, (iv) becomes self-evident, since $dQ = \frac{\partial Q^*}{\partial T_A} dT_A + \frac{\partial Q^*}{\partial T_B} dT_B$.

C3. Proof of Proposition 3.2

To prove $S^I > S^{II}$, we first apply the mean value theorem (MVT) to $\frac{\partial S}{\partial T_B}$, we then have

$$\Delta \frac{\partial S}{\partial T_B} = \Delta T_A \frac{\partial^2 S}{\partial T_B \partial T_A} + \Delta T_B \frac{\partial^2 S}{\partial T_B^2} \qquad (C.28)$$

Where $\frac{\partial^2 S}{\partial T_B \partial T_A}$ and $\frac{\partial^2 S}{\partial T_B^2}$ are evaluated at $(T_A^I,\ \tilde{T}_B)$, $\Delta \frac{\partial S}{\partial T_B} = \left.\frac{\partial S}{\partial T_B}\right|_{\boldsymbol{T}=(T_A^I, \bar{T}_B)} - \left.\frac{\partial S}{\partial T_B}\right|_{\boldsymbol{T}=(T_A^I, T_B^I)}$, $\Delta T_B = \bar{T}_B - T_B^I, \Delta T_A = 0$, $\tilde{T}_B$ is some value between T_B^I and $\bar{T}_B$, while $\bar{T}_B$ can have any value between T_B^I and T_B^{II}. Since $\frac{\partial^2 S}{\partial T_B^2} < 0$ (second-order condition), for any $\bar{T}_B$, we have $\Delta \frac{\partial S}{\partial T_B} < 0$. Adopting the assumption $(\alpha s + \beta) < aks^2$ mentioned before, we can confirm that $\left.\frac{\partial S}{\partial T_B}\right|_{\boldsymbol{T}=(T_A^I, T_B^I)} < 0$,thus $\left.\frac{\partial S}{\partial T_B}\right|_{\boldsymbol{T}=(T_A^I, \bar{T}_B)} < 0$.

Next, applying the MVT to S, we have

$$\Delta S = \Delta T_A \frac{\partial S}{\partial T_A} + \Delta T_B \frac{\partial S}{\partial T_B} \qquad (C.29)$$

Where $\Delta T_A = T_A^{II} - T_A^I = 0$, $\Delta T_B = T_B^{II} - T_B^I > 0$. Since $\left.\frac{\partial S}{\partial T_B}\right|_{\boldsymbol{T}=(T_A^I, \bar{T}_B)} < 0$, thus $\Delta S = S(T_B^{II}, T_B^{II}) - S(T_B^I, T_A^I) < 0, S^I > S^{II}$.

To prove $S^I > S^{IV}$, we first convert $S(T_A, T_B)$ into a function with single variable $S(T_U)$ by setting $T_U = T_A = T_B$. Then we can obtain the stationary point of $S(T_U)$ as

$T_U = [c(-C_1^2(2C_2 n_A n_B(n_A + n_B + 2) + k(2n_A n_B + n_A + n_B)^2(\beta + \alpha s)) + C_2 C_1 n_A n_B(C_2(n_A + n_B) + 4k(2n_A n_B + n_A + n_B)(\beta + \alpha s)) - 4C_2^2 k n_A^2 n_B^2(\beta + \alpha s) + C_1^3(n_A n_B(n_A + n_B + 4) + n_A + n_B)) + C_1^2(2C_2 n_A n_B(s(r(n_A + 1)(n_B + 1) + n_A + n_B + 2) - \gamma(n_A + 1)(n_B + 1)) + ks(2n_A n_B + n_A + n_B)^2(\beta + \alpha s)) + C_2 C_1 n_A n_B(-\gamma C_2(2n_A n_B + n_A + n_B) + C_2 s(n_A(2rn_B + r - 1) + (r - 1)n_B) - 4ks(2n_A n_B + n_A + n_B)(\beta + \alpha s)) +$

$2C_2^2 n_A^2 n_B^2 (C_2(\gamma - rs) + 2ks(\beta + \alpha s)) + C_1^3(\gamma(n_A + 1)(n_B + 1)(2n_A n_B + n_A + n_B) + s(-r(n_A + 1)(n_B + 1)(2n_A n_B + n_A + n_B) + n_A(-n_B)(n_A + n_B + 4) - n_A - n_B))]/ (C_1^2(k(2n_A n_B + n_A + n_B)^2(\beta + \alpha s) - 2C_2 n_A n_B(n_A n_B - 1)) - 2C_2 C_1 n_A n_B(C_2(n_A n_B + n_A + n_B) + 2k(2n_A n_B + n_A + n_B)(\beta + \alpha s)) + 2C_2^2 n_A^2 n_B^2(C_2 + 2k(\beta + \alpha s)) + C_1^3(n_A^2(2n_B(n_B + 1) + 1) + 2n_A n_B^2 + n_B^2))$ $(C.30)$

we can then confirm that $T_U^* < T_U^I < T_U^{IV}$. We can also confirm that $S(T_U)$ is concave. Thus, $S^I > S^{IV}$. We omit the tedious process.

C4. Numerical results of the social surplus comparison in Case 1

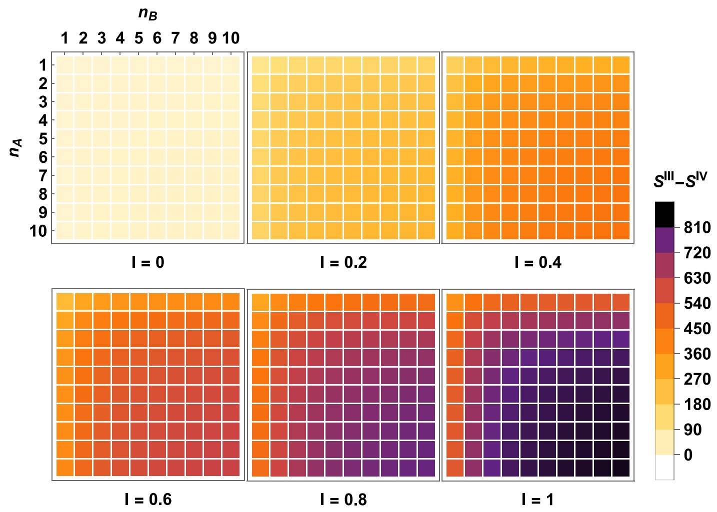


Fig A.1 Numerical results of $S^{III} - S^{IV}$

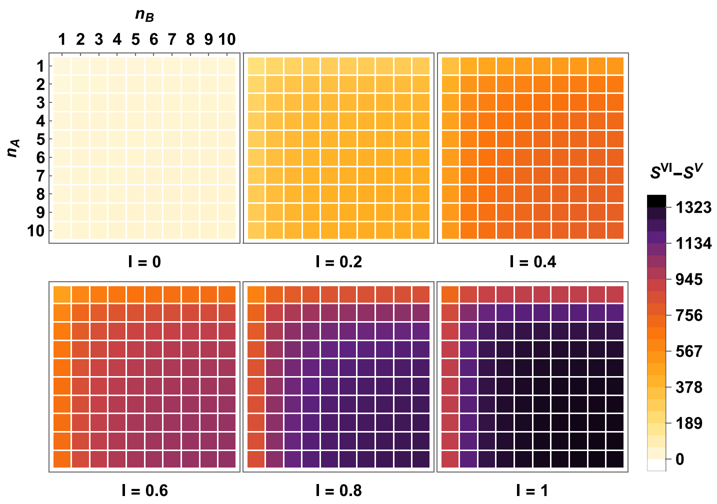


Fig A.2 Numerical results of $S^{VI} - S^{V}$

Appendix DEffect of the relaxation of the perfect substitute assumption

Let l denotes the cross effect between every two airlines. For airlines in different terminals, their cross effect is $l * a$, and this is also true for airlines in same terminal, unlike the basic modelling. From the perspective of passengers, airlines provide heterogeneous services, and no airline can be perfect substitute to others, as long as $l \neq 1$.

In such a setting, the quadratic utility function becomes:

$$U = Q_A + Q_B - \frac{1}{2}\left[a\left(\sum_i^{n_A} q_{Ai}^2 + \sum_j^{n_B} q_{Bj}^2\right) + 2al\left(\sum_{i>j} q_i q_j\right)\right] \qquad (D.1)$$

Inverse demand function of airline i at terminal h is denoted as:

$$\rho_{hi} = w_h + p_{hi} + \alpha\left(\frac{Q}{k}\right) = \frac{\partial U}{\partial q_{hi}} = 1 - aq_{hi} - al(Q - q_{hi}) \qquad (D.2)$$

Adopting the same processes of backward induction, we can obtain the equilibrium pricings of each business model:

$$T_A^I = T_A^{II} = T_B^I = \frac{1}{2}(s + \gamma - c - rs)$$

$$T_B^{II} = \frac{cC_2(4 - 3n_A) + \gamma C_2(3n_A - 2) + C_2 s(-3rn_A + 3n_A + 2r - 4) - 8cC_1 + 4\gamma C_1 - 4C_1(r-2)s}{6(C_2(n_A - 1) + 2C_1)}$$

$T_A^{III} = (c(-16C_1^2(n_A + n_B) - 2C_2C_1((9n_A - 8)n_B + 4(n_A - 2)n_A + 3n_B^2) + C_2^2(-3(n_A - 1)n_B^2 + (-3(n_A - 3)n_A - 4)n_B + 4(n_A - 1)n_A)) - 8C_1^2(n_A + n_B)((r-2)s - \gamma) + 2C_2C_1(\gamma(n_A + n_B)(2n_A + 3n_B - 4) + s(-r(n_A + n_B)(2n_A + 3n_B - 4) + 9n_An_B + 4n_A^2 - 8n_A + 3n_B^2 - 8n_B)) + C_2^2(\gamma(n_A - 1)(3n_B - 2)(n_A + n_B) + s(-r(n_A - 1)(3n_B - 2)(n_A + n_B) + 3n_A^2n_B + 3n_An_B^2 - 9n_An_B - 4n_A^2 + 4n_A - 3n_B^2 + 4n_B)))/(24C_1^2(n_A + n_B) + 4C_2C_1(n_A(7n_B - 6) + 3n_A^2 + 3(n_B - 2)n_B) + 2C_2^2(3n_A^2(n_B - 1) + n_A(n_B(3n_B - 7) + 3) - 3(n_B - 1)n_B))$

$T_B^{III} = (c(-16C_1^2(n_A + n_B) - 2C_2C_1(n_A(9n_B - 8) + 3n_A^2 + 4(n_B - 2)n_B) + C_2^2(-3n_A^2(n_B - 1) + n_A(-3(n_B - 3)n_B - 4) + 4(n_B - 1)n_B)) - 8C_1^2(n_A + n_B)((r-2)s - \gamma) + 2C_2C_1(\gamma(n_A + n_B)(3n_A + 2n_B - 4) + s(n_A(-5rn_B + 9n_B + 4r - 8) - 3(r-1)n_A^2 - 2(r-2)(n_B - 2)n_B)) + C_2^2(\gamma(3n_A - 2)(n_B - 1)(n_A + n_B) + s(3n_A^2(r(-n_B) + n_B + r - 1) + n_A(n_B(-3rn_B + 3n_B + 5r - 9) - 2r + 4) + 2(r-2)(n_B - 1)n_B)))/(24C_1^2(n_A + n_B) + 4C_2C_1(n_A(7n_B - 6) + 3n_A^2 + 3(n_B - 2)n_B) + 2C_2^2(3n_A^2(n_B - 1) + n_A(n_B(3n_B - 7) + 3) - 3(n_B - 1)n_B))$

$$T_A^{IV} = \frac{1}{3}(\gamma + (2-r)s - 2c)$$

$$T_B^{IV} = \frac{1}{3}(\gamma + (2-r)s - 2c)$$

$$T_A^{V} = \frac{1}{2}(s + \gamma - c - rs)$$

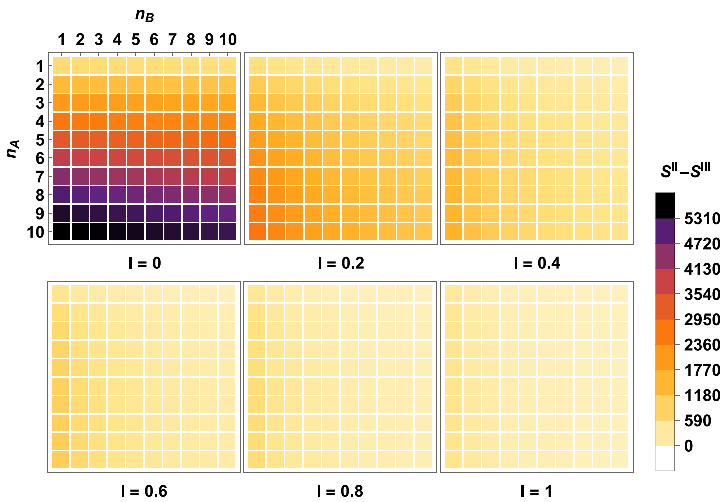
$$T_B^{V} = \frac{1}{2}(s + \gamma - c - rs)$$

$T_A^{VI} = -c(2C_1 - C_2)(C_2(2n_A + n_B - 2) + 4C_1) + \gamma(C_2(n_A - 1) + 2C_1)(C_2(3n_B - 2) + 4C_1) - rs(C_2(n_A - 1) + 2C_1)(C_2(3n_B - 2) + 4C_1) + (2C_1 - C_2)s(C_2(2n_A + n_B - 2) + 4C_1)/8C_2C_1(n_A + n_B - 2) + C_2^2(n_A(3n_B - 4) - 4n_B + 4) + 16C_1^2$

$T_B^{VI} = -c(2C_1 - C_2)(C_2(n_A + 2n_B - 2) + 4C_1) + \gamma(C_2(3n_A - 2) + 4C_1)(C_2(n_B - 1) + 2C_1) - rs(C_2(3n_A - 2) + 4C_1)(C_2(n_B - 1) + 2C_1) + (2C_1 - C_2)s(C_2(n_A + 2n_B - 2) + 4C_1)/8C_2C_1(n_A + n_B - 2) + C_2^2(n_A(3n_B - 4) - 4n_B + 4) + 16C_1^2$

Adopting similar approach in Appendix C, we can easily prove that $T_A^{IV} > T_A^{III} > T_A^{II} = T_A^{I} = T_A^{V} > T_A^{VI}$; $T_B^{IV} > T_B^{III} > T_B^{II} > T_B^{I} = T_B^{V} > T_B^{VI}$, which has the same order with that derived from the original modelling.

Ranking of social surplus can also be proved in similar approach used in original modelling as $S^I = S^V > S^{II}; S^I > S^{IV}$. Comparison of social surplus between other business models are conducted through numerical example (Fig A.3).



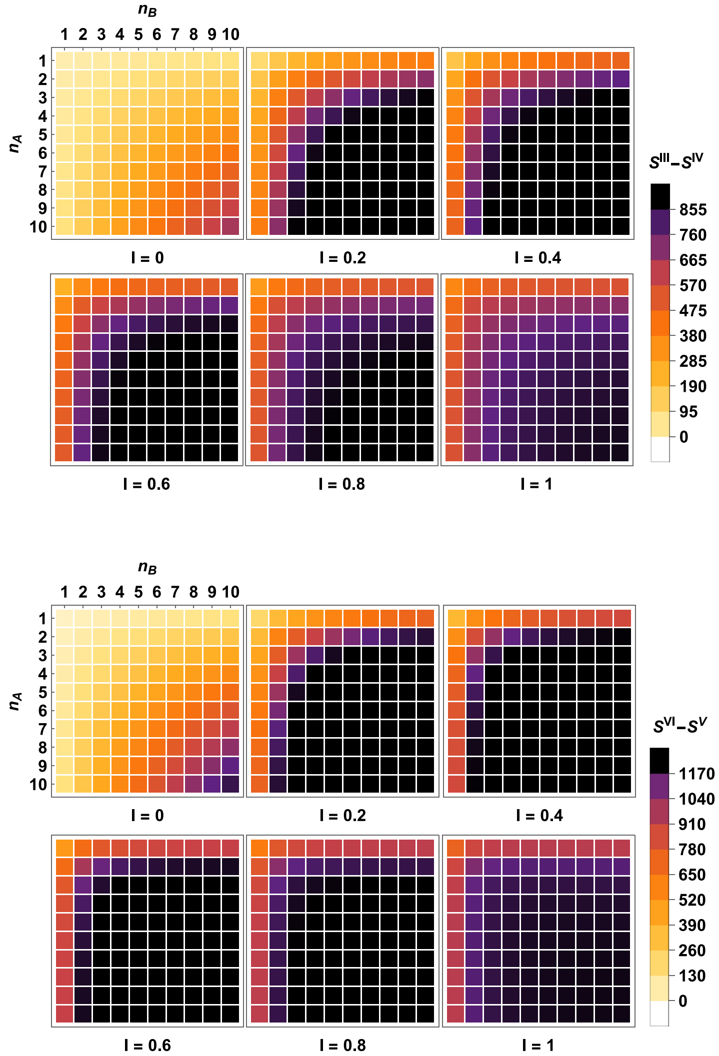


Fig A.3 Numerical result of the comparison of social surplus between Models

As a result, the ranking of business models in terms of social surplus also coincides with that in the original modelling. Distinction is in the extent of the difference of pricing and social surplus between different business models. For example, in the result of $S^{II} - S^{III}$, the surplus difference of the alternative modelling is much greater than that of the original modelling when l is small. The reason is that a lower cross-price effect will lead to greater quantities. When $l = 0$, for instance, the effect between airlines in same terminal remains full-scale in the original modelling, while the cross-price effect between all pairs vanishes in the all-different modelling, so the quantity level thereof is much higher. A higher quantity level makes the quantity loss, consequentially the social surplus loss switching from model II to III greater. In conclusion, we can say that the assumption of perfect substitutes would not affect the primary results of the study

Appendix E Results and Proofs of Section 3.2.4

E1. Curves of maximum profit given optimal charges in Case 2

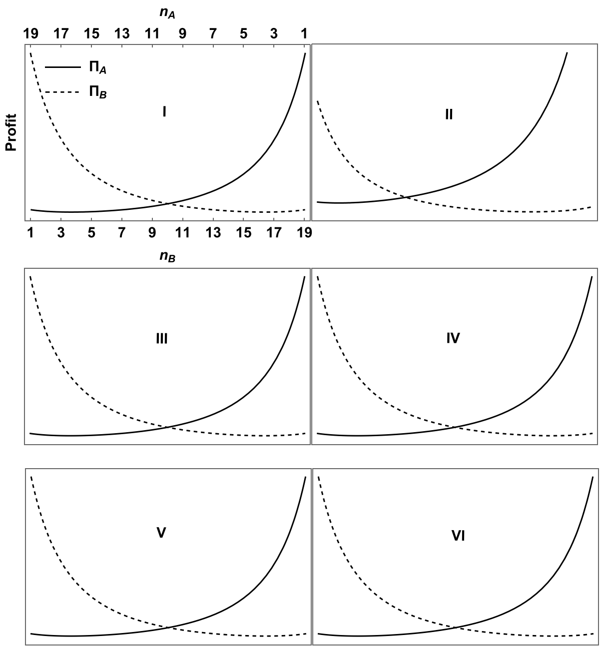


Fig A.4 Curves of airlines' maximum profit given optimal charges in Case 2

E2. Proof of Proposition 3.4

Concavity of $S(T_A, T_B)$ can be confirmed from following SOCs:

$$|H_1| = \frac{\partial^2 S}{\partial T_A^2} = -\frac{k^2\left(NC_1\left((N+2)C_2+Nk(\beta+\alpha s)\right)-N^2C_2\,\mathrm{k}(\beta+\alpha s)+(N(N+2)+2)C_1^2\right)}{(C_1-C_2)\left((N+2)C_1+NC_2\right)^2} < 0 \qquad (E.1)$$

$$|H_2| = \begin{vmatrix} \frac{\partial^2 S}{\partial T_A^2} & \frac{\partial^2 S}{\partial T_A \partial T_B} \\ \frac{\partial^2 S}{\partial T_B \partial T_A} & \frac{\partial^2 S}{\partial T_B^2} \end{vmatrix} = \frac{N^2k^4\left(C_1+C_2+2k(\beta+\alpha s)\right)}{(C_1-C_2)\left((N+2)C_1+NC_2\right)^2} > 0 \qquad (E.2)$$

As a quadratic function, $S(T_A, T_B)$ can be written as:

$$S = \boldsymbol{x^T}\boldsymbol{\mathcal{A}}\boldsymbol{x} + \boldsymbol{b^T}\boldsymbol{x} + c$$

Where $\boldsymbol{x^T} = [T_A \;\; T_B]$

Since $S(T_A, T_B)$ is concave, its contours are ellipses. Directions of ellipses' axes are same with directions of eigenvectors of matrix $\boldsymbol{\mathcal{A}}$, obtained as:

$$\boldsymbol{v_1} = [1 \quad 1]; \boldsymbol{v_2} = [-1 \quad 1]$$

We then rebuild the coordinate system of contour graph of S by setting maximum point of S as new origin and the eigenvectors as new axes (Fig A.5). In this new system, if a vector can be written as the linear combination of unit vectors with coefficients that have same signs with the coordinates of its quadrant, it is a descending direction. Therefore, we can intuitively find that $S^{II} < S^{I} < S^{VI}$ and $S^{IV} < S^{III} < S^{I} = S^{V}$ from Fig A.5.

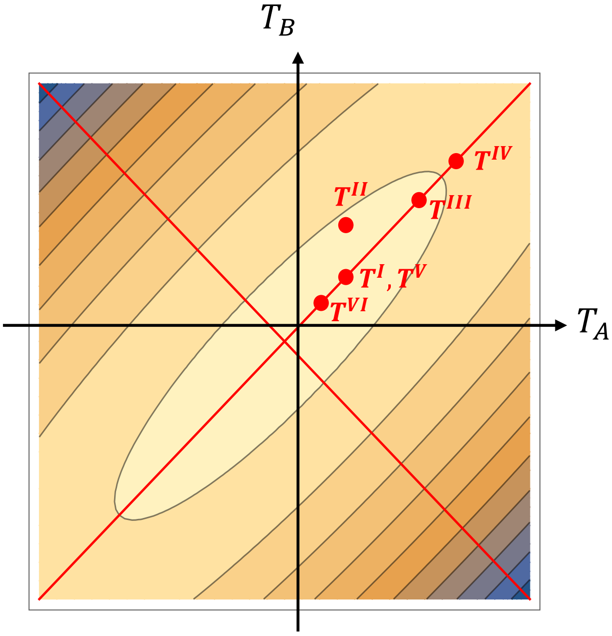


Fig A.5 Contour graph of *S*

E3. Numerical example of the comparison between S^{II} and S^{III} in Case 2

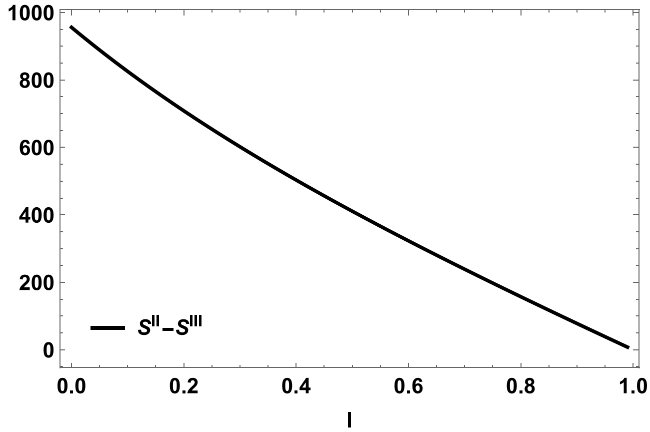


Fig A.6 Graph of $S^{II} - S^{III}$ in Case 2

Appendix F Results of Section 3.3.1

F1. Important values of Fig. 5

$$\hat{T}_B^{HII} = (c(-C_1^2(C_2 n_A(n_A(n_B+2)+2n_B+3)+k(n_A+1)(3n_An_B+n_A+2n_B)(\beta+\alpha s)) + C_2C_1n_A(k(6n_An_B+n_A+5n_B)(\beta+\alpha s)+2C_2n_B)+C_2^2n_A^2n_B(C_2-3k(\beta+\alpha s))+2C_1^3(n_A+1)^2)+C_1^2(C_2n_A(n_A(n_B+2)+2n_B+3)(sr_A-\gamma+s)+k(n_A+1)(\beta+\alpha s)(-\gamma n_A(n_B+1)+sn_A((r_A+3)n_B+r_A+1)+2sn_B))+C_2C_1n_A(2C_2n_B(s(n_Ar_B+r_B-1)-\gamma(n_A+1))+k(\beta+\alpha s)(\gamma(2n_An_B+n_A+n_B)+s((r_A+5)(-n_B)-n_A(2(r_A+3)n_B+r_A+1))))+C_2^2n_A^2n_B(C_2(s(-r_A-1)+\gamma)+k(\beta+\alpha s)(s(r_A+3)-\gamma))-2C_1^3(n_A+1)^2(s(n_Br_B+r_B+1)-\gamma(n_B+1)))/(2n_B(C_1^2k(n_A+1)^2(\beta+\alpha s)-C_2C_1n_A(C_2(n_A+2)+2k(n_A+1)(\beta+\alpha s))+C_2^2kn_A^2(\beta+\alpha s)+C_1^3(n_A+1)^2)) \quad (F.1)$$

The intercept of $T_B^{HII} = T_B^{HI}$ axis r_B is

$$I_1 = -\frac{(C_1n_A + C_1 - C_2n_A)(s-c-\gamma)}{C_1 s(n_A+1)} \quad (F.2)$$

The intercept of $T_B^{HI} - \hat{T}_B^{HI}$= $\hat{T}_B^{HI} - T_B^{HI}$ at axis r_B is:

$$I_2 = ((c+\gamma-s)(C_1^3(n_A+1)(-C_2n_A(7n_An_B+12n_A+13n_B+18)-k(n_A+1)(11n_An_B+6n_A+5n_B)(\beta+\alpha s))-C_2C_1^2n_A(n_A+1)(C_2(7n_A+2)n_B-3k(7n_An_B+2n_A+5n_B)(\beta+\alpha s))+C_2^2C_1n_A^2n_B(C_2(7n_A+8)-9k(n_A+1)(\beta+\alpha s))-C_2^3kn_A^3n_B(\beta+\alpha s)+C_1^4(n_A+1)^3(7n_B+12)))/(C_1s(n_A+1)(-5C_1^2k(n_A+1)^2n_B(\beta+\alpha s)+C_2C_1n_An_B(10k(n_A+1)(\beta+\alpha s)-C_2(7n_A+2))-5C_2^2kn_A^2n_B(\beta+\alpha s)+C_1^3(n_A+1)^2(7n_B+12))) \quad (F.3)$$

The intercept of $T_B^{HI} = \hat{T}_B^{HII}$ at axis r_B is:

$$I_3 = -(((c+\gamma-s)(C_1^2(-C_2 n_A((n_A+2)n_B+2n_A+3)-k(n_A+1)(2n_A n_B+n_A+n_B)(\beta+\alpha s))+C_2C_1n_A(k(4n_An_B+n_A+3n_B)(\beta+\alpha s)-C_2n_An_B)+C_2^2n_A^2n_B(C_2-2k(\beta+\alpha s))+C_1^3(n_A+1)^2(n_B+2)))/(s(C_1^2k(n_A+1)^2n_B(\beta+\alpha s)+C_2C_1n_An_B(C_2n_A-2k(n_A+1)(\beta+\alpha s))+C_2^2kn_A^2n_B(\beta+\alpha s)+C_1^3(-(n_A+1)^2)(n_B+2)))) \quad (F.4)$$

By judging their differences, we can confirm that $I_1 < I_2 < I_3$. We omit the detailed process as it's arduous.

F2. Numerical example of social surplus comparison

Parameters: in addition to these used previously, we set $l = 0.8$, $n_A = 4$, $n_B = 8$.

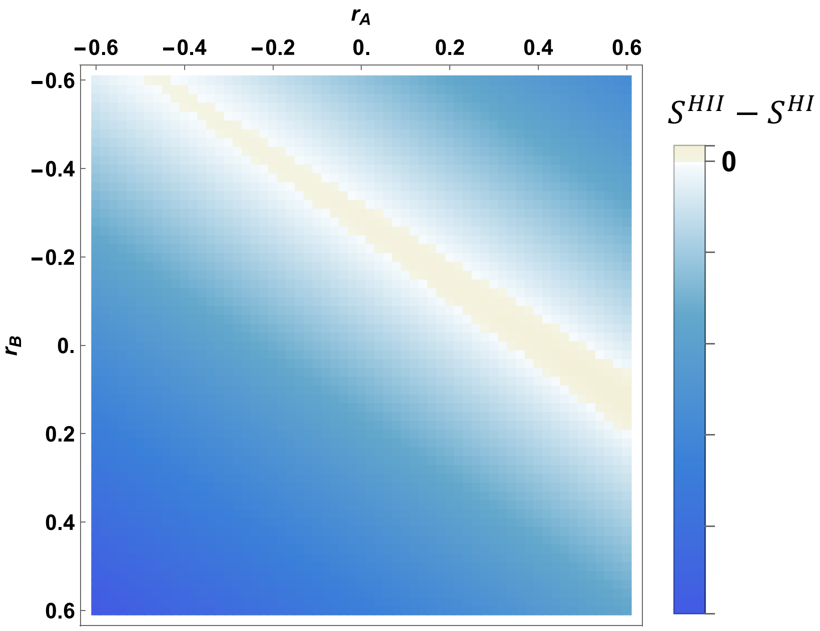


Fig A.7 Numerical example of social surplus comparison in Extension 1

References

ACI, 2018. Privatization Can Provide a Viable Solution to Global Airport Infrastructure Gap, press release 19 June. Available at. https://aci.aero/Media/748146c0-df07-48de-9818-b08cf4731f07/pn504w/News/Releases/2018/19%20June%202018%20WAGA/Policy%20Brief/ACI_PolicyBrief_2018_PressRelease_KeyFindings_FINAL.pdf.

Adler, N., Liebert, V., 2014. Joint impact of competition, ownership form and economic regulation on airport performance and pricing. Transp. Res. Part A Policy Pract. 64, 92–109. https://doi.org/10.1016/j.tra.2014.03.008

Arya, A., Mittendorf, B., Sappington, D.E.M., 2008. Outsourcing, vertical integration, and price vs. quantity competition. Int. J. Ind. Organ. 26, 1–16. https://doi.org/10.1016/j.ijindorg.2006.10.006

Ball, M., Barnhart, C., Dresner, M., Hansen, M., Neels, K., Odoni, A., Peterson, E., Sherry, L., Trani, A., Zou, B., Britto, R., Fearing, D., Swaroop, P., Uman, N., Vaze, V., Voltes, A., 2010. Total Delay Impact Study. Nextor 5–14, 25–30.

Balliauw, M., Kort, P.M., Zhang, A., 2019. Capacity investment decisions of two competing ports under uncertainty: A strategic real options approach. Transp. Res. Part B Methodol. 122, 249–264. https://doi.org/10.1016/j.trb.2019.01.007

Balliauw, M., Onghena, E., 2020. Expanding airport capacity of cities under uncertainty: Strategies to mitigate congestion. J. Air Transp. Manag. 84. https://doi.org/10.1016/j.jairtraman.2020.101791

Barbot, C., 2006. Low-cost airlines, secondary airports, and state aid: An economic assessment of the Ryanair-Charleroi Airport agreement. J. Air Transp. Manag. 12, 197–203. https://doi.org/10.1016/j.jairtraman.2006.04.001

Barbot, C., 2009. Airport and airlines competition: Incentives for vertical collusion. Transp. Res. Part B Methodol. 43, 952–965. https://doi.org/10.1016/j.trb.2009.04.001

Barbot, C., 2011. Vertical contracts between airports and airlines: Is there a trade-off between welfare and competitiveness? J. Transp. Econ. Policy 45, 277–302.

Basso, L.J., 2008. Airport deregulation: Effects on pricing and capacity. Int. J. Ind. Organ. 26, 1015–1031. https://doi.org/10.1016/j.ijindorg.2007.09.002

Basso, L.J., Zhang, A., 2007. Congestible facility rivalry in vertical structures. J. Urban Econ. 61, 218–237. https://doi.org/10.1016/j.jue.2006.10.002

Basso, L.J., Zhang, A., 2008. On the relationship between airport pricing models. Transp. Res. Part B Methodol. 42, 725–735. https://doi.org/10.1016/j.trb.2008.01.005

Bel, G., Fageda, X., 2010. Privatization, regulation and airport pricing: An empirical analysis for Europe. J. Regul. Econ. 37, 142–161. https://doi.org/10.1007/s11149-009-9110-7

Benoot, W., Brueckner, J.K., Proost, S., 2013. Intercontinental-airport regulation. Transp. Res. Part B Methodol. 52, 56–72. https://doi.org/10.1016/j.trb.2013.03.001

Bilotkach, V., Mueller, J., 2012. Supply side substitutability and potential market power of airports: Case of Amsterdam Schiphol. Util. Policy 23, 5–12. https://doi.org/10.1016/j.jup.2012.07.005

Boyaci, T., Ray, S., 2003. Product Differentiation and Capacity Cost Interaction in Time and Price Sensitive Markets. Manuf. Serv. Oper. Manag. 5, 18–36. https://doi.org/10.1287/msom.5.1.18.12757

Brander, J.A., Zhang, A., 1990. Market conduct in the airline industry: an empirical investigation. RAND J. Econ. 21 (4), 567–583.

Chen, Y., 2001. On Vertical Mergers and Their Competitive Effects. RAND J. Econ. 32, 667. https://doi.org/10.2307/2696387

Cheung, T.K.Y., Wong, C.W.H., Zhang, A., 2020. The evolution of aviation network: Global airport connectivity index 2006–2016. Transp. Res. Part E Logist. Transp. Rev. 133, 101826. https://doi.org/10.1016/j.tre.2019.101826

Czerny, A.I., Zhang, A., 2011. Airport congestion pricing and passenger types. Transp. Res. Part B Methodol. 45, 595–604. https://doi.org/10.1016/j.trb.2010.10.003

D’Alfonso, T., Nastasi, A., 2012. Vertical relations in the air transport industry: A facility-rivalry game. Transp. Res. Part E Logist. Transp. Rev. 48, 993–1008. https://doi.org/10.1016/j.tre.2012.03.003

D’Alfonso, T., Nastasi, A., 2014. Airport–Airline interaction: Some food for thought. Transp. Rev. 34, 730–748. https://doi.org/10.1080/01441647.2014.971470

Dangl, T., 1999. Investment and capacity choice under uncertain demand. Eur. J. Oper. Res. 117, 415–428. https://doi.org/10.1016/S0377-2217(98)00274-4

Daughety, A.F., 1990. Beneficial concentration. Am. Econ. Rev. 80, 1231–1237.

De Borger, B., De Bruyne, D., 2011. Port activities, hinterland congestion, and optimal government policies: The role of vertical integration in logistic operations. J. Transp. Econ. Policy 45, 247–275.

De Borger, B., Van Dender, K., 2006. Prices, capacities and service levels in a congestible Bertrand duopoly. J. Urban Econ. 60, 264–283. https://doi.org/10.1016/j.jue.2006.03.001

De Langen, P.W., Pallis, A.A., 2006. Analysis of the benefits of intra-port competition. Int. J. Transp. Econ. 33, 69–85. https://doi.org/10.1400/16960

Décamps, J.P., Mariotti, T., Villeneuve, S., 2006. Irreversible investment in alternative projects. Econ. Theory 28, 425–448. https://doi.org/10.1007/s00199-005-0629-2

Department for Transport, 2009. Reforming the Framework for the Economic Regulation of Airports Decision Document. Department for Transport, London. https://www.gatwickairport.com/globalassets/publicationfiles/business_and_community/all_public_publications/2009/dft_rer_decision_doc_10dec09.pdf

Department for Transport, 2013. Impact Assessment: Reforming the Framework for the Economic Regulation of Airports. Department for Transport, London. https://www.legislation.gov.uk/ukia/2013/64/pdfs/ukia_20130064_en.pdf

Dixit, A. K., Pindyck, R. S., 1994. Investment under uncertainty. Princeton, NJ: Princeton University Press.

Dixit, A., 1993. Choosing among alternative discrete investment projects under uncertainty. Econ. Lett. 41, 265–268.

Eurocontrol, 2018. European aviation in 2040, challenges of growth.

Ferguson, J., Kara, A.Q., Hoffman, K., Sherry, L., 2013. Estimating domestic US airline cost of delay based on European model. Transp. Res. Part C Emerg. Technol. 33, 311–323. https://doi.org/10.1016/j.trc.2011.10.003

Flores-Fillol, R., Iozzi, A., Valletti, T., 2018. Platform pricing and consumer foresight: The case of airports. J. Econ. Manag. Strateg. 27, 705–725. https://doi.org/10.1111/jems.12253

Forsyth, P., 2008. Airport policy in Australia and New Zealand: Privatization, light-handed regulation and performance. Aviation infrastructure performance: A study in comparative political economy, pp.65-99.

Forsyth, P., Gillen, D., Mueller, J., Niemeier, H.-M. (Eds.)., 2010. Airport competition. Aldershot: Ashgate.

Fu, X., Homsombat, W., Oum, T.H., 2011. Airport-airline vertical relationships, their effects and regulatory policy implications. J. Air Transp. Manag. 17, 347–353. https://doi.org/10.1016/j.jairtraman.2011.02.004

Fu, X., Yang, H., 2017. Airport–airline arrangements: An interpretive review of industry practices and recent studies. Adv. Airl. Econ. 6, 97–122. https://doi.org/10.1108/S2212-160920170000006005

Gelhausen, M.C., Berster, P., Wilken, D., 2020. Capacity utilisation at airports worldwide, Airport Capacity Constraints And Strategies For Mitigation. https://doi.org/10.1016/b978-0-12-812657-8.00003-8

Gillen, D., Henriksson, L., Morrison, W., 2001. Airport Financing, Costing, Pricing and Performance in Canada. Final Report to the Canadian Transportation Act Review Committee, Waterloo (Canada).

Gillen, D., Mantin, B., 2014. The importance of concession revenues in the privatization of airports. Transp. Res. Part E Logist. Transp. Rev. 68, 164–177. https://doi.org/10.1016/j.tre.2014.05.005

Graham, A., 2011. The objectives and outcomes of airport privatisation. Res. Transp. Bus. Manag. 1, 3–14. https://doi.org/10.1016/j.rtbm.2011.05.004

Graham, A., 2018. Managing Airports: An International Perspective, fifth ed. Routledge, London.

Graham, A., Morrell, P., 2016. Airport finance and investment in the global economy. Taylor & Francis.

Graham, P.A., 2020. Airport privatisation: A successful journey? J. Air Transp. Manag. 89, 101930. https://doi.org/10.1016/j.jairtraman.2020.101930

Guiomard, C., 2016. Practical Difficulties in Airport Benchmarking - The Case of Dublin Airport. https://ssrn.com/abstract=2770070

Hagspiel, V., Huisman, K.J.M., Kort, P.M., 2016. Volume flexibility and capacity investment under demand uncertainty. Int. J. Prod. Econ. 178, 95–108. https://doi.org/10.1016/j.ijpe.2016.05.007

Hamilton, J. D., 1994. Time Series Analysis. Princeton University Press.

Hu, R., Xiao, Y. bin, Jiang, C., 2018. Jet fuel hedging, operational fuel efficiency improvement and carbon tax. Transp. Res. Part B Methodol. 116, 103–123. https://doi.org/10.1016/j.trb.2018.07.012

IATA, 2018. Airlines Urge Caution on Airport Privatisation press release 5 June. Available at. https://www.iata.org/en/pressroom/pr/2018-06-05-04/.

Irish Department of Transport, 2003. Dublin Airport—review of expressions of interest for an independent terminal—Panel Report to Minister for Transport. Irish Department of Transport, Dublin. http://dttas.old.gov.ie/sites/default/files/node/add/content-publication/Feb%202003%20Dublin%20Airport%20Independent%20Terminal%20Panel%20Report.pdf

Jorge, J.D., de Rus, G., 2004. Cost-benefit analysis of investments in airport infrastructure: A practical approach. J. Air Transp. Manag. 10, 311–326. https://doi.org/10.1016/j.jairtraman.2004.05.001

Juan, E., 1996. Privatizing airports—options and case studies. In: Public Policy for the Private Sector. World Bank, Washington, DC (Note Number 82).

Kaselimi, E.N., Notteboom, T.E., de Bruno, B., 2011. A game theoretical approach to competition between multi-user terminals: The impact of dedicated terminals. Marit. Policy Manag. 38, 395–414. https://doi.org/10.1080/03088839.2011.588260

Kidokoro, Y., Lin, M.H., Zhang, A., 2016. A general-equilibrium analysis of airport pricing, capacity, and regulation. J. Urban Econ. 96, 142–155. https://doi.org/10.1016/j.jue.2016.10.001

Kidokoro, Y., Zhang, A., 2018. Airport congestion pricing and cost recovery with side business. Transp. Res. Part A Policy Pract. 114, 222–236. https://doi.org/10.1016/j.tra.2017.12.003

Kuchinke, A.B., Sickmann, J., 2005. The joint venture terminal 2 at Munich airport and the consequences: a competition economic analysis. Paper Presented at the 4th Conference on Applied Infrastructure Research, Berlin, 8 October 2005.

Martín, J.C., Voltes-Dorta, A., 2011. The econometric estimation of airports' cost function. Transp. Res. Part B Methodol. 45, 112–127. https://doi.org/10.1016/j.trb.2010.05.001

Matsumura, T., Matsushima, N., 2012. Airport Privatization and International Competition. Japanese Econ. Rev. 63, 431–450. https://doi.org/10.1111/j.1468-5876.2012.00584.x

McLay, P., Reynolds-Feighan, A., 2006. Competition between airport terminals: The issues facing Dublin Airport. Transp. Res. Part A Policy Pract. 40, 181–203. https://doi.org/10.1016/j.tra.2005.06.002

Noruzoliaee, M., Zou, B., Zhang, A., 2015. Airport partial and full privatization in a multi-airport region: Focus on pricing and capacity. Transp. Res. Part E Logist. Transp. Rev. 77, 45–60. https://doi.org/10.1016/j.tre.2015.02.012

Oum, T.H., Adler, N., Yu, C., 2006. Privatization, corporatization, ownership forms and their effects on the performance of the world's major airports. J. Air Transp. Manag. 12, 109–121. https://doi.org/10.1016/j.jairtraman.2005.11.003

Oum, T.H., Yan, J., Yu, C., 2008. Ownership forms matter for airport efficiency: A stochastic frontier investigation of worldwide airports. J. Urban Econ. 64, 422–435. https://doi.org/10.1016/j.jue.2008.03.001

Oum, T.H., Zhang, A., Zhang, Y., 1993. Inter-firm rivalry and firm-specific price elasticities in deregulated airline markets. J. Transport Econ. Policy 27, 171–192.

Oxera Consulting LLP, 2017. The Continuing Development of Airport Competition in Europe. Oxera, London. https://www.oxera.com/publications/the-continuing-development-of-airport-competition-in-europe/

Perloff, J. M., 2017. Microeconomics (7th ed.), Boston: Pearson.

Petrakis, E., Roy, S., 1999. Cost-reducing investment, competition, and industry dynamics. Int. Econ. Rev. (Philadelphia). 40, 381–401. https://doi.org/10.1111/1468-2354.00020

Pindyck, R., Rubinfeld, D., 1998. Econometric models and economic forecasts (4th ed.). Irwin/McGraw Hill

Randrianarisoa, L.M., Zhang, A., 2019. Adaptation to climate change effects and competition between ports: Invest now or later? Transp. Res. Part B Methodol. 123, 279–322. https://doi.org/10.1016/j.trb.2019.03.016

Reynolds-Feighan, A.J., 2010. Airport competing terminals: Recent developments at Dublin airport. In: Forsyth, P., Gillen, D., Müller, J., Niemeier, H.M. (Eds.), Airport Competition: The European Experience. Ashgate Publishing, Berlin.

Rikhy, H., Roberts, J. and Cheung, S., 2014. Global airport privatisation: Trends, recent developments and challenges ahead, Journal of Airport Management, 8(4): 300–04.

Saeed, N., Larsen, O.I., 2010. Container terminal concessions: A game theory application to the case of the ports of Pakistan. Marit. Econ. Logist. 12, 237–262. https://doi.org/10.1057/mel.2010.8

Saraswati, B., Hanaoka, S., 2014. Airport-airline cooperation under commercial revenue sharing agreements: A network approach. Transp. Res. Part E Logist. Transp. Rev. 70, 17–33. https://doi.org/10.1016/j.tre.2014.06.013

Smit, H.T.J., 2003. Infrastructure Investment as a Real Options Game: The Case of European Airport Expansion. Financ. Manag. 32, 27. https://doi.org/10.2307/3666135

Starkie, D., 2008. The Airport Industry in a Competitive Environment: A UK Perspective, OECD/ITF Discussion Paper No. 2008–2015, July.

Sun, Y., Schonfeld, P., 2015. Stochastic capacity expansion models for airport facilities. Transp. Res. Part B Methodol. 80, 1–18. https://doi.org/10.1016/j.trb.2015.06.009

Teraji, Y., Morimoto, Y., 2014. Price competition of airports and its effect on the airline network. Econ. Transp. 3, 45–57. https://doi.org/10.1016/j.ecotra.2014.03.001

Tretheway, M.W., 2001. Airport Ownership, Management and Price Regulation. Report to the Canadian Transportation Act Review Committee, Ottawa.

Truong, C., Trück, S., Mathew, S., 2018. Managing risks from climate impacted hazards – The value of investment flexibility under uncertainty. Eur. J. Oper. Res. 269, 132–145. https://doi.org/10.1016/j.ejor.2017.07.012

Vives, X., 1999. Oligopoly Pricing: Old Ideas and New Tools. The MIT Press, Cambridge, MA.

Wan, Y., Basso, L.J., Zhang, A., 2016. Strategic investments in accessibility under port competition and inter-regional coordination. Transp. Res. Part B Methodol. 93, 102–125. https://doi.org/10.1016/j.trb.2016.07.011

Wang, F., Zhuo, X., Niu, B., 2017. Strategic entry to regional air cargo market under joint competition of demand and promised delivery time. Transp. Res. Part B Methodol. 104, 317–336. https://doi.org/10.1016/j.trb.2017.08.002

Xiao, Y. bin, Fu, X., Oum, T.H., Yan, J., 2017. Modeling airport capacity choice with real options. Transp. Res. Part B Methodol. 100, 93–114. https://doi.org/10.1016/j.trb.2017.02.001

Xiao, Y., Fu, X., Zhang, A., 2013. Demand uncertainty and airport capacity choice. Transp. Res. Part B Methodol. 57, 91–104. https://doi.org/10.1016/j.trb.2013.08.014

Xiao, Y., Ng, A.K.Y., Yang, H., Fu, X., 2012. An Analysis of the Dynamics of Ownership, Capacity Investments and Pricing Structure of Ports. Transp. Rev. 32, 629–652. https://doi.org/10.1080/01441647.2012.709888

Zhang, A., Fu, X., Yang, H., 2010. Revenue sharing with multiple airlines and airports. Transp. Res. Part B Methodol. 44, 944–959. https://doi.org/10.1016/j.trb.2010.02.001

Zhang, A., Zhang, Y., 2003. Airport charges and capacity expansion: Effects of concessions and privatization. J. Urban Econ. 53, 54–75. https://doi.org/10.1016/S0094-1190(02)00500-4

Zhang, A., Zhang, Y., 2006. Airport capacity and congestion when carriers have market power. J. Urban Econ. 60, 229–247. https://doi.org/10.1016/j.jue.2006.02.003

Zhang, A., Zhang, Y., 2010. Airport capacity and congestion pricing with both aeronautical and commercial operations. Transp. Res. Part B Methodol. 44, 404–413. https://doi.org/10.1016/j.trb.2009.09.001

Zhang, S.X., Babovic, V., 2011. An evolutionary real options framework for the design and management of projects and systems with complex real options and exercising conditions. Decis. Support Syst. 51, 119–129. https://doi.org/10.1016/j.dss.2010.12.001

Zheng, S., Fu, X., Jiang, C., Ge, Y., 2020. Airline investments in exclusive airport facilities: Timing decisions under demand ambiguity. Transp. Res. Part B 139, 343–363. https://doi.org/10.1016/j.trb.2020.05.004