# 國立交通大學

## 運輸科技與管理學系

## 博 士 論 文

# 應用小世界理論於航空網路之研究

# Small-World Theory in the Study of Air Transportation Network

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## ABSTRACT

This dissertation aims to investigate the positive and negative influences that small-world properties have on an air transportation network as well as a social network of passengers. A series of models are systematically constructed in accordance with four important issues emphasized on: small-world network theory in the study of network connectivity and efficiency of complementary international airline alliances; transmission and control of an emerging influenza pandemic in a small-world airline network; word-of-mouth marketing in a small-world network for low-cost carriers; and the application of small-world theory to airport delay problem. The first part of this dissertation attempts to conceptually apply the shortcuts of a small-world network to explore the effects of international airline alliances on the connectivity of airline networks, and to examine whether the airline alliance network is a small-world network or not. The difference in the connectivity efficiency between pre- and post-alliance situations is also measured. The second part of this dissertation aims to explore the human-to-human transmission of emerging influenza via air travel activities. Two dynamic models that illustrate the transmission behaviors of the influenza virus on scheduled flights and at airport terminals are formulated so as to evaluate the expected burdens of the pandemic without and with control measures. The third part of this dissertation turns the emphasis on the first-purchase behavior of potential passengers for low-cost carriers (LCCs). It aims to explore how the WOM information is transmitted through the social connections in a small-world social network, how the perception of LCCs is revised over time, and how the WOM affects the adoption of LCCs by short-haul business passengers. The last part of this dissertation focuses on exploring the influences of small-world properties of an airport network on the delay propagation across flights and airports. An epidemic-like model is used to illustrate

the delay propagation over flights and airports. Several capacity-allocation strategies are proposed and are evaluated in terms of the total cost.

A series of case studies are performed to demonstrate the applications of this dissertation. The results show that the connectivity of the alliance network is better than before, and it exhibits small-world properties. The alliance effectively improves accessibility from high-medium traffic airports to low traffic airports. After the alliance, the shortest paths between origin-destination pairs will involve more transfers but less total travel time. The results also show that, as soon as the influenza is spread to the top 50 global airports, the transmission is greatly accelerated. Under the constraint of limited resources, a strategy that first applies control measures to the top 50 airports after day 13 and then soon afterwards to all other airports may result in remarkable containment effectiveness. As the infectiousness of the disease increases, it will expand the scale of the pandemic, and move the start time of the pandemic ahead. In addition, the results show that it may cause a mistaken forecast of adoption if without taking into account the influence of WOM. As soon as the ratio of the price of a LCC to the price of a FSC is over a half, the attractiveness of the LCC to business passengers is gradually diminished. The comparisons of different societies show that LCC may apply a slightly higher price to a lower risk-averse society, while this pricing strategy does not markedly affect its adoption pattern since LCC still has an advantage of price over FSC. In the average pattern for all 265 airports, the total cost and the total number of affected flights for a strategy that tends to allocate slots to long-haul flights are the lowest among all strategies, which is the same as those observations at past studies. When an airport has a high proportion of inter-regional flights scheduled to arrive and has low capacity due to weather condition, a strategy that uses the first-scheduled-first-served allocation principle will be an economic and equitable allocation strategy for this kind of airport. This strategy is also the best allocation strategy for those airports that are highly connected to other airports. Finally, based on the average patterns of all airports, a strategy that tends to allocate slots to long-haul flights not only decreases the total cost, but also indirectly reduces the occurrence and the scope of the inter-regional delay propagation.

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在交通大學待了十年光陰，今年終於可以光榮地從交通大學畢業了。在這漫長的日子裡，很感謝在學術研究及日常生活上都得到貴人的相助。首先，非常感謝恩師 許巧鶯老師在我博士生涯中帶給我光明、輝煌及燦爛的學術體驗，讓我學習到許多學術研究上的精髓，瞭解從事研究所應堅持的理念與態度，恩師更帶領我從複雜問題中抽絲剝繭出重要的發現與價值，使我的研究不僅在學術上，也能在實務上對社會有所貢獻。學生謹言慎行遵從恩師的教導，並期許能傳授給後續學子以發揚恩師的教誨。

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# CHAPTER 1

# Introduction

The main issues of interest in this dissertation are the positive and negative influences of small-world properties on air transportation network with respect to connectivity efficiency, disease pandemic, word-of-mouth marketing and flight delay. This chapter presents an overview of the motivation, problem specification, research objectives and methodology, and the framework of this dissertation.

## 1.1 Motivation and background

In recent years a series of new research studies have emerged that explored the issue of connectivity of a variety of networks. These studies mainly followed the work of Watts and Strogatz (1998) who developed a small-world theory to investigate distinctive characteristics in some real networks, such as social, technological and biological networks. Watts and Strogatz (1998) demonstrated that the structural properties of a small-world network are significantly different from the conventional assumptions of network property at past studies. Past studies ordinarily assumed the network as completely regular graphs, with highly clustered and highly separated, or as completely random graphs, with lowly clustered and lowly separated. However, the small-world network lies in between regular and random graphs, and has a distinctive combination of structure properties, high clustering at the local scale and low separation at the global scale, due to the function of introducing a few shortcuts (long-range links) into the network. Watts and Strogatz (1998) quantified the structural properties of networks by their clustering coefficient and characteristic path length, and showed that the small-world networks are highly clustered, like regular graphs, yet have small characteristic path lengths, like random graphs. This kind

of property combination does differ from those investigated by past research, and may play an important role in the study of the influence of the network property on the dynamics of social processes or any kind of communication. Watts and Strogatz (1998) also demonstrated that some social, technological and biological networks in the real world are all small-world networks.

These small-world phenomena also seem to exist at the air transportation network. Airlines can apply those inter-regional or inter-continental routes to enable passengers to fly between airports that are located at various geographic regions worldwide. At the same time, airlines can apply those intra-regional or short-haul routes to provide air travel services within one or more local regions. In other words, each destination or airport is highly connected to others that are located at the same local region, and is also inter-regionally connected to others that are located at distant and different regions in air transportation network. Those inter-regional routes indirectly reduce the separation between various geographic regions worldwide, and serve as an important bridge that allows passengers to travel from one region to another in an efficient way. As a result, these inter-regional routes mimic the shortcuts of a small-world network. Furthermore, the emergence of the airline alliances in recent years enables airlines to provide inter-regional air travel services by alliance routes at the global scale, and to retain intra-regional services by their own routes at the local scale. In other words, the airline alliances make the small-world phenomenon of air transportation network more obvious. However, this small-world phenomenon may easily cause the transmission and pandemics of infectious diseases by inter-regional air travel activities, and may also easily result in inter-regional delay propagation across airports that are located at various regions and their scheduled flights. In addition, on the demand side of air transportation, the word-of-mouth communication between passengers who form a small-world social network may affect the purchase decisions and adoption of a

given air services or products sold by airlines. Past studies have rarely explored the small-world properties of air transportation network, and thereby may have neglected some important results and observations that indeed exist in the network and may result in unexpected influences. To sum up, the important issues about the influences of small-world properties deserve further investigation, especially for air transportation network due to the lack of emphasis and theoretical formulation in the literature. In particular, it is necessary to explore the positive and negative influences that small-world properties have on the interaction among passengers, airlines and airports involved in air transportation network. The following paragraphs describe the developments associated with each research topic mentioned above up to the present.

International aviation markets have been globalized and have become increasingly competitive in recent years. There are more and more carriers using international airline alliances to access new markets, extend their networks and strengthen their competitive advantage under air traffic rights and resource limitations. The number of new alliance agreements has increased every year since 2001, and more than 110 new alliances were formed in 2004 (Kemp et al., 2005). Besides, the top three alliance groups, Star Alliance, Oneworld, and SkyTeam collectively account for over 80% of the North Atlantic traffic and for over half of world passenger traffic (Field, 2005). These data show that the emergence of international airline alliances has become mainstream in today's international airline industry.

An international airline alliance is an agreement between two or more air carriers cooperating in a commercial relationship or jointly operating activities in various fields, such as integrated marketing strategies and reservation service, coordinated flight frequency and schedule, joint use of ground facilities, joint frequent flyer programs, and others. Alliances

provide opportunities for the partner carriers to extend their networks, service more parts of the world, increase the volume of passenger traffic and the load factor, and consequently strengthen their competitive positions and improve profitability. Code-sharing agreements are a mainstream practice of an alliance, whereby each carrier's designator code is shown on his partner's flights, such that carriers can offer services to destinations that they themselves do not physically serve. In the literature, Park (1997) and Oum et al. (2004) discussed the effects of airline alliances in detail.

Emerging infectious diseases, such as the avian influenza and severe acute respiratory syndrome (SARS), have rapidly caused numerous infected persons, negatively affecting human life and the economy. For instance, SARS led to an immediate economic loss of close to 2 percent of the GDP for the East Asian region in the second quarter of 2003 (Brahmbhatt, 2005). Avian influenza virus H5N1 may transform into a new human influenza virus through genetic reassortment, and develop the ability for increased and sustained transmission between humans (Capua and Alexander, 2002). H5N1 is showing a serious pandemic threat to the human population (Ferguson et al., 2005). Most people are easily infected with this new type of influenza because they have no immunity to the disease, thereby resulting in a serious pandemic.

Disease outbreak and pandemics will obstruct social and economic activities worldwide. In the past, the most noted influenza pandemic was the one beginning in 1918 with a mortality rate that resulted in the death of possibly 50 million people worldwide (Ligon, 2005). It shows that influenza pandemics are a serious health threat, and it is critical that one should understand how an emerging influenza spreads, how to predict the influences of a pandemic, and how to design control measures for mitigation. On the other hand, an empirical research indicated that passengers who took the same airplane flight with a SARS

patient would possibly become suspect or probable cases of SARS (Centers for Disease Control and Prevention, 2003). Another study also showed a high rate of transmission of SARS on aircraft (Olsen et al., 2003). These findings show that air travel facilitates the spread of infectious diseases, and plays an important role in the transmission of diseases worldwide and the appearance of serious pandemics with health and life threats. In particular, passengers of air transportation may infect with influenza during air travel activities, such as passenger consolidation, conveyance and distribution in airports and on scheduled flights.

In the scope of consumer behavior, one of the most widely accepted notions is that word-of-mouth communication (hereafter WOM) plays an important role in shaping consumers' attitudes and behaviors (Brown and Reingen, 1987). Many studies pointed out that WOM is the most powerful form of marketing on earth. The impact of WOM is ten times more effective than TV or print advertising, and four times as effective as personal selling in influencing consumers (Katz and Lazarsfeld, 1955; Hughes 2005). Rosen (2000) indicated that there are 53% moviegoers relying on a recommendation from someone they know; 70% Americans relying on the advice of others when selecting a new doctor; and 65% customers getting information about products from another person. So, WOM is the most important source of influence in the purchase of consumer products and services, as well as in determining the speed and shape of the diffusion process of a new product in a social system (Mahajan et al., 1990).

For passengers of air transportation, low-cost carriers (hereafter LCCs) can be seen as a new product since their rapid emergence at many aviation markets in recent years. LCCs have reshaped the competitive environment within liberalized markets and have made significant impacts in the world's passenger markets, which had previously been dominated

by full-service carriers (hereafter FSCs) (O'Connell and Williams, 2005). LCCs accounted for a 43% share of the UK domestic market and 28% of the US, and the market share is predicted to grow further (Clarke, 2004). The characteristics of LCCs include a simplified fare structure, use of secondary airports, point-to-point direct flights, short turnaround time, a single type of aircraft, payment for in-flight service, and so on. The simplification of operations and high level of utilization enable LCCs to gain significant cost advantages and charge passengers low fare.

Although the original focus of LCCs was on leisure and tourism travelers, recent evidence indicated that 74% of UK business travelers said that they had used the service of LCCs for business trips (Company Barclaycard, 2005). Business travelers have increasingly used LCCs, while the number of short-haul European business trips that are taken in business class has dramatically dropped, where 79% of short-haul travelers thought that the business class service did not offer value for money (Mason, 2001). It suggested that LCCs were more likely to attract these short-haul business travelers.

Congestion problems are becoming increasingly serious in many major international airports due to the rapid growth of traffic demand. Such problems usually results in significant economic losses of airlines, passengers and airports (Janić, 2005). Traffic congestion arises when the traffic demand overcomes the airport capacity that is heavily influenced by weather conditions. One of solution approaches to the congestion problem is the ground-holding policy, termed as a short-term approach (Vranas et al., 1994). The task of the policy is that aircraft may be held on the ground before take-off whenever congestion is expected on its route, so that it can arrive at its destination airport without waiting in the air. The motivation of the policy is due to the fact that holding aircraft on the ground is safer than holding them in the air, and the delay cost of the former is less than that of the latter.

The problem of determining how much each aircraft must be held on the ground before take-off to minimize the total delay cost is referred to as the ground-holding problem (Vranas et al., 1994), which can be further divided into two categories, single-airport and multi-airports. The single-airport ground-holding problem is to decide the arrival slot allocation to various flights based on the landing capacity of a destination airport (Mukherjee and Hansen, 2007). The multi-airport ground-holding problem is shifted to consider an entire network of airports and incorporate the effect of delay propagation, in which when aircraft is delayed the next flight performed by the same aircraft will also be delayed. Hall (1999) pointed out that there was an average of 1.6 ground-holding programs implemented per day between September of 1998 and April of 1999, showing its high frequency of occurrence. Therefore, the ground-holding problem is an important topic for air traffic management research.

The literature on international airline alliances can be classified into three major categories: theoretical, empirical and comprehensive. Theoretical studies are focused on analyzing the economic benefits for alliances, such as outputs and profitability (Park, 1997; Wen and Hsu, 2006; Lin, 2004). The empirical studies collect data to investigate the current status of the alliances, the impact, features, strategies, and so on (Brueckner, 2003; Goh and Uncles, 2003; Albers et al., 2005; Iatrou and Alamdari, 2005). The comprehensive works not only developed theoretical models, but also conducted the empirical analyses of the effects of the alliances (Park et al., 2001; Chen and Chen, 2003). The majority of the above mentioned research investigated how alliances contributed to the economic outcomes of airlines. Little research, however, has been carried out on exploring the small-world properties of an alliance network as well as their effects on the connectivity efficiency of air transportation.

There are several studies have focused on reviewing infectious diseases and analyzing their impacts (Brahmbhatt, 2005; Capua and Alexander, 2002; Donnelly et al., 2003; Ligon, 2005; Meijer et al., 2004), as well as the design and evaluation of control measures (Ferguson et al., 2005; King et al., 2004). For example, Ferguson et al. (2005) modeled the spread of a pandemic in Thailand by incorporating random contacts associated with day-to-day movements to work within the country, and then evaluated the potential effectiveness of containment strategies. In addition, numerous studies have proposed mathematical epidemic models to evaluate and describe the dynamic evolution and the severity of epidemics in the population (e.g. Allen and Burgin, 2000; Colizza et al., 2006, 2007; Massad et al., 2005; Méndez and Fort, 2000). For example, Colizza et al. (2006, 2007) developed a metapopulation stochastic epidemic model on a global scale, and used a stochastic transport operator to describe the dynamics of individuals based on travels between cities. They concluded that a cooperative strategy where countries with large antiviral stockpiles share a part of their resources with other countries results in a global deceleration of the pandemics. However, few of the previous studies have discussed the influences of passenger consolidation, conveyance and distribution as well as small-world properties of an air transportation network on the spatiotemporal evolution of an influenza pandemic.

Attracting passengers is one of the most important goals for the operation of airlines. A number of studies have applied the utility function to investigate the airline choices of passengers, and found that there exists preference heterogeneity among passengers (e.g. Espino et al., in press; Rose et al., 2005). However, few of these studies have considered that passengers may change their perceptions of a product over time in their learning process, in which they receive additional WOM information about the product from other people. The dynamics in the perceptions may thus change passengers' purchase decisions

and adoption timing of the product. If one neglects the changing perceptions of passengers, then it will result in a mistaken forecast of product adoption.

The literature of ground-holding problem can mainly be divided into four categories, static, dynamic, deterministic and stochastic versions. The static version of ground-holding problem makes the hold decisions once at the beginning of daily operations (Vranas et al., 1994), whereas the dynamic version makes the decisions within time of the day as better capacity estimates become available (Richetta and Odoni, 1994). The deterministic version considers airport capacities as fixed (Janić, 2005), whereas the stochastic version takes into account the uncertainty in airport capacities (Mukherjee and Hansen, 2007). These models conventionally minimized the total (ground plus airborne) delay cost to decide the number of time periods that each flight is held on the ground before take-off, with various heuristic algorithms for integer solutions from the linear programming (LP) relaxation. In the ground-holding problem, the use of linear cost functions tends to assign the arrival slot to flights with high delay cost. Recently, the model of Mukherjee and Hansen (2007) allows for applying nonlinear cost functions, showing it tends to obtain more equitable slot allocation across flights than linear cost functions. In the field of multiairport ground-holding problem, the research was restricted to the case when aircraft is delayed, the next flight performed by the same aircraft will also be delayed. Few studies, however, have explored the influences of small-world properties of air transportation network on the duration and propagation of flight delay.

Following Watts and Strogatz (1998), there are several studies investigating whether specific real-world networks reveal small-world properties or not (Sen et al., 2003; Guimerà and Amaral, 2004; Jiang and Claramunt, 2004). In particular, Latora and Marchiori (2001, 2002) found that the model of Watts and Strogatz (1998) has some problems regarding its

application to transportation systems, and then proposed global and local efficiency models to overcome problems. These studies have considered the physical distance between two nodes for weighted networks, but few studies have taken travel time between two nodes into account. Unfortunately, travel time is one of the most significant measures of performance in the air transportation system. More importantly, for transportation systems, it has been well recognized that mobility and accessibility are more appropriate for measuring system performance and effectiveness than the efficiency models proposed by Latora and Marchiori (2001, 2002). In the literature, there are also some studies proposing epidemic models to evaluate the dynamics of epidemics in small-world networks (Kuperman and Abramson, 2001; Saramäki and Kaski, 2005; Small and Tse, 2005), but not incorporating the influence of air travel activities into model formulation. On the other hand, the effects of small-world properties on the diffusion process of new products or services within a social network and on the flight delay of air transportation network have rarely been explored in the literature (Jun et al., 2006).

To sum up, several important issues about the influences of small-world properties on air transportation network deserve further investigation. However, these issues have been rarely emphasized and theoretically formulated in the literature. This dissertation aims to explore the positive and negative influences of small-world properties on air transportation network with respect to connectivity efficiency, disease pandemic, word-of-mouth marketing and flight delay. A series of models are formulated to systematically investigate the connectivity efficiency with and without alliances, influenza transmission via air travel activities, and duration and propagation of flight delay within an air transportation network with small-world properties. Furthermore, the scope of this dissertation is also extended to the aspect of passengers of air transportation, exploring how the WOM information affects the adoption of LCCs by short-haul business passengers on dynamic small-world social

networks at the micro level, where the changing revision of perception, dynamic properties of network structure and social heterogeneity are together incorporated.

## 1.2 Research objectives

The overall goal of this dissertation is to explore the influences of small-world properties in detail, and to make contributions in providing guideline of management strategies for responding to the influences. Specifically, the purpose of this dissertation is to investigate the positive and negative impacts small-world properties have on an air transportation network as well as a social network of passengers. The positive impacts are referred to the improvement in connectivity efficiency of network and the high level of penetration of LCCs, whereas the negative impacts are referred to the pandemic of influenza and the propagation of flight delay. In view of these topics, a series of models are constructed in accordance with issues emphasized. Based on the characteristics and significance of issues, there are four distinct parts involved in this dissertation: small-world network theory in the study of network connectivity and efficiency of complementary international airline alliances; transmission and control of an emerging influenza pandemic in a small-world airline network; word-of-mouth marketing in a small-world network for low-cost carriers; and application of small-world theory to airport delay problem. These four parts are illustrated more explicitly as follows.

In the first part of this dissertation, this study attempts to conceptually apply the shortcuts of small-world networks in order to explore the effects of international airline alliances on the connectivity of airline networks. In particular, the mobility and accessibility are used to investigate the effects of alliances by taking travel time into consideration, which allow us to quantify the difference of the connectivity between pre- and post-alliance situations. Mobility at the global and local scales is further used to examine whether the

airline alliance network is a small-world network or not. The connection between the proposed models and the economic benefits of airlines is also discussed in order to provide practical applications.

The second part of this dissertation aims to explore the human-to-human transmission of emerging influenza via air travel. The effects of air travel activities (i.e. passenger consolidation, conveyance and distribution in airports and scheduled flights) on the influenza pandemic are investigated in terms of the spatiotemporal evolution in a small-world airline network. This study also attempts to investigate how the influenza spreads to different geographic regions worldwide based on the connectivity properties of the small-world network. The transmission behaviors of the influenza virus on scheduled flights and at airport terminals are discussed, respectively, in order to evaluate the expected burdens of the influenza pandemic without and with control measures.

The third part of this dissertation turns the emphasis on the first-purchase behavior of potential passengers for LCCs in an aviation market dominated by FSCs before. This study aims to explore how the WOM information affects the adoption of LCCs by short-haul business passengers in dynamic small-world social network at the micro level. A dynamic approach is used to investigate the first-purchase behavior of potential passengers, where we allow passengers to revise their perceptions of LCCs over time based on the receipt of updated WOM information from their social neighbors. This revision in turn affects the dynamics of each passenger's adoption probability and LCC's adoption timing. Furthermore, the dynamic properties of network structure and the social heterogeneity are together incorporated into the modeling of passenger adoption behavior.

In the last part of this dissertation, this study focuses on exploring the influences of structural properties of an airport network on the delay propagation. When the arrival

capacity of an airport is reduced due to the weather condition, it may result in the delay of flights scheduled to land the airport. These delayed flights will be held on the ground for the cost and safety considerations, which is referred to the ground-holding policy. This study applies the small-world theory to explore the structural properties of the airport network, and uses the concept of shortcuts to analyze the characteristics of various flights, which in turn affect the delay propagation over scheduled flights and airports. This study further analyzes the influence of delay on scheduled flights with different length of haul. Other factors influencing the pattern of propagation, including the duration of delay and its probability of occurrence, the impacts of inter-regional long-haul flights and the level of connectivity of airports, are also investigated in the study.

Specifically, the objectives and contributions of each part of this dissertation are discussed as follows, respectively.

(1) This study explores the effects of international airline alliances on the connectivity of airline networks by conceptually applying the shortcuts of small-world networks, and develops the mobility and accessibility models to investigate the effects of alliances based on travel time. This study defines a traveler's travel time between airports as the sum of his/her flying time on the flights and transfer time incurred at intermediate airports. The mobility model is constructed at the global and local scales, respectively, and is shown that it is more appropriate for measuring the system performance and effectiveness than the efficiency model proposed in the literature. The global and local structural properties of the alliance network are evaluated using mobility model, so as to examine whether it is a small-world network or not. This study also shows the degeneration and normalization of models, and discusses the connection between the models and the economic benefits of airlines in order to provide practical applications.

(2) This paper develops dynamic transmission models that illustrate the transmission behaviors of an influenza virus on scheduled flights and at airport terminals where air travel activities consisting of passenger consolidation, conveyance and distribution are carried out. The transmission of influenza via air travel is evaluated in terms of the dynamical evolution and spatial distribution in a small-world airline network. For the realism of our models, links of the network were weighted by the flying time and the number of passengers, and different values of the infection parameters were designed for flights and airports, respectively. The influences of small-world properties of an air transportation network on the pandemic evolution are also investigated. Furthermore, this study not only predicts the patterns of the influenza pandemic under various situations, but also proposes several control measures to mitigate the pandemic and further evaluates the effectiveness of performing these measures.

(3) This study uses a dynamic approach to investigate the first-purchase behavior of potential passengers, which allows passengers to change their perceptions of LCCs over time as they learn more information about LCCs from WOM communication in the diffusion process. The WOM information is transmitted through interpersonal channels where the strength of social ties with other people is different across all population and is affected by the connections of a small-world network with dynamic structural properties. This study develops an intensity model of WOM information to determine whether or not a passenger adopts LCCs based on the receipt of updated WOM information and his/her own perceived utility. In contrast to past studies, social heterogeneity with respect to the size of company that passengers work for, the level of connectivity with other people, the tie strength between persons and the adoption timing of LCCs are together incorporated into our model. In addition, this study investigates

how the dynamic properties of the small-world network resulting from its partially random structure affects the temporal pattern of adoption of LCCs.

(4) This study develops an epidemic-like model, which can be interpreted as the propagation of delay across flights and airports in a small-world network. In the model, two kinds of state transition occur. One is when a flight or an airport is delayed due to severe weather, and the other is when the delay of the flight or airport is eliminated or the flight is cancelled due to its delay over the maximum allowed delay. This study applies the concept of shortcuts of a small-world network to investigate the characteristics of various flights, and further analyzes the influence of flights with shortcut functions on the propagation pattern of delay. The influences that the duration of delay, the inter-regional long-haul flights and the level of connectivity of airports have on the propagation are also investigated. Furthermore, this study proposes several allocation strategies of the limited airport capacity to flights, and then evaluates their effectiveness in terms of the total cost.

## 1.3 Research scope

This dissertation aims at exploring a series of important issues with respect to the positive and negative influences of small-world properties on the field of air transportation. The networks investigated in this dissertation include a transportation network comprising scheduled passenger-flights and airports located at different regions, and a social network consisting of passengers who have various personal characteristics and social neighbors. The research scope of each part of this dissertation is different from each other, and is described as follows. The research scope of the first part of this dissertation is on an airport network constructed by the allied airlines of an international alliance, in which this dissertation will show this network is a small-world network. Based on the small-world

network of the first part mentioned above, the research scope of the second part is further extended to the influenza transmission on the scheduled passenger-flights and the airports within the network, and that of the fourth part is to the delay propagation along with ground-holding policies. However, the research scope of the third part is on the choice behavior of short-haul business passengers between FSCs and LCCs, in which passengers form a small-world social network and the WOM information is passed through interpersonal relationships. The study objects of this dissertation are the international airlines (FSCs and LCCs) and airline alliances, airports worldwide, and passengers who have social relationships with other people. Furthermore, this dissertation investigates the airline choices of passengers in an aviation market that is previously dominated by FSCs and now has a new entrant, LCCs. The interrelations among the study objects are also incorporated in this dissertation.

## 1.4 Dissertation framework

The framework and organization of this dissertation is shown as Figure 1.1, which depicts the content and key factors of each part of this dissertation, and shows the relationships among all parts. The research subjects at Chapters 4 and 6 are investigated based on the small-world airport network constructed at Chapter 3 and using the same flight database and airport traffic statistics as Chapter 3. On the other hand, the analysis from the perspective of passengers at Chapter 3 is further extended to investigate the perception of passengers about air travel services or products sold by airlines at Chapter 5 on the demand side, which focuses on the airline choice behavior of passengers and the influence of WOM.

Chapter 1 illustrates the overview of this dissertation with respect to the motivation and background, research objectives, spectrum and framework. Chapter 2 presents the review of literature in relevant topics and issues, and briefly discusses the key papers. The

discrimination of this dissertation from past studies is also discussed and identified in this chapter, in order to highlight the contributions of each part of this dissertation. Chapter 3 investigates one of positive influences of small-world properties, where the shortcut functions of complementary international airline alliances are discussed using the small-world theory. This dissertation considers travel time as a determinant to develop accessibility and mobility models, and the latter is further formulated at the global and local scales to analyze the global and local structure properties, respectively. For examining whether the alliance network is a small-world network or not, model normalization and degeneration are carried out. In the analysis of an actual case study of a complementary international airline alliance, the flight timetables of allied airlines and the worldwide flight data are collected for the real case and ideal case, respectively. The proposed models as well as the shortest path algorithm are then applied to compare the network connectivity and efficiency between the pre- and post-alliance situations, which enable us to evaluate the benefit of alliance routes and to examine the small-world properties of the airport network.

Chapter 4 investigates one of negative influences of small-world properties, which focuses on the transmission of influenza caused by air travel activities of passengers in a small-world airport network constructed at Chapter 3. The susceptible-infected epidemic model is applied to illustrate the influenza transmission, i.e. passengers are divided into the susceptible subpopulation and infected subpopulation. This dissertation develops two transmission models that illustrate the transmission behavior happened on scheduled flights and at airport terminals, respectively, with different values of infection parameters. Furthermore, basic control measures are designed to be practiced at the departure and arrival procedures of passengers in order to constrain the transmission and pandemic of influenza. The start time and target of practice for control strategies differ from each other, which result in various control effectiveness in terms of cumulative number of infected

individuals and cumulative percentage of airports with infected cases. The relationship between the containment results of strategies and the level of connectivity of airports is also investigated, thereby providing helpful insights for the authorities.

Chapter 5 explores the other positive influence of small-world properties, which focuses on investigating the diffusion evolution of LCCs with WOM transmission and influence in small-world social networks. Passengers are allowed to revise their perceptions of LCCs over time as they receive more WOM information from social neighbors. The revision of perceptions will change the intensity of WOM information, and the level of the change is affected by passengers' personal characteristics, such as the social connectivity and tie strength with other persons, and the number of neighbors who have adopted LCCs. As soon as the intensity of WOM information is over the threshold value, the probability that a passenger adopts LCC will be increased. This dissertation also investigates how the dynamic structural properties of small-world networks and the dynamics in the perception revision affect the adoption timing and pattern of LCC. The influences of the culture difference on the diffusion of LCC are also analyzed, which may further affect the designs of management and marketing strategies for carriers.

Chapter 6 investigates the other negative influence of small-world properties, and applies the small-world airport network constructed at Chapter 3 to explore the problem of delay propagation. The level of connectivity of airports is affected by the small-world properties of the airport network. This dissertation uses a typical epidemic model, susceptible-infected-removed model, to illustrate the propagation of delay across flights and airports. There are several key factors are incorporated into the model, such as the delay duration and the level of connectivity of airports. This dissertation also considers the influences of weather conditions and probability of delay occurrence on the propagation

pattern. For solving the delay problem, the ground-holding policy, one of the short-term approaches, is applied. The policy holds flights on the ground before take-off, which involves how to efficiently and effectively allocate the limited capacity to flights. Several allocation strategies are proposed for mitigation and are evaluated for finding the optimal one. Furthermore, this dissertation investigates how the shortcut functions of specific flights facilitate the delay propagation using the small-world theory. Finally, Chapter 7 summarizes the important findings as well as some conclusions and management implications with respect to each part of this dissertation.

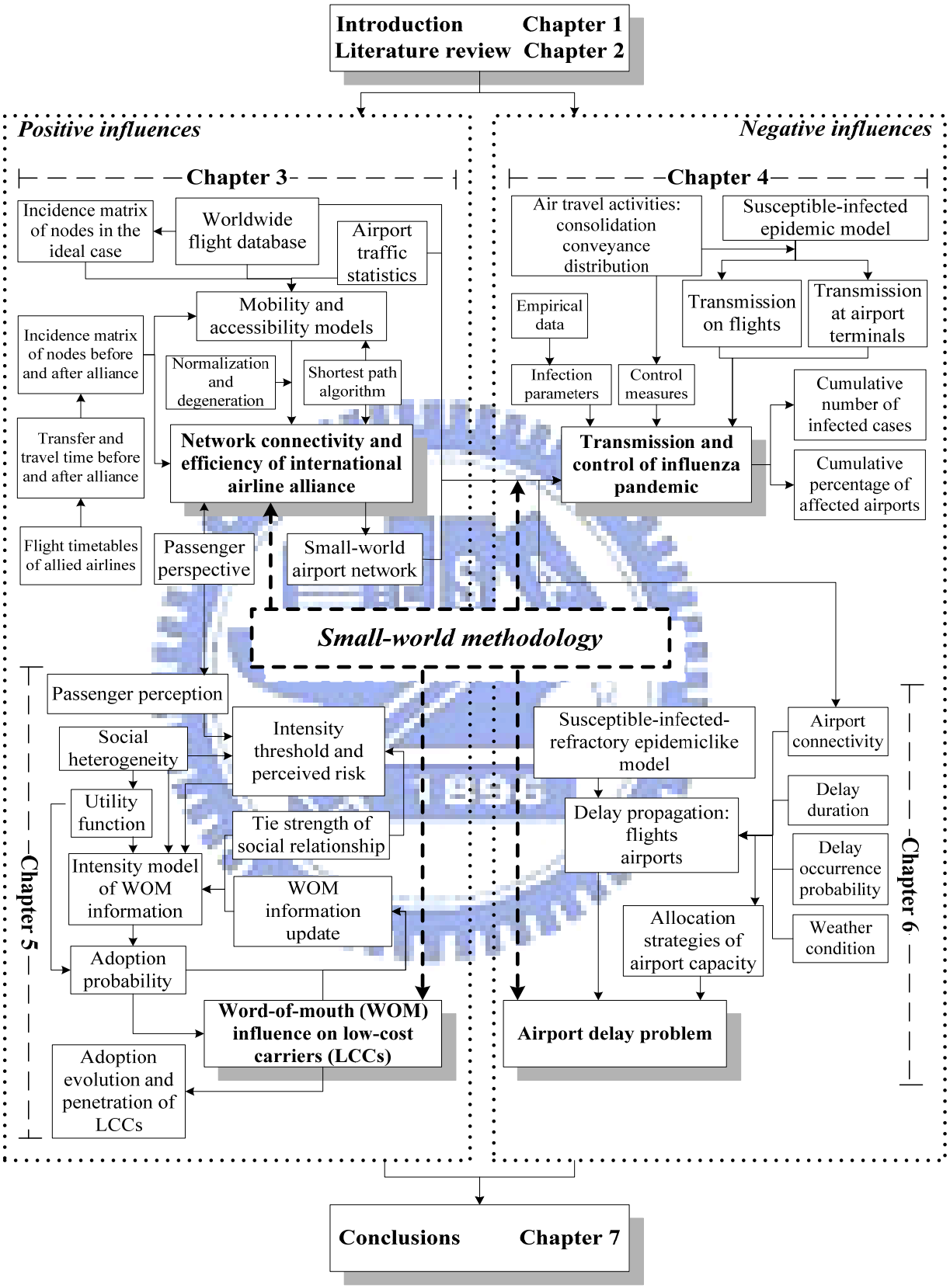


Figure 1.1 Framework of this dissertation

This dissertation depicts the flowchart of research process as Figure 1.2, and describes each step in detail as follows.

1. Define the research problems

Based on the motivation and background, this dissertation identifies the research issues, topics, scope, problems and objectives at first.

2. Literature review

To better understand the problems and identify the important objectives of research, this dissertation comprehensively and systematically reviews the existing literature on the relevant issues, such as the airline alliances, disease transmission and pandemics, airline choices of passengers, evolution of LCCs, airport congestion and delay, and so on. By doing so, this dissertation can clarify and highlight the contributions of this research, as well as can take into account the key factors when formulating models and designing management strategies.

3. Small-world theory and methodology

Next, the small-world theory and methodology are investigated in detail. The distinctive structure characteristics affecting the flow and spread of any communication or social process are identified. The understanding of the small world is the fundamentals of the model constructions.

4. Network connectivity analysis

Since the small-world properties affect the connectivity of components of a given network according to the understanding of the small world in Step 3, this dissertation

applies several quantitative variables for evaluating the network connectivity. Travel time is one of them, and is also one of the most significant measures of performance in an air transportation system. From the perspective of passengers, mobility and accessibility are used to evaluate, respectively, the ease of movement for passengers to and from cities, and the extent to which passengers can reach their destinations for accomplishing socioeconomic activities.

5. Network of international airline alliances

For evaluating the connectivity and efficiency of an alliance network, this dissertation defines the nodes and links of the network in advance. The mobility and accessibility models are then used to evaluate the network connectivity and efficiency before and after the alliance, and investigate the benefits contributed from the alliance. The small-world properties of the network are also examined.

6. Disease transmission model

This dissertation discusses how the influenza spreads to other regions of the world via the air travel activities of passengers, and develops the transmission models. The small-world properties and travel time between two airports are critical factors affecting the influenza transmission. This dissertation also investigates the transmission behavior of the influenza virus within the airport terminals, which have different infection parameters from that on scheduled flights.

7. Control strategies

This dissertation further designs several control strategies to mitigate the pandemic of influenza. There exist differences in the time that a strategy is carried out and in the target

which carries out the strategy across all strategies. This variation affects the containment results of strategies.

8. Ground-holding policy

This dissertation focuses on investigating the practice of ground-holding policies, involving how to effectively allocate the limited arrival capacity of an airport to flights. The issues that the policies affect the delay cost and duration of flights are also discussed in this dissertation.

9. Airport delay model

A typical epidemic model is applied to explore the airport delay problem and to formulate a delay model. This model can be used to examine how a given delay is propagated to other relevant flights and airports via shortcuts of a small-world network. Based on the policies in Step 8, this dissertation further uses the model to evaluate the effectiveness of each allocation strategy.

10. Social influence and perception revision

This dissertation turns the emphasis on the airline choice behavior of passengers, in which the LCC is the subject of analysis. In a social network that has been demonstrated as a small-world network, the issue how the social influence results in the adoption decisions of potential passengers is discussed in detail. The social influence comes from the social neighbors who have adopted the LCC before and pass WOM information to potential passengers. This dissertation also develops the scheme of the perception revision of potential passengers, which dynamically affects the adoption behavior of passengers.

11. Word-of-mouth intensity model

Based on Step 10, this dissertation further proposes an intensity model, incorporating the tie strength of social relationship between persons and the adoption decisions of social neighbors, to analyze that how much the intensity of WOM information is will increase the adoption probability of potential passengers. Several key factors affecting the adoption probability are also discussed.

12. Dynamic structure of network

Since the dynamic properties of network structure have been demonstrated as a factor of influencing the spread of any communication, this dissertation dynamically change the structure of the social network with partial randomness. The influence of dynamic properties is evaluated in terms of the diffusion evolution of adoption at a two-dimensional space.

13. Case studies and sensitivity analyses

Case studies are provided at each part of this dissertation to illustrate the application and to demonstrate the effectiveness of the proposed models. This dissertation also applied the sensitivity analyses of models to evaluate the results and patterns under various scenarios.

14. Conclusions and suggestions

Finally, this dissertation presents the concluding remarks, management suggestions and recommendations for future research.

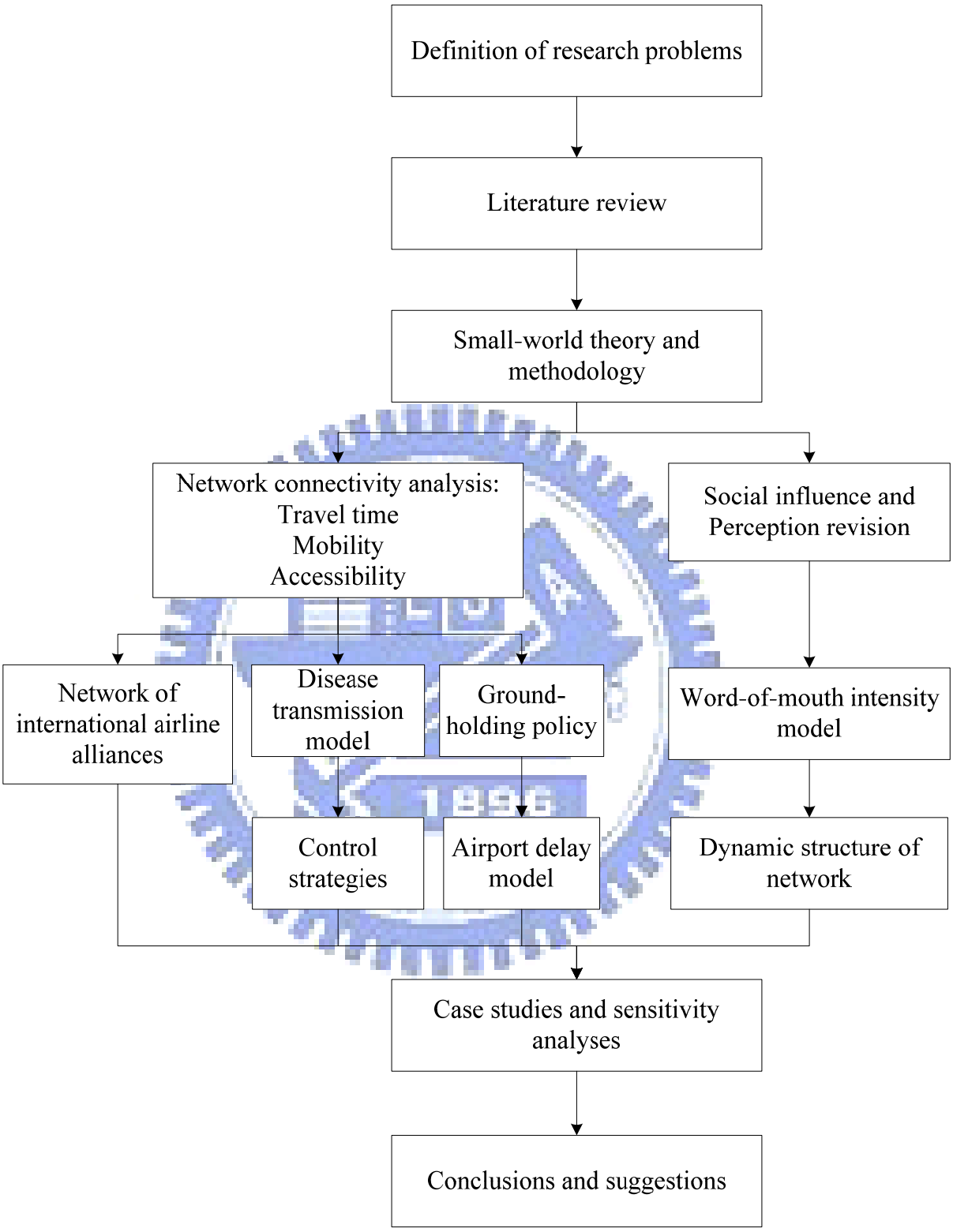


Figure 1.2 Flowchart of research process

# CHAPTER 2

# Literature review

This chapter reviews the literature on related areas and issues. The following subsections are organized as: 2.1 Small-world related issues; 2.2 Airline alliances related issues; 2.3 Mobility and accessibility models; 2.4 Disease related issues; 2.5 Low-cost carriers related issues; and 2.6 airport delay problems. The research issues, methodology and important findings of the related studies are also discussed and summarized in this chapter. The final subsection identifies and highlights the contributions of this dissertation.

## 2.1 Small-world related issues

The small-world phenomenon was first observed by Stanley Milgram (1967) of Harvard University. In the late 1960's, he distributed a number of letters to a random selection of people in Nebraska and Kansas, and asked these people to send the letters to a stockbroker in Boston by passing letters from person to person. For each person, the strategy of passing the letter was that the person would pass his/her letter to someone he/she presumed was more likely to know the Boston stockbroker. The receivers of letters would also subsequently pass letters based on the same strategy. Milgram kept track of the letters and the demographic characteristics of the letter receivers, by requiring each intermediary to report their receipt of the letter. A reasonable number of letters eventually reached their destination, i.e. the Boston stockbroker, with a medium chain length of about six. Therefore, Milgram concluded that six was the average number of acquaintances separating any two people in the world. This situation has been labeled as "six degrees of separation", a popular phrase in the social network. There were certainly possible sources of error in Milgram's experiment, and the number six is probably not very accurate. However, the important result

that any two randomly chosen persons can be connected by only a short chain of intermediate acquaintances has been subsequently verified and is now widely accepted. This result is referred to as the small-world phenomenon.

In the late 1990's, Watts and Strogatz (1998) pointed out that the connection topology was ordinarily assumed to be either completely regular or completely random, but many biological, technological and social networks lay somewhere between these two extremes. Therefore, they explore simple models of networks that can be tuned through this middle ground: regular networks 'rewired' to introduce increasing amounts of disorder. They found that these networks can be highly clustered, like regular lattices, yet have small characteristic path lengths, like random graphs. They called them 'small-world' networks, by analogy with the small-world phenomenon (Milgram, 1967). To interpolate between regular and random networks, they considered the following random rewiring procedure. They started from a ring lattice with $n$ vertices and $k$ edges per vertex, and then rewired each edge at random with probability $p$. This construction allowed them to 'tune' the graph between regularity ($p$=0) and disorder ($p$=1), and thereby to probe the intermediate region $0<p<1$, about which little was known. They further quantified the structural properties of these graphs by their characteristic path length $L(p)$ and clustering coefficient $C(p)$. $L(p)$ was defined as the number of edges in the shortest path between two vertices, averaged over all pairs of vertices. And $C(p)$ was defined as follows. Suppose that a vertex $v$ has $k_v$ neighbors, then at most $k_v(k_v-1)/2$ edges can exist between them (this occurs when every neighbor of $v$ is connected to every other neighbor of $v$). Let $C_v$ denote the fraction of these allowable edges that actually exist. Define $C(p)$ as the average of $C_v$ over all $v$. For friendship networks, these statistics had intuitive meanings: $L(p)$ was the average number of friendships in the shortest chain connecting two people; $C_v$ reflected the extent to which friends of $v$ are also friends of each other; and thus $C(p)$ measured the cliquishness of a

typical friendship circle. In other words, $L(p)$ measured the typical separation between two vertices in the graph (a global property), whereas $C(p)$ measured the cliquishness of a typical neighborhood (a local property).

From a numerical example, Watts and Strogatz (1998) found that the regular lattice at $p$=0 was a highly clustered, large world where $L(0)$ grew linearly with $n$, whereas the random network at $p$=1 was a poorly clustered, small world where $L(1)$ grew only logarithmically with $n$. These limiting cases might lead one to suspect that large $C(p)$ is always associated with large $L(p)$, and small $C(p)$ with small $L(p)$. On the contrary, there was a broad interval of $p$ over which $L(p)$ was almost as small as $L(1)$ but $C(p)$ was much larger than $C(1)$ in the example. These small-world networks resulted from the immediate drop in $L(p)$ caused by the introduction of a few long-range edges. For small $p$, each of such 'shortcuts' had a highly nonlinear effect on $L(p)$, contracting the distance not just between the pair of vertices that it connected, but between their immediate neighborhoods, neighborhoods of neighborhoods and so on. By contrast, an edge removed from a clustered neighborhood to make a shortcut had, at most, a linear effect on $C(p)$. Hence, $C(p)$ remained practically unchanged for small $p$ even though $L(p)$ dropped rapidly. To test the above ideas obtained from a numerical example, Watts and Strogatz (1998) had computed $L$ and $C$ for the collaboration graph of actors in feature films, the electrical power grid of the Western United States, and the neural network of the nematode worm *Caenorhabditis elegans*. The graph of film actors was a surrogate for a social network. The graph of the power grid was relevant to the efficiency and robustness of power networks. And *Caenorhabditis elegans* was the sole example of a completely mapped neural network. The $L$ and $C$ for three graphs compared to random graphs with the same number of vertices ($n$) and average number of edges per vertex ($k$) were shown in Table 2.1. All three real graphs showed the small-world phenomenon, in which their $L$ were as small as $L(1)$ but $C$ were much larger than $C(1)$.

These examples were not hand-picked; they were chosen because of their inherent interest and because complete wiring diagrams were available. Thus the small-world phenomenon was not merely a curiosity of social networks nor an artifact of an idealized model. It was probably generic for many networks.

Table 2.1 Characteristic path length and clustering coefficient for three real graphs

| | $n$ | $k$ | $L_{actual}$ | $L(1)$ | $C_{actual}$ | $C(1)$ |
|---|---|---|---|---|---|---|
| Film actors | 225,226 | 61 | 3.65 | 2.99 | 0.79 | 0.00027 |
| Power grid | 4,941 | 2.67 | 18.7 | 12.4 | 0.080 | 0.005 |
| *Caenorhabditis elegans* | 282 | 14 | 2.65 | 2.25 | 0.28 | 0.05 |

Following Watts and Strogatz (1998), some studies were proposed to investigate whether specific real-world networks reveal small-world properties or not. In particular, Latora and Marchiori (2001, 2002) pointed out that the mathematical formalism of Watts and Strogatz (1998) suffered from severe limitations: (1) it applied only to some cases, whereas in general the two quantities *L* and *C* were ill-defined; (2) it worked only in the topological abstraction, where the only information retained was about the existence or the absence of a like, and nothing was known about the physical length of the link. Therefore, Latora and Marchiori (2001, 2002) proposed global and local efficiency models, and confirmed that their models can drop all restrictions in the model of Watts and Strogatz (1998). They defined the shortest path length $d_{ij}$ between two generic nodes *i* and *j* as the smallest sum of the physical distances throughout all the possible paths in the graph from *i* to *j*. The efficiency $\varepsilon_{ij}$ in the communication between nodes *i* and *j* was then defined to be inversely proportional to the shortest distance between them, i.e. $\varepsilon_{ij} = 1/d_{ij}$. When there was no path in the graph between nodes *i* and *j*, $d_{ij} = +\infty$ and, consistently, $\varepsilon_{ij} = 0$. The global efficiency of a generic weighted (and possibly even nonconnected) graph $\overline{\mathbf{G}}$, is formulated as $E_{glob}(\overline{\mathbf{G}}) = \sum_{i \neq j \in \overline{\mathbf{G}}} \frac{1}{d_{ij}} \Big/ (\|\overline{\mathbf{N}}\|(\|\overline{\mathbf{N}}\|-1))$, where $\|\overline{\mathbf{N}}\|$ is the total number of nodes in $\overline{\mathbf{G}}$. The local efficiency of $\overline{\mathbf{G}}$ is formulated as $E_{loc}(\overline{\mathbf{G}}) = \frac{1}{\|\overline{\mathbf{N}}\|} \sum_{i \in \overline{\mathbf{G}}} \left( \sum_{l \neq m \in \overline{\mathbf{G}}_i} \frac{1}{d_{lm}} \Big/ (V_i(V_i-1)) \right)$, where $V_i$ is the number of nodes that connect to node *i*, and $\overline{\mathbf{G}}_i$ is the subgraph of node *i*. Latora and Marchiori (2001, 2002) confirmed that a small-world network is a network with both high global and high local efficiency. They also showed that if the Boston subway transportation system (MBTA) is combined with its bus system, then this extended system is a small-world network.

Sen et al. (2003) investigated the structural properties of the Indian railroad network (IRN) to examine whether or not some of the general behavior obtained for many complex networks may also be present in IRN. Stations are considered as nodes, and an arbitrary pair of stations is considered as connected by a link when at least one train stops at both stations. With the definition of links, the mean distance of the network is a measure of how good is the connectivity of the network. They found that IRN behaves like a small-world network and believed that it is typical of the railroad network of any other country. Guimerà and Amaral (2004) investigated the world-wide airport network using the degree, defined as the number of non-stop connections to a given city, and the betweenness centrality, defined as the number of shortest paths going through a given city. They found that the degree and betweenness centrality of the airport network both distributed as those patterns with truncated power-law decay. A surprising finding is that the most connected cities that have the largest degree are typically not the most central cities that have the largest betweenness centrality. It led the authors to propose a model that can explain this finding in terms of the geo-political constraints. They also showed that the world-wide airport network is a small-world network. Jiang and Claramunt (2004) carried out a topological analysis of large urban street networks, and wanted to examine which streets are important for a city in terms of connectivity and how each given street intersects with every other. Therefore, they focused on a 'named-streets'-oriented view for topological analysis. 'Named streets' represented a functional modeling element of large urban street networks whose structure should be retained by a structural analysis. For evaluating the degree to which streets are interconnected versus segregated in a given city, they designed a graph at a modeling level, in which the nodes denoted those named streets and edges denoted connections between those named streets (note that in such a view a node denoted not a street segment but an entire named street). Without loss of generality, a named street that was separated into two

or more parts (for example, South Queen Street and North Queen Street) was semantically aggregated. One of the objectives in the study of Jiang and Claramunt (2004) was to explore such an alternative graph model. This named-street-centred network model was denoted as a topological network model. The urban street networks of three cities (Gävle, Munich and San Francisco) located at different countries were used, and the result showed that these networks are small-world networks.

There are several studies applying the small-world network to explore the spread of diseases or rumors. Kuperman and Abramson (2001) proposed a model to analyze the spread of an infection at different population structures. The interactions between the elements of the population were described by a small-world network, ranging from ordered lattices to random graphs. The links represented the contact between subjects, and infection can proceed only through them. The result showed a transition at a finite value of a disorder parameter in a small-world network. The epidemic behavior changed from an irregular and low-amplitude evolution at a small value of the parameter to a spontaneous state of wide amplitude oscillations at a large value of the parameter. Zanette (2001) developed an epidemiclike model to interpret the propagation of a rumor. The result exhibited critical behavior at a finite randomness of the underlying small-world network. That is, the transition occurred between a regime where the rumor dies within a small neighborhood of its origin, and a regime where it spreads over a finite fraction of the entire population. The influence of the network connectivity on the critical randomness was also discussed, showing that the critical randomness decreases as the connectivity grows, and that the dependence of the critical randomness on the connectivity is distributed as a pattern with power-law decay.

Zanette and Kuperman (2002) investigated the propagation of epidemics on a small-world network under the action of immunization, and focused on the combined effect of the structure of the small-world network and the immunization process. They showed that the infection level decreases monotonically as the fraction of vaccinated individuals grows, and that the threshold for the propagation of the disease grows with the fraction of vaccinated individuals. Furthermore, the targeted immunization, where the individuals chosen to be vaccinated are those with the highest number of social connections, produced a substantial improvement in disease control. Saramäki and Kaski (2005) proposed a model for the spread of randomly contagious diseases such as influenza. The model was based on a stochastic susceptible-infected-removed mechanism on small-world networks, where randomly occurring long-range links were introduced in order to take into account the inherent randomness of spreading. The equations for the epidemic threshold and spreading dynamics were derived, and were used to examine how the epidemic saturation time, defined as the time when 95% of the susceptible population has become infected, scales with the system size and initial conditions. The comparison of the numerical result from the model with real-world data showed a good agreement.

Small and Tse (2005) developed a four-state model for disease transmission, in which the community was modeled as a small-world network of interconnected nodes, and transmission could only propagate between linked nodes. They used the model to exhibit two typical features of an epidemic, geographically localized outbreaks and super-spreaders, and showed that super-spreaders may occur even if the infectiousness of all infected individuals is constant. The result also showed that large-scale transmission occurs when a large number of clusters are exhibited, and indicated that quarantine, travel restrictions and closure of schools and work places are all effective control strategies for the epidemic.

Table 2.2 summarizes main issues and features as well as important results in the existing literature on small-world networks.

Table 2.2 Main issues, features and results on small-world related literature

| Authors | Main issues and features | Important results |
|---|---|---|
| Watts and Strogatz (1998) | First propose the small-world theory | Clustering coefficient and characteristic path length can measure the distinctive properties of small-world networks |
| Kuperman and Abramson (2001) | Propose a model to analyze the spread of an infection at different structures | A transition at a finite value of a disorder parameter is shown in a small-world network |
| Latora and Marchiori (2001, 2002) | Propose the global and local efficiency models | The proposed models can drop all restrictions of previous models, and an extended transportation system embracing the MBTA is a small-world network, with both high global and high local efficiency |
| Zanette (2001) | Develop an epidemiclike model to interpret the propagation of a rumor | The transition occurs between a regime where the rumor dies within a small neighborhood of its origin, and a regime where it spreads over a finite fraction of the entire population. |
| Zanette and Kuperman (2002) | Investigate the propagation of epidemics on a small-world network under the action of immunization | The infection level decreases monotonically as the fraction of vaccinated individuals grows, and the targeted immunization produces a substantial improvement in disease control |
| Sen et al. (2003) | Investigate the structural properties of the Indian railroad network (IRN) | The IRN behaves like a small-world network and is typical of the railroad network of any other country |

Source: this dissertation

Table 2.2 (continued)

| Authors | Main issues and features | Important results |
|---|---|---|
| Guimerà and Amaral (2004) | Use the degree and betweenness centrality to investigate the world-wide airport network | The world-wide airport network is a small-world network, and the most connected cities are typically not the most central cities |
| Jiang and Claramunt (2004) | Carry out a topological analysis of large urban street networks | The urban street networks of three cities located at different countries are small-world networks |
| Saramäki and Kaski (2005) | Propose a model for the spread of randomly contagious diseases | The numerical results of the proposed models match the real-world data well |
| Small and Tse (2005) | Develop a four-state model for disease transmission in a small-world network | Super-spreaders may occur even if the infectiousness of all infected individuals is constant, and that large-scale transmission occurs when a large number of clusters are exhibited |

Source: this dissertation

**Summary:**

There are extensive studies exploring the small-world properties of specific real-world networks, and further applying them to analyze the spread of diseases and rumors. These studies usually took into account the physical distance between two nodes when analyzing the weighted networks. However, few studies have taken travel time between two nodes into account. Travel time is one of the most significant measures of performance in the air transportation system, and a short distance between two nodes is not always equivalent to a short travel time. Travel time also depends on airport availability, capacity and delay, air traffic control, airline operating efficiency, and other factors. In addition, these small-world related studies have rarely investigated the effects of international alliances on the connectivity of airline networks, and rarely incorporated the air travel activities into the spread models of diseases.

## 2.2 Airline alliances related issues

The literature on international airline alliances can be classified into three major categories: theoretical, empirical and comprehensive. Theoretical studies are focused on analyzing the economic benefits for alliances, such as outputs and profitability. Park (1997) examined the effects of alliances on carriers' outputs and profits, air fare and economic welfare. The profits of allied carriers were increased after the introduction of the alliance. For the complementary alliance, air fares decreased in the aviation markets, and thus consumers in the markets were better off due to the alliance. On the other hand, air fares increased in the market where the parallel alliance occurred, while air fares decreased in the other markets. In addition, for the complementary alliance case, economic welfare increased when the size of the markets was sufficiently large, while it decreased for the parallel

alliance case under the same condition. Wen and Hsu (2006) developed an interactive airline network design procedure to determine international code-share alliance-based networks. The bargaining interactions between two partner-airlines and various objective functions of partner airlines in alliance negotiations were also incorporated into their model. They showed that all alliance partners enjoyed more profit under alliance conditions than before alliance. Under complementary alliance conditions, the allied airlines increased their flight frequencies, which further increased their market shares. Under parallel alliance conditions, the allied airlines may produce less if their market shares were lower, so they were more likely to establish a parallel alliance in the markets where they had large market shares. Lin (2004) applied the Stackelberg model to analyze the economic impacts of strategic alliances. It was shown that the joint profits of the allied airlines increased while the profits of the unallied airline decreased, and the consumer surplus of the connecting passengers increased. However, the alliance decreased the consumer surplus of the direct international passengers although their total demand was larger than that of the connecting passengers.

The empirical studies collect data to investigate the current status of the alliances, the impact, features, strategies, and so on. Brueckner (2003) focused on three measures of cooperation, alliance membership, codesharing and antitrust immunity, and showed that these three forms of cooperation lead to a substantial 27 percent reduction in interline fares. It also showed that the immunity enjoyed by the Star Alliance's partners generated an aggregate benefit of around $80 million per year for interline passengers in 1991, and codesharing among Star partners yielded a further annual benefit of around $20 million. Goh and Uncles (2003) carried out an empirical study of the perceptions of consumers, showing that a sizeable minority was unsure of the benefits of global alliances. It also showed that no major differences were perceived in the benefits offered by Star Alliance

and Oneworld. The importance of global alliance benefits in determining airline choice by business travelers was also analyzed, showing that the global alliance benefits were rated relatively low, and the reputation for safety was the most important factor. Oum et al. (2004) examined the effect of horizontal alliances on airline performance in terms of productivity and profitability based on empirical panel data from 22 international airline companies. They showed that the horizontal alliances made a significant contribution to productivity gains but had no overall significant and positive impact on profitability. Furthermore, the alliances involving high-level cooperation were found to have a stronger significant and positive effect on both productivity and profitability than those alliances involving low-level cooperation.

Albers et al. (2005) explored the relationship between airlines and airports from a strategic management perspective, using the case of the alliance between Lufthansa and Munich airport. Advantages for Munich airport can be realized by the cost saving and risk reduction, where the reduction of costs was achieved by lower investments in airport expansion because the airline paid a share. Iatrou and Alamdari (2005) focused on investigating the perceived impacts by the airlines of alliances, and carried out a survey of the alliance management departments of airlines participating in the major alliance groups. The results showed that alliances brought about an increase in passenger traffic with a parallel increase in load factors and some reduction in costs, indicating a clear improvement of revenue. In addition, the increase in traffic had mostly been experienced on hub-to-hub routes.

The comprehensive works not only developed theoretical models, but also conducted the empirical analyses of the effects of the alliances. Park and Zhang (1998) examined the effects of airline alliances on partner airlines' traffic, and formulated a theoretical model

and conducted an empirical analysis using panel data from four major alliances in North Atlantic markets during the 1992-1994 periods. They showed that most of the partners had greater traffic increases on their alliance routes than those on their non-alliance routes. It was due to the facts that partner airlines tended to feed domestic traffic onto their alliance routes but not onto non-alliance routes, and that partner airlines may re-route domestic traffic through their alliance routes.

Park et al. (2001) developed a model to investigate the effect of airline alliances on market outcome, and used panel data of trans-Atlantic alliance routes to estimate the model. They found that a complementary alliance enabled partner airlines to attract more passengers, which had an adverse effect on the performance of rival airlines. Collaboration between the partners was likely to improve the quality of their connecting services and to decrease the air fares of their connecting services. However, a parallel alliance was likely to decrease total output and increase full price in a market where the alliance was formed. Chen and Chen (2003) developed a theoretical model and conducted an empirical analysis of the effects of complementary and parallel codesharing on the load factors of international airline operations. They showed that as demand increased resulting from the expansion of a global network, an airline of a complementary alliance needed to increase the seat supply as well in order to maintain a satisfactory level of service convenience. For an airline of a parallel alliance, however, the presence of alliance partners on the same route made a difference, because it could supply fewer seats than its complementary counterpart by conducting risk pooling with alliance partners. As a result, the load factor of the airline of the complementary alliance did not increase significantly as did the load factor of the airline of the parallel alliance. Table 2.3 summarizes main issues and features as well as important results in the existing literature on airline alliances.

Table 2.3 Main issues, features and results on airline alliances related literature

| Authors | Main issues and features | Important results |
|---|---|---|
| Park (1997) | Examine the effects of alliances on carriers' outputs and profits, air fare and economic welfare | For the complementary alliance case, economic welfare increases when the size of the markets is sufficiently large, while it decreases for the parallel alliance case under the same condition |
| Park and Zhang (1998) | Examine the effects of airline alliances using panel data from four major alliances | Most of the partners have greater traffic increases on their alliance routes than those on their non-alliance routes |
| Park et al. (2001) | Develop a model to investigate the effect of airline alliances on market outcome, and use panel data of trans-Atlantic alliance routes to estimate the model | Collaboration between the partners is likely to improve the quality of their connecting services and to decrease the air fares of their connecting services, and a parallel alliance is likely to decrease total output and increase full price in a market where the alliance is formed |
| Brueckner (2003) | Focus on the measures of alliance membership, codesharing and antitrust immunity | The immunity enjoyed by the Star Alliance's partners generates an aggregate benefit of around $80 million per year for interline passengers, and codesharing among Star partners yields a further annual benefit of around $20 million |
| Chen and Chen (2003) | Conduct an empirical analysis of the effects of complementary and parallel codesharing on the load factors of international airline operations | Only parallel codesharing leads to higher load factors, since parallel alliance airlines can supply fewer seats than their complementary counterparts by conducting risk pooling with alliance partners |

Source: this dissertation

Table 2.3 (continued)

| Authors | Main issues and features | Important results |
|---|---|---|
| Goh and Uncles (2003) | Carry out an empirical study of the perceptions of consumers | No major differences are perceived in the benefits offered by Star Alliance and Oneworld |
| Lin (2004) | Apply the Stackelberg model to analyze the economic impacts of strategic alliances | The alliance decreases the consumer surplus of the direct international passengers although their total demand is larger than that of the connecting passengers |
| Oum et al. (2004) | Examined the effect of horizontal alliances on airline performance in terms of productivity and profitability | The alliances involving high-level cooperation are found to have a stronger significant and positive effect on both productivity and profitability than those alliances involving low-level cooperation |
| Albers et al. (2005) | Explore the relationship between airlines and airports from a strategic management perspective | Advantages for Munich airport can be realized by the cost saving and risk reduction, where the reduction of costs is achieved by lower investments in airport expansion because the airline paid a share |
| Iatrou and Alamdari (2005) | Focus on investigating the perceived impacts by the airlines of alliances | Alliances bring about a clear improvement of revenue, and the increase in traffic has mostly been experienced on hub-to-hub routes |
| Wen and Hsu (2006) | Develop an interactive airline network design procedure | Under complementary alliance conditions, the allied airlines increase their flight frequencies, which further increase their market shares |

Source: this dissertation

**Summary:**

The majority of the above mentioned research investigated how alliances contributed to the economic outcomes of airlines by constructing theoretical models and/or using empirical data to estimate models. These outcomes include profits, air fare, welfare, flight frequency, market shares, productivity, passenger traffic and load factor. Little research, however, has been carried out on the effects these alliances have on the connectivity of airline networks, nor on the transportation efficiency to and from cities, nor on access to new cities. That is, there have been few attempts to explore the improvement of mobility and accessibility of passengers contributed by the establishment of international airline alliances, although mobility and accessibility are the most significant measures of system performance and effectiveness for transportation systems.

## 2.3 Mobility and accessibility models

There are many studies defining mobility in various ways and developing mathematical models to explore different issues. For example, Meyer (1995) defined mobility as the ability and knowledge to travel from one location to another in a reasonable amount of time for an acceptable cost. Schafer and Victor (2000) used several factors to develop a new technique for projecting future mobility and mode of transport in all eleven world regions from 1990 to 2050. They showed that all world regions illustrated the same phenomenon of shifting from slow to faster modes as income and the demand for mobility rose, and variations among regions largely reflected the historical legacy of infrastructures. In the case of North America, the high-speed-transport share of mobility would rise fourfold to 71% by 2050, but only 17% of the average person's travel time budget would be spent

moving at high speeds. It also showed that the average American's mobility would rise by a factor of 2.6 by 2050, to 58,000 km/year.

Levine and Garb (2002) defined mobility as an ease of movement, and provided a theoretical grounding for current accessibility-based thinking in transportation policy and delineated and distinguished mobility-based from accessibility-based congestion pricing policies. They pointed out that a mobility-based congestion pricing promised to alleviate congestion but threatened to deteriorate from overall regional accessibility as it accelerated metropolitan deconcentration. However, an accessibility-based congestion pricing avoided acceleration of sprawl by incorporating policies to ensure that drivers tolled off roads were replaced with residents and travelers arriving at previously congested areas by other means. They argued that a mobility-based policy would tend to concentrate benefits at the high end of the income spectrum, while an accessibility-based policy would spread benefits more broadly and equitably. Alsnih and Hensher (2003) took a close look at the evidence on the mobility needs and travel patterns of individuals over 64, distinguishing between the young elderly (aged 65-75 years) and the old elderly (over 75 years). They showed that differences existed between the young elderly travel patterns and needs and the old elderly travel patterns and needs, and that mobility reductions became more evident as people reached 80 years of age. Although women on average live longer than men, older women had a higher disability rate than comparable men and were more likely to require greater assistance in relation to transport activities and mobility.

Cameron et al. (2003) defined mobility as the ratio of the actual total annual private motorized passenger kilometers to the potential total annual private motorised passenger kilometers, and developed a model of urban private motorised mobility based on empirical data from a wide range of cities. They pointed out that as private motorised mobility was

based on vehicle kilometers of travel, which in turn was a surrogate for urban transportation emissions, urban air quality was directly linked to urban structure. Siren and Hakamies-Blomqvist (2004) aimed at describing the present situation in older persons' mobility options and resources in Finland in order to identify groups of elders with reduced mobility. A mail survey was sent to 2500 Finnish citizens aged 65 and over, and showed that there were a considerable number of older persons experiencing reduced mobility for certain types of trips, mainly leisure-related ones. In addition, older persons were heterogeneous in their mobility options and resources, and demographics were strongly associated with their mobility. After controlling for the interaction and cumulative effects of the background demographic factors, driver license and urban type of residence were the only significant predictors for higher mobility. It implied that the poorer mobility of certain sub-groups was principally due to the lack of driver license and to geographic inequalities in infrastructure and land use.

At the same time, there are some studies investigating accessibility, defining it in different ways and analyzing the impacts of different transportation systems on it. Meyer (1995) defined accessibility as the means by which an individual can accomplish some economic or social activity by having access to that activity. Gutiérrez and Gómez (1999) analyzed the impact of orbital motorways on intra-metropolitan accessibility using the Madrid M-40 orbital motorway as an example. They showed that after establishment, the area around the M-40 had become highly accessible. It also showed that the new orbital motorway had brought about relevant changes in intra-metropolitan accessibility, and the changes in accessibility were greater in the accessibility to population indicators than in those of accessibility to employment. Geurs and van Wee (2004) defined accessibility as the extent to which land-use and transport systems enable individuals to reach activities or destinations by means of a transport mode, and described a set of theoretical criteria related

to the different components of accessibility. These criteria included theoretical basis, interpretability and communicability, and data requirements of the measures. They indicated that location- and utility-based accessibility measures could be considered effective measures of accessibility, which could also be used as input for social and economic evaluations. Person-based accessibility measures were potentially very useful for social evaluations, and may also be tied to the utility-based approach, which opened up the possibility of using them in economic evaluations. They also pointed out that the potential accessibility measures (also called gravity-based measures) were appropriate as social indicators for analyzing the level of access to social and economic opportunities for different socio-economic groups.

Zhu and Liu (2004) investigated the impact of the mass rapid transit (MRT) network on accessibility in Singapore using an integrated GIS tool, and assessed the accessibility to the central business district, to working population, to industrial and commercial opportunities. The analyses showed that the construction of the new North-East line had greatly improved accessibility of the northeastern areas, but had insignificant impact on accessibility of the northern, northwestern and eastern parts of the country. For smaller zones, it should use more accurate estimates of accessibility in the zone, as accessibility could vary greatly across small distances. It also showed that the closer to the central area of Singapore and the East-West MRT line a location was, the higher accessibility it attained. Dong et al. (2006) defined accessibility as the expected maximum utility over a choice situation faced by an individual, and proposed a new measure of accessibility and compared it to traditional measures of accessibility. They pointed out that activity-based accessibility measure was generated not by examining a particular trip, but by examining all trips and activities throughout the day, while the traditional trip-based measures of accessibility were focused on one trip purpose and did not incorporate scheduling or trip chaining. The

activity-based accessibility measure was shown to be successful in capturing taste heterogeneity across individuals, and in combining different types of trips into a unified measure of accessibility. The kind of accessibility measure improved the ability to quantify the ease and convenience of access to spatially distributed opportunities. Table 2.4 summarizes the main issues and features as well as important results in the existing literature on mobility and accessibility models.

Table 2.4 Main issues, features and results on mobility and accessibility related literature

| Authors | Main issues and features | Important results |
|---|---|---|
| Gutiérrez and Gómez (1999) | Analyze the impact of orbital motorways on intra-metropolitan accessibility | The changes in accessibility are greater in the accessibility to population indicators than in those of accessibility to employment |
| Schafer and Victor (2000) | Apply several factors to develop a new technique for projecting future mobility and mode of transport in all eleven world regions from 1990 to 2050 | All world regions illustrate the same phenomenon of shifting from slow to faster modes as income and the demand for mobility rise, and variations among regions largely reflect the historical legacy of infrastructures |
| Levine and Garb (2002) | Distinguish mobility-based from accessibility-based congestion pricing policies | A mobility-based policy would tend to concentrate benefits at the high end of the income spectrum, while an accessibility-based policy would spread benefits more broadly and equitably |
| Alsnih and Hensher (2003) | Take a close look at the evidence on the mobility needs and travel patterns of individuals over 64 | Although women on average live longer than men, older women have a higher disability rate than comparable men and are more likely to require greater assistance in relation to transport activities and mobility |
| Cameron et al. (2003) | Develop a model of urban private motorised mobility based on empirical data from a wide range of cities | As private motorised mobility is based on vehicle kilometers of travel, urban air quality is directly linked to urban structure |

Source: this dissertation

Table 2.4 (continued)

| Authors | Main issues and features | Important results |
|---|---|---|
| Geurs and van Wee (2004) | Describe a set of theoretical criteria related to the different components of accessibility | Location- and utility-based accessibility measures can be considered effective measures of accessibility, which can also be used as input for social and economic evaluations |
| Siren and Hakamies-Blomqvist (2004) | Aim at describing the present situation in older persons' mobility options and resources in Finland | There are a considerable number of older persons experiencing reduced mobility for leisure-related trips, and older persons are heterogeneous in their mobility options and resources, and demographics are strongly associated with their mobility |
| Zhu and Liu (2004) | Investigate the impact of the mass rapid transit (MRT) network on accessibility in Singapore using an integrated GIS tool | The construction of the new North-East line had greatly improved accessibility of the northeastern areas, but had insignificant impact on accessibility of the northern, northwestern and eastern parts of the country |
| Dong et al. (2006) | Propose a new measure of accessibility and compare it to traditional measures of accessibility | The activity-based accessibility measure is shown to be successful in combining different types of trips into a unified measure of accessibility, and. improves the ability to quantify the ease and convenience of access to spatially distributed opportunities |

Source: this dissertation

**Summary:**

There is a substantial amount of research carried out on the definitions and formulations of mobility and accessibility, and on investigating the impacts of transportation systems on them. The literature indicated that the potential model is usually used to evaluate the intensity of the interaction between socioeconomic groups at different locations, and is also suitable as a social indicator for measuring the level of access to socioeconomic opportunities. In addition, travel time is the most common and significant component in formulating mobility and accessibility models in the literature. However, there is scant literature available that has investigated the impacts of operations of airlines on the mobility and accessibility of air transportation network. In particular, the issue how international airline alliances influence the mobility and accessibility of air travel for improving the transportation efficiency and connectivity of airline networks has rarely been explored.

## 2.4 Disease related issues

In recent years emerging infectious diseases, such as the avian influenza and severe acute respiratory syndrome (SARS), have rapidly caused many infected cases in humans, negatively affecting human life and the economy. There are some studies focusing on reviewing infectious diseases and analyzing their impacts. Capua and Alexander (2002) reviewed the evolution of avian influenza and discussed its relation to human health. They showed that new strains mostly certainly emerged after reassortment of genes of viruses of avian and human origin in a permissive host, and an H5N1 avian influenza virus was recognized as the cause of death of 6 of 18 infected patients, a very high mortality rate, during 1997 in Hong Kong. Centers for Disease Control and Prevention (2003) showed that

of the 131,132 persons who were quarantined during the SARS epidemic in Taiwan, the highest percentage of persons who had suspect or probable SARS diagnosed were persons who sat near a SARS patient on the same airplane flight. Olsen et al. (2003) indicated a high rate of transmission of SARS on aircraft, and believed that the most plausible explanation for the development of SARS in the passengers and crew members of a given flight was that they were infected while on board the aircraft, although other explanations were possible.

Brahmbhatt (2005) pointed that the avian influenza H5N1 will change into a form that is highly infectious for humans and spreads easily from person to person, if given enough opportunities. Given that H5N1 would be a global disease and would last longer than SARS, he predicted that H5N1 would result in a loss of around $800 billion around the world. Since the bird flu virus could also be carried to another region over the world by wild birds or by illegal trade, he said this may lead to genetic reassortment and the start of a human pandemic in some other region, not restricted to East Asia area. Ligon (2005) reviewed information about the virus itself and its spread among poultry, migrating birds, mammals and humans, and indicated that the next pandemic would result in the deaths of at least 2 to 7 million people. He defined an influenza pandemic as a global outbreak of disease that occurs when a new strain of influenza A virus emerges in the human population, causes serious illness and then spreads easily from person to person worldwide. To prevent and control the spread of H5N1, he showed several activities implemented by Hong Kong, such as preparing a pandemic preparedness plan, conducting human and poultry surveillance programs, stockpiling antiviral drugs for treatment and prophylaxis, and raising public awareness of issues related to an influenza pandemic.

There are also some studies focusing on the design and evaluation of disease control measures. For example, King et al. (2004) established animal and human virological

surveillance systems to monitor evolutional changes of influenza viruses in the same and different hosts/geographical areas over years. They showed that the integrated surveillance was very useful in disease control and understanding conditions for the emergence of novel influenza viruses with pandemic potential. Ferguson et al. (2005) modeled the spread of a pandemic in Thailand by incorporating random contacts associated with day-to-day movements to work within the country, and then evaluated the potential effectiveness of containment strategies. They showed that containment and elimination of an emergent pandemic strain of influenza at the point of origin was feasible using a combination of antiviral prophylaxis and social distance measures. Rapid identification of the original case cluster, effective delivery of treatment to a high proportion of the targeted population, and sufficient stockpiles of drug were the key criteria must be met for a high probability of success in disease control.

In addition, numerous studies have proposed mathematical epidemic models to evaluate and describe the dynamic evolution and the severity of epidemics in the population. For example, Massad et al. (2005) proposed a dynamical model to assess the expected burden of the epidemic in the absence of control measures and the impact of adopting well-known precaution methods. The proposed model was applied to the communities of Hong Kong and Toronto, and projected that the final number of cases would be 320,000 in Hong Kong and 36,900 in Toronto in the absence of control. With control measures, the expected final number of cases was reduced to 1778 in Hong Kong and 226 in Toronto. Colizza et al. (2006, 2007) developed a metapopulation stochastic epidemic model on a global scale, and used a stochastic transport operator to describe the dynamics of individuals based on travels between cities. They concluded that a cooperative strategy where countries with large antiviral stockpiles shared a part of their resources with other countries resulted in a global deceleration of the pandemics. For highly contagious viruses, even the

unrealistic use of antiviral drug supplies corresponding to the treatment of approximately 20% of the population, there was still 30%-50% of the population infected. They also demonstrated that in the case of limited antiviral drug supplies, the more cooperative the strategy, the more effective were the containment results in all regions of the world. Table 2.5 summarizes the main issues and features as well as important results in the existing literature on disease related issues.

Table 2.5 Main issues, features and results on disease related literature

| Authors | Main issues and features | Important results |
|---|---|---|
| Olsen et al. (2003) | Investigate the transmission of SARS on aircraft | There is a high rate of transmission of SARS on aircraft |
| King et al. (2004) | Establish animal and human virological surveillance systems | The integrated surveillance is very useful in disease control and understanding conditions for the emergence of novel influenza viruses |
| Brahmbhatt (2005) | Discuss the impact of the avian influenza H5N1 | H5N1 would result in a economic loss of around $800 billion around the world |
| Ferguson et al. (2005) | Model the spread of a pandemic in Thailand, and then evaluate the potential effectiveness of containment strategies | Containment and elimination of an emergent pandemic strain of influenza at the point of origin is feasible using a combination of antiviral prophylaxis and social distance measures |
| Ligon (2005) | Review information about the virus and its spread | The next pandemic would result in the deaths of at least 2 to 7 million people |
| Massad et al. (2005) | Propose a dynamical model to assess the expected burden of the epidemic | The pandemic is effectively mitigated by the practice of precaution methods in Hong Kong and Toronto |
| Colizza et al. (2006, 2007) | Develop a stochastic epidemic model on a global scale and assess control strategies | A cooperative strategy where countries with large antiviral stockpiles share a part of their resources with other countries results in a global deceleration of the pandemics |

Source: this dissertation

**Summary:**

Past studies have demonstrated the impacts of diseases on the human population. At the same time, there are many works developing transmission models to analyze the spread of diseases. However, the influences of the air travel activities of passengers and the small-world properties of air transportation network on the spatiotemporal evolution of diseases have rarely been incorporated into the construction of transmission models, and have rarely been explored in the literature. In fact, the transmission of diseases may occur during air travel activities of passengers, such as consolidation, conveyance and distribution on scheduled flights and at airport terminals. Besides, the small-world properties of air transportation network may facilitate the spread of diseases. So, the influences of these activities and distinctive properties deserve further investigation.

## 2.5 Low-cost carriers related issues

In the airline industry, low-cost carriers (hereafter LCCs) have reshaped the competitive environment within liberalized markets and have made significant impacts in the world's passenger markets, which had previously been dominated by full-service carriers (hereafter FSCs) (O'Connell and Williams, 2005). Mason (2000) pointed out that LCCs could achieve a significantly lower cost base than FSCs by adopting operational and commercial strategies that differed from those of FSCs, and LCCs tended to focus on short-haul routes operated using only one aircraft type to reduce maintenance costs, and maximize crew flexibility. He further used a stated preference survey of European business travelers to assess the propensity for these travelers to use short-haul LCCs. The results showed that price was the most important purchase factor, and most business passengers that had adopted the low-cost product would consider using it again for future business trips.

He also demonstrated the effect of company size on traveler's selection of airlines and the utilities placed on the variables examined. Mason (2001) indicated that although the capture of UK short-haul business travel traffic by LCCs has been viewed as unplanned when LCCs entered markets, the business travelers sector now represents a major market for LCCs. He also carried out a survey of short-haul business travelers, and found that travelers were becoming increasingly price sensitive, and a half of those travelers on FSCs indicated that their companies encouraged the use of LCCs. It also showed that there is a group of travelers who had begun travelling for business since the prices offered on LCCs made such travel worthwhile. There were 79% of travelers who thought that business class service did not offer value for money for short-haul travel, suggesting that LCCs were more likely to attract these travelers. Importantly, 98.7% of the travelers using easyJet would consider using LCCs for business in the future.

Clarke (2004) indicated that the market share of LCCs had increased to 20% of European airline passengers, and believed that the market still offered considerable growth opportunities. He further showed that LCCs had a 43% share of the UK domestic market, compared to 28% in the US. Company Barclaycard (2005) showed that although the original focus of LCCs was on leisure and tourism travelers, 74% of UK business travelers said that they had used the service of LCCs for business trips. O'Connell and Williams (2005) pointed out that LCCs had pursued simplicity, efficiency, productivity and high utilization of assets to offer low fares to passengers. Specifically, the characteristics of LCCs include a simplified fare structure, use of secondary airports, point-to-point direct flights, short turnaround time, a single type of aircraft, payment for in-flight services, and so on. They indicated that prior to 2002, there were no significant LCCs operating in the Asia Pacific rim, so the experience of LCCs was a relatively new phenomenon in the region with much of the necessary management experience brought in from outside the region. They

further conducted a survey of passengers in both Europe and Asia to compare passengers' selection criteria between FSCs and LCCs. It showed that the positioning of secondary airports long distances from the major cities did not seem to pose a significant barrier to the use of LCCs, and if FSCs reduced their fares by 30%, then 43% on average of LCCs' passengers would switch over to FSCs.

Fourie and Lubbe (2006) indicated that there were some differences in the European, Brazilian and South African airline operating environments, and then conducted a survey of passengers in South Africa to investigate factors that may influence business travelers in their selection of FSCs or LCCs. They found that compared to similar studies, travelers in different countries viewed service attributes such as frequent flyer programs (FFPs), the flight frequency, in-flight service and business lounge options in a similar way. However, they showed that for those travelers who preferred LCCs and those who preferred FSCs, there was no significant difference between them when they placed the importance on price. It may due to that the domestic FSC of South Africa had been competing strongly on price in recent years, with its price often the same as that of LCC. Huse and Evangelho (2007) investigated business traveler heterogeneity using data from a survey carried out amongst airline passengers, and used factor analysis techniques to find types of travelers through grouping of preferred attributes. The results showed that passengers who had previously used LCC services did not value FFPs as highly, i.e. there was a negative and significant effect on the valuation of this attribute. It also indicated that previous exposure to the LCC made passengers re-evaluate their preferences towards in-flight service in a way that was more favorable to the LCC. In addition, a substantial portion of business travelers, who previously did not fly for business reasons, would use LCCs. Table 2.6 summarizes the main issues and features as well as important results in the existing literature on low-cost carriers.

**Summary:**

The literature on LCCs focused on investigating the behavior of LCCs' passengers and FSCs' passengers, and the heterogeneity and differences existing between them. These studies demonstrated that a significant number of business travelers are using LCCs for short-haul services, although this kind of travelers is not the original focus of LCCs. These travelers were showed to reassess the valuation of some service attributes after they used LCCs, and said that they will consider using LCCs again for future business trips. It suggests that LCCs are more likely to attract these travelers than FSCs. However, the literature has rarely explored how the behavior of travelers is affected by the social influences or word-of-mouth influences, which come from the opinions and information of social neighbors around travelers, and which may have a certain level of power to adjust travelers' purchase decisions. In addition, few studies have investigated the influences of small-world properties of a social network on the traveler decisions and the LCCs diffusion in the network.

Table 2.6 Main issues, features and results on low-cost carriers related literature

| Authors | Main issues and features | Important results |
|---|---|---|
| Mason (2000) | Conduct a stated preference survey of European business travelers to assess the propensity for these travelers to use short-haul LCCs | Most business passengers that have adopted the low-cost product would consider using it again for future business trips, and the company size affects the traveler's selection of airlines and the utilities placed on the variables examined |
| Mason (2001) | Conduct a survey of short-haul business travelers to investigate similarities and difference between them | A half of those travelers on FSCs indicate that their companies encourage the use of LCCs, and 98.7% of the travelers using easyJet would consider using LCCs for business in the future |
| O'Connell and Williams (2005) | Carry out a survey of passengers in both Europe and Asia to compare passengers' selection criteria between FSCs and LCCs | There were no significant LCCs operating in the Asia Pacific rim prior to 2002, and if FSCs reduced their fares by 30%, then 43% on average of LCCs' passengers would switch over to FSCs |
| Fourie and Lubbe (2006) | Conduct a survey of business passengers in South Africa to investigate factors influencing traveler's selection of FSCs or LCCs | Compared to similar studies, travelers in different countries view service attributes such as FFPs, flight frequency, in-flight service and business lounge options in a similar way |
| Huse and Evangelho (2007) | Investigate business traveler heterogeneity using data from a survey carried out amongst airline passengers | Previous exposure to the LCC make passengers re-evaluate the valuation of some service attributes in a way that is more favorable to the LCC |

Source: this dissertation

## 2.6 airport delay problems

In the US and Europe, the passenger demand and flight traffic at airports have been rapidly increasing, while airport capacity has been limited due to a huge cost involved in capacity expansion. It results in severe congestion and delay problems for airports and airlines. Ground-holding policy is a short-term approach to solve the congestion and delay problems, in which optimally controlling the flow of aircraft by adjusting their release times into the airspace is a cost effective method to reduce the impact of congestion on the air traffic system (Bertsimas and Stock Patterson, 1998).

The literature of ground-holding problem can mainly be divided into four categories, static, dynamic, deterministic and stochastic versions. The static version of ground-holding problem makes the hold decisions once at the beginning of daily operations. For example, Vranas et al. (1994) formulated and studied several integer-programming models to assign ground-holding delays optimally in a general network of airports with the assumption that these ground holds were decided once at the beginning of the day. For each case, they further compared the optimal objective function values for three mathematical optimization problems: the integer problem, the corresponding linear programming relaxation, and the decomposed program defined as the integer program without the connections between flights. The results showed that when cost functions differed and/or when capacities were not uniform, the difference between the optimal objective function values of the integer and the decomposed problems could be large. It also showed that finite departure capacities had negligible impact if they were assumed not to influence arrival capacities, and as far as the model with flight cancellations was concerned, high cancellation costs were impractical because they resulted in no flights ever being cancelled.

In contrast to the static version of ground-holding problem, the dynamic version makes the holding decisions of aircraft during time of the day as better capacity estimates become available. Richetta and Odoni (1994) extended the ground-holding problems from a static version to a dynamic version. They proposed a dynamic model that optimally solved the problem by allowing decisions to be made with the most up-to-date forecast information, and by simplifying the structure of the control mechanism, in which they exercised ground holding on groups of aircraft instead of individual flights. Rather than assigning holds to all flights at once, they assigned holds as the scheduled departure time approached. They also demonstrated that using the linear-programming model they could solve the problem for one of the largest airports in the US, and then illustrated the advantage of the dynamic solution over the static solution and the passive strategy of no ground-holding.

The deterministic version of ground-holding problem considers airport capacities as fixed. For example, Janić (2005) developed an analytical model for quantification of the economic consequence of the large-scale disruptions of an airline single hub-and-spoke network with deterministic practical capacity of the hub airport. The economic consequences had been measured by the total airline costs of the delayed and cancelled complexes of flights. The disruptive event was assumed to affect the airport capacity with different intensity, and was characterized in terms of duration, intensity of impact and the time of occurrence. The results showed that the disruption costs had generally increased with increasing duration and intensity of impact of the disruptive event on the airport capacity. The larger and more expensive affected complexes and flights with the higher proportion of the passengers given up had the higher disruption costs.

In contrast with the deterministic version, the stochastic version takes into account the uncertainty in airport capacities. For example, Mukherjee and Hansen (2007) proposed a

stochastic dynamic optimization model that assigned ground delays to individual flights under time-varying arrival capacity to optimize some objective related to quantities of airborne and ground delay, and that allowed for the revision of ground delays for flights that had not yet departed in response to updated information. In the stochastic aspect, they represented the evolution of airport arrival capacity by a scenario tree, in which each branch of the tree represented a capacity scenario or a group of scenarios realized as the day progressed. A capacity scenario corresponded to a possible time-varying arrival capacity profile. The results showed the proposed model produced lower expected total delay cost than a previous model, and this performance gap increased under a stringent ground-holding policy as well as when an early ground delay program cancellation. In cases where airborne delays were permitted, the proposed model would sometimes hold a flight in anticipation of better information about weather clearance times. It also showed that the choice of ground delay cost component in the objective function strongly affected the allocation policy. When it was linear, the optimal solution involved releasing the long-haul flights at or near their scheduled departure times and using the short-haul flights to absorb delays When it was convex, the spread of ground delay was more uniform across all categories of flights, obtaining an equitable solution. Table 2.7 summarizes the main issues and features as well as important results in the existing literature on airport delay problems.

Table 2.7 Main issues, features and results on airport delay problems related literature

| Authors | Main issues and features | Important results |
|---|---|---|
| Vranas et al. (1994) | Formulate several integer-programming models of ground-holding delays using a static approach | When cost functions differ and/or when capacities are not uniform, the difference between the optimal objective function values of the integer and the decomposed problems could be large |
| Richetta and Odoni (1994) | Propose a dynamic model that optimally solved the problem by assigning holds to flights as the scheduled departure time approaches | The linear-programming model can solve the problem for one of the largest airports in the US, and the advantage of the dynamic solution is over the static solution |
| Janić (2005) | Develop an analytical model for quantification of the economic consequence of the large-scale disruptions with deterministic practical capacity of the hub airport | The disruption costs have generally increased with increasing duration and intensity of impact of the disruptive event on the airport capacity, and larger and more expensive affected complexes and flights with the higher proportion of the passengers given up have the higher disruption costs |
| Mukherjee and Hansen (2007) | Propose a stochastic dynamic optimization model that assigns ground holds to individual flights under time-varying arrival capacity | The proposed model produces lower expected total delay cost than a previous model, in which this performance gap increases when an early ground delay program cancellation, and the choice of ground delay cost component in the objective function strongly affects the allocation policy |

Source: this dissertation

**Summary:**

There is an amount of literature on airport delay problems. These proposed models in the literature conventionally minimized the total (ground plus airborne) delay cost to optimally decide the number of time periods that each flight is held on the ground before take-off. These models were usually accompanied with various heuristic algorithms for yielding integer solutions from the linear programming relaxation. When solving ground-holding problems, the use of linear cost functions tends to assign the arrival slots to those flights with high delay cost. A recent study (Mukherjee and Hansen, 2007) allows for applying nonlinear cost functions, showing it tends to obtain more equitable slot allocation across flights than linear cost functions. There is scant research on investigating multiairport ground-holding problems, which were generally restricted to the case when aircraft is delayed, the next flight performed by the same aircraft will also be delayed. Few studies, however, have explored the influences of small-world properties of air transportation network on the duration and propagation of flight delay, so as to investigate how the network connectivity facilitates the delay propagation across flights and airports in response to different allocation strategies.

## 2.7 Summary

There have been numerous studies exploring the small-world properties of specific real-world networks, and further applying small-world networks to analyze the spread of diseases and rumors. These studies usually applied the physical/geographic distance between two nodes in their proposed models. However, few studies have taken into account travel time between two nodes, which is one of the most significant measures of performance in an air transportation system. In addition, a short distance between two nodes

is not always equivalent to a short travel time, implying that applying physical distance to the air transportation system may not be appropriate. Furthermore, these small-world related studies have rarely investigated the effects of international alliances on the connectivity of airline networks, and rarely incorporated the air travel activities into the spread models of diseases. The social influences among passengers who compose a small-world social network as well as the delay propagation due to the small-world properties of air transportation network are also rarely explored.

The majority of the airline alliances related research focused on investigating how alliances contributed to the economic outcomes of airlines by constructing theoretical models and/or using empirical data to estimate models. Little research, however, has been carried out on the effects the alliances have on the connectivity of airline networks. That is, there have been few attempts to explore the improvement of mobility and accessibility of passengers contributed by the establishment of international airline alliances, although mobility and accessibility are the most significant measures of system performance and effectiveness for transportation systems.

There has been a substantial amount of research carried out on the definitions and formulations of mobility and accessibility for various topics. These works also further investigated the impacts of transportation systems on mobility and accessibility. The literature indicated travel time is the most common and significant component in formulating mobility and accessibility models. However, there is scant literature available that has investigated the impacts of airline operations, such as the establishment of alliances, on the mobility and accessibility of air transportation network. In particular, the issue how international airline alliances influence the mobility and accessibility of air travel in terms

of improving the transportation efficiency and connectivity of airline networks has rarely been explored.

Past studies have demonstrated the impacts of diseases on the human population and the economy. At the same time, there have been many works developing transmission models to analyze the spread of diseases. However, the influences of the air travel activities of passengers and the small-world properties of air transportation network on the spatiotemporal evolution of diseases have rarely been incorporated into the construction of transmission models, and have rarely been explored in the literature. On the other hand, there have been numerous studies investigating the behavior of LCCs' passengers and FSCs' passengers, and the heterogeneity and differences existing between them. These studies demonstrated that LCCs have increasingly attracted short-haul business travelers, although these travelers are not the original focus of LCCs. However, little research has been done on exploring how the behavior of travelers is affected by the social influences or word-of-mouth influences, which come from the opinions and information of social neighbors around travelers, and which may have a certain level of power to adjust travelers' purchase decisions. Furthermore, few studies have investigated the influences of small-world properties of a social network on the traveler decisions and the LCCs diffusion in the network.

There is an amount of literature carried out on airport delay problems in terms of single airport and multiairport ground-holding problems with the static, dynamic, deterministic and stochastic versions. In the case of multiairport ground-holding problem, it was restricted to the situation when a given aircraft is delayed, the next flight performed by the same aircraft will also be delayed. Few studies, however, have explored the influences of

small-world properties of air transportation network on the delay propagation across flights and airports in response to different allocation strategies.

To sum up, several important issues about the influences of small-world properties on air transportation network deserve further investigation. However, these issues have been rarely emphasized and theoretically formulated in the literature. This dissertation aims to explore the positive and negative influences of small-world properties on air transportation network with respect to connectivity efficiency, disease pandemic, word-of-mouth marketing and flight delay. A series of models are formulated to systematically investigate the connectivity efficiency with and without alliances, influenza transmission via air travel activities, and duration and propagation of flight delay within an air transportation network with small-world properties. Furthermore, the scope of this dissertation is also extended to the aspect of passengers of air transportation, exploring how the WOM information affects the adoption of LCCs by short-haul business passengers on dynamic small-world social networks. At the micro level, the changing revision of perception, dynamic properties of network structure and social heterogeneity between passengers are all incorporated into the model formulation.

This study explored the influences of small-world properties of an air transportation network on delay propagation and combined the ground-holding problems with small-world properties to investigate the inter-regional delay propagation. An epidemic-like model was applied to illustrate delay propagation across airports located at various regions and their scheduled flights. The concept of shortcuts of a small-world network was used to analyze the characteristics of inter-regional flights, which in turn affected the delay duration and the pattern of propagation over scheduled flights and airports. This study also investigated the influences that the duration of delay, the probability of delay occurrence, the inter-regional long-haul flights and the level of connectivity of airports had on the propagation. At the same time, several allocation strategies of the limited airport capacity were proposed to mitigate the effects of delay, and then their effectiveness was evaluated in terms of the total cost. The proposed model was applied to a real case study of a small-world air transportation network in order to demonstrate the applicability of the model and to compare the effectiveness of the proposed allocation strategies when the shortcut-functional inter-regional flights existed in the network.

The results showed that the majority of all flights had short flying time, but there were a few flights that had long flying time and provided inter-regional air travel services, which were served as shortcuts in the small-world air transportation network. The connectivity of airports did not reflect a power-law distribution on a log-log plot. In the average pattern for all 265 airports, the total cost and the total number of affected flights for Strategy 1 were lower than those for Strategies 2 and 3. This result was the same as those observations at past studies.

However, we observed several important results that have never been discussed at past studies. First, when an airport has a high proportion of inter-regional flights scheduled to arrive and has low capacity due to weather condition, Strategy 3 will be an economic and equitable allocation strategy for this kind of airport. That is, Strategy 3 will change to be the best one among all strategies in this case. Next, the selection of the best strategy depends on the level of connectivity of airports, and Strategy 3 is the best allocation strategy for those airports that are highly connected to other airports. Finally, based on the average patterns of all airports, Strategy 1 not only decreases the total cost, but also indirectly reduces the occurrence and the scope of the inter-regional delay propagation, i.e. it mitigates the inter-regional delay propagation. These important results obtained from our case study may provide helpful insights for the authorities so as to select the best allocation strategy according to the characteristics of airports and scheduled flights. It is worthy to note that these important results mentioned above have never been observed or discussed at past studies.

# CHAPTER 7

# Conclusions

This chapter summarizes the important findings as well as some managerial implications with respect to each part of this dissertation. Furthermore, future research areas that extend from this dissertation and might produce interesting results are also discussed.

## 7.1 Research summary

The purpose of this dissertation is to investigate the positive and negative influences of small-world properties on air transportation network. The methodology and important findings of each part of this dissertation are summarized as follows.

In the first part of this dissertation, we attempted to examine the small-world properties of an international airline alliance network. The effects of the alliance were evaluated by mobility and accessibility models that were formulated based on travel time. The mobility model was demonstrated to be more appropriate to capture the characteristics of air transportation network than the efficiency model. The results showed that the mobility and accessibility of the post-alliance situation are better than those of the pre-alliance situation, and both situations reveal small-world properties. An alliance can effectively improve the connectivity between airports with high-medium traffic and those with low traffic, and may indirectly induce socioeconomic activities in the latter. After the alliance, some shortest paths may involve more transfers but shorter travel time. The results suggested that airlines should form alliance routes to strengthen the competitiveness of airports with high-medium traffic because alliances can bring

great advantages to such airports and to the airlines involved. That is, airlines can apply our findings to re-design their networks so as to increase their number of passengers and profit. Since the network performance of the three-airlines alliance is better than that of the two-airlines alliance, it suggests that the present alliance can form further alliances with other international airlines to increase the connectivity and efficiency of their networks.

In the second part of this dissertation, we focused on investigating the effects of air travel activities on the transmission of influenza in a small-world air transportation network. We incorporated the air travel activities (passenger consolidation, conveyance and distribution) at airports and on scheduled flights to formulate the transmission models of influenza. For realism of the proposed model, we have weighted each link of the network by the flying time and the number of passengers on the flight. The effects of small-world properties of air transportation network on disease transmission were also discussed. The transmission models were further used to illustrate the spatial and dynamical evolution of disease transmission in the network, and to evaluate the effectiveness of control measures. The results showed that the number or infected individuals and the geographic scope of transmission increased with time, and those airports with a huge number of passengers would accelerate the transmission of disease and cause a much larger pandemic than the average level. This new finding suggests that the public health authorities should avoid the influenza being spread to these airports using complete control strategies. Under the constraint of limited resources, the authorities could in turn practice control measures at airports of different categories, which is an economic and effective approach to mitigate the disease transmission. However, once the influenza grows up its infectiousness over expectation, the authorities should practice control measures as quickly as possible.

In the third part of this dissertation, we focused on the demand side of air transportation network, in which the first purchase behavior of passengers was investigated in order to illustrate the dynamic adoption pattern of products sold by airlines. Passengers were formed as a small-world social network, i.e. they were not only highly clustered with their friends and acquaintances, but also connected to unfamiliar persons of different social groups by the weak connections. Passengers who obtained the WOM information from their social neighbors would revise their perceptions about products over time, thereby influencing the purchase probability and decision. We incorporated the facts mentioned above into the formulation of the intensity model of WOM information, in which passengers would increase their purchase probability if the intensity of WOM is more than a given threshold. The intensity model of WOM information has never been formulated or discussed in the literature, and may be helpful for relevant airlines and authorities. The results showed that the diffusion pattern of the small-world network lie in between those of regular and random graphs. Without considering the WOM influence in the small-world network, it will result in a mistaken prediction. If the price of LCC is close to that of FSC, then LCC would lose its competitive advantage. However, the LCC could apply a slightly higher price to a lower risk-averse society. These important results provide several managerial implications: (1) applying the same strategy to different characteristic societies may have great risk associated with the failure of marketing; (2) LCCs should pay more attention to the use of WOM communication, and they may release a certain number of free tickets so as to increase the number of passengers with LCC experience, thereby increasing the resulting adopted rate through the transmission of WOM; and (3) LCCs should develop a strategy for enhancing the willingness of passengers to actively or passively share WOM with other people in order to increase the adopted rate.

In the last part of this dissertation, we applied the small-world properties of air transportation network to airport delay problems. The shortcut functions and effects of inter-regional long-haul flights were investigated to illustrate how they cause inter-regional delay propagation across airports and their scheduled flights. The arrival capacity of a given airport was affected by the local weather condition over time, and combining it with different allocation strategies would cause ground holds and delay to flights. We applied an epidemic-like model to illustrate the behavior of delay propagation across airports and flights, in which each airport had two states of disease, whereas each flight had three states of disease. According to the delay duration and the probability of delay occurrence, each flight may incur a certain delays and will not be released until its ground holds is finished. The results showed that according to the average pattern for all airports, a strategy that tends to allocate slots to long-haul flights is the best one among all allocation strategies. However, for those airports that have a high proportion of inter-regional flights scheduled to arrive and provide low capacity to flights due to severe weather, a strategy that is based on the first-scheduled-first-served allocation principle will change to be the best strategy. This kind of strategy is also the best strategy for those airports with a high level of connectivity to other airports. These important and new findings that have never been observed before indicated that, the selection of the best strategy depends on the characteristics of airports, and applying the same strategy to all airports would not result in an optimum condition as one expects before. The results mentioned above may provide helpful insights for the authorities so as to select the best allocation strategy.

The contributions of this dissertation are discussed as follows. This dissertation is the first one to examine the small-world properties of airline alliance networks and to incorporate the air travel activities to construct the models of influence transmission.

This dissertation is also the first one to construct the intensity model of WOM information, and to combine various kinds of social heterogeneity to explore how the adoption behavior of passengers changes over time, and how it is affected by the dynamic properties of network structure. In addition, this dissertation is the first one to combine the small-world properties and an epidemic-like model with the ground-holding policies in order to re-interpret the airport delay problem. This systematical methodology enables us to observe some important results that have never been discussed in the literature. These important results obtained from this dissertation may provide helpful managerial implications for the authorities, airports and airlines when they deal with relevant issues and make decisions.

## 7.2 Directions for future research

According to the proposed models and important findings of this dissertation, we discuss several directions for future research. First, although we have found that the performance of the three-airlines alliance is better than that of the two-airlines alliance, the effectiveness of increasing alliance routes may not justify the cost involved. Therefore, we suggest that future studies may further evaluate the trade-off between the effectiveness brought by alliances and the cost involved so as to optimize alliances. Next, for realism we have weighted each link of air transportation network by the flying time and the number of passengers on the flight. However, for predicting the transmission of influenza more realistically, we suggest that future studies should combine the air transportation network with other transportation systems.

In the study of WOM influence on the adoption of products, some social heterogeneity has been incorporated into our model. Future studies could further apply other preference heterogeneity existing in the population to their model formulation, in

order to fit the real population. In addition, we suggest that future studies could investigate the influences that the alliances between different industries have on the spread of information across different social groups and industries, and on the designs of effective marketing strategies. Finally, it is necessary to apply real data that are available in the aviation industry to the calibration of parameters of the models, in order to make the results more realistic to the current environment.

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# GLOSSARY OF SYMBOLS

Part I: *Small-world network theory in the study of network connectivity and efficiency of complementary international airline alliances*

| | |
|---|---|
| $\mathbf{G}^{x}(\mathbf{N}^{x},\mathbf{A}^{x})$ | The network of airline 'x' before it enters an international alliance, where $\mathbf{N}^{x}$ and $\mathbf{A}^{x}$ represent, respectively, the set of nodes and the set of links in graph $\mathbf{G}^{x}$ |
| $\left\|\mathbf{N}^{x}\right\|$ | The total number of nodes in graph $\mathbf{G}^{x}$ |
| $\left\|\mathbf{A}^{x}\right\|$ | The total number of links in graph $\mathbf{G}^{x}$ |
| $\mathbf{J}^{x}$ | The set of all origin-destination (OD) pairs served by airline 'x' |
| $\left\|\mathbf{J}^{x}\right\|$ | The total number of OD pairs in graph $\mathbf{G}^{x}$ |
| $\mathbf{S}^{c}$ | The set of the allied airlines with airline 'x' |
| $\mathbf{N}_{c}^{xy}$ | The set of additional nodes for airline 'x' after it has signed a complementary alliance agreement with airline 'y' |
| $\mathbf{A}_{c}^{xy}$ | The set of additional links for airline 'x' after it has signed a complementary alliance agreement with airline 'y' |
| $\mathbf{J}_{c}^{xy}$ | The set of additional OD pairs for airline 'x' after it has signed a complementary alliance agreement with airline 'y' |
| $\mathbf{N}^{xyc}$ | The set of nodes of the airline 'x' network in the post-alliance situation |
| $\mathbf{A}^{xyc}$ | The set of links of the airline 'x' network in the post-alliance situation |
| $\mathbf{J}^{xyc}$ | The set of OD pairs of the airline 'x' network in the post-alliance situation |
| $\mathbf{G}^{xy}(\mathbf{N},\mathbf{A})$ | The alliance network of airlines 'x' and 'y', where $\mathbf{N}$ and $\mathbf{A}$ are the set of nodes and the set of links, respectively |

| | |
|---|---|
| $t_{ij}$ | The travel time between OD pair *i*-*j* ( $i \neq j \in \mathbf{G}^{xy}$ ) |
| $t_{ij}^{m}$ | The shortest travel time between OD pair *i*-*j* |
| $M_{glob}(\mathbf{G}^{xy})$ | The global mobility of $\mathbf{G}^{xy}$ |
| $M_{glob}(\mathbf{G}_{ideal}^{xy})$ | The global mobility of the ideal case of $\mathbf{G}^{xy}$ |
| $M_{glob}^{N}(\mathbf{G}^{xy})$ | The normalized global mobility of $\mathbf{G}^{xy}$ |
| $\mathbf{G}^{xy'}$ | The pre-alliance network of airlines ‘x’ and ‘y’ |
| $\mathbf{R}$ | OD pairs with changed shortest paths after the alliance |
| $k_i$ | The number of neighbor-nodes of node *i* |
| $\mathbf{G_i}$ | The subgraph of node *i*, $i \notin \mathbf{G_i}$ |
| $t_{pq}^{m}$ | The shortest travel time between OD pair *p*-*q*, where both nodes *p* and *q* are the neighbor-nodes of node *i* |
| $M_{loc}(\mathbf{G}^{xy})$ | The local mobility of $\mathbf{G}^{xy}$ |
| $M_{loc}(\mathbf{G}_{i}^{ideal})$ | The local mobility of the ideal case of $\mathbf{G_i}$ |
| $M_{loc}^{N}(\mathbf{G}^{xy})$ | The normalized local mobility of $\mathbf{G}^{xy}$ |
| $A_i$ | The accessibility of origin node *i* |
| $A(\mathbf{G}^{xy})$ | The accessibility of $\mathbf{G}^{xy}$ |
| $P_j$ | The attraction of destination node *j* |
| $\alpha$ | The decay parameter of the shortest travel time |

Part II: *Transmission and control of an emerging influenza pandemic in a small-world airline network*

| | |
|---|---|
| $\mathbf{G}(\mathbf{V},\mathbf{E})$ | A small-world airline network, where $\mathbf{V}$ is the set of nodes and $\mathbf{E}$ is the set of links |
| $I_j(t)$ | The number of infected individuals on flight $j$ at time $t$ |
| $t_j$ | The time on which flight $j$ departs from its origin airport |
| $I_j^o$ | The initial number of infected individuals on flight $j$ at time $t_j$ |
| $j'$ | One of the upstream flights connectable to flight $j$ at the origin airport of flight $j$ |
| $\mathbf{U}_j$ | The set of upstream flights of flight $j$ |
| $I_{j'}^f$ | The number of infected individuals on flight $j'$ when the flight arrives at its destination airport |
| $\alpha_{jj'}$ | The proportion of infected individuals on flight $j'$ who transfer to flight $j$ |
| $Z_j(t_j)$ | The number of infected individuals who board the airplane from the origin airport of flight $j$ at time $t_j$ |
| $N_j$ | The total number of passengers of flight $j$ |
| $j^o$ | The origin airport of flight $j$ |
| $Y_{j^o}(t)$ | The cumulative number of infected individuals in the restricted areas of airport $j^o$ at time $t$ |
| $v_j$ | The proportion of $Y_{j^o}(t)$ who board flight $j$ |
| $S_j(t)$ | The number of susceptible individuals on flight $j$ at time $t$ |

| | |
|---|---|
| $\beta$ | The infection parameter on flights |
| $F_j$ | The total elapsed flying time of flight $j$ |
| $\bar{t}_j$ | The time flight $j$ arrives at its destination airport |
| $I_j^f$ | The final total number of infected individuals in the cabin of flight $j$ at time $\bar{t}_j$ |
| $j^d$ | The destination airport of flight $j$ |
| $\rho_{j^d}$ | The average number of contacts that lead to infection per infected individual per unit of time within the restricted areas of the terminals of airport $j^d$ |
| $X_{j^d}(t)$ | The number of infected individuals within the restricted areas of destination airport $j^d$ at time $t$ |
| $\hat{j}$ | One of the downstream flights connectable to flight $j$ |
| $\mathbf{L}_j$ | The set of the downstream flights of flight $j$ |
| $\lambda_{j\hat{j}}$ | The proportion of $I_j^f$ who stay and wait for transferring to flight $\hat{j}$ |
| $W_{\hat{j}}$ | The waiting time needed for transferring to flight $\hat{j}$ from flight $j$ |
| $\gamma_{\hat{j}}$ | An indicator variable, $\gamma_{\hat{j}}=1$ if $\bar{t}_j \le t < \bar{t}_j + W_{\hat{j}}$; $\gamma_{\hat{j}}=0$ if $t \ge \bar{t}_j + W_{\hat{j}}$ |
| $\mathbf{E}^m$ | The set of those flights whose destination airport, $j^d$, is airport $m$ |
| $Y_m(0)$ | The initial number of infected individuals in the restricted areas of airport $m$ |
| $I(t)$ | The cumulative number of infected individuals in the whole airline network up to time $t$ |

| | |
|---|---|
| $N_o$ | The initial number of infected individuals in the network at time $t = 0$ |
| $\phi_j$ | An indicator variable, $\phi_j = 1$ if $t_j < t < \bar{t}_j$; $\phi_j = 0$ if $t \geq \bar{t}_j$ |
| $H(t)$ | The cumulative percentage of airports with infected cases occurring at time $t$ |
| $\|\mathbf{V}\|$ | The total number of airports in the network |
| $\delta_m$ | An indicator variable, $\delta_m = 1$ if $Y_m(t) > 0$; otherwise $\delta_m = 0$ |

Part III: *Word-of-mouth marketing in a small-world network: the case of low-cost carriers*

| | |
|---|---|
| $p$ | The probability of rewiring links, called network randomness |
| $P_x$ | The probability that a potential passenger adopts LCC based on the information acquired from mass media communication |
| $V_F$ | The observed utility of FSC |
| $V_L$ | The observed utility of LCC |
| $s_q$ | The strength of the social relationship of neighbor $q$ to a given potential passenger $i$ |
| $a_q(t)$ | An indicator, $a_q(t) = 1$ if neighbor $q$ has adopted LCC at time $t$; otherwise, $a_q(t) = 0$ |
| $r_q$ | The probability that neighbor $q$ gives WOM information to potential passenger $i$ |
| $W_i(t)$ | The intensity of WOM information received by potential passenger $i$ at time $t$ |

| | |
|---|---|
| $P_{iL}(t)$ | The probability that potential passenger $i$ adopts LCC at time $t$ according to mass media and WOM communications |
| $\theta_i(t)$ | The adjustment factor of potential passenger $i$ used to alter the probability of adoption at time $t$ |
| $\Omega$ | A threshold of the intensity of WOM |

Part IV: *Application of small-world theory to airport delay problem*

| | |
|---|---|
| $\mathbf{G}(\mathbf{V},\mathbf{E})$ | A small-world airport network, where $\mathbf{V}$ is the set of nodes and $\mathbf{E}$ is the set of links |
| $\Gamma = \{1, 2, ..., T+1\}$ | The set of time periods |
| $M_i$ | The planned arrival capacity of airport $i$ |
| $k_i$ | The number of links connected to node $i$ |
| $\Theta$ | The set of capacity profile scenarios |
| $P\{q\}$ | The probability of occurrence of a scenario $q \in \Theta$ |
| $\tilde{M}_i^q(t)$ | The practical arrival capacity of a specific scenario $q$ of airport $i$ at time $t$ |
| $\varsigma_{ij}(t)$ | The state of a link connecting origin-destination (OD) pair $i$-$j$ at time $t$ |
| $\varsigma_i(t)$ | The state of node $i$ at time $t$ |
| $D_j$ | The expected duration that severe weather at node $j$ lasts |
| $\tau_{ij}$ | The scheduled departure time of a link connecting OD pair $i$-$j$ |
| $F_{ij}$ | The elapsed flying time from node $i$ to node $j$ for a link connecting OD |

| | |
|---|---|
| | pair *i-j* |
| $D_{ij}$ | The delay duration incurred by the link connecting OD pair *i-j* |
| $p(D_{ij})$ | The probability that the link connecting OD pair *i-j* incurs a delay with the duration of $D_{ij}$ time periods |
| $A$ | The matching level between the characteristics of link *ij* and the implemented allocation strategy at node *j* |
| $n_j(t)$ | The number of links that are scheduled to arrive at node *j* at time *t* |
| $G_{ij}$ | The maximum number of time periods that link *ij* may be held on the ground |
| $\beta_{ij}$ | The capacity cut caused by the ground hold of link *ij* |
| $Z$ | The total cost of a given allocation strategy |
| $\mathbf{E}^d$ | The set of delayed links |
| $\mathbf{E}^c$ | The set of cancelled links |
| $c_{ij}^d$ | The delay cost of link *ij* per time period |
| $c_{ij}^c$ | The cancellation cost of link *ij* |
| $N_R$ | The total number of links that have been delayed or cancelled at any past time period |

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## A. Journal Papers

1. Chaug-Ing Hsu and Hsien-Hung Shih, 2008, "Small-World Network Theory in the Study of Network Connectivity and Efficiency of Complementary International Airline Alliances," Journal of Air Transport Management, Vol. 14 (3), pp. 123-129. (SSCI)
2. Chaug-Ing Hsu, Hsien-Hung Shih and Wei-Che Wang, 2008, "Applying RFID to Reduce Delay in Import Cargo Customs Clearance Process," Computers & Industrial Engineering. (SCI, EI) (Accepted and in press)

Working papers:

3. Chaug-Ing Hsu and Hsien-Hung Shih, 2008, "Transmission and Control of an Emerging Influenza Pandemic in a Small-World Airline Network," Paper submitted to International Journal.
4. Chaug-Ing Hsu and Hsien-Hung Shih, 2008, "Word-of-Mouth Marketing in a Small-World Network: the Case of Low-Cost Carriers," Paper preparing for submitting to International Journal.
5. Chaug-Ing Hsu and Hsien-Hung Shih, 2008, "Application of Small-World Theory to Airport Delay Problem," Paper preparing for submitting to International Journal.

## B. Conference Papers

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