國立交通大學

交通運輸研究所

博 士 論 文

航空網路中航班延誤之因果模式

A Causal Model for Flight Delays in an Airline Network

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博 士 論 文

A Dissertation
Submitted to Institute of Traffic and Transportation
College of Management
National Chiao Tung University
in Partial Fulfillment of the Requirements
for the Degree of
Doctor of Philosophy
in
Management

August 2012

Taipei, Taiwan, Republic of China

中華民國一0一年八月

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摘要

航班延誤由於會造成航空公司與旅客的不便和額外之成本，因此為一值得關心之議題，本研究旨在針對航機於多機場間之延誤擴散及航空公司之改善延誤的方法之效果提出分析方法。由於航班之地面與空中運作存在隨機變化的特質，本研究分析航班之抵達與離開機場之延誤背後的因素，以釐清航空公司之班表運作過程中各階段可能受到的干擾因子。

本研究利用一家台灣之航空公司的國內線航班資料，以 Cox 等比例危險模式構建航班抵達與離開機場之延誤模式，本模式可顯示在航班運作過程中之航班延誤擴散的形成。分析結果顯示，起飛之航班所受到的延誤因素較多，相對而言，抵達機場的航班所受到的影響因素主要為氣候及航路與擬降落機場的航管因素，因此，大部分抵達機場的航班之延誤除了起飛機場已形成的延誤外，均非航空公司所能控制，隱含的意義為避免起飛機場的延誤才是根本解決抵達延誤的有效方法。本研究所求出的危險比例可用來衡量在不同情境下延誤的航班恢復正常運作的機會大小，並可分析個別的延誤影響因子對於航空公司班表的可靠度之影響程度。

為減少航班延誤所造成的影響，航空公司無不積極投入地面與空中運作的不確定性事件之預防工作，因此，本研究進一步利用所構建的航班抵達與離開機場之延誤模式，分析航空公司所採取的改善延誤之方法的有效

性，其中包括對於縮短地面作業時間及增加地面與空中運作的緩衝時間之效果的評估，主要的作法為針對投入改善的成本和所減少的延誤之利益進行淨效益的估算。

雖然增加緩衝時間可以減少一些航班的延誤時間，研究發現在考量到緩衝時間的成本之情況下，這種改善延誤的作法對航空公司不一定有利，研究結果並發現，在動態的運作環境中，增加緩衝時間不一定能大幅改善航班的延誤狀況。因此，航空公司可能需要進一步分析真正影響航班延誤的背後之主要因素，在採取許多複雜的改善方法之前，應該先有一套適切的延誤管理計畫。本研究對於航空公司班表與航班延誤擴散之關係提供進一步的了解，因此，對於班表運作的控制及延誤的管理有相當大的助益。

關鍵字:航班延誤擴散、存活分析、Cox 等比例危險模式、延誤成本

A Causal Model for Flight Delays in an Airline Network

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Abstract

Flight delays are a source of great concern as they generate disruptions and increase costs for airlines and passengers. The aim of this research is to propose approaches to examine flight delay propagation in a multiple-airport environment and to evaluate the effectiveness of delay improvement schemes adopted by airlines. Due to the stochastic characteristics of turnaround and block operations, this research investigates the factors behind the mechanisms of departure and arrival delays to clarify the phases and activities involved in flight delays through an airline schedule.

The Cox proportional hazards model, a method widely applied in survival analysis, is used to develop departure and arrival delay models involving a Taiwanese domestic airline. The proposed models show how flight delay propagation can be formulated through repeated chain effects in aircraft rotations. The results shows that whilst outbound flights are subject to a wider range of difficulties leading to delays, inbound flights can be delayed by weather or air traffic control restrictions en-route or at destination airport. Hence, most arrival delays are beyond the control of airlines except for delays that develop at departure airports. This implies that developing the means to prevent departure delays could be the key to reducing arrival delays from the origin. The hazard ratios obtained provide measures of the chances of recovering from flight delays under a variety of situations and the effects that

individual contributing factors of flight delays have on airline schedule reliability.

To manage flight delays, airlines are prepared for the unexpected stochastic events of turnaround and block operations. This research further uses the obtained departure and arrival delay models to examine delay improvement schemes, including shorting required ground handling time and increasing buffer time for turnaround and en-route aircraft. The costs of schemes and the savings of delay costs are investigated to evaluate the net benefits of schemes by recursively combining the departure and arrival delay models.

Though buffer time may save some delays, it is found that it may not be cost effective for airlines when the costs of buffer minutes are taken into account. The results also reveal that delays may not be greatly improved through this measure in the dynamic operating environment. Thus, airlines may investigate the significant contributing factors of delays and design a suitable delay management program before jumping into some sophisticated measures. The findings provide a better understanding of the relationship between planned schedules and delay propagation, and are thus useful for schedule control and delay management.

Keywords: Flight delay propagation, Survival analysis, Cox proportional hazards model, Delay costs

誌謝

進修博士學位一路走來要感謝的人實在太多，感謝諸多師長、學長姐、同學、同事、好友的鼓勵與協助，學業才得以完成。

感謝恩師汪進財教授不論在研究觀念、邏輯思考及論文撰寫皆給予悉心指導與斧正，使學生受益匪淺，僅此致上最深的敬意與謝忱。研究所修課與論文研討，承蒙徐淵靜教授、黃承傳教授、黃台生教授、藍武王教授、馮正民教授、許鉅秉教授、陳穆臻教授、邱裕鈞教授給予專業知識上的指導與建議，對於我的課業學習與論文的進行有相當大的助益，感恩之情，永難忘懷。論文口試時，承蒙顏上堯教授、顏進儒教授、周榮昌教授、陳穆臻教授、邱裕鈞教授不吝指正，提供意見與建議，使本論文更臻完備，在此致上誠摯之謝意。

在學期間，感謝文健學長、政棋學長、劍雲學姐、銘德學長、輝煌學長、其華學長、益三學長、慧娟學姐、素如學姐、孟佑學長、國洲、日新、易詩、昭宏、永祥、群明、文斌、士軒、彥斐、志偉的關心與鼓勵；同學嘉惠、志誠、嘉新不斷相互切磋，以及同學彥蘅在我研究遇到瓶頸時陪我一起努力，皆是無形之助力。

好友崇良、世賢、能博、明政提供許多寶貴的實務資料與建議，使論文能夠順利完成及更具實用價值，感激之情，莫能言喻。同事凌鳳儀主任、孫台興主任的提攜與照顧，在此特表謝意。

漫長的求學期間，爸媽和家人的體諒與支持，使我無後顧之憂，感謝您們長期的付出與陪伴。最後，僅以此論文獻給我辭世的爸爸，以及所有關心、鼓勵我的人。

蔡世昌　謹誌
於交通大學交通運輸研究所
2012 年 8 月

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CHAPTER 1 INTRODUCTION

This chapter consists of four sections. Section 1.1 addresses the background and motivation of analyzing flight delay propagation and evaluating delay improvement schemes. The research objective is presented in Section 1.2. Research scope and research framework are introduced in Sections 1.3 and 1.4, respectively.

1.1 Background and Motivation

Flight delays are a source of great concern because they generate disruptions and costs to airlines, airport operators, ground handlers and passengers. A common assumption in airline schedule planning is that flights will operate as planned. However, aircraft rotations among airports can be disrupted by many factors, such as delays at previous airports, weather, mechanical or logistical problems with aircraft, late-boarding passengers, and late-arriving crews, and therefore this optimistic situation rarely occurs.

Flight delays may occur at different phases of aircraft rotations. When an aircraft is delayed, the airline suffers delay costs since the aircraft and crew in service are fixed in the schedule. Passengers surely are also dissatisfied with the delayed flight and change their loyalties towards the airline due to the unpunctuality of the schedule. Passenger complaints concerning delays, cancellations, and denied boarding have prompted the U.S. Congress to consider stronger measures to ensure passenger protection (U.S. Government Accountability Office, 2011). Of the total delay costs analyzed by Austrian Airlines, only 22% can be attributed directly to the effect of delays. In fact, 24% of these costs come from the permanent loss of passenger loyalty and 54% come from induced knock-on delays in aircraft rotation schedules (Airline Business, 1999). United Airlines estimated that it saved approximately $1.6 million by using a flight delay projection model during the first quarter of 2004 (Abdelghany et al., 2004). Both of these cases suggest that the consequences of delays and their propagation in the air transport system, including decrease of productivity of aircraft as well as loss of time and loyalty of passengers, cannot be neglected.

The general optimization objective of schedule planning is to reduce flight delays while maximizing the utilization of aircraft. Certainly, airlines may or may not be able to control delay causes. Since delays occur randomly, airlines often embed buffer time to schedules for turnaround and block operations to account for stochastic characteristics of delays. Nevertheless, delays will occur when the accumulated delays exceed scheduled buffer time. Though the scheduling of buffer time stabilizes schedule punctuality and reduces delay costs, airlines may incur costs of additional resources by using this improvement measure. The benefits of delay improvement therefore need to be further investigated.

In aircraft's daily operations, delays in one flight might easily propagate to successive flights to have further disruptions. Accordingly, how to obtain the overall effects of an initial flight delay in an airline schedule is essential to solve the problem of flight delays. To achieve this goal, airlines have to understand the mechanisms of flight delay propagation as well as to find out the way to identify the origins and effects of flight delays.

1.2 Research Objective

The objectives of this research include:

1. Propose an approach to explore the problem of flight delay propagation in a dynamic operating environment by considering the stochastic characteristics of turnaround and block operations and clarifying the relationship between flight delays and the associated causes:

   The duration of a delay represents a period of time the delay has *survived* before it comes to an end. To fit the survival characteristics of flight delays, survival analysis is employed to model flight delays in a multiple-airport environment.

2. Propose an approach to evaluate the effectiveness of delay improvement schemes by exploring the costs invested for delay improvement and the

costs of delay saved:

Because arrival and departure delays are stochastic in nature, delay costs need to be investigated by calculating the expected costs incurred in the delays. Thus, an approach including survival distributions of flight delay propagation in an airline network and the associated expected delay costs will be developed. The incurred delay costs will then be used to compare with the costs invested for delay improvement to evaluate the effectiveness of delay improvement schemes.

1.3 Research Scope

This research is to explore the problem of flight delay propagation in airlines' daily operation network. To find out the way to reduce flight delays, the party of interest in this research is airline companies instead of airports. The historical data collected was scheduled flights, which included delayed and on-time flights, collected from a Taiwanese domestic airline. In addition, to explore the effects of flight delay propagation, we need the information of an extensive flight network with a very high frequency of flights. Thus, the analysis will focus on only its domestic air routes. International air routes operated by the company will not be analyzed in this research. The general problems, including departure and arrival delays, will be the main subjects to be addressed. By combining the effects of departure and arrival delays, flight delay propagation in an airline network can be therefore investigated through repeated chain effects.

1.4 Research Framework

Given the objectives, the research framework is illustrated in Figure 1.1. Chapter 1 explains the background of flight delay problems existing in airline operations and the motivation to find out the way to solve the problems. The objectives and scope of the research are then defined. Prior to analyzing the problems of flight delays, Chapter 2 reviews the studies and applications regarding types and causes, assessment and forecast, and control measures of flight delays to have a better understanding of the relevant issues. Research regarding system costs incurred in flight delays is also reviewed. Chapter 3 first discusses flight delay mechanisms to identify the relationship among flight delays. Two approaches to explore the problem of flight delay propagation are then presented. The first one is to model flight delays in an airline network. The second one is undertaken to analyze the effectiveness of delay improvement schemes using the flight delay models obtained by the first approach. Chapter 4 shows the empirical study using a historical flight data collected from a Taiwanese domestic airline. Chapter 5 makes the conclusions and suggestions.

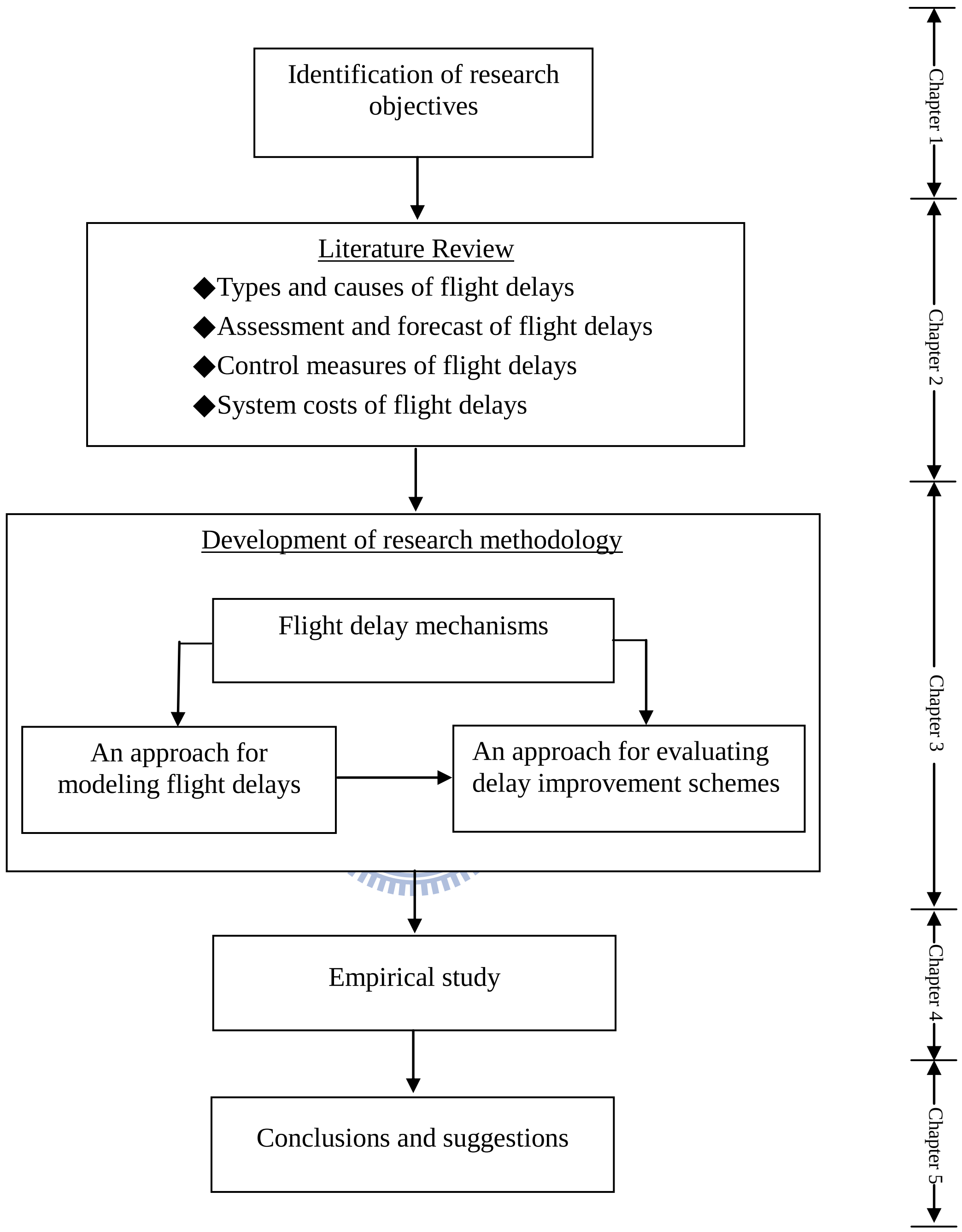


Figure 1.1 Research framework.

CHAPTER 2 LITERATURE REVIEW

This chapter reviews studies and applications regarding flight delays, which include research on types and causes, assessment and forecast, and control measures of flight delays. Because this research will evaluate the effectiveness of delay improvement schemes normally adopted by airlines, research concerning system costs incurred in flight delays is also reviewed.

2.1 Types and Causes of Flight Delays

Airline flight schedules are particularly sensitive to individual flight delays because the operating resources are linked together. The delay of one flight tends to propagate down line to many others. In order to evaluate the reliability of airline operating schedule, it is important to clarify the causes of flight delay and evaluate the effect of an initial flight delay as a whole.

Delay is defined in many different ways, depending upon the context. Scheduled departure and arrival delays are how late a flight departs or arrives compared to an airline's schedule. Flights can incur delays while airborne or on the ground, for example as aircraft taxi between the runway and gate (Wang et al., 2003). Shaw (1987) addressed that there are five different kinds of delays: (1) traffic handling delays, (2) aircraft turnaround delays, (3) aircraft technical delays, (4) air traffic control and airport delays, and (5) weather delays. Jong (2000) illustrated three types of flight delays and their causes:

1. Direct delay to aircraft.

   This delay can be caused by (1) weather: thunderstorm, typhoon, (2) mechanical problem: on the ground or en route, (3) airport-related problem: the shortage of runway or terminal capacities, (4) additional demand: charter flight, (5) staff: lateness or absence of staff, (6) maintenance scheduling: change of scheduling, (7) demand change: re-dispatch different types of aircraft, and (8) others: war, strike, etc.

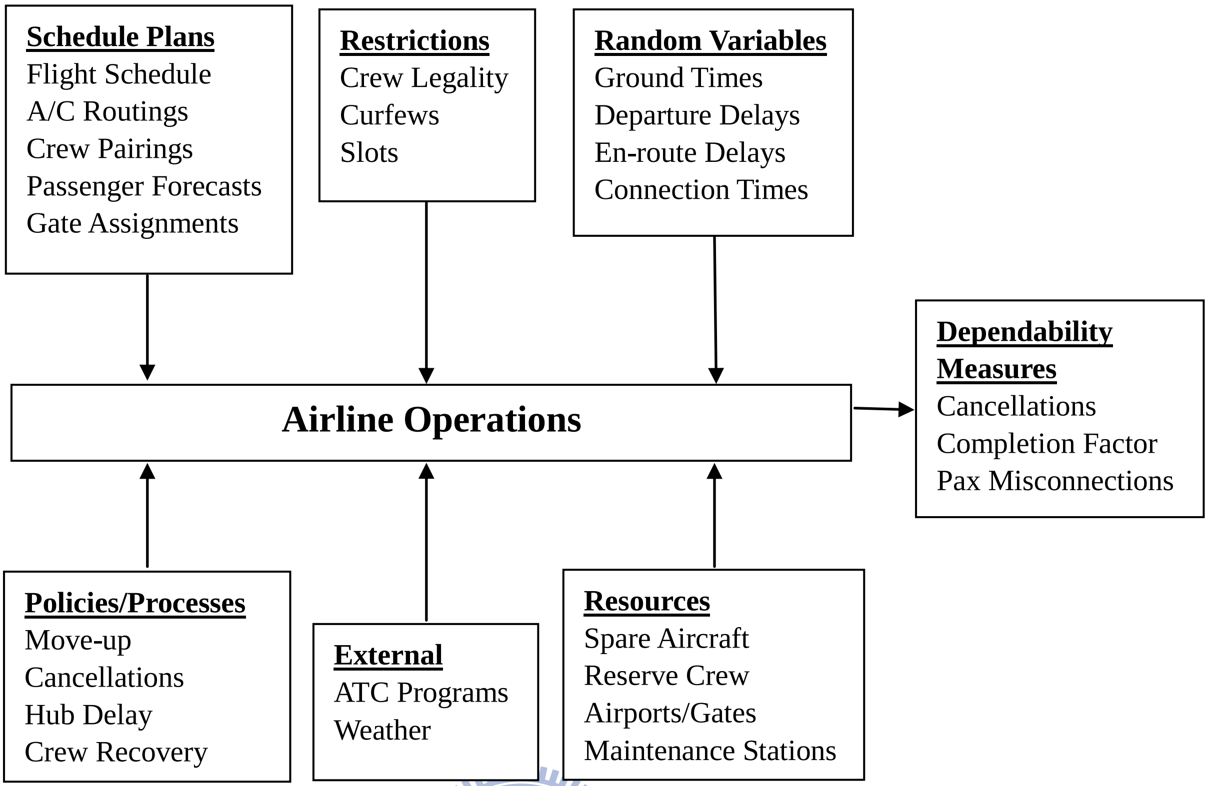
2. Knock-on delay to other aircraft.

   The knock-on delay usually results from the causes of too many aircraft held on the ground or the shortage of runway or gate. It is not unusual that when an aircraft arrives at an airport, the gate is still occupied by previous flight. The inbound flight will then need to hold until the gate becomes available, and thus the outbound flight may not be able to depart on time.

3. Delay due to late connections.

During daily operations, airlines usually arrange an aircraft to take another consecutive flight after arrival. Therefore, the delay of the previous flight will propagate to the next flight if there is not enough buffer time before departure. It is also quite often that passengers have to transfer to another flight to continue their trips at a hub airport. The outbound flight will need to hold for the connection of inbound flight under the circumstances of the delay of the inbound flight.

To evaluate airline schedules for operational dependability, Green (2002) pointed out that the delay inputs include (1) departure delay, (2) unscheduled maintenance delay, (3) block delay: taxi-out and runway queue, air-time delay distribution, and taxi-in and gate queue, and (4) external delay: weather, others. The inputs and outputs of airline operations are illustrated in Figure 2.1.



Source: Green, T., 2002. Evaluating airline schedules for improved operational dependability, American Airlines.

Figure 2.1 Inputs and outputs of airline operations.

A great deal of research attention has been devoted to identifying the causes of delays. Major contributing factors to delay are congestion at the origin airport, convective weather, reduced ceiling and visibility, continuously increasing demand and even changes in air traffic management (ATM) initiatives such as Ground Delay Programs (GDP) (Xu, 2005). Allan et al. (2001) analyzed the delay causality at Newark International Airport. The conclusion of the study was that weather was the dominant cause of overall delay. The different types of delays (gate delay, taxi-out delay, airborne delay, and arrival delay) were broken out to assess the contributions of the different types of weather events (i.e., terminal convection, high winds, low ceilings and visibility, and en route weather) to each.

Wang et al. (2003) presented a simple analytical model that explicitly separated the controllable factors that influence delays and propagation of delays in the National Airspace System (NAS) from those factors that are random variables in a given scenario. The controllable and variable factors are as follows:

1. Controllable factors:

(1) Slack for airport turnaround time.

It is equal to 'scheduled airport turnaround time' minus 'minimum airport turnaround time'.

(2) Flight time allowance.

It is equal to 'scheduled flight time between airports' minus 'minimum flight time between airports'.

2. Variable factors:

(1) Airport turnaround time between flights.

This aggregates all delays that affect airport turnaround time (taxi and gate delays, runway queue, delays due to weather conditions and mechanical problems, as well as other unexpected events).

(2) Flight time between airports.

This aggregates delays that affect flights between airports (delays due to weather conditions, congestion, miles-in-trail restrictions, and runway queue).

However, the causes of delay propagation, which have different impacts to flight schedule reliability, were still not discussed thoroughly in the study.

EUROCONTROL (2003) presented the effect of flight delay propagation which was done through the study of repeated itineraries of the major French airports. The flight delays were classified into two categories:

1. ATFM (air traffic flow management) delays.

   The delays are due to ATFM regulation.

2. Non-ATFM delays.

   The delays include (1) exceptional events: passengers (e.g. VIP), airports (e.g. mandatory security), airlines (e.g. late arrival of aircraft, non availability of aircrew, and plane technical breakdown), and (2) organization of airlines' ground operations (boarding/unboarding, checking, plane handling, etc.)

In the study, it presented that delays on arrival could be predicted essentially from the delay on departure (80%) and to some extent from the load factor (16%). In addition, delays on departure could be predicted essentially from the departure aircraft load factor (70%) when the aircraft is not lengthily delayed on arrival. Tu et al. (2008) identified and studied major factors influencing flight departure delays, and developed a strategic departure delay prediction model. The model employed nonparametric methods for daily and seasonal trends and used a mixture distribution to estimate the residual error. To overcome problems with local optima in the mixture distribution, the study developed a global optimization version of the Expectation Maximization algorithm borrowing ideas from Genetic Algorithms.

Based on the above literature reviewed, the controllable and uncontrollable causes of flight delays (from the perspective of airlines) are shown in Table2.1.

Table 2.1 Causes of flight delays

Category	Controllable Cause	Uncontrollable Cause
En route delay		
Flight time allowance	✓	
Airspace capacity		✓
Miles-in-trail restriction		✓
Air traffic control delay		
Air traffic flow management		✓
Ground delay program (GDP)		✓
Weather delay		
Thunderstorm		✓
Typhoon		✓
Low ceiling and visibility		✓
High wind		✓
Airport turnaround delay		
Capacity of runway		✓
Capacity of taxiway (taxi-in and taxi-out)		✓
Number of gate		✓
Capacity of apron		✓
Airport closed		✓
Terminal capacity		✓
Pre-departure event		✓
Workforce/per flight	✓	
Buffer time	✓	
Required handling time	✓	
Mandatory security		✓
Crewmember delay		
Lateness or absence of crewmembers	✓	
Passenger delay		
Checking	✓	
Missing	✓	
Miss of connection	✓	
Boarding/unboarding (load factor)	✓	
VIP	✓	

Table 2.1 Causes of flight delays (continued)

Category	Controllable Cause	Uncontrollable Cause
Maintenance delay		
Maintenance scheduling	✓	
Unexpected event		✓
Additional demand		
Charter flight	✓	
0thers		
Strike		✓
War		✓

Source: Collated and tabled by the author

2.2 Assessment and Forecast of Flight Delays

Delay propagation occurs when late arrivals at an airport cause late departures, which in turn cause late arrivals at the destination airport. Many studies have dealt with both schedule optimization and schedule recovery strategies (Barnhart et al., 1998), and a large number of airline planning tools have also been developed (AhmadBeygi et al., 2008). Nevertheless, a prerequisite to the development of tools for building more robust airline schedules is an understanding of the relationship between planned schedules and delay propagation. Thus, to design a robust airline schedule and increase its reliability, researchers have attempted to quantify flight delays or to model the scale of flight delay propagation to find a way to minimize the effect of flight delay propagation on airline networks (Beatty et al., 1998; Schaefer and Millner, 2001; Wu, 2005; Xu et al., 2005; AhmadBeygi et al., 2008).

Wong (1995) presented an analytical structure for modeling flight delays at C.K.S. International Airport, which took into account not only the stochastic characteristics of flight delays, but also the required minimum ground handling time. The results revealed that arrival delay is stochastically distributed and that it is strongly correlated (R^2=0.84) between the insufficient ground time and departure delay.

Abdelghany et al. (2004) proposed a deterministic model to predict the propagated delays along aircraft routes based on the concept of resource networks and shortest paths. As operated, an aircraft is ready after its required service/maintenance activities are completed. A crewmember is ready after connecting from the arrival gate to the next departure gate, or after receiving the required legal rest between two successive duties. In the normal operating conditions, all resources are planned to be ready before the scheduled departure time of their next assigned flights by some buffer time. However, it was pointed out in the study that flight schedules are often subject to numerous sources of irregularities: (1) misconnect break, (2) rest break, (3) duty break, and (4) ground delay program (GDP). It is noted that this flight delay model ignores the stochastic issues of flight delays.

To analyze the impact of micro airport-level causes on macro system-level performance, Xu et al. (2005) proposed to use Bayesian Networks to investigate propagation of delays among airports instead of using linear and nonlinear regression methods. Although traditional linear and nonlinear regression methods have been applied to understand and explain the influences of weather, demand and other factors in the aviation system, the application has generally been limited to either single-airport analyses or aggregate analysis of the whole system. The methodology presented in the paper combined multiple individual-airport Bayesian network models into a system-level model capable of representing interactions between airports and quantifying how flight delays from a single airport propagate to impact other airports.

Liou (2004) developed a real-time air traffic flow management (ATFM) program for a multi-airport and multi-period system. This program predicted 15-minute traffic demand, traffic flow and capacity for certain time frame in advance and then determined number of departure flights for each airport, based on the predicted flow and capacity. Hsu (2002) applied probability and statistical methods to model flight delay propagation effects, allowing for behavioral response.

In order to analyze the performance of airport operations and the flight delays due to runway direction change, a SIMMOD-based multi-airport simulation model, including both Taipei and Kaohsiung airports as well as the airspace in between, was developed, calibrated and validated using the ATC data and observed operational data (Wu, 2004). The result demonstrated that because of the required transitional operations from one network configuration to the other, only two or three flights could be allowed to use the runway in the first 15 minutes after the runway direction change. As a consequence, the following flights would somehow be delayed. In addition, the simulation showed that if ATC could separate the arrivals effectively, the first departure flight could reduce delay by 21%, and the total propagation time could be shortened. However, the assumption of this study was that all flights will operate as schedule without cancellation of flights while the destination airports are closed. This may not always happen in airlines' operations. In addition, an interesting future research would be to generate a national-wide model that could be applied across all major airline/airport combinations.

Schaefer and Millner (2001) used the 'Detailed Policy Assessment Tool' to model delay propagation in a network of airports when facing inclement weather conditions. It showed that when only Visual Meteorological Conditions (VMC) exists at all airports, delays are not significant, and therefore the propagation effect is unobservable. Locally, delay increases with increasing duration of Instrument Meteorological Conditions (IMC). Propagated effect is significant for the 1st leg after leaving an IMC airport and diminishes from leg to leg. At an airport with a high capacity-to-demand ratio, IMC operations can be accommodated without significantly increasing delay. The analysis focused on delays incurred due to inclement weather at one airport. However, when multiple airports are experiencing inclement weather, it would be desirable to develop a method to assign delays to previous airports to determine defects caused by each airport, in addition to accumulating effects from all airports.

To better understand the total effects of airline flight delays produced by the FAA's Ground Delay Program (GDP), Beatty et al. (1998) used a numerical 'delay multiplier' (DM), which was based on the length of the initial delay and the time of day it occurs. This was an attempt to develop a generic total value of both the initial delay and its continuing consequences on the airline schedule rather than to predict the actual down line effect any given flight delay would produce. The paper found that large delays early in the day are most disruptive and that the delay multiplier grows nonlinearly with the size of the initial delay. Therefore, reducing a large initial delay by any amount will have a significant effect on total delay for an airline.

Tu et al. (2008) attempted to characterize the underlying mechanisms behind flight delays. Rather than studying the impact of each factor alone, factors were grouped into three major categories: (1) seasonal trend, (2) daily propagation pattern, and (3) random residues, in order to estimate flight departure delay distributions.

2.3 Control Measures of Flight Delays

Flight delays or cancellations occur almost everyday and have made airlines seriously suffer from the perturbation of flight schedule. Wong and Lu (1996) developed an analytical structure of aircraft dispatching strategy for irregular flight incidents beginning with a description of the causes and characteristics of irregular incidents. These irregular incidents were then classified by available resources on the sites of the incidents and the level of the incident impact to the airlines. After the classification, a framework of aircraft dispatching strategy for irregular flight incidents was developed. In the framework, aircraft swapping was one of the important components suggested. Following that, a procedure to find and evaluate feasible aircraft dispatching alternatives was proposed. However, the constraints of aircraft maintenance requirement and the availability of staff were not thoroughly discussed in the study. Also, while confronting with irregular flight incidents, the evaluation of the cost of flight cancellation and the cost of dispatching aircraft will be essential before making an aircraft dispatching decision.

Jong (2000) established a set of delay-controlled strategies on controlling the propagation of flight delays caused by incidents. This study explored the propagation conditions of flight delays for different situations, including gate uses, connecting flights and transfer requirements, and then derived the extent of flight delay propagation. This study also showed that buffer time affects flight delay propagation greatly, and flight delay propagation will be serious if buffer time is short.

Wu and Caves (2002) developed a simulation model to simulate aircraft rotation in a multiple airport environment. The developed aircraft rotation model consisted of two sub-models, namely the aircraft turnaround model and the en route model. In fact, the modeling of the aircraft turnaround process had been studied in the literature by using analytical methods as well as critical path methods (Braaksma and Shortreed, 1971; Hassounah and Steuart, 1993). However, these models had not been successful to capture the stochastic characteristics of aircraft turnaround operations such as the uncertainty from the ground service time of an aircraft and the influence of operational disruptions to aircraft turnaround operations. Hence, in the study the Markov Chain concept was employed in the aircraft turnaround model to simulate the stochastic occurrence of operational disruptions to aircraft turnaround and to model the stochastic service time of turnaround activities.

Vranas et al. (1994) addressed the multi-airport Ground-Holding Problem (GHP) in a dynamic environment. In the study, algorithms were proposed to update ground-holding decisions as time progressed and more accurate weather (hence capacity) forecasts became available. This study proposed several pure IP formulations (most of them 0-1), which had the important advantages of being remarkably compact while capturing the essential aspects of the problem and of being sufficiently flexible to accommodate various degrees of modeling details.

Since the air traffic congestion is cause by the limited capacity, which is heavily influenced by the weather conditions such as visibility, precipitation and wind, it is important to study the interactions of aircraft between airports. Liou et al. (2001) addressed the multi-airport air traffic control (ATC) problem of the Taipei Flight Information Region (FIR) to determine how many aircraft must be held on the ground before take-off and to minimize the total holding (airborne and grounding) costs. This problem was formulated as an integer programming problem in which the flight flow balance and the capacity constraints of airports were considered.

Wu and Caves (2000) investigated the relationship between flight schedule punctuality and aircraft turnaround efficiency at airports in order to minimize system operational costs and meanwhile to maintain a required level of schedule punctuality. A mathematical model was proposed to simulate aircraft turnaround performance by taking into account stochastic effects of schedule punctuality and delay absorption effects of schedule buffer time.

Wong (1992) presented an optimization model for airport gate assignment. In the study, factors affecting the gate assignment were discussed. The objectives of this model were (1) to minimize the total passengers' travel distance, (2) to minimize the total passengers' delay, and (3) to minimize the weighted sum of total passengers' travel distance and delay. Furthermore, Wong and Lu (1994) evaluated the performance of apron operations of C.K.S. International Airport and suggested adopting a dynamic gate assignment strategy. Experimental results indicated that aircraft should be assigned to gates not only depending on flights schedules, but depending on their actual behavior relative to those schedules and aircraft servicing requirements. Also, more effort is required to assign flights optimally over low utilized gates. Because knock-on delays often result from the shortage of gates, a dynamic gate assignment will help airlines reduce flight delays. In addition, to handle the increasing number of aircraft, shortening buffer time by improving the efficiency of gate use is worth pursuing as well.

Stamatopoulos et al. (2004) developed an integrated set of models that had been developed to assist airport operators and managers in planning strategically for expanding and optimizing the airfield (runways, taxiways, aprons) and for improving operating procedures or managing demand ('slot control and allocation'). Although the goal of MACAD (MANTEA Airfield Capacity and Delays model), the decision support system described in this study, was to provide such a tool for performing this type of analysis quickly, reliably and with limited effort, the analysis of the congestion problem of terminal area was not available in this model.

Optimizing the utilization of aircraft resources requires that airline business models employ tight turnaround time between flights, which can increase the likelihood of delays in subsequent flights. The typical approach to dealing with disruptions is to re-optimize the schedule; however, a more proactive approach is to build robustness into the schedule in the planning stage. Various statistical models and simulation techniques have been developed to assist in the planning of airline schedules and to minimize the impact of delay propagation in an airline network (Tu et al., 2008; Xu et al., 2005; Lan et al., 2006; Lee et al., 2007). Yan and Tu (1997) developed a framework to assist carriers in fleet routing and flight scheduling for schedule perturbations in the operations of multifleet and multistop flights. The framework was based on a basic multifleet schedule perturbation model constructed as a timespace network from which strategic models were developed to research incidental scheduling. Yan et al. (2002) further developed a network model together with a solution algorithm that could directly manage the interrelationships between passenger trip demands and flight suppliers, in order to effectively assist airlines' scheduling.

To limit flight delays, considerable efforts have been made to develop proactive schedule recovery models. Progress in this field has advanced our understanding of complex issues related to schedule recovery. Lan et al. (2006) developed a delay propagation model on a flight basis by fitting the distribution curves of flight delay data for the aircraft routing optimization problem. Results showed that significant improvement of schedule robustness can be gained by considering delay propagation in schedule planning.

Flight delay analysis is important for managing and reducing delays in future schedule planning and operations. Delays in airline schedules may be the results of many different causes. However, most studies have emphasized the technical aspects of optimizing airline schedules and failed to consider the critical role played by airline ground operations and other delay causes in contributing and controlling delays in daily operations. Wu and Wong (2007) aimed to address the problem of delay propagation in an airline network by explicitly considering the stochastic characteristics of airline ground operations at airports and the delay propagation mechanism among flights in the airline network. A multiple regression model was developed to describe the departure and arrival delays of individual flights. However, the occurrence probabilities of flight delays and their impacts on propagated flights, which may vary under different circumstances, were ignored in this study.

2.4 System Costs of Flight Delays

Flight delays, for example, can be caused by mechanical problems, gate occupancy, or crew's legality. Flights can also be delayed if safety issues arise due to severe weather or other causes. In the industry there have been many discussions about how to reduce flight delays while maximizing the utilization of aircraft with very tight connections between flights. Flight delays can be divided into three phases: delays on the ground at gate, delays while taxiing at origin or destination airport, and delays while airborne (en-route and holding). When an aircraft is delayed, the airline suffers system costs, which include delay costs and buffer costs. The delay cost is the cost for the delay incurred on the day of flight operations, and the buffer cost is the cost of adding buffer time to schedule, which is planned in advance in anticipation of delays (Cook and Tanner, 2011). It is in the sense that schedules are designed with buffer time built into the schedules to absorb the unpredictability of delays in day-to-day operations. However, the schedule buffer minutes may reduce the number of aircraft rotations in a given day, and are the 'hidden costs' associated with airline schedules no matter whether they are fully used or not (Cook et al., 2004). Wu and Caves (2002) developed a cost minimization model to optimize the scheduling of aircraft rotation by balancing the use of aircraft and delay costs. The regularity analysis of the optimized schedule also suggested that the robustness and reliability of schedule implementation can be improved after optimization. Thus, taking into account both the profitability of a schedule and the propagation of delays in operation presents an important opportunity and is also a challenge for airline planners.

The elements of system costs are shown in Table 2.2. The delay costs include ‘*aircraft delay costs*’, comprising of fuel costs, maintenance costs, crew costs, and aeronautical charges, and *‘passenger delay costs to airlines*’. The buffer costs, on the other hand, include ‘*aircraft delay costs*’, summing only fuel costs, maintenance costs, and crew costs, and ‘*fleet costs*’.

Table 2.2 Elements of system costs

Cost Element	Delay Cost	Buffer Cost
Aircraft delay costs		
Fuel costs	✓	✓
Maintenance costs	✓	✓
Crew costs	✓	✓
Aeronautical charges	✓	
Passenger delay costs to airlines	✓	
Fleet costs (depreciation, rentals, and leases)		✓

2.4.1 Aircraft Delay Costs

The aircraft delay costs are the costs of an aircraft incurred during the delay of daily operations. The elements of the costs, following the studies of Wu and Caves (2000, 2002, 2004), are discussed as below.

● Fuel Costs

The fuel costs of delays depend on the fuel burn rates of aircraft types, the fuel price, and the phase where the flight is delayed. A flight delayed on the ground at gate (with APU and engines off for majority of time) is with fuel cost taken to be zero, while the fuel cost of delay per minute en-route and airborne holding is much higher than that at taxi. In calculation of fuel costs, the value of buffer costs is taken to be the same as that of delay costs (Cook et al., 2004).

●Maintenance Costs

The marginal maintenance costs incurred by delayed aircraft during operations relate to factors such as the mechanical attrition of aircraft waiting at gates or accepting longer re-routes to obtain a better departure slot (Cook and Tanner, 2011). As described in the report of Cook et al. (2004), Airbus indicates that 65% of the typical maintenance burden for short-haul operations can be allocated to airframe plus components and the rest of the burden can be allocated to powerplants. The phases, such as takeoffs and landings, are where there is a very high proportion of wear and tear on the airframe and powerplants. However, no delays will be experienced during a takeoff roll or landing. It also indicates that the maintenance cost per minute in airborne operation is approximately twice the value of the ground cost per minute because most of the time spent on the ground is at the gate with engines and auxiliary power unit (APU) off. There will be relatively little wear and tear on the airframe at this ground operation phase as well. Whereas the maintenance costs in delays are related to aircraft utilization and treated as marginal costs, the maintenance costs of using buffer minutes are treated as unit costs, including the costs related and unrelated to aircraft utilization.

●Crew Costs

The crew payment schemes vary greatly among airlines. It can be based on calculations taking into account total duty hours, flight duty hours, time spent at outstations (with corresponding allowances), overtime hours, experience and rating. Accordingly, it is a difficult matter to assign crew costs to particular incidences of delays (Cook et al., 2004). Airlines could suffer no additional cost for delays in some cases. For example, with payments made on a sector-flown basis, an airborne delay would have no effect on crew cost as this payment is based on cycles flown. Similarly, an at-gate delay would have no effect on crew cost paid by block-hours as this payment is based on the operational time between gates (Cook and Tanner, 2009). The marginal crew costs in delays can therefore range from zero extra costs to possibly substantial overtime payments. On the other hand, the crew costs involved in scheduling of buffer minutes are treated as unit costs, which include the costs related and unrelated to aircraft utilization. Hence, the crew costs such as fixed salaries and pensions, amortization of training costs, and insurance, which do not change as a result of flying hours, can only be assigned as buffer costs.

●Aeronautical Charges

The aeronautical charging systems are in many instances imposed and governed by the national authorities. These charges (e.g. landing charge, parking charge, aerobridge charge) are applied in different ways at different airports, depending on the facilities and services provided. Thus, a departure delay at one airport may increase an airline's aeronautical charges, whilst it may not have an effect on the aeronautical charges at other airport. Taking parking charge as an example, it may be charged according to the length of time parked (per 15 minutes, per hour, or per 24 hours), with or without certain free-parking period. Under this circumstance, whether an airline has to pay more parking charge for a departure delay is subject to the length of time delayed and the free-parking period provided by the airport. Whereas the aeronautical charges of delays are calculated as marginal costs, it is assumed that there is no extra aeronautical cost to be incurred for buffer minutes.

2.4.2 Passenger Delay Costs to Airlines

Passenger delay costs to airlines are treated as marginal costs and comprise 'hard' and 'soft' costs. The hard costs are such as the costs for re-accommodation (rebooking/rerouting passengers, ticket reimbursements and compensation) and care (meal vouchers, hotel accommodation, frequent-flyer program miles) (Cook et al., 2009), and are difficult to fully ascribe to a given flight due to accounting complications (Cook and Tanner, 2009). The soft costs may incur on the occasion that a passenger is dissatisfied with a delayed flight originally booked and decides to take an on-time flight of another airline. Thus, soft costs can be considered as the potential loss of revenue in future market share as a result of unpunctuality (Cook et al., 2004; Cook and Tanner, 2011). Passenger delay costs can also be estimated through the 'value of time' of passengers, which is considered as the opportunity costs to passengers. However, this estimation is not addressed in this research.

2.4.3 Fleet Costs

Fleet costs refer to the costs of depreciation, rentals, and leases of flight equipment, which are determined by service hours and are very weakly related to utilization. Therefore, these costs are wholly allocated to the costs of buffer time as unit costs, and are unchanged by the delay outcome. If an airline leases most of the fleet, there will be very low depreciation costs. Conversely, an airline will have relatively low rental costs if it owns most of the fleet (Cook et al., 2004; Cook and Tanner, 2011).

Using cost minimization model, the relationship between the use of buffer time to control schedule punctuality and the delay costs imposed on passengers and airlines was investigated in the studies of turnaround operations (Wu and Caves, 2000, 2004). On the other hand, the effect of using buffer time on the reliability of aircraft rotation schedule was explored by Wu and Caves (2002). To manage flight delays, airlines are prepared for the unexpected stochastic events of turnaround and block operations. Nevertheless, there seems a lack of good tools to measure the effectiveness of the delay improvement schemes.

2.5 Concluding Remarks

With the increase in air traffic volume, the flight delay problem becomes worse and the factors to be considered in air network operations have increased significantly. The major problem faced today is how to minimize delays to departing and arriving flights. Major shortcomings of using airline dependability statistics include the fact that the measurement is an ex post measure and that it reveals only the results of schedule delays without further investigation into determining factors such as schedule design and airline operations (Wu and Caves, 2002). Given the complex procedures of flight operations and their unexpected disruptions, airline companies must clarify the causes of flight delays and evaluate the overall effects of an initial flight delay to design a robust airline schedule.

Many studies have dealt with both schedule optimization and schedule recovery strategies. To design a robust airline schedule and increase its reliability, researchers have attempted to quantify flight delays or to model the scale of flight delay propagation to find a way to minimize the effects of flight delay propagation on airline networks. Various statistical models and simulation techniques have also been developed to assist in the planning of airline schedules. However, most studies have emphasized the technical aspects of optimizing airline schedules and failed to consider the delay causes that contribute and control delays in daily operations.

In aircraft rotations, the time required for operating activities such as taxi time, airborne time, and ground handling time are often subject to numerous sources of irregularities. The state of flight delays may also vary from one aircraft type to another, or in different flight routes. In addition, different causes of flight delays may have different effects on airline schedule reliability, and the effects of flight delays resulting from the same delay cause may not be the same in all cases. Therefore, arrival and departure delays are stochastic in nature. Though scheduled buffer time can lessen the degree of flight delays, available buffer time is stochastic in nature as well because it can be longer or shorter, depending on the length of previous delay time occurred in the recursive operations between departures and arrivals. However, the stochastic effects of flight delay propagation have not been thoroughly captured in previous studies.

In addition, adding buffer minutes to schedule is an easy way to improve flight delays; nevertheless, the costs and effectiveness of the improvement are worth exploring. The approaches appropriate to investigate the causal relationship of flight delay propagation and to evaluate delay improvement schemes will be presented in next chapter.

CHAPTER 3 METHODOLOGY

This chapter is to introduce the methodology applied in this research. Section 3.1 presents flight delay mechanisms which explain the relationships among flight delays in an airline schedule. Section 3.2 discusses the survival analysis appropriate for flight delay data. The application of survival model for evaluating delay improvement schemes is presented in Section 3.3.

3.1 Flight Delay Mechanisms

An airline schedule is comprised of flights among various destinations operated by aircraft fleets that may contain different aircraft types. The flights assigned to the same aircraft during one cycle (usually one day for domestic operations and one week for international operations) form the ‘routes’ on which the aircraft is operated. An aircraft operating on the routes is usually referred as aircraft rotation (or aircraft routing), and involves multiple departure, arrival, and turnaround operations at airports and block operations between airports (Wu, 2005).

The turnaround of an aircraft is defined as the ground operation process to service an aircraft from the ‘on-chock’ time at an airport gate to the ‘off-chock’ time the aircraft is to depart for the next flight. The turnaround time represents the time required to finish all turnaround activities (de-boarding/boarding passengers, unloading/loading baggage, cleaning, catering, fuelling, and engineering check) and manage the delays from disruptions. On the other hand, the duration of block operations is defined in terms of the times needed at the phases of taxi-out at the origin airport, airborne operation between airports, and taxi-in at destination airport. During the daily operations of an aircraft, the arrival delay of an inbound aircraft is influenced by the departure delay of the aircraft at the origin airport and the block delay between airports. On the contrary, departure delay of an outbound aircraft is influenced by the arrival delay of the aircraft and the ground delay at airport. Flight delays therefore represent the ‘survival distributions’ of the delays in aircraft operations. The delays can be managed by built-in turnaround and block buffer time.

According to Abdelghany et al. (2004), buffer times play an important role in the implementation of recovering schemes associated with irregular operations. Turnaround buffer time, which is the extra time scheduled beyond the time required for ground handling, is usually built-in to accommodate potential delays from late inbound aircraft and aircraft turnaround operations. Scheduled block buffer time is the extra time added to a flight's scheduled arrival time to permit a degree of variability in flight operations between airports. Although a published airline schedule generally incorporates buffer time, flight delays can occur when accumulated delays exceed the buffer time. Since all flights are connected in aircraft rotations, the flight delay mechanisms presented here include departure and arrival delay in a network.

3.1.1 Departure Delay

Figure 3.1 illustrates the relationships among flight delays in an airline schedule. The solid arrows represent the original schedule of departures and arrivals for flight legs *i-1* and *i*. STD and STA refer to scheduled time of departure and scheduled time of arrival, respectively, and STA_{-1} refers to scheduled time of arrival of flight f_{i-1}. The dotted arrows represent the actual departures and arrivals of these flight legs. ATD and ATA refer to actual time of departure and actual time of arrival, respectively, and ATA_{-1} refers to actual time of arrival of flight f_{i-1}. Equation (3.1) describes the relationship between the scheduled time of arrival of flight f_{i-1} (STA_{-1}), the on-chock time, and the scheduled time of departure of flight f_i (STD), the off-chock time. The scheduled turnaround time of flight f_i (T^S) is the scheduled interval between the arrival of flight f_{i-1} at the gate and the time at which this aircraft departs for flight f_i, comprising two parts: the scheduled required ground handling time (g^S) and scheduled turnaround buffer time (b^{sg}) (Equation (3.2)).

$$STD = STA_{-1} + T^S \tag{3.1}$$

$$T^S = g^S + b^{sg} \tag{3.2}$$

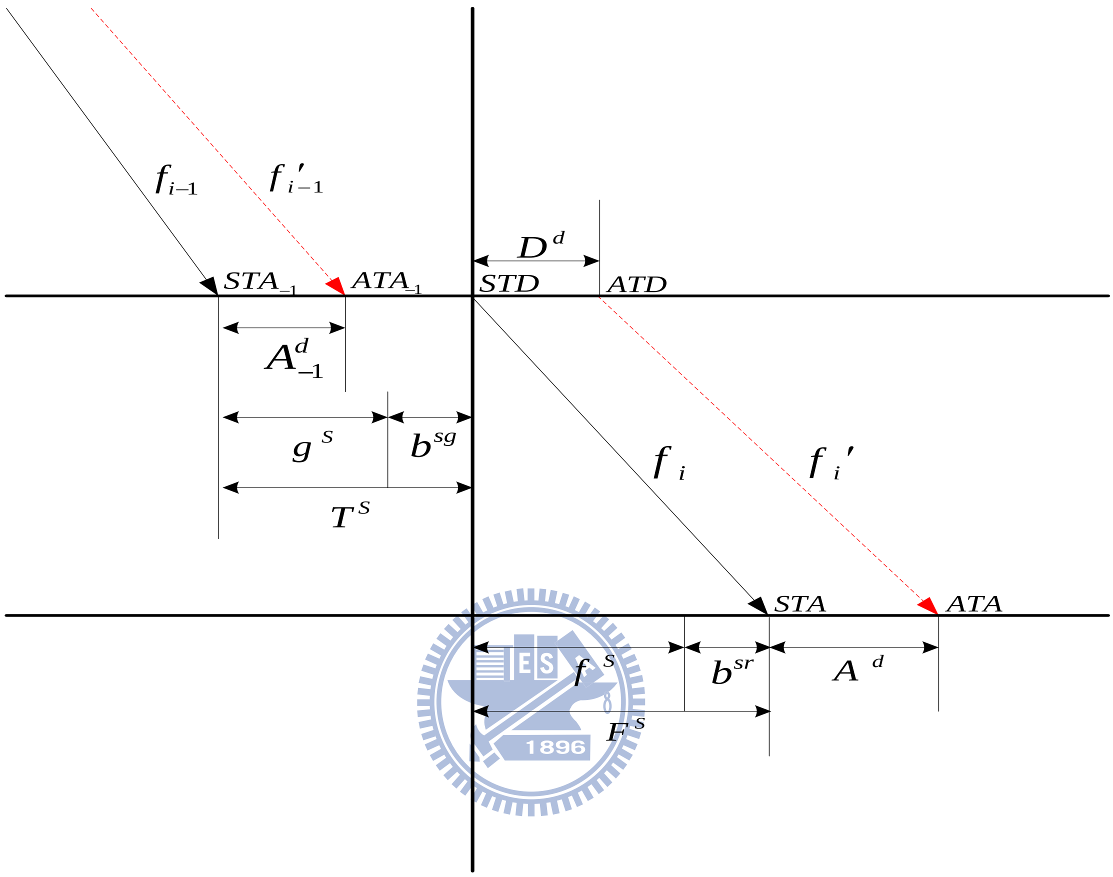


Figure 3.1 Relationships among flight delays in an airline schedule.

If the delay in an aircraft's arrival is shorter than the scheduled turnaround buffer time, the scheduled turnaround buffer time is capable of absorbing it. However, a delay in arrival exceeding the scheduled turnaround buffer time might cause a delay in the departure of the next flight. Given the interactions between fixed flight schedules and stochastic disruptions associated with turnaround operations, there might also be a ground delay for flight f_i (G^d). If the scheduled turnaround buffer time is incapable of absorbing this ground delay, it could lead to a delay in subsequent departure. Thus, the departure delay of flight f_i (D^d) can be caused by the arrival delay of the previous flight

(A_{-1}^{d}) and a ground delay at the current airport (G^{d}). Equation (3.3) shows that the scheduled turnaround buffer time (b^{sg}) may be able to absorb these delays.

$$D^{d} = \max\left\{0,\ A_{-1}^{d} + G^{d} - b^{sg}\right\} \qquad (3.3)$$

3.1.2 Arrival Delay

The scheduled block time of flight f_i (F^{s}) includes the scheduled required block operation time (f^{S}), the minimum time required to complete the activities of taxi-out, airborne operation, and taxi-in, and the scheduled block buffer time (b^{sr}) (Figure 1). This buffer is expected to absorb any potential delays at the origin airport and in the block operations. Inbound flight f_i might also have a block delay (R^{d}) resulting from problems such as severe weather or air traffic control restrictions en-route or at destination airport. This would result in an arrival delay if the scheduled block buffer time (b^{sr}) cannot absorb this block delay. Therefore, the arrival delay of flight f_i (A^{d}) can be influenced by a departure delay at the origin airport (D^{d}) and a block delay between airports (R^{d}), which might be absorbed by the scheduled block buffer time (b^{sr}). Equation (3.4) describes this relationship.

$$A^{d} = \max\left\{0,\ D^{d} + R^{d} - b^{sr}\right\} \qquad (3.4)$$

By combining the mechanisms of departure and arrival delays, flight delay propagation in an airline network can be formulated through repeated chain effects. The challenge is to model the departure and arrival delays with their associated causes. Because of the survival characteristics of flight delays, survival analysis is therefore an appropriate approach to explore the problem of flight delays and to analyze the distributions of delays propagated throughout an airline network.

3.2. Survival Analysis

Survival analysis (Kleinbaum and Klein, 2005) is a method of analyzing survival data or failure time data and has been used in several applied areas of statistics with different emphases. The outcome variable of interest is ‘time to event’, usually referred to as survival time or failure time. In aircraft rotation, the ‘duration’ of a delay represents the period of time that the delay has survived before coming to an end. Therefore, ‘survival time’ refers to the number of minutes from the beginning of an individual flight delay until an event occurs, while an ‘event’ means that the delay of an individual flight has come to an end. For inbound aircraft, the survival time of arrival delay ends when the aircraft arrives at an airport gate; for outbound aircraft, the survival time of departure delay ends when the aircraft departs from an airport gate.

In survival analysis, the object of primary interest is the survival function, which is defined as

$$S(t) = \Pr(T > t) \tag{3.5}$$

The survival function indicates the probability that a flight delay survives longer than specified time t. The survival distribution is plotted as a function that starts with the survival probability of 1 and descends down to the survival probabilities approaching zero for very long delays. Another key concept is the hazard function (Equation (3.6)), which gives the instantaneous probability for an event to occur conditional on survival to time t and specifies the related survival function as well.

$$h(t) = \lim_{\Delta t \to 0} \frac{\Pr(t \le T < t + \Delta t \mid T \ge t)}{\Delta t} = \frac{f(t)}{S(t)}. \tag{3.6}$$

Our focus is to investigate the impact of delay contributing factors on flight delays. To examine the relationship between the survival distributions of flight delays and associated covariates, we employ the Cox proportional hazards (PH) model (Equation (3.7)), a method widely applied in survival analysis, to model flight delays in a multiple-airport environment.

$$h(t \mid X) = h_0(t, \alpha) \exp(\beta' X) \tag{3.7}$$

This model provides a hazard expression for a flight at delayed time t with a given specification of explanatory variables that is being modeled to predict the hazard of a flight delay. If all the X’s are equal to zero, then the formula reduces to the baseline hazard function. This model makes it possible to compute a hazard ratio (HR) (Equation (3.8)), which is defined as the hazard for one case divided by the hazard for a different case. The hazard ratio can be written as the estimate of $h(t|X^*)$ divided by the estimate of $h(t|X)$, where X^* denotes the set of predictors for one case, and X denotes the set of predictors for the other case.

$$\hat{HR} = \frac{\hat{h}(t|X^*)}{\hat{h}(t|X)} = \frac{\hat{h}_0(t,\alpha)\exp(\hat{\beta}X^*)}{\hat{h}_0(t,\alpha)\exp(\hat{\beta}X)} = \exp\left[\hat{\beta}(X^* - X)\right] \tag{3.8}$$

In this ratio, the baseline hazards are cancelled out, and the only difference in the numerator and denominator is the $X^{*'}s$ versus the $X^{'}s$.

If there is a one-unit increase in x_k while other covariates' values remain fixed, the hazard ratio can be expressed as

$$\frac{\hat{h}(t|x_k + 1)}{\hat{h}(t|x_k)} = e^{\hat{\beta}_k}. \tag{3.9}$$

Therefore, $e^{\hat{\beta}_k}$ is the hazard ratio associated with one-unit increase in the k^{th} covariate x_k. Taking the logarithm of both sides of Equation (3.9), we can rewrite the formula as

$$\log\left[\frac{\hat{h}(t|x_k + 1)}{\hat{h}(t|x_k)}\right] = \log(\hat{h}(t|x_k + 1)) - \log(\hat{h}(t|x_k)) = \hat{\beta}_k. \tag{3.10}$$

Accordingly, $\hat{\beta}_k$ is the log hazard ratio (or the increase in log hazard) with one-unit increase in x_k. Equation (3.9) can be expanded and expressed as

$$\frac{\hat{h}(t|x_k + 1) - \hat{h}(t|x_k)}{\hat{h}(t|x_k)} = e^{\hat{\beta}_k} - 1. \tag{3.11}$$

Then, $e^{\hat{\beta}_k} - 1$ can be interpreted as the percentage change (increase or decrease) in the hazard of flight delay with a one-unit increase in x_k, while other covariates remain unchanged.

3.3 Delay Improvement Schemes

3.3.1 Survival distributions of Flight Delays

Because this research is aimed to investigate the expected delay costs incurred in the delays, which represent the effects of both the delay duration and the occurrence probabilities of delays, the survival functions, indicating the probability of a flight delay surviving to a specific value of time, need to be obtained. In computing the hazard ratio, it is not necessary to estimate the baseline hazards ($h_0(t)$) because they are cancelled out in the computation. However, the baseline hazards need to be estimated in order to obtain the survival functions of flight delays.

The Cox hazard function's associated survival function is defined as

$$S(t|X,\beta) = S_0(t)^{\exp(\beta' X)}. \tag{3.12}$$

To calculate the survival function to examine how flight delays survive in a flight network, the baseline survival function which is derived from the baseline hazard function needs to be obtained. Assume a discrete time formulation with baseline hazard $h_0(t_j) = 1 - \alpha_j$ at specified delay time t_j, $j=1,...,k$ (Cameron and Trivedi, 2005). The baseline survival function is then as

$$S_0(t) = \prod_{j|t_j \le t} \alpha_j. \tag{3.13}$$

Using Equation (3.14), $\hat{\alpha}_j$ can be estimated (Kalbfleisch and Prentice, 2002),

$$\sum_{l \in D(t_j)}^{k} \frac{\exp(\hat{\beta} X_l)}{1 - \hat{\alpha}_j^{\exp(\hat{\beta} X_l)}} = \sum_{m \in R(t_j)} \exp(\hat{\beta} X_m), \text{ j=1,…,k.} \tag{3.14}$$

where $D(t_j)$ denotes the individuals that die at time t_j, and $R(t_j)$ denotes the individuals at risk at time t_j. Given the estimated baseline hazard $\hat{h}_0(t_j) = 1 - \hat{\alpha}_j$, the estimator for the cumulative baseline hazard function is defined as

$$\hat{H}_0(t) = \sum_{t_j \le t} \hat{h}_0(t_j). \tag{3.15}$$

Then, the estimators for the baseline survival function (Equation (3.16)) and the survival function (Equation (3.17)) can be derived as

$$\hat{S}_0(t) = e^{-\hat{H}_0(t)}, \tag{3.16}$$

$$\hat{S}(t|X, \hat{\beta}) = \hat{S}_0(t)^{\exp(\hat{\beta}X)}. \tag{3.17}$$

Thus, the probability of a flight delay surviving to time t_{j+1} can be defined as

$$\hat{\Pr}(T = t_{j+1}) \approx \hat{S}(t_j) - \hat{S}(t_{j+1}). \tag{3.18}$$

The expected cost of a flight delay can be approximately calculated accordingly.

3.3.2 Formulation of System Costs of Flight Delays

When there is a departure delay, the delay costs of departure flight i (C^D) include aircraft delay costs (C^D_{AC}) and passenger delay costs to airlines (C^D_P) incurred at the origin airport. Similarly, when there is an arrival delay, the delay costs of arrival flight i (C^A) include aircraft delay costs (C^A_{AC}) and passenger delay costs to airlines (C^A_P) incurred between airports. Therefore, the expected delay costs of departure flight i (${}^eC^D$) and arrival flight i (${}^eC^A$), representing the effects of both the delay duration and the occurrence probability of the delays, can be expressed by Equations (3.19) and (3.20).

$${}^eC^D = E[C^D(t)] = E[C^D_{AC}(t)] + E[C^D_P(t)], \tag{3.19}$$

$${}^eC^A = E[C^A(t)] = E[C^A_{AC}(t)] + E[C^A_P(t)], \tag{3.20}$$

where t means delay time.

It is assumed that the expected aircraft delay costs can be formulated by a linear cost function (Wu and Caves, 2000, 2002, 2004). However, as discussed in Section 2, lower marginal delay cost should be given when calculating the costs of departure delay whilst higher marginal delay cost should be given in the calculation of the costs of arrival delay. For passenger delay costs to airlines, on the other hand, longer delays tend to cause higher hard costs, e.g. re-accommodation and care costs. Passengers are also more likely to be dissatisfied with longer delays, resulting in higher soft costs. Accordingly, the expected passenger delay costs to airlines can be formulated by a step cost function with higher marginal delay costs for longer delays as demonstrated in the report of Cook and Tanner (2011).

The use of schedule buffer time in aircraft rotations can stabilize schedule punctuality, but it reduces revenue-generating hours. The cost function of adding turnaround buffer for departure flight i (B^D) and block buffer for arrival flight i (B^A) is assumed to be a linear function (Cook et al., 2004; Cook and Tanner, 2011). These buffer costs, treating each buffer minute as an equal minute of unit cost, are calculated based on the length of buffer minutes scheduled by an airline. Hence, the system costs, including delay costs and buffer costs, for departure flight i ($C_{f_i}^{SD}$) and arrival flight i ($C_{f_i}^{SA}$) can be expressed by Equations (3.21) and (3.22).

$$C_{f_i}^{SD} = C^D + B^D =^e C^D + B^D(b) = \{E[C_{AC}^D(t)] + E[C_P^D(t)]\} + B^D(b), \qquad (3.21)$$

$$C_{f_i}^{SA} = C^A + B^A =^e C^A + B^A(b) = \{E[C_{AC}^A(t)] + E[C_P^A(t)]\} + B^A(b), \qquad (3.22)$$

where b means buffer time.

The total system costs of delayed segments in the rotations of an airline schedule (C_f) can be modeled by Equation (3.23).

$$C_f = \sum_i C_{f_i} \qquad \forall i \in \{1, 2, 3, ..., n\}, \text{ for delayed segments,} \qquad (3.23)$$

where

$$C_{f_i} = C_{f_i}^{SD} + C_{f_i}^{SA}.$$

3.3.3 Effectiveness of Delay Improvement Schemes

Airlines can reduce departure and arrival delays by shortening required ground handling time and required block operation time, respectively. However, the improvement of required block operation time is usually in a small extent due to the limited control of airlines in block operations, especially for short-haul routes. The ground handling efficiency can be improved by adding more resources (e.g. staff and equipment) or simply using appropriate management skills without extra resources invested, depending on the circumstances that may exist. Alternatively, airlines can directly increase buffers for turnaround and en-route aircraft with additional costs of resources (e.g. aircraft and crew) to reduce flight delays. The costs of increasing buffers therefore represent a trade-off for the costs of delays saved by the buffers. Though assigning spare aircraft to replace a scheduled aircraft or cancellation of a seriously delayed flight are also the measures frequently taken by airlines to remedy flight delays, they are not discussed in this paper.

When ground handling time is shortened, turnaround buffer time becomes longer. Though airlines may incur the costs of additional ground handling resources, the costs of turnaround buffer will not increase since no extra minutes are scheduled. The net benefit of shortening required ground handling time (NB_g^{SD}) can be evaluated by Equation (3.24).

$$NB_g^{SD} = \sum_i C_{f_i}^{SD} - \sum_i C_{f_i}^{SD^*} \quad \forall i \in \{1,2,3,...,n\}, \text{ for delayed segments,} \qquad (3.24)$$

where

$$C_{f_i}^{SD} = C^D + B^D = {}^{e}C^D + B^D(b) = \{E[C_{AC}^D(t)] + E[C_P^D(t)]\} + B^D(b),$$

$$C_{f_i}^{SD^*} = C^{D^*} + B^{D^*} + \mathrm{G}(\theta) = {}^{e}C^{D^*} + B^{D^*}(b) + \mathrm{G}(\theta) = \{E[C_{AC}^D(t-\theta)] + E[C_P^D(t-\theta)]\} + B^D(b) + \mathrm{G}(\theta),$$

θ : decreased ground handling time, $\theta \geq 0$,

$\mathrm{G}(\theta)$: costs of additional ground handling resources.

On the other hand, if extra minutes of turnaround buffer are scheduled, airlines will incur the resulted additional costs. Therefore, the net benefit of increasing turnaround buffer time (NB_b^{SD}) can be evaluated by Equation (3.25).

$$NB_b^{SD} = \sum_i C_{f_i}^{SD} - \sum_i C_{f_i}^{SD^*} \quad \forall i \in \{1,2,3,...,n\}, \text{ for delayed segments,} \qquad (3.25)$$

where

$$C_{f_i}^{SD} = C^D + B^D = {}^{e}C^D + B^D(b) = \{E[C_{AC}^D(t)] + E[C_P^D(t)]\} + B^D(b),$$

$$C_{f_i}^{SD^*} = C^{D^*} + B^{D^*} = {}^{e}C^{D^*} + B^{D^*}(b) = \{E[C_{AC}^D(t-\lambda)] + E[C_P^D(t-\lambda)]\} + B^D(b+\lambda),$$

λ : increased turnaround buffer time, $\lambda \geq 0$.

Similarly, the net benefit of increasing block buffer time (NB_b^{SA}) can be evaluated by Equation (3.26).

$$NB_b^{SA} = \sum_i C_{f_i}^{SA} - \sum_i C_{f_i}^{SA^*} \quad \forall i \in \{1,2,3,...,n\}, \text{ for delayed segments,} \qquad (3.26)$$

where

$$C_{f_i}^{SA} = C^{A} + B^{A} = {}^{e}C^{A} + B^{A}(b) = \{E[C_{AC}^{A}(t)] + E[C_{P}^{A}(t)]\} + B^{A}(b),$$

$$C_{f_i}^{SA^*} = C^{A^*} + B^{A^*} = {}^{e}C^{A^*} + B^{A^*}(b) = \{E[C_{AC}^{A}(t-\alpha)] + E[C_{P}^{A}(t-\alpha)]\} + B^{A}(b+\alpha),$$

α : increased block buffer time, $\alpha \geq 0$.

To manage flight delays, measures for turnaround and block operations can be taken simultaneously. By combining Equation (3.24) and Equation (3.26), the net benefit of shortening required ground handling time and increasing block buffer time for delayed segments in the rotations of an airline schedule ($NB_{\mathrm{gb}}^{\mathrm{S}}$) can be obtained as formulated by Equation (3.27).

$$NB_{gb}^{S} = (\sum_i C_{f_i}^{SD} - \sum_i C_{f_i}^{SD^*}) + (\sum_i C_{f_i}^{SA} - \sum_i C_{f_i}^{SA^*}) = \sum_i C_{f_i} - \sum_i C_{f_i}^{*} = C_f - C_f^{*}$$

$$\forall i \in \{1,2,3,\ldots,n\}, \text{ for delayed segments,} \tag{3.27}$$

where

$$C_{f_i} = C_{f_i}^{SD} + C_{f_i}^{SA},$$

$$C_{f_i}^{*} = C_{f_i}^{SD^*} + C_{f_i}^{SA^*},$$

where

$$C_{f_i}^{SD} = C^{D} + B^{D} = {}^{e}C^{D} + B^{D}(b) = \{E[C_{AC}^{D}(t)] + E[C_{P}^{D}(t)]\} + B^{D}(b),$$

$$C_{f_i}^{SD^*} = C^{D^*} + B^{D^*} + \mathrm{G}(\theta) = {}^{e}C^{D^*} + B^{D^*}(b) + \mathrm{G}(\theta) = \{E[C_{AC}^{D}(t-\theta)] + E[C_{P}^{D}(t-\theta)]\} + B^{D}(b) + \mathrm{G}(\theta),$$

$$C_{f_i}^{SA} = C^{A} + B^{A} = {}^{e}C^{A} + B^{A}(b) = \{E[C_{AC}^{A}(t)] + E[C_{P}^{A}(t)]\} + B^{A}(b),$$

$$C_{f_i}^{SA^*} = C^{A^*} + B^{A^*} = {}^{e}C^{A^*} + B^{A^*}(b) = \{E[C_{AC}^{A}(t-\alpha)] + E[C_{P}^{A}(t-\alpha)]\} + B^{A}(b+\alpha).$$

Likewise, by combining Equation (3.25) and Equation (3.26), the net benefit of increasing turnaround and block buffer time for delayed segments in the rotations of an airline schedule ($NB_{\mathrm{bb}}^{\mathrm{S}}$) can be obtained as expressed by Equation (3.28).

$$NB_{bb}^{S} = (\sum_i C_{f_i}^{SD} - \sum_i C_{f_i}^{SD^*}) + (\sum_i C_{f_i}^{SA} - \sum_i C_{f_i}^{SA^*}) = \sum_i C_{f_i} - \sum_i C_{f_i}^{*} = C_f - C_f^{*}$$

$$\forall i \in \{1,2,3,\ldots,n\}, \text{ for delayed segments,} \tag{3.28}$$

where

$$C_{f_i} = C_{f_i}^{SD} + C_{f_i}^{SA},$$

$$C_{f_i}^{*} = C_{f_i}^{SD^*} + C_{f_i}^{SA^*},$$

where

$$C_{f_i}^{SD} = C^{D} + B^{D} = {}^{e}C^{D} + B^{D}(b) = \{E[C_{AC}^{D}(t)] + E[C_{P}^{D}(t)]\} + B^{D}(b),$$

$$C_{f_i}^{SD^*} = C^{D^*} + B^{D^*} = {}^{e}C^{D^*} + B^{D^*}(b) = \{E[C_{AC}^{D}(t-\lambda)] + E[C_{P}^{D}(t-\lambda)]\} + B^{D}(b+\lambda),$$

$$C_{f_i}^{SA} = C^{A} + B^{A} = {}^{e}C^{A} + B^{A}(b) = \{E[C_{AC}^{A}(t)] + E[C_{P}^{A}(t)]\} + B^{A}(b),$$

$$C_{f_i}^{SA^*} = C^{A^*} + B^{A^*} = {}^{e}C^{A^*} + B^{A^*}(b) = \{E[C_{AC}^{A}(t-\alpha)] + E[C_{P}^{A}(t-\alpha)]\} + B^{A}(b+\alpha).$$

CHAPTER 4 EMPIRICAL STUDY

This chapter is to demonstrate the methodology presented in Chapter 3. Prior to the demonstrations, the data adopted is introduced in Section 4.1. Modeling of flight delay propagation is presented in Section 4.2. The results of delay models and delay improvement schemes are shown in Section 4.3 and Section 4.4, respectively.

4.1 Basic Statistics

We collected flight data from a Taiwanese domestic airline ('Airline A') to explore the effects of flight delay propagation that requires an extensive flight network with a very high frequency of flights. After the launch of high-speed rail services along the west coast of Taiwan in January 2007, many passengers switched from traveling by airlines to high-speed rail, forcing airlines to reduce flight frequency and terminate some services. Our flight data was collected over twelve months in 2005, prior to the commencement of the high-speed rail service. It includes 16 domestic short-haul routes operated by two types of aircraft, Fokker 50 and Fokker 100, with up to 25,058 scheduled flights. The total number of delayed flights is 1971, which is 7.87% of the total scheduled flights. This lists the state of the departing and arriving aircraft as they rotated through the airport system and indicates the causes of delays in the operations.

The data was first analyzed from the perspective of delay cause, aircraft type, route, hourly period, and season.

●*Delay Cause*

Airlines usually adopt the IATA delay coding scheme, in which delay causes are coded by numbers (from 00 to 99). It helps airlines standardize why a commercial flight leaves late from its departure airport. Since some codes are too general to describe a problem, there are variations in how individual airlines identify the codes used. In the data, any delayed departure flight was entered into the Airline A's reporting system by recording the causes of the delay associated with appropriate delay codes. Although a delay might result from more than one cause, only two causes which more seriously influenced the delay were entered into the system. Table 4.1 shows the delay causes of Airline A in nine categories.

Although the cause of a delay is recorded when an aircraft departs from an airport gate, an inbound flight can also be delayed during taxi-out, airborne operation, or taxi-in prior to arrival at an airport gate. The delay in arrival can be due to weather en-route or weather at the destination or at an alternative airport, which can also be the cause of departure delay if ground-holding policies are implemented (Vranas et al., 1994). Similarly, air traffic control restrictions en-route or at the destination airport can be the cause of arrival delay, or the cause of departure delay when ground holding policies are imposed. Hence, of the delay causes of Airline A, 'weather' and 'air traffic control restrictions' are the causes of arrival delays. On the other hand, departing flights can be disrupted by any of the causes listed in Table 4.1 (Wu and Wong, 2007; Vranas et al., 1994; Tu et al., 2008; Abdelghany et al., 2004; Wang et al., 2003; Eurocontrol, 2003; Fricke and Schultz, 2009), which are therefore considered as the causes of departure delays.

Table 4.1 shows that 'technical and aircraft equipment', 'reactionary', and 'weather' cause more delayed flights than other categories. It is noted that 48.81 percent of the total delayed flights are due to 'reactionary' and that the means of departure and arrival delay times caused by 'weather' are above 45 minutes. Figure 4.1 depicts the box of C7 ('weather') for departure delay has the widest width, indicating the highest degree of dispersion for the delays. Moreover, the box of C7 for arrival delay is upper than that of C8 ('air traffic control restrictions'). That is, the distributions of flight delays caused by 'weather' are longer than those caused by 'air traffic control restrictions'. In addition, most of the boxplots in Figure 4.1 reveal that the distributions of delay times are "right-skewed", meaning that there exist more short delays and fewer long delays.

●*Aircraft Type*

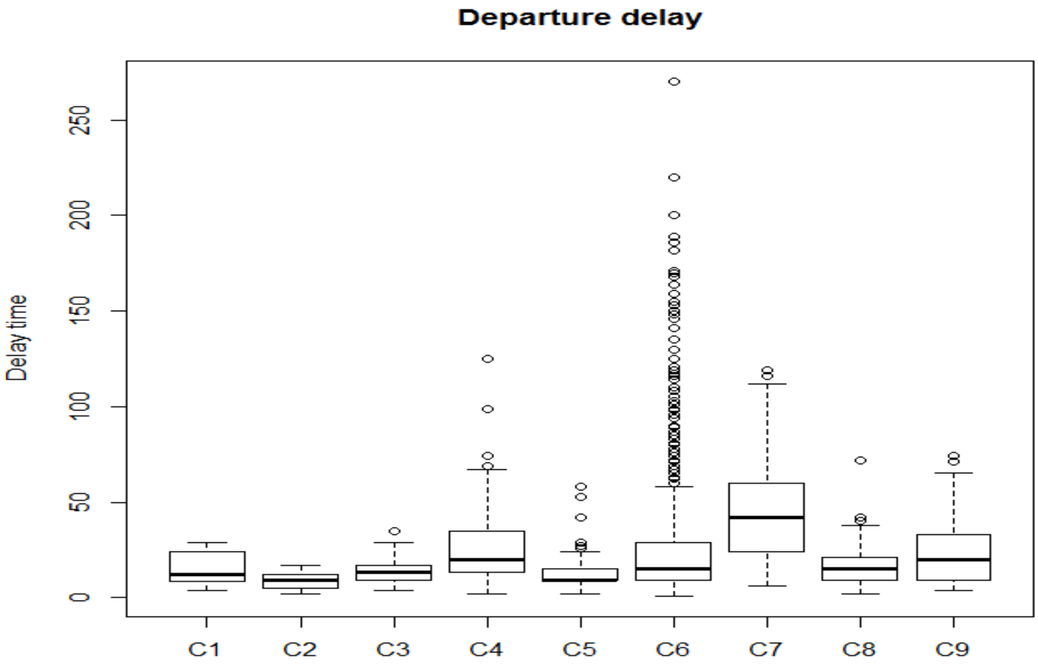
The delay times of each aircraft are presented in Table 4.2. The first four aircraft are Fokker 50, and the last six aircraft are Fokker 100. Although there is no big difference on the number of scheduled flights for Fokker 50 and Fokker 100 aircraft, Fokker 50 aircraft tend to have a higher percent of flights delayed and a higher mean of delay time. In Figure 4.2 the boxes of Fokker 50 aircraft for both of departure and arrival delays are wider and upper than those of Fokker 100 aircraft. This implies that Fokker 50 aircraft have more serious problems in flight delays.

Table 4.1 Delay causes of Airline A

No.	Description of Category	Delay Cause	No. of Delayed Flights	Percent of Total Delayed Flights (%)	Mean of Departure Delay Time (min.)	Mean of Arrival Delay Time (min.)
1	Airport facilities or governmental authorities (C1)	Airport facilities (air bridge, gates, conveyor belts, etc)	13	0.66	19	22
		CIQ (congestion, short of personnel, negligence, etc)	5	0.25	13	18
		Security (bomb threat, fire, etc)	6	0.30	11	17
		Restrictions at departure/destination airport (runway, etc)	17	0.86	20	23
		Ramp congestion/gate occupancy	4	0.20	13	23
2	Flight operations and crewing (C2)	Cabin crew late in position	2	0.10	22	27
		Cabin crew change	1	0.05	20	26
		Cockpit crew late in position	6	0.30	11	10
		Revision of flight plan	144	7.31	23	26
3	Cargo and mail handling (C3)	Late positioning of cargo/mail	7	0.36	10	18
		Readjustment of cargo/bag position or change of load plan	25	1.27	16	24
4	Technical and aircraft equipment (C4)	Unable to release aircraft for maintenance reason	141	7.15	29	33
		Awaiting engineers/AOG spares	3	0.15	21	28
		GPU needed for engine start	3	0.15	29	40
		Late release of scheduled maintenance from workshop	22	1.12	7	13

Table 4.1 Delay causes of Airline A (Continued)

No.	Description of Category	Delay Cause	No. of Delayed Flights	Percent of Total Delayed Flights (%)	Mean of Departure Delay Time (min.)	Mean of Arrival Delay Time (min.)
		Non-scheduled maintenance/special checks	14	0.71	23	26
		Aircraft change for maintenance reason	61	3.09	35	38
5	Passenger and baggage handling (C5)	Group late check-in	14	0.71	11	17
		Passenger missing/cancel trip	12	0.61	13	21
		Awaiting transit passenger and baggage	5	0.25	13	24
		Acceptance of passenger from other flight/carrier	9	0.46	18	21
		Paging passenger	26	1.32	13	15
		Check-in counter late opening or closing	9	0.46	11	19
		Other passengers' reason	93	4.72	11	14
6	Reactionary (C6)	Late arrival of aircraft	962	48.81	25	29
7	Weather (C7)	Weather at departure airport below operating limit	143	7.26	55	60
		Weather at destination/alternative airport below operating limit	149	7.56	57	65
		Other weather reason	16	0.81	45	59
8	Air traffic control restrictions (C8)	ATC restriction en-route or capacity	12	0.61	23	25
		ATC restriction at destination airport	11	0.56	26	31
		ATC restriction due to weather at destination airport	9	0.46	29	32
9	Miscellaneous (C9)	Cargo/passenger computer system breakdown	6	0.30	38	46
		Not covered by any of other defined codes	21	1.07	25	35



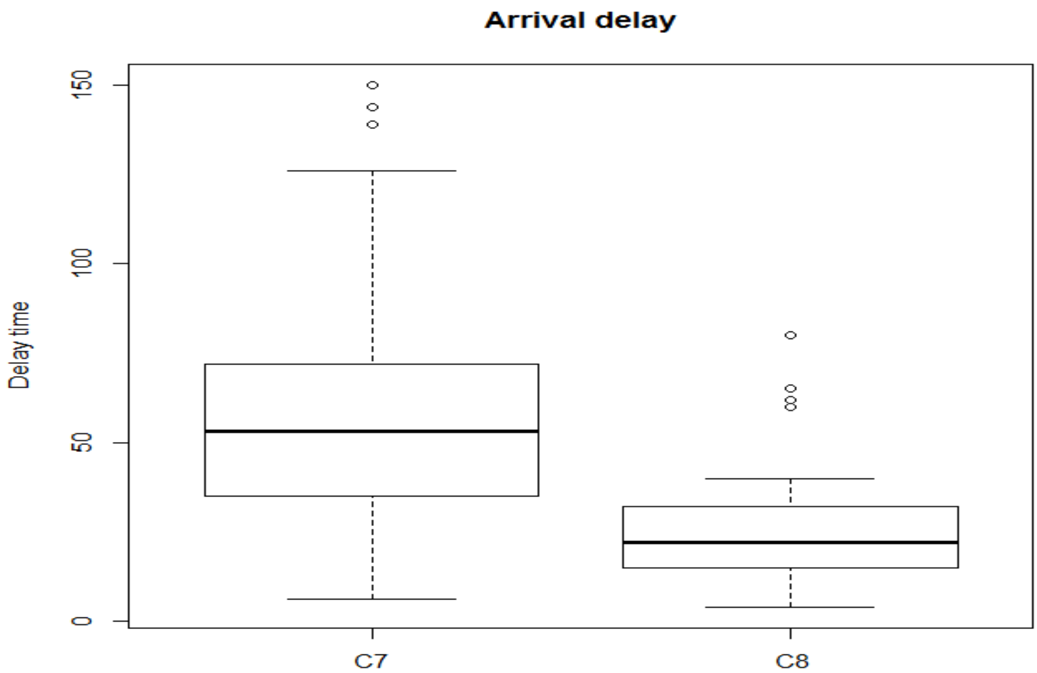


Figure 4.1 Boxplots of various categories of delay causes.

Table 4.2 Delay times of various types of aircraft

Aircraft No.	No. of Scheduled Flights	Operations		Percent of Scheduled Flights Delayed (%)	Mean of Departure Delay Time (min.)	Mean of Arrival Delay Time (min.)
		No. of Delayed Flights	No. of On-time Flights			
Fokker 50						
B12272	2323	209	2114	9.00	40	42
B12273	2218	196	2022	8.84	43	46
B12275	2368	208	2160	8.78	46	49
B12276	2499	225	2274	9.00	41	45
Fokker 100						
B12291	2736	174	2562	6.36	23	29
B12292	2635	157	2478	5.96	23	29
B12293	2391	132	2259	5.52	24	30
B12295	2473	157	2316	6.35	23	28
B12296	2711	183	2528	6.75	23	29
B12297	2704	330	2374	12.20	24	40

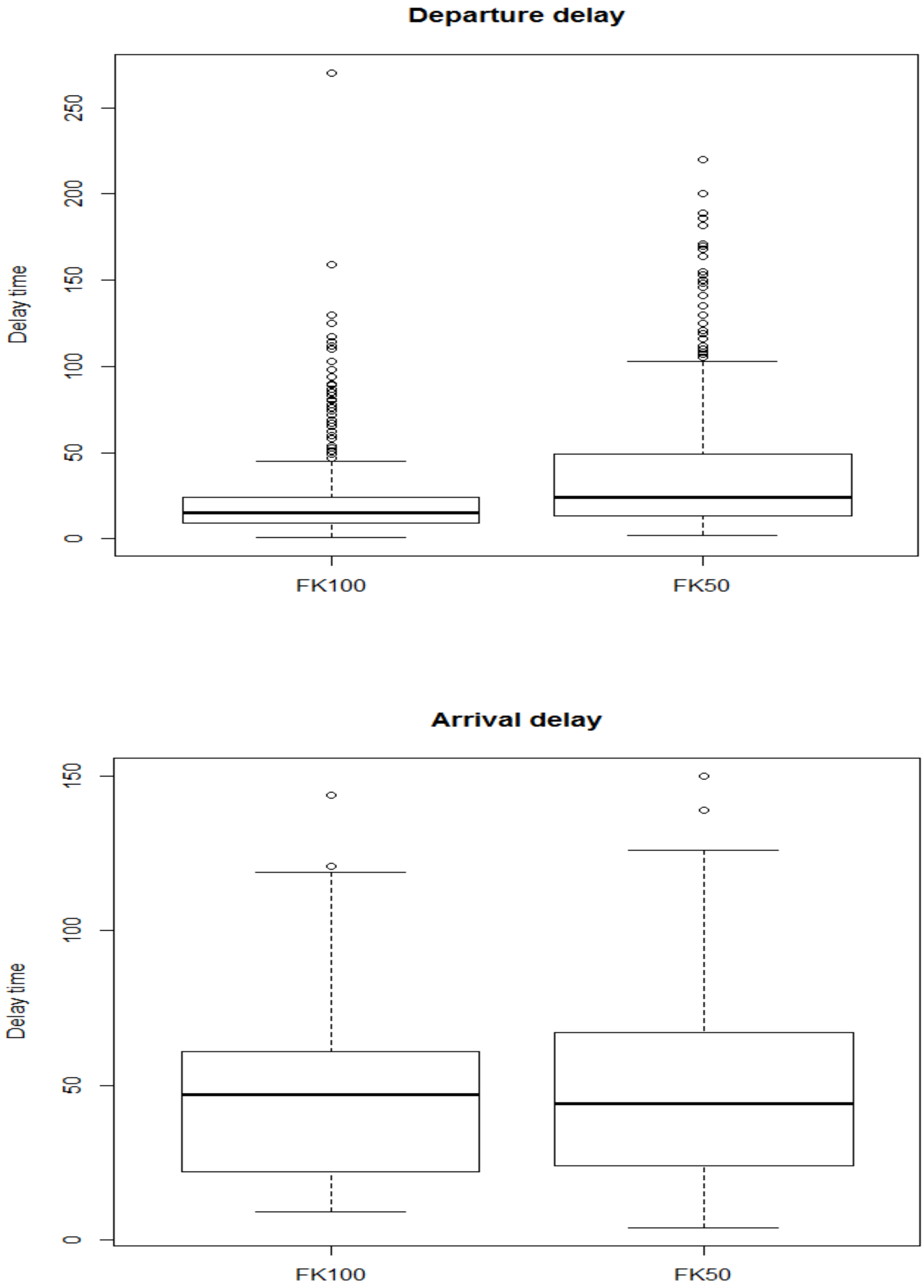


Figure 4.2 Boxplots of various types of aircraft.

●*Route*

Among the 16 routes operated, 7 routes are with more than 10 percent of scheduled flights delayed (Table 4.3). The origin airports of these include KNH, RMQ, TSA, and TTT. Furthermore, flights depart from RMQ and HUN have high means of departure and arrival delay times. Figure 4.3 shows that R2 (HUN→RMQ), R7 (MZG→RMQ), R8 (RMQ→HUN), R10 (RMQ→MZG), and R15 (TSA→RMQ) have higher degree of spread in distributions of departure and arrival delays, represented by their wider width of boxes.

●*Hourly Period*

The delay times of hourly periods in Table 4.4 reveal that 10:00-13:00, 14:00-15:00, and 17:00-19:00 are with higher percent of flights delayed. Because the peak hours are defined as 7:00-9:00, 11:00-14:00, and 17:00-19:00, most of the periods with higher percent of flights delayed are in peak hours. However, it is interesting that many periods in off-peak hours are with high means of departure and arrival delay times. The means of delay times are low at the beginning and the late night of the day as normally expected. The boxes of peak and off-peak hours for departure delay are quite similar to each other, and the box of off-peak hour for arrival delay is slightly wider than that of peak hour (Figure 4.4).

Table 4.3 Delay times of various routes

Route	No. of Scheduled Flights	Operations		Percent of Scheduled Flights Delayed (%)	Mean of Departure Delay Time (min.)	Mean of Arrival Delay Time (min.)
		No. of Delayed Flights	No. of On-time Flights			
HUN→KHH (R1)	946	28	918	2.96	47	51
HUN→RMQ (R2)	1254	92	1162	7.34	59	61
KHH→HUN (R3)	946	57	889	6.03	35	35
KHH→TSA (R4)	6103	405	5698	6.64	18	22
KNH→RMQ (R5)	738	52	686	7.05	40	45
KNH→TSA (R6)	1110	181	929	16.31	21	25
MZG→RMQ (R7)	968	91	877	9.40	50	52
RMQ→HUN (R8)	1262	117	1145	9.27	43	43
RMQ→KNH (R9)	744	103	641	13.84	36	46
RMQ→MZG (R10)	972	125	847	12.86	43	46
RMQ→TSA (R11)	1181	135	1046	11.43	36	37
RMQ→TTT (R12)	213	22	191	10.33	42	43
TSA→KHH (R13)	6101	285	5816	4.67	21	31
TSA→KNH (R14)	1105	158	947	14.30	26	36
TSA→RMQ (R15)	1203	98	1105	8.15	48	49
TTT→RMQ (R16)	212	22	190	10.38	46	49

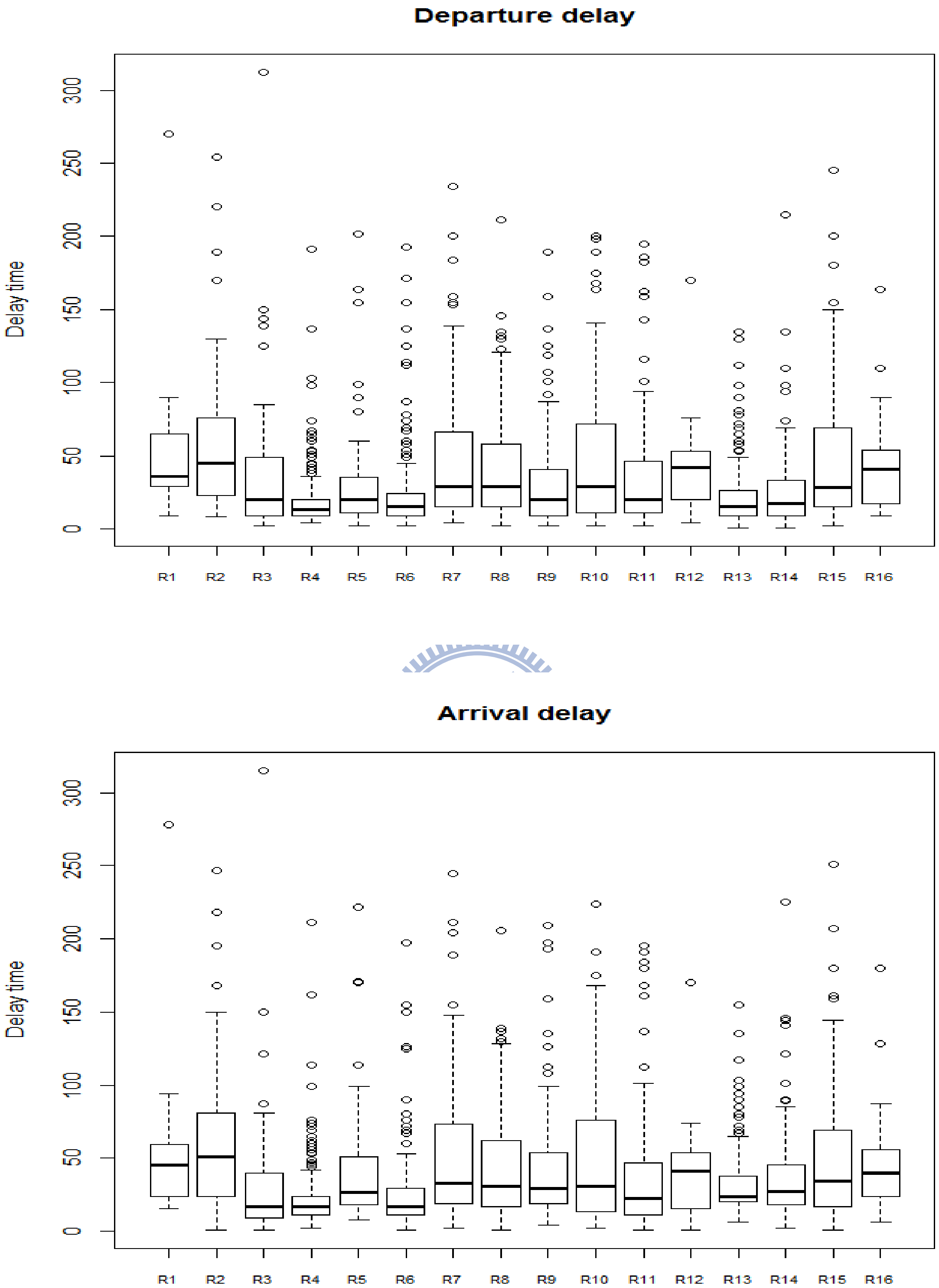


Figure 4.3 Boxplots of various routes.

Table 4.4 Delay times of hourly periods

Time	No. of Scheduled Flights	Operations		Percent of Scheduled Flights Delayed (%)	Mean of Departure Delay Time (min.)	Mean of Arrival Delay Time (min.)
		No. of Delayed Flights	No. of On-time Flights			
6:00-7:00	364	6	358	1.65	13	20
7:00-8:00	1693	56	1637	3.31	17	26
8:00-9:00	1992	144	1848	7.23	17	22
9:00-10:00	1899	103	1796	5.42	41	47
10:00-11:00	1232	216	1016	17.53	29	35
11:00-12:00	2448	221	2227	9.03	27	31
12:00-13:00	1143	97	1046	8.49	55	60
13:00-14:00	1857	144	1713	7.75	41	47
14:00-15:00	1433	143	1290	9.98	36	39
15:00-16:00	1810	136	1674	7.51	32	36
16:00-17:00	1400	109	1291	7.79	38	42
17:00-18:00	1514	171	1343	11.29	29	33
18:00-19:00	1879	166	1713	8.83	28	30
19:00-20:00	1595	98	1497	6.14	37	42
20:00-21:00	1184	67	1117	5.66	33	36
21:00-22:00	1615	94	1521	5.82	24	26

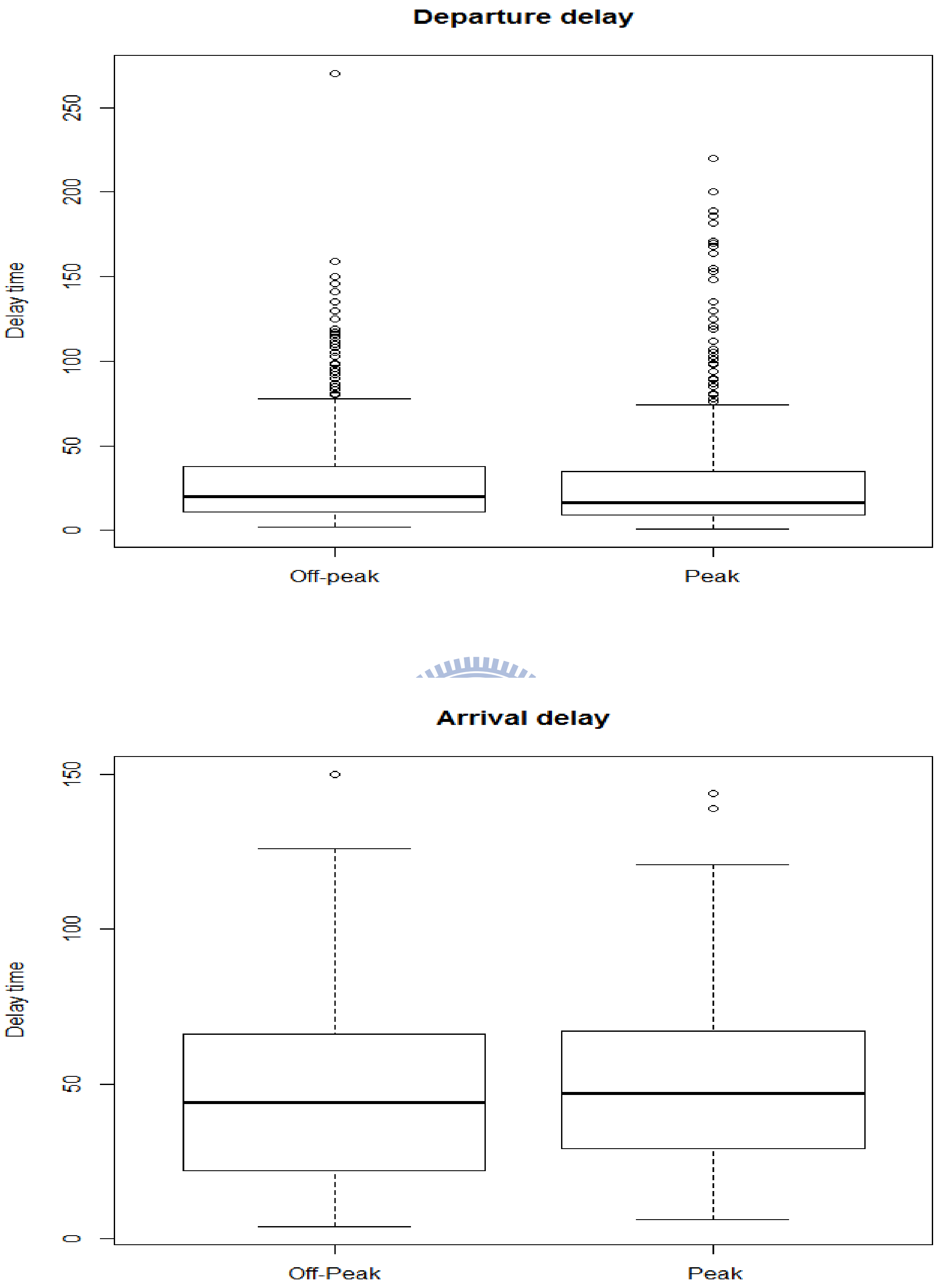


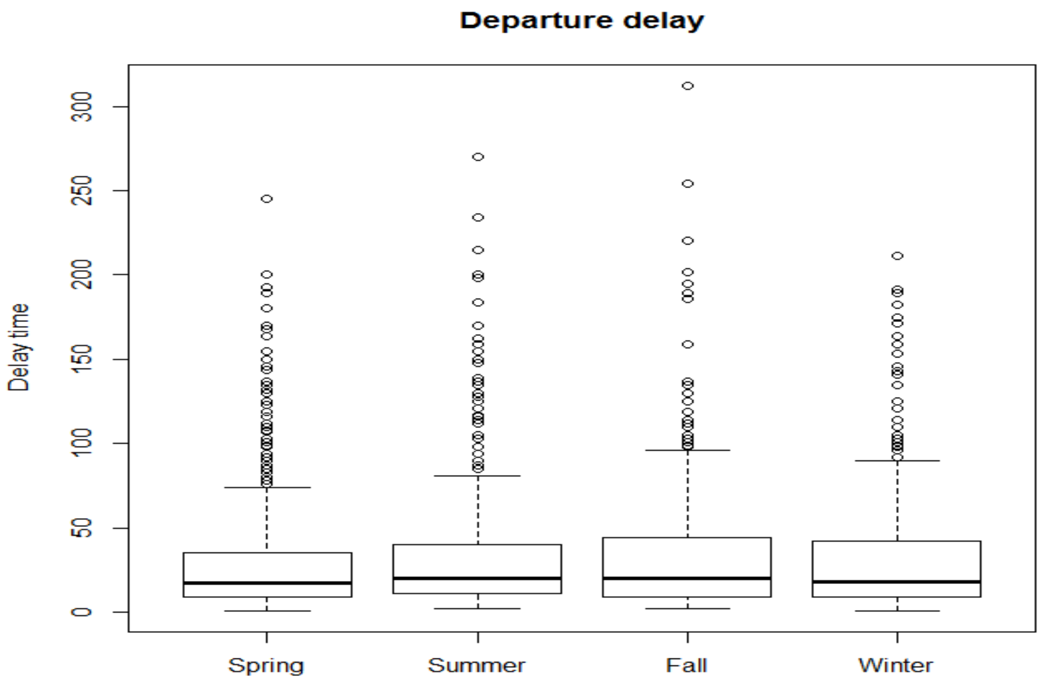
Figure 4.4 Boxplots of peak/off-peak hours.

●*Season*

Table 4.5 shows that spring and summer have higher percent of flights delayed and that spring, summer and fall have almost the same means of departure and arrival delays. Winter is with lower percent of flights delayed and means of departure and arrival delays. These are depicted and proved in Figure 4.5.

Table 4.5 Delay times of seasons

Season	No. of Scheduled Flights	Operations		Percent of Scheduled Flights Delayed (%)	Mean of Departure Delay Time (min.)	Mean of Arrival Delay Time (min.)
		No. of Delayed Flights	No. of On-time Flights			
Spring	6397	671	5726	10.49	33	37
Summer	6487	628	5859	9.68	33	38
Fall	6286	376	5910	5.98	32	37
Winter	5888	296	5592	5.03	26	29



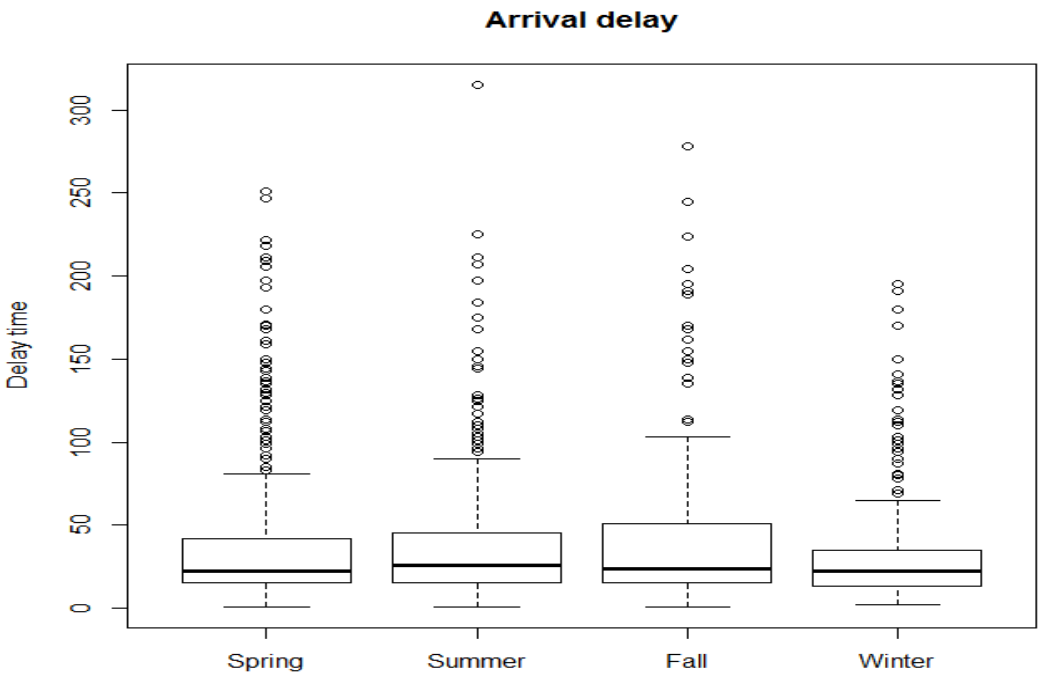
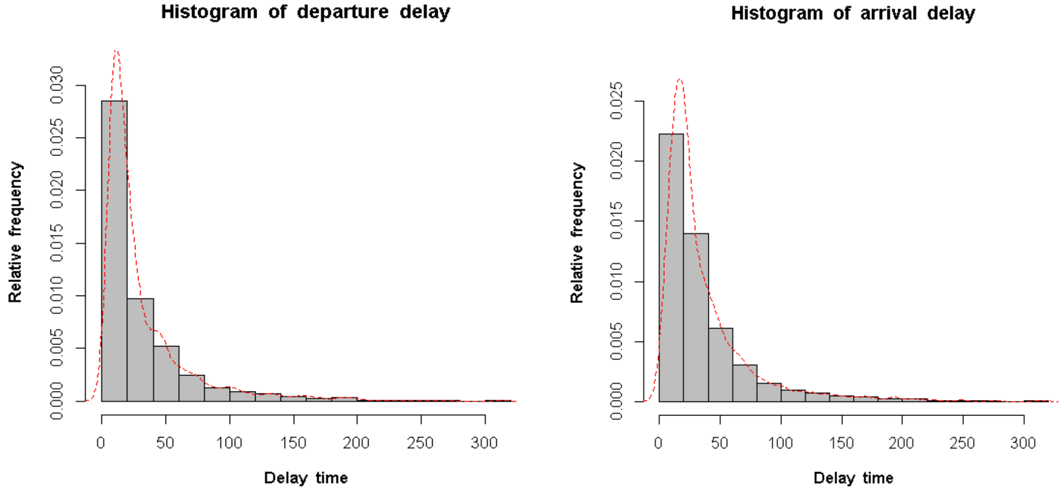


Figure 4.5 Boxplots of seasons.

4.2 Delay Modeling

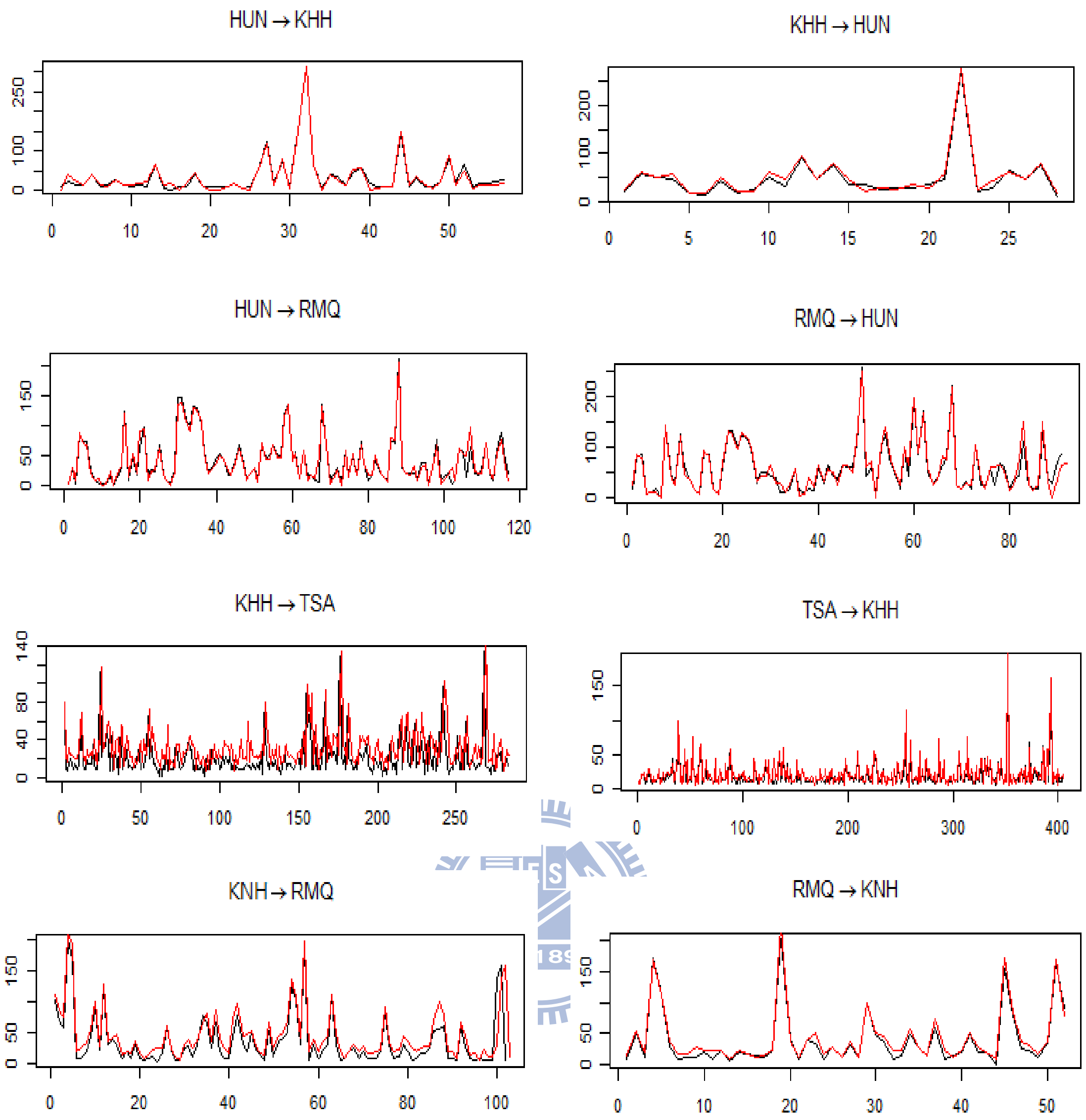
This research employs the Cox PH model to develop departure and arrival delay models to explore the problem of flight delay propagation in an airline network. The *actual* turnaround and block operation times (instead of *scheduled* times) of Airline A are then used to estimate the models. Because Airline A operates short-haul routes with many of its aircraft flying up to 10 consecutive segments in a day, delays in one segment could easily propagate to following flights. Figure 4.6 shows that the distribution of delay time is "right-skewed," indicating that the airline has more short delays and fewer long delays. Meanwhile, the relationship between departure and arrival delays is analyzed as presented in Figures 4.7 and 4.8. Figure 4.7 reveals that departure and arrival delays are closely related as the lines for them are close to each other. That is, longer departure delays normally cause longer arrival delays, while shorter departure delays usually result in shorter arrival delays. This relationship is also proved in Figure 4.8 with a Pearson's correlation coefficient of 0.978. Thus, this research considers the factors influencing turnaround and block operations, including arrival delay, ground handling time, turnaround buffer time, departure delay, taxi-out time, airborne time, taxi-in time, and block buffer time, as the covariates for developing the flight delay models.



[a] Delay times are measured in minutes.

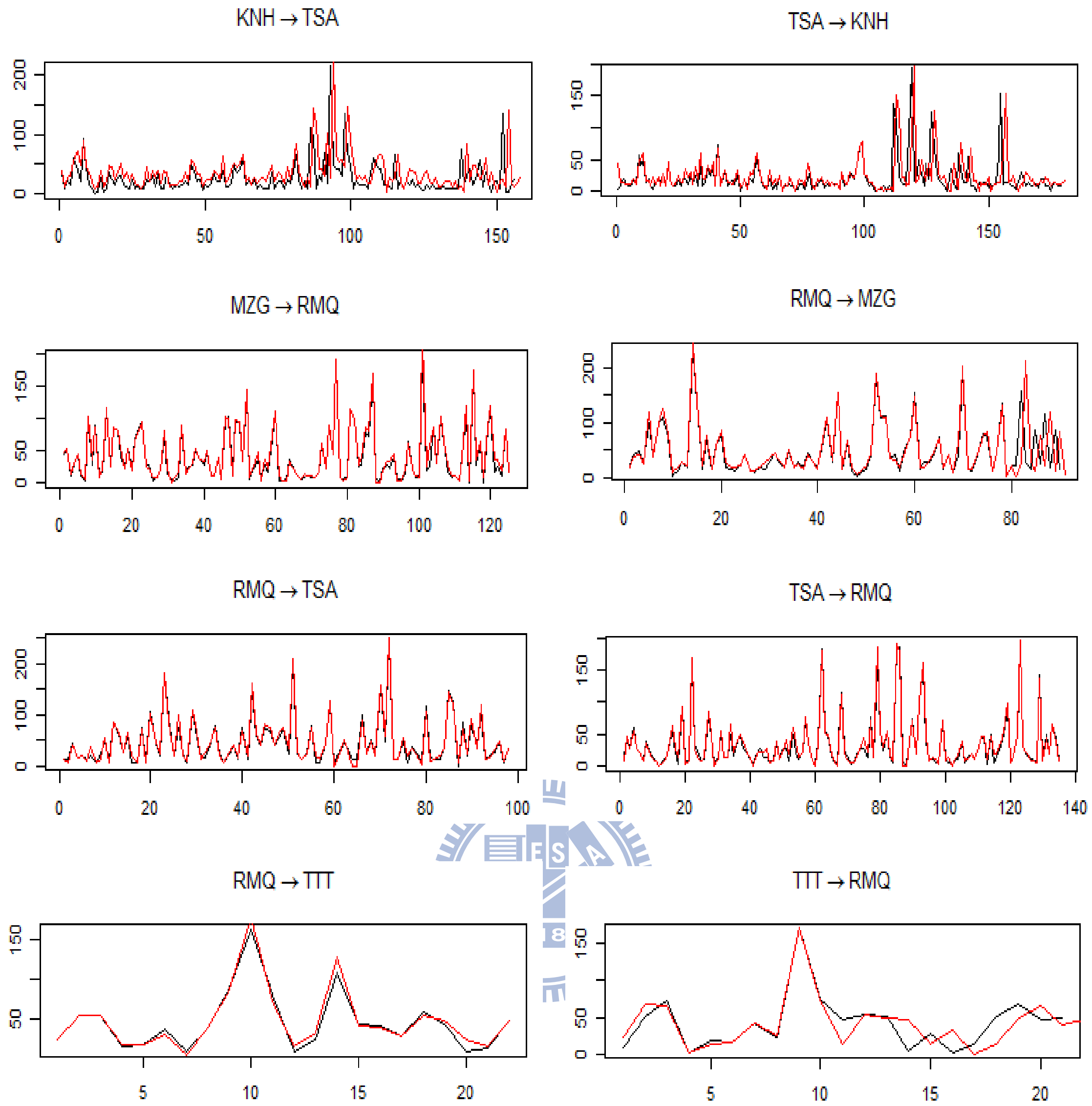
[b] Dotted lines represent the fitted density curves.

Figure 4.6 Histograms of departure delays and arrival delays.



[a] Vertical axis and horizontal axis denote delay time (measured in minute) and the associated delayed flights (excluding cancelled flights) according to the sequence of flights in schdeule, respectively.
[b] Black line and red line represent departure delays and arrival delays, respectively.

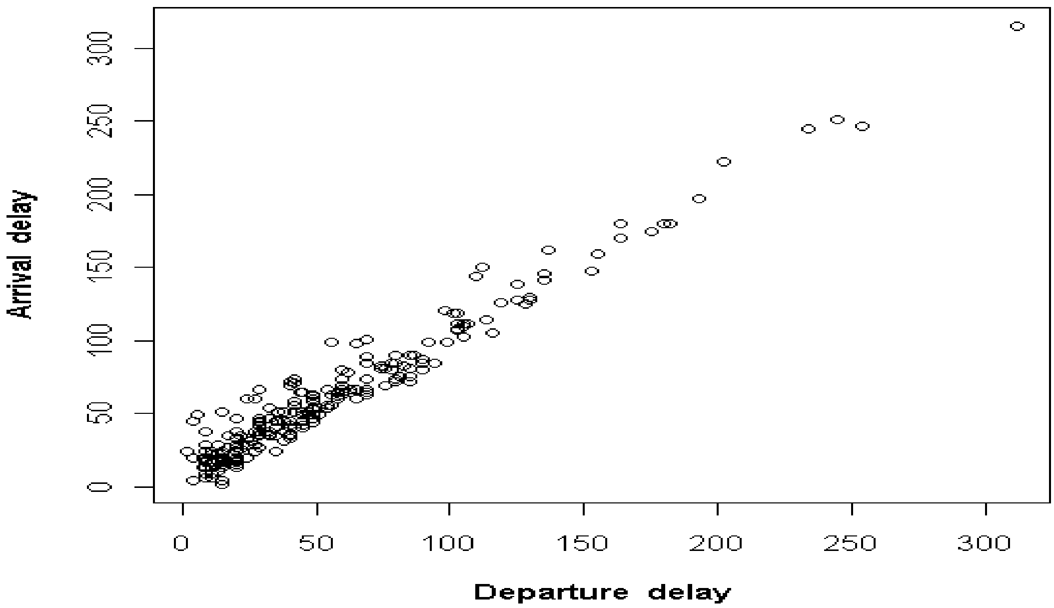
Figure 4.7 Departure and arrival delays of various routes.



[a] Vertical axis and horizontal axis denote delay time (measured in minute) and the associated delayed flights (excluding cancelled flights) according to the sequence of flights in schdeule, respectively.

[b] Black line and red line represent departure delays and arrival delays, respectively.

Figure 4.7 Departure and arrival delays of various routes (Continued).



[a] Vertical and horizontal axes are measured in minutes.

[b] Pearson's correlation coefficient equals 0.978 (p-value=0.000).

Figure 4.8 Correlation of departure delays and arrival delays.

Although airline companies normally schedule buffer times within turnaround operations at airports in addition to the ground handling time required, the information related to actual turnaround buffer time was unavailable in the dataset of Airline A. To obtain this information, the actual turnaround times of flights in each route were ordered from the smallest to the largest. The 25th percentile (1st quartile) of the ordered actual turnaround times was selected as the required ground handling time, the minimum time required to complete all turnaround activities. Therefore, for every outbound aircraft,

$$\textit{actual turnaround buffer time} = \textit{scheduled time of departure} - \textit{actual time of arrival} - \textit{required ground handling time}. \quad (4.1)$$

This means that after an inbound aircraft arrives at the gate, the difference between the actual time of arrival and the scheduled time of departure for the next flight is the time available for the turnaround of the aircraft. The actual turnaround buffer time can be derived by subtracting the required ground handling time from the available turnaround time. Thus, the actual turnaround buffer time is positive if the available turnaround time exceeds the required ground handling time, and negative (generally resulting from a late flight arrival) if the available turnaround time is shorter than the required ground handling time.

Conversely, the block time includes block buffer time and required block operation time, which is the minimum time required to complete the activities of taxi-out, airborne operation, and taxi-in. However, the obtained dataset did not contain the information related to actual block buffer time. To derive this information, the actual block times of flights in each route were ordered from the smallest to the largest. The 25th percentile of the ordered actual block times was then selected as the required block operation time. Therefore, for every inbound aircraft,

$$\begin{aligned} \textit{actual block buffer time} &= \textit{scheduled time of arrival} - \textit{actual time of departure} \\ &\quad - \textit{required block operation time}. \end{aligned} \tag{4.2}$$

In other words, after an outbound aircraft departs from the airport gate, the difference between the actual time of departure and the scheduled time of arrival represents the time available for the block operation of the aircraft. The actual block buffer time can be derived by deducting the required block operation time from the available block time. Thus, the actual block buffer time is positive if the available block time exceeds the required block operation time, and negative (generally resulting from a late flight departure) if the available block time is shorter than the required block operation time.

Because airlines often assign different types of aircraft to various routes in aircraft daily operations, the distributions of flight delays may be influenced by aircraft type, route, peak/off-peak hour, and season, in addition to delay cause (Wu and Wong, 2007; Vranas et al., 1994; Tu et al., 2008; Eurocontrol, 2003; Allan et al., 2001; Santos and Robin, 2010; Fricke and Schultz, 2009), which are also discussed in Section 4.1. Therefore, the survival curves of flight delays using the Kaplan-Meier estimator are used to examine the possible impact of factors on delays in departure and arrival.

●*Aircraft Type*

In aircraft's daily operations, turnaround times vary for different aircraft designs and depend on the amount of resources allocated to a turnaround at a specific airport. Bigger aircraft typically need more ground handling time to complete the activities required at airports. In addition, Cavcar and Cavcar (2004) compared different aircraft types and concluded that the rate of climb and cruising speeds of different aircraft types have different effects on air traffic delays. Table 4.6 shows the routes, represented by the origin airport codes and the destination airport codes, and assigned aircraft types of Airline A. The delays of the two types of aircraft are analyzed and illustrated in Figure 4.9. Although Fokker 100 aircraft is larger than Fokker 50 aircraft, the survival curves reveal that Fokker 50 aircraft tend to have longer survival times of delays than Fokker 100 aircraft. This may be due to better performance of Fokker 100 aircraft. Besides, according to the delay causes recorded by Airline A, most of the airports at which Fokker 100 aircraft operate exhibit better management of turnaround activities. On the contrary, Fokker 50 aircraft have more technical problems and a higher frequency of not being able to be released because of maintenance reasons. Also, some of the airports at which Fokker 50 aircraft operate often have runway closures because the weather is below safe operating limits.

Table 4.6 Routes and assigned aircraft types

Route	Aircraft Type	Route	Aircraft Type
HUN→KHH	Fokker50	RMQ→KNH	Fokker50
HUN→RMQ	Fokker50	RMQ→MZG	Fokker50
KHH→HUN	Fokker50	RMQ→TSA	Fokker50
KHH→TSA	Fokker100	RMQ→TTT	Fokker50
KNH→RMQ	Fokker50	TSA→KHH	Fokker100
KNH→TSA	Fokker100	TSA→KNH	Fokker100
MZG→RMQ	Fokker50	TSA→RMQ	Fokker50
RMQ→HUN	Fokker50	TTT→RMQ	Fokker50

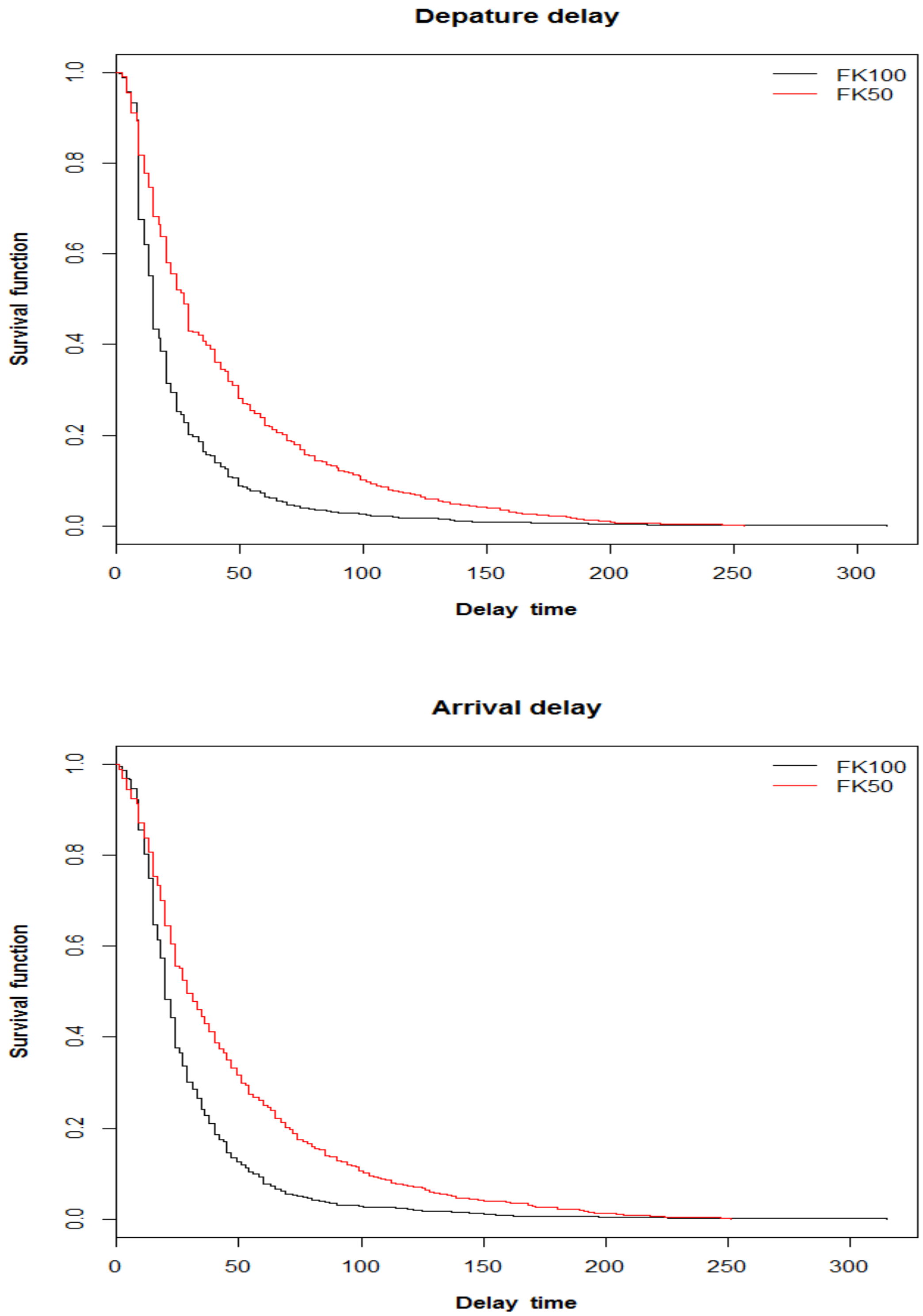


Figure 4.9 Survival curves of various types of aircraft.

●*Route*

The survival curves for the 16 routes indicate that delays are different from individual to individual for both departure and arrival (Figure 4.10). Since all aircraft operate short-distance flights with various block times from 40 to 70 minutes, it is usually difficult to make up the flight delays in the air. The recorded delay causes show that the facilities and management efficiency vary from one airport to another. For instance, TSA and KHH have better airport facilities and management. By contrast, at KNH flight delays are sometimes caused by insufficient airport facilities. RMQ and KNH, on the other hand, often have foggy weather, leading to runway closures. The problem gets worse since RMQ is the home base of Airline A with the company's maintenance hangar located here. Because of many flights operating between RMQ and other airports, runway closures at RMQ prevent flights from operating to other segments and even propagate delays to several segments. Similarly, MZG often has flight delays resulting from windy weather.

Table 4.6 shows that Fokker 100 aircraft operate only four routes: KHH→TSA, KNH→TSA, TSA→KHH, and TSA→KNH. Particularly, TSA and KHH are with better airport facilities and management as mentioned above. On the contrary, Fokker 50 aircraft operate 12 of the total 16 routes, to which flight delays tend to happen. Especially, the flight delays for routes between RMQ and other airports have serious effects on schedule reliability. Therefore, flight delays are closely related to the types of the aircraft used and the routes to which the aircraft are assigned.

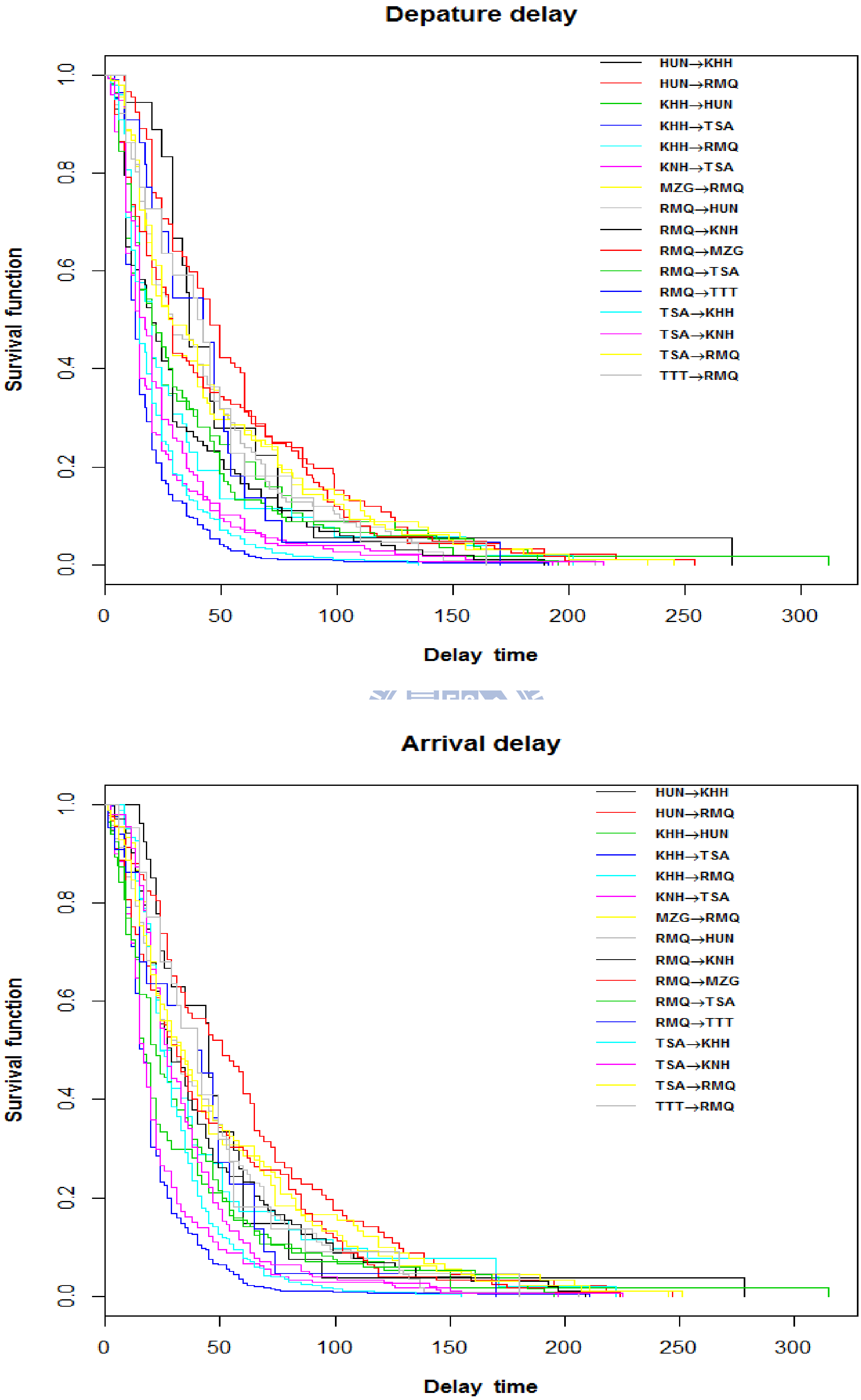


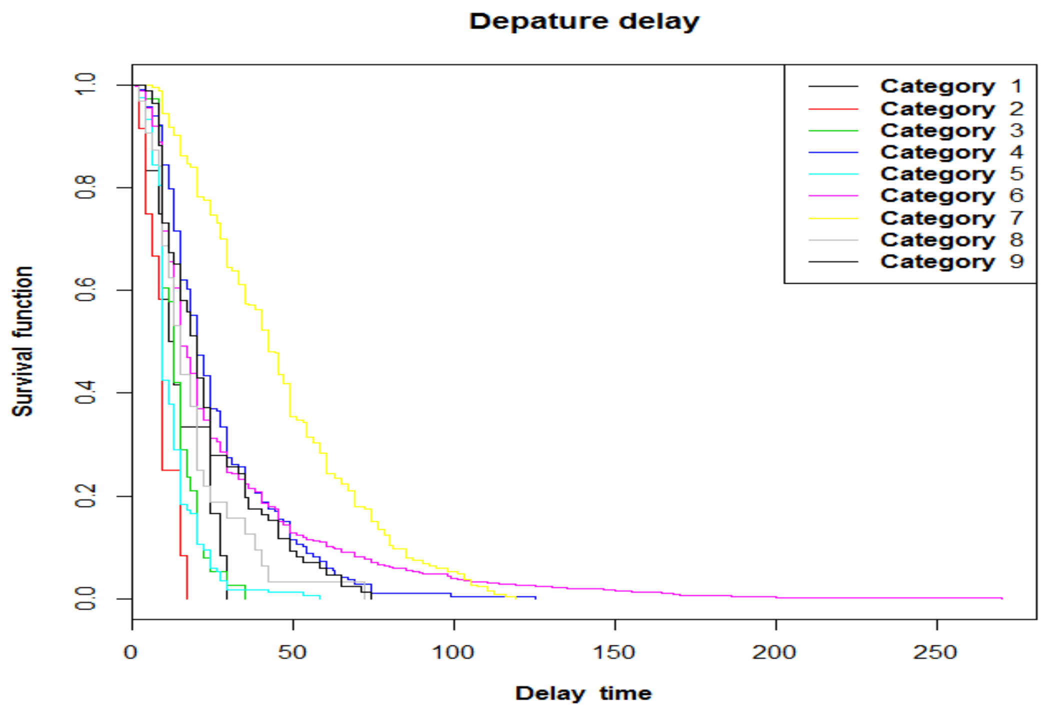
Figure 4.10 Survival curves of various routes.

●*Delay Cause*

Because flight delays may have a wide range of causes and the associated disturbances may result in various durations of flight delays, it is worthwhile investigating the relationship between delays and their causes. Figure 4.11 shows that 'weather' and 'technical and aircraft equipment' tend to result in longer departure delays. 'Reactionary,' which corresponds to the delays due to late arrival of aircraft from previous segments, is also a major cause for departure delays. On the other hand, the survival curves for arrival delays show that 'weather' has much serious impact on flight operations than 'air traffic control restrictions'. The analysis reveals that different categories of delay causes have different effects on flight delays.

●*Peak/Off-peak*

In most cases, the flights operating in peak hours are more likely to be delayed. This may be, for example, because passengers are held up at check-in, security controls, and customs, or aircraft wait a long time in queue to obtain clearances to take off. The survival curves of peak hour show only slightly different from those of off-peak hours for both departure and arrival delays (Figure 4.12). This indicates that flights operating in off-peak hours may be disturbed by some important factors, which are worth investigating.



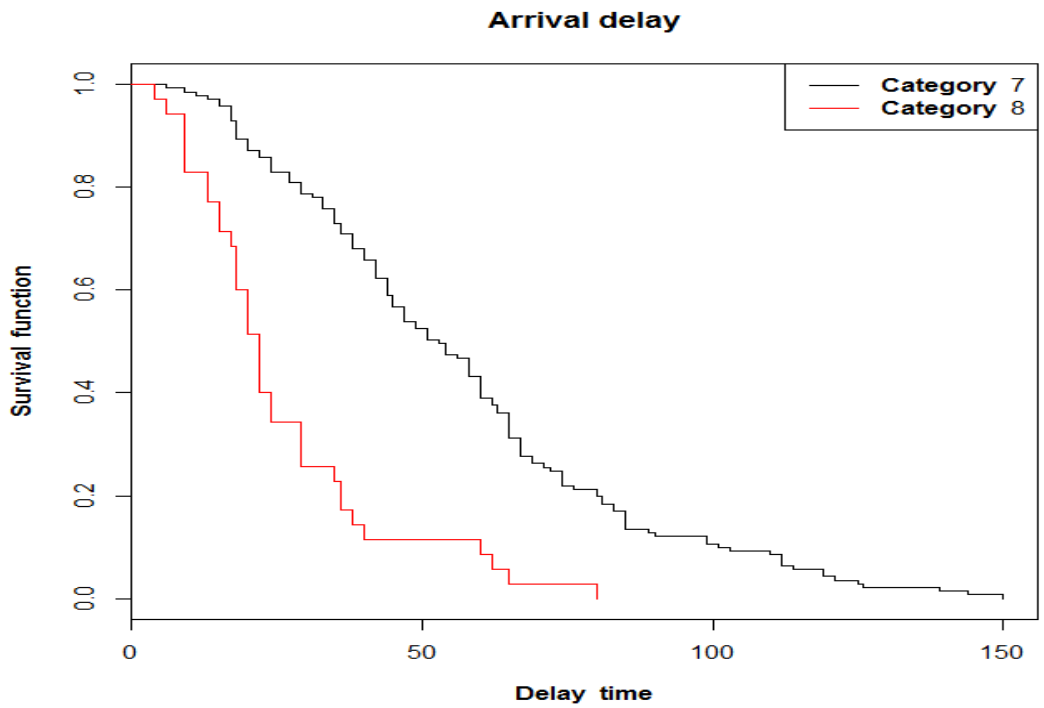


Figure 4.11 Survival curves of various categories of delay causes.

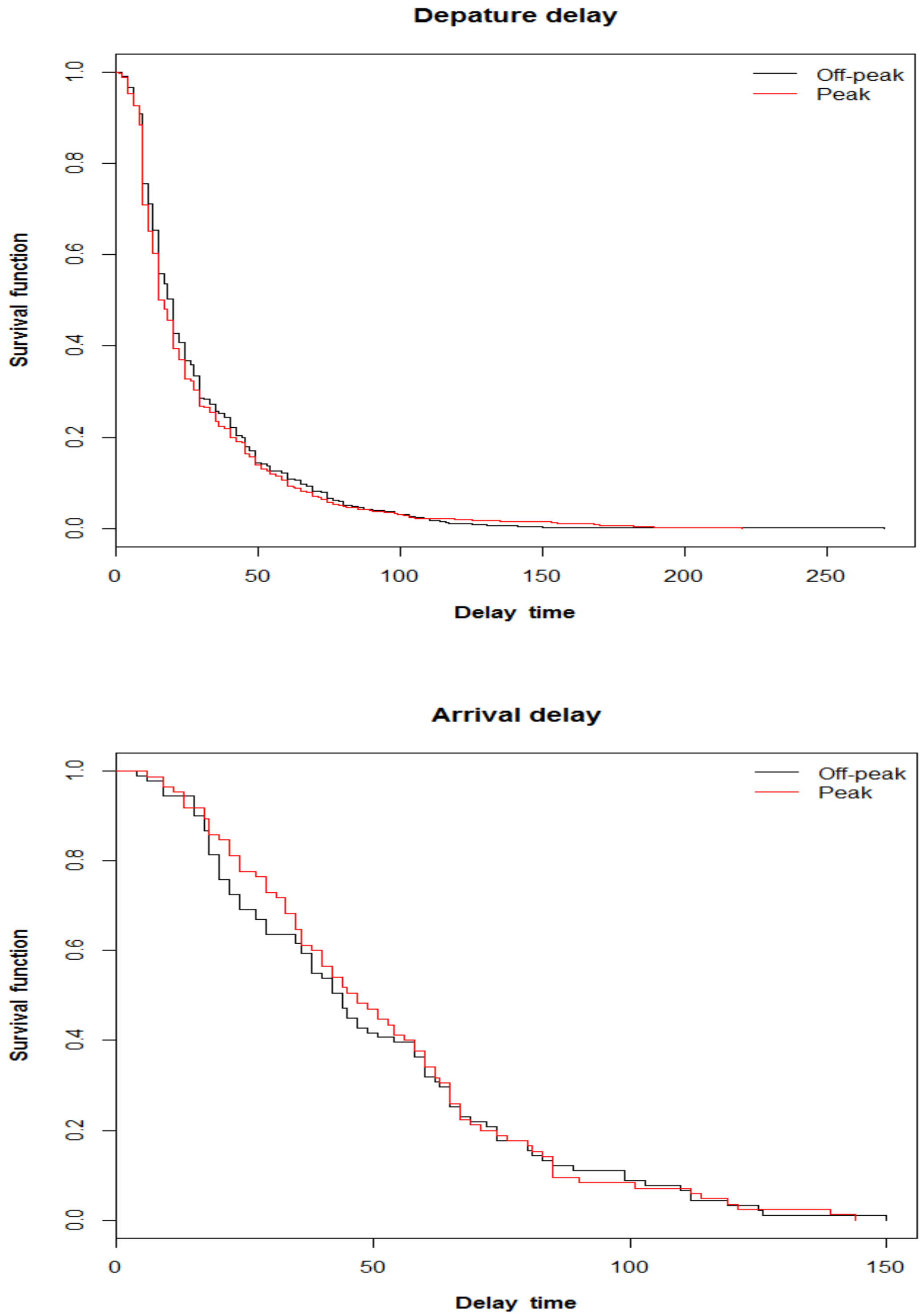
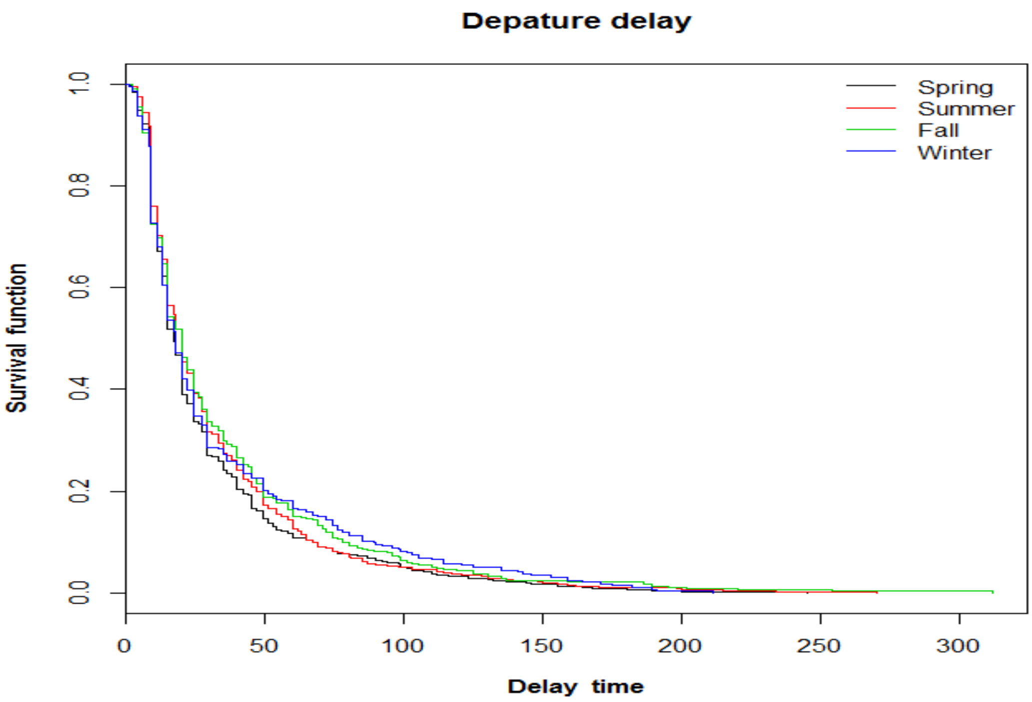


Figure 4.12 Survival curves of peak/off-peak hours.

●*Season*

The recorded delay causes reveal that the foggy weather in spring often results in runway closures, especially at RMQ and KNH. The initial delays even propagate to several flight segments in the network. On the other hand, it features in rainy weather in summer and fall, which also frequently causes runway closures, especially at TSA, RMQ, KNH, MZG, and HUN. In winter, the operations of most flight routes are influenced by monsoons. Though weather conditions in different seasons often cause flight delays, Figure 4.13 shows that the survival curves of different seasons are quite close to one another for both departure and arrival delays.



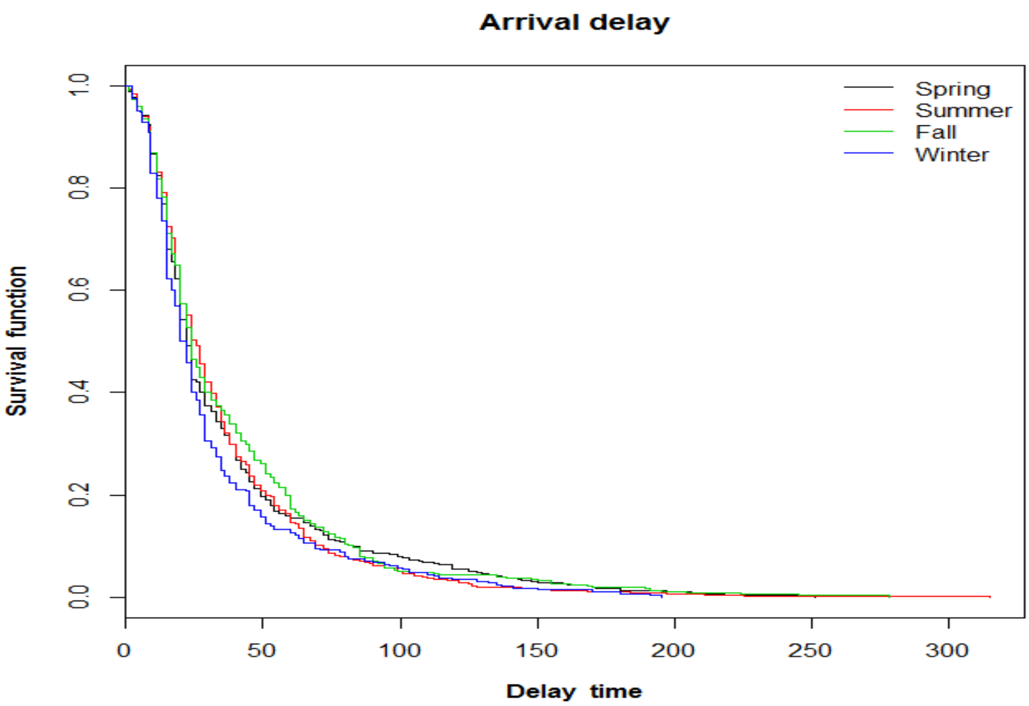


Figure 4.13 Survival curves of seasons.

Using the log-rank tests, the results in Table 4.7 indicate significant differences in the survival distributions of flight delays for the selected variables. Therefore, in addition to the variables influencing turnaround and block operations, aircraft type, route, delay cause, peak/off-peak hour, and season are also considered as the covariates for developing the flight delay models.

Table 4.7 Difference test of survival curves

Factor	Departure/Arrival Delay	Chi-square
Aircraft type	Departure delay	158.2***
	Arrival delay	107.4***
Route	Departure delay	305.3***
	Arrival delay	271.1***
Delay cause	Departure delay	373.8***
	Arrival delay	10.1***
Peak/off-peak hour	Departure delay	11.8**
	Arrival delay	12.3**
Season	Departure delay	7.6***
	Arrival delay	10.7***

Significance levels: 0%***, 0.1% **, 1%*.

To formulate a departure delay model, the relationship between variables must be further clarified. First of all, there will be a longer buffer time in turnaround operations if ground handling activities are completed rapidly; conversely, there will be a shorter turnaround buffer time if more time is required to complete ground handling activities. In addition, the late arrival of flights also results in a reduction in turnaround buffer time. Therefore, to avoid any bias resulting from the highly correlated relationship with ‘turnaround buffer time’, ‘arrival delay’ and ‘ground handling time’ should be deleted from the model. Similarly, the routes of Airline A are operated using different types of aircraft, and flight delays are subject to the routes to which the aircraft are assigned. Accordingly, ‘route’ should also be removed from the model because the delays associated with a ‘route’ are already reflected in the delays of the ‘aircraft type’, and a bias would be generated if both ‘route’ and ‘aircraft type’ are used as covariates. Furthermore, a delay caused by 'late arrival of an aircraft', recorded as 'reactionary' by airlines, is already counted as an 'arrival delay' and reflected in 'turnaround buffer time' in the model. Consequently, 'reactionary' should also be deleted from the delay causes considered. Thus, the departure delay model is formulated as Equation (4.3).

$$\begin{aligned} &h(departure\ delay | \text{covariates}) \\ &= h_0(departure\ delay)\exp(\beta_1 \times turnaround\ buffer\ time + \beta_2 \times aircraft\ type \\ &\quad + \sum_{i=1}^{8} \beta_{i+2} \times category\ of\ delay\ cause_i + \beta_{11} \times peak/off-peak\ hour \\ &\quad + \sum_{j=1}^{3} \beta_{j+11} \times season_j) \end{aligned} \tag{4.3}$$

In aircraft rotations, a shortened taxi-out time, airborne time, and taxi-in time will result in a longer buffer time in block operations. By contrast, the block buffer time is shortened when taxi-out time, airborne time, and taxi-in time are longer. In addition, the late departure of flights also results in a reduction in block buffer time. Because the lengths of taxi-out time, airborne time, and taxi-in time depend on whether aircraft are operating in peak or off-peak hours, the delay information associated with these factors can also be obtained from 'peak/off-peak hour' in the model. Therefore, 'departure delay', 'taxi-out time', 'airborne time', and 'taxi-in time' should be removed from the model to avoid an interdependent relationship between these covariates and the 'block buffer time'. Similarly, 'route' should also be deleted to avoid simultaneously including both 'route' and 'aircraft type', as discussed in the establishment of the departure delay model. The arrival delay model is therefore formulated as Equation (4.4).

$$\begin{aligned} &h(arrival\ delay | \text{covariates}) \\ &= h_0(arrival\ delay)\exp(\beta_1 \times block\ buffer\ time + \beta_2 \times aircraft\ type \\ &\quad + \beta_3 \times category\ of\ delay\ cause + \beta_4 \times peak/off-peak\ hour \\ &\quad + \sum_{j=1}^{3} \beta_{j+4} \times season_j) \end{aligned} \tag{4.4}$$

Therefore, the variables used in the departure and arrival delay models for capturing the chain effects of flight delay propagation are listed in Table 4.8.

Table 4.8 Variables used in departure and arrival delay models

Variable	Departure Delay Model	Arrival Delay Model	Dummy Code	Description
Turnaround buffer time	✓		—	—
Block buffer time		✓	—	—
Aircraft type	✓	✓	0	Fokker 100
			1	Fokker 50
Category of delay cause	✓		0	Airport facilities or governmental authorities
			1	Flight operations and crewing, cargo and mail handling, technical and aircraft equipment, passenger and baggage handling, weather*, air traffic control restrictions, miscellaneous
		✓	0	Air traffic control restrictions
			1	Weather#
Peak/off-peak hour	✓	✓	0	Peak hour
			1	Off-peak hour
Season	✓	✓	0	Spring
			1	Summer, fall, winter

[a] *: Including ground handling impaired by adverse weather conditions, weather at departure airport, weather en-route, and weather at destination or alternative airport.

[b] #: Including "only" weather en-route and weather at destination or alternative airport.

[c] Dummy code 0: Base type.

Due to the strong causal relationship between departure and arrival delays via aircraft routing, flight delay propagation can be investigated by recursively combining the departure and arrival delay models. Here, 'recursively' means that the output of the departure delay model serves as the input of the arrival delay model, and the output of the arrival delay model serves as the input of the departure delay model.

4.3 Results of Delay Models

4.3.1 Departure Delay Model

The results of the departure delay model are shown in Table 4.9; because 'season' and 'peak/off-peak hour' were not statistically significant, they were deleted. The higher the hazard is for an event to occur, the more likely the flight delay will end. Thus, for each 1-min increase in turnaround buffer time, which varies depending on arrival time or ground handling time, the chance of ending departure delays increases by only 0.4%. This reveals that departure delays may not be greatly improved though turnaround operations include built-in buffer time. Therefore, airlines may investigate other reasons behind the flight delays before taking the measure of increasing buffer time. With respect to aircraft type, Fokker 50 aircraft have a 35.9% lower chance of ending departure delays than Fokker 100 aircraft.

Table 4.9 Results of departure delay mode

Factor	β	$\left(e^{\beta}-1\right)\times 100\%$
Turnaround buffer time	0.004 *	0.4%
Aircraft type	-0.445 *	-35.9%
Category of delay cause		
Flight operations and crewing	-0.539	-41.7%
Cargo and mail handling	-0.749 *	-52.7%
Technical and aircraft equipment	-0.622 *	-46.3%
Passenger and baggage handling	-0.511 *	-40.0%
Weather	-0.575 *	-43.7%
Air traffic control restrictions	-0.294	-25.4%
Miscellaneous	-0.316	-27.1%

[a] LR = 81.11, p-value = 0.000.

[b] *:Statistically significant at 5% level.

Compared to the delays caused by 'airport facilities or governmental authorities', departure delays resulting from 'flight operations and crewing', including crew arriving late for their position, crew change, crew legality, etc., have a 41.7% lower chance of recovery. As it is understood, an aircraft will be grounded unless problems associated with crew assignment are fixed. Departure delays caused by 'cargo and mail handling' and 'passenger and baggage handling', on the other hand, have 52.7% and 40.0% lower chances of recovery, respectively. In addition, departure delays resulting from 'technical and aircraft equipment' have lower chance of recovery by 46.3%. Each of these significant contributing factors is related to airline operations, suggesting that potential improvements could be achieved through a suitable delay management program. Departure delays caused by 'weather' are with 43.7% lower chance of recovery and are beyond the control of airlines. Nevertheless, a well-designed contingency plan and useful management techniques could be helpful for airlines to alleviate the consequences of delays caused by weather. Air traffic control restrictions en-route or at the destination airport can be the cause of departure delay when ground-holding policies are imposed. It reveals that departure delays caused by 'air traffic control restrictions' have a 25.4% lower chance of recovery.

4.3.2 Arrival Delay Model

Table 4.10 shows the calibrated results of the arrival delay model. Note that ‘aircraft type’, ‘season’, and ‘peak/off-peak hour’ were not statistically significant variables and were therefore deleted from the model. The results indicate that the key contributing factors of arrival delays include ‘block buffer time’ and ‘weather’. For each 1-min increase in block buffer time, which varies depending on departure time or block operation time, the chance for arrival delays to end increases by 6.8%. Most arrival delays are beyond the control of airlines except for delays that develop at departure airports. This implies that developing the means to prevent departure delays could be the key to reducing arrival delays from the origin.

Table 4.10 Results of arrival delay model

Factor	β	$\left(e^{\beta}-1\right)\times 100\%$
Block buffer time	0.066*	6.8%
Category of delay cause		
Weather	-0.957*	-61.6%

[a] LR = 294.3, p-value = 0.000.
[b] *:Statistically significant at 5% level.

Whilst outbound flights are subject to a wider range of difficulties leading to delays, inbound flights can be delayed by ‘weather’ or ‘air traffic control restrictions’ en-route or at destination airport. Compared to the delays caused by ‘air traffic control restrictions’, arrival delays resulting from ‘weather’ have a 61.6% lower chance of recovery. As found in both the departure and arrival delay models, ‘weather’ is the cause of delays that tends to result in longer departure and arrival delays.

4.4 Results of Delay Improvement Schemes

In computing the hazard ratio, it is not necessary to estimate the baseline hazard ($h_0(t)$) because they are cancelled out in the computation. According to Tables 4.9 and 4.10, the calibrated delay models are as Equations (4.5) and

(4.6). However, since this research is to examine the effectiveness of flight delay improvement schemes by measuring survival distributions of flight delay propagation and the costs of the scheme and the savings of the delay costs, the probability of a flight delay surviving to a specific value of time and the expected delay cost associated need to be calculated. The baseline hazards ($h_0(t)$) in Equations (4.5) and (4.6) are therefore required to further obtain the complete survival functions of the departure and arrival delay models.

Departure delay model:

$$
\begin{aligned}
& h(\textit{departure delay} \mid \text{covariates}) \\
& = h_0(\textit{departure delay})\exp(0.004 \times \textit{turnaround buffer time} - 0.445 \times \textit{aircraft type} \\
& \quad - 0.539 \times \textit{flight operations and crewing} - 0.749 \times \textit{cargo and mail handling} \\
& \quad - 0.622 \times \textit{technical and aircraft equipment} - 0.511 \times \textit{passenger and baggage} \\
& \quad \textit{handling} - 0.575 \times \textit{weather} - 0.294 \times \textit{air traffic control restrictions} \\
& \quad - 0.316 \times \textit{miscellaneous})
\end{aligned}
\tag{4.5}
$$

Arrival delay model:

$$
\begin{aligned}
& h(\textit{arrival delay} \mid \text{covariates}) \\
& = h_0(\textit{arrival delay})\exp(0.066 \times \textit{block buffer time} - 0.957 \times \textit{weather})
\end{aligned}
\tag{4.6}
$$

Using Equations (4.5) and (4.6), this research first esimtates the baseline hazards and finally derives the survival functions according to the methodology discussed in Section 3.3.1. Table 4.11 shows an example of a schedule of Airline A, assuming a 30-min arrival delay caused by weather for the first flight of the day. Using this scenario of airline schedule, delay improvement schemes, including shortening required ground handling time and directly increasing buffers for turnaround and en-route aircraft, will be demonstrated to compare the results before improvement to investigate the effectiveness of these delay improvement schemes. The survival functions of departure and arrival flights, indicating the propagated delays in aircraft rotations, and the costs of the resources invested and the savings of the delay costs will be obtained in the recursive process between departure and arrival delay models.

Table 4.11 Example of rotation schedule of Airline A

Flight	Origin Airport	Scheduled Time of Departure	Destination Airport	Scheduled Time of Arrival
1	KHH	6:55	TPE	7:45 *
2	TPE	8:20	KHH	9:10
3	KHH	9:45	TPE	10:35
4	TPE	11:10	KHH	12:00

[a] *: Assume there is a 30-min arrival delay caused by weather.

[b] The required ground handling time and turnaround buffer time are 20 minutes and 15 minutes respectively; the required block operation time and block buffer time are 40 minutes and 10 minutes respectively.

Because of the unavailability of detailed financial information of Airline A, the values of system costs in Table 4.12 are calculated approximately for the purpose of the demonstration. All values presented are subject to change and must be revised by potential users to ensure values are appropriate to the circumstances in which they are to be used. In Table 4.12, the 'aircraft delay costs' are the sum of fuel costs, maintenance costs, crew costs, and aeronautical charges. As the assumption of step cost function, the 'passenger delay costs to airlines' are given various values with respect to the duration of delays. The 'buffer costs', which are unit costs planned in advance, are the total of fuel costs, maintenance costs, crew costs, and fleet costs. It is noted that 'the aircraft delay costs' included in the 'delay costs' and 'buffer costs' of arrival delay model are given higher values than those of departure delay model to reflect the higher costs incurred in block operations as discussed in Section 2.4.

Table 4.12 Values of system costs of departure and arrival delay models

System Costs	Departure Delay Model	Arrival Delay Model
Delay costs		
Aircraft delay costs	11.97	51.28
Passenger delay costs to airlines		
≤5min	5.65	5.65
≤15min	16.25	16.25
≤30min	34.62	34.62
≤60min	77.73	77.73
≤90min	103.88	103.88
≤120min	117.30	117.30
≤180min	136.38	136.38
≤240min	153.34	153.34
≤300min	170.30	170.30
Buffer costs	15.00	62.00

[a] Sources:

Cook, A.J., Tanner, G., Anderson, S., 2004. *Evaluating the true cost to airlines of one minute of airborne or ground delay: Final Report.* Eurocontrol, Brussels, Belgium.

Cook, A.J., Tanner, G., 2011. *European airline delay cost reference values: Final Report.* Eurocontrol, Brussels, Belgium.

[b] All costs are in US dollars per minute, per flight, and are updated to 2012 value levels.

[c] The values of passenger delay costs to airlines are calculated with an average load factor of 0.7.

To calculate the expected delay costs of departure and arrival flights, let $cost = g(T)$, where $g(T)$ is an increasing function of delay time T. The 'expected aircraft delay costs' and the 'expected passenger delay costs to airlines' then can be calculated by Equation (4.7).

$$E(Cost|X) = E(g(T)|X) = -\int g(t)dS(t|X), \qquad (4.7)$$

where

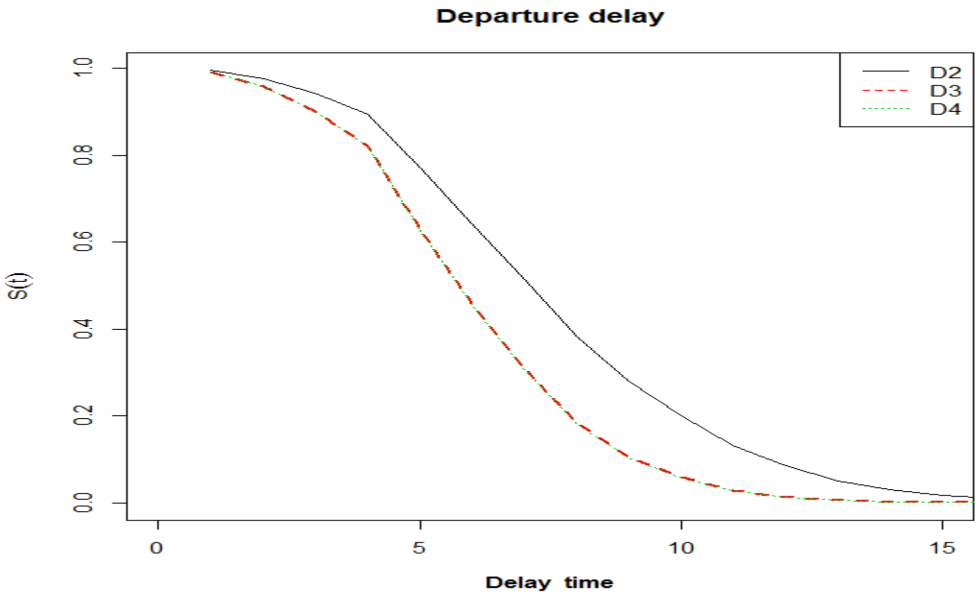
$X = (x_1, x_2, \ldots, x_P)$, a vector of p covariates.

4.4.1 Before Delay Improvement

Using the schedule in Table 4.11, the output of the first arrival flight serves as the input of the second departure flight, and the output of the second departure flight serves as the input of the second arrival flight. Then, flight delay propagation can be investigated by recursively combining the departure and arrival delay models. The results in Table 4.13 present the expected departure and arrival delay time propagated and the expected delay costs associated, and the buffer costs incured for next flight segments, following the arrival delay of the first flight. Note that the buffer minutes are planned in advance and therefore the resulted costs are fixed no matter whether the buffer minutes are fully used or not. The survival curves in Figiure 4.14 reveal that departure delays are short in length whilst a vast proportion of arrival delays is surviving longer.

Table 4.13 Results before delay improvement

	Expected Departure Delay Time	Expected Arrival Delay Time	Expected Aircraft Delay Costs	Expected Passenger Delay Costs to Airlines	Buffer Costs
2nd departure flight (D2)	14.65		175.34	393.54	225
2nd arrival flight (A2)		31.68	1624.51	2046.68	620
3rd departure flight (D3)	11.99		143.57	256.49	225
3rd arrival flight (A3)		30.20	1548.89	1877.56	620
4th departure flight (D4)	11.97		143.30	255.49	225
4th arrival flight (A4)		30.19	1548.28	1876.17	620
Total			5183.89	6705.93	2535
			11889.82		



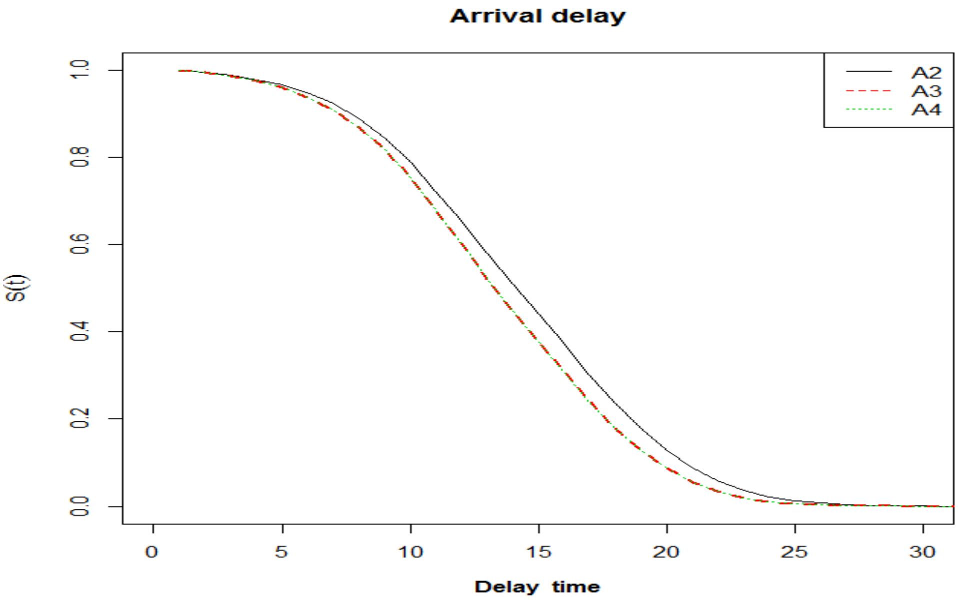


Figure 4.14 Survival curves of departure and arrival delays before delay improvement.

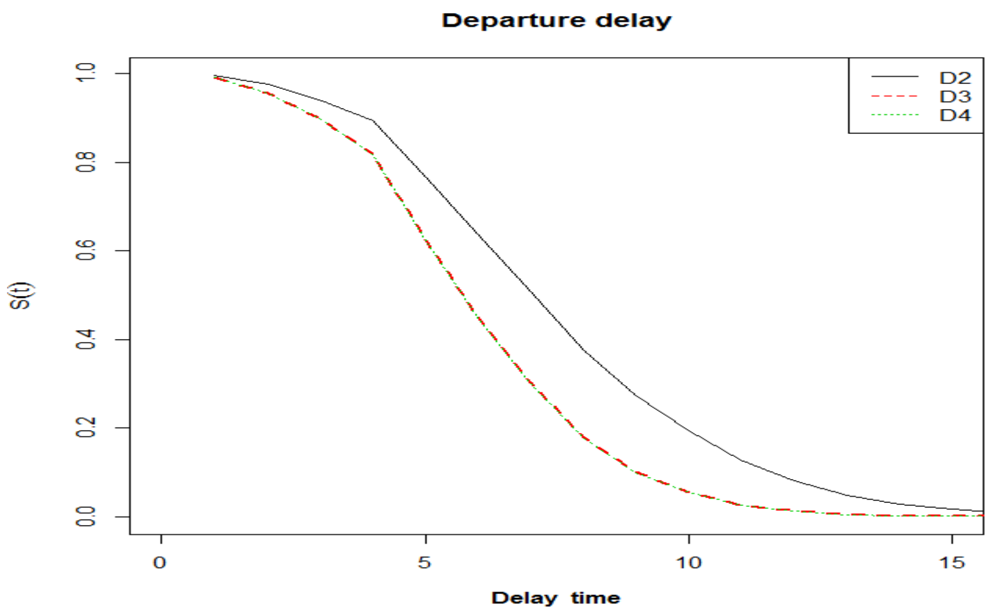
4.4.2 After Turnaround Operation Improvement

When turnaround buffer time is increased by a certain amount, it will cause a decrease in departure delays. To evaluate the effect of the extra buffer minutes added, we assume that the required ground handling time is shortened by 5 minutes, resulting in a 5-min increase in turnaround buffer time. The results are shown in Table 4.14 and Figure 4.15.

Compare to the results of Table 4.13, the delay costs are reduced by US$37.99. However, the buffer costs are the same as those before the improvement since no extra minutes of buffers are scheduled. Thus, if the costs of shortening 5-min required ground handling time are less than US$37.99 of the delay costs saved, this can be a measure to take from the perspective of costs invested and saved. Additionally, the expected departure and arrival delay times do not have great decrease and end after the improvement. The survival curves of departure and arrival delays in Figure 4.15 also illustrate the facts. This reveals that 5-min improvement in turnaround operations may not be helpful in the reduction of delays in this dynamic operating environment. Thus, airlines may investigate other reasons behind the flight delays.

Table 4.14 Results after turnaround operation improvement

	Expected Departure Delay Time	Expected Arrival Delay Time	Expected Aircraft Delay Costs	Expected Passenger Delay Costs to Airlines	Buffer Costs
2nd departure flight (D2)	14.55		174.17	387.86	225
2nd arrival flight (A2)		31.62	1621.69	2040.45	620
3rd departure flight (D3)	11.92		142.67	253.10	225
3rd arrival flight (A3)		30.16	1546.81	1872.84	620
4th departure flight (D4)	11.90		142.42	252.13	225
4th arrival flight (A4)		30.15	1546.21	1871.48	620
Total			5173.97	6677.86	2535
			11851.83		



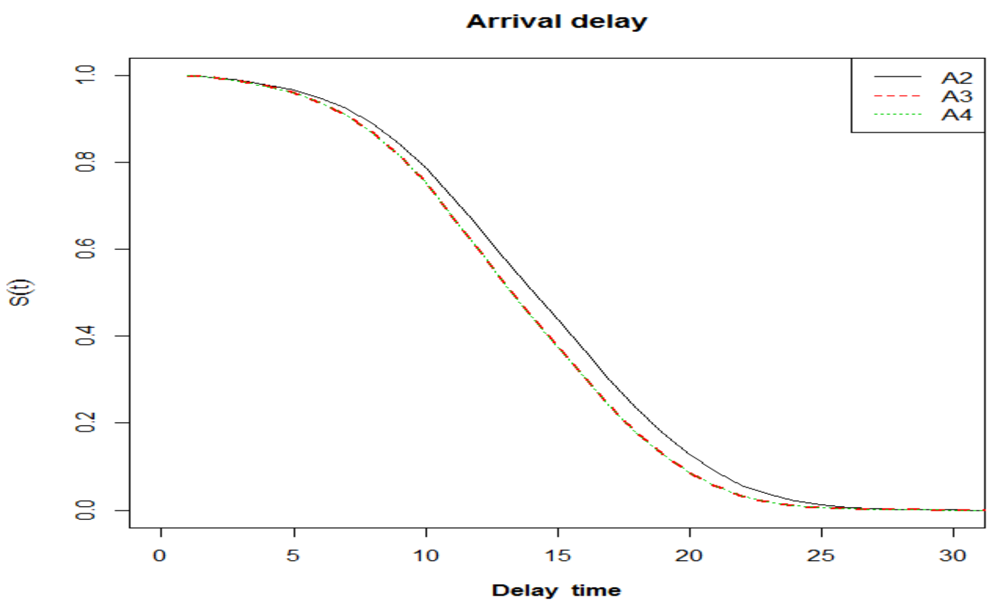


Figure 4.15 Survival curves of departure and arrival delays after turnaround operation improvement.

Alternatively, airlines can directly increase turnaround buffer time by 5 minutes to the original schedule. Nevertheless, the expected departure and arrival delay times propagated and the expected delay costs saved will be the same as those by shortening 5-min required ground handling time. Since the

5-min increase in turnaround buffer time will result in US$225 of additional buffer costs, which is greater than US$37.99 of delay costs saved, it is not a good measure to take under the circumstances.

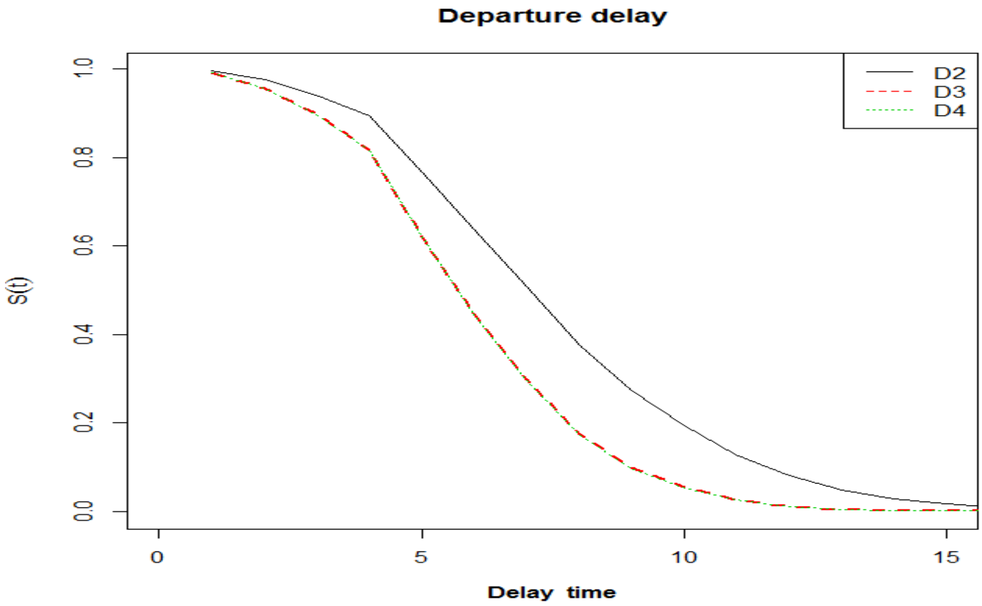
4.4.3 After Turnaround and Block Operation Improvement

Airlines may improve turnaround and block operations at the same time to reduce flight delays. By shortening 5-min required ground handling time and directly increasing 5-min block buffer time, the results are shown in Table 4.15 and Figure 4.16. Compare to the results of Table 4.13, this improvement reduces US$1398.81 of delay costs and increases US$930 of buffer costs. Therefore, if the costs of shortening 5-min required ground handling time plus US$930 of buffer costs invested are less than US$1398.81 of delay costs saved, this can be a measure to take. It is also found that the expected departure delay times are almost the same as those before the improvement. On the other hand, the expected arrival delay times have a few minutes decrease by directly increasing block buffer time in additional to shortening required ground handling time in this scenario. Both the expected departure and arrival delay times do not end though improvement in turnaround and block operations has been made. This can be also seen from the survival curves of departure and arrival delays in Figure 4.16.

Increasing buffer minutes while operating on the ground or in the air are frequently used by airlines. However, the results reveal that delays may not be greatly improved through this measure. Thus, airlines may investigate the significant contributing factors of delays and design a suitable delay management program before increasing buffers. For instance, whilst outbound flights are subject to a wider range of difficulties leading to delays, inbound flights can be delayed by weather or air traffic control restrictions en-route or at destination airport. Hence, most arrival delays are beyond the control of airlines except for delays that develop at departure airports. This implies that developing the means to prevent departure delays could be the key to reducing arrival delays from the origin.

Table 4.15 Results after turnaround and block operation improvement

	Expected Departure Delay Time	Expected Arrival Delay Time	Expected Aircraft Delay Costs	Expected Passenger Delay Costs to Airlines	Buffer Costs
2nd departure flight (D2)	14.55		174.17	387.86	225
2nd arrival flight (A2)		28.90	1481.76	1723.75	930
3rd departure flight (D3)	11.88		142.20	251.30	225
3rd arrival flight (A3)		27.52	1410.99	1558.69	930
4th departure flight (D4)	11.86		141.96	250.39	225
4th arrival flight (A4)		27.57	1410.47	1557.47	930
Total			4761.55	5729.46	3465
			10491.01		



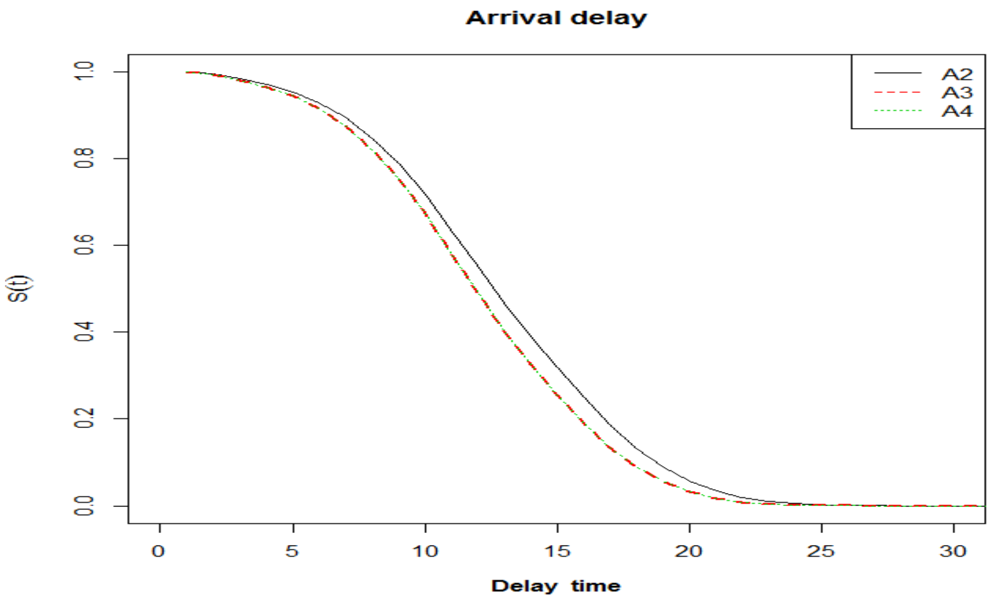


Figure 4.16 Survival curves of departure and arrival delays after turnaround and block operation improvement.

Instead of taking the way of shortening 5-min required ground handling time and directly increasing 5-min block buffer time, airlines can directly increase 5-min buffer time to both turnaround and block operations. The expected departure and arrival delay times propagated and the expected delay costs saved will be the same for these two senarios. However, ailines will incur US$225 of turnaround buffer costs and US$1155 in total of turnaound and block buffer costs for the latter. Since US$1155 of buffer costs invested is less than US$1398.81 of delay costs saved, this can be a measure to take by airlines. In addition, due to the same effects of the two scenarios on expected delay times and costs, airlines may choose the one with lower costs invested from them.

CHAPTER 5 CONCLUSIONS AND SUGGESTIONS

The objectives of this research are to propose an approach to explore the problem of flight delay propagation in a dynamic operating environment and an approach to evaluate the effectiveness of delay improvement schemes. The conclusions of the work performed are described in Section 5.1. Suggestions for further research are drawn in Section 5.2.

5.1 Conclusions

When irregularities occur, airlines might need to provide additional resources to resume normal operations, resulting in extra operating expenses. Hence, planning a schedule control program that allows greater schedule flexibility and reliability against disruptions is important in solving the problem of flight delays. To achieve this goal, airlines have to find out the ways to investigate the effects that individual factors of flight delays may have on airline schedules. For example, how the effect of an arrival delay may have on a departure delay, how a block delay can be improved by built-in buffer time, and how the differences in the chances of recovering from flight delays between different aircraft types are.

Due to the stochastic characteristics of aircraft rotations, there has been a great deal of discussion regarding how to reduce flight delays while maximizing the utilization of aircraft with very tight connections between flights. If a flight schedule is, however, only designed to absorb stochastic delays without addressing the root problem of flight delays, the schedule might not be adequately robust for future operations. Therefore, this research investigates the factors behind the mechanisms of departure and arrival delays to clarify the phases and activities involved in flight delays through an airline schedule. Because of the survival characteristics of flight delays, survival analysis is appropriate for the investigation of flight delays in a dynamic operating environment.

In aircraft's daily operations, delays in one flight might easily propagate to successive flights to have further disruptions. Accordingly, how to obtain the overall effects of an initial flight delay in an airline schedule is essential to solve the problem of flight delays. The findings of this research show that departure delays and arrival delays are closely related and that delays associated with different aircraft types, routes, delay causes, times of the day (peak/off-peak), and seasons can be different. The models for departure and arrival delays developed are able to capture the dynamic characteristics of flight delays and differ from the methods used in previous studies such as simulation models or statistical analyses. Cox regression analysis reveals that the key contributing factors of departure delays include ‘turnaround buffer time’, ‘aircraft type’, ‘cargo and mail handling’, ‘technical and aircraft equipment’, ‘passenger and baggage handling’, and ‘weather’, whilst the key contributing factors of arrival delays include ‘block buffer time’ and ‘weather’. The hazard ratios obtained enable airlines to examine the chances of recovering from flight delays. This provides airlines the direction of how to allocate resources to maintain a well-designed schedule. The approach proposed in this research is, especially, suitable for evaluating the performance of airline schedules operating in busy and short distant city-pairs.

Although airlines may or may not be able to control the factors influencing flight delays, they still require both preventive and reactive measures to cope with flight delays in daily operations. For example, to avoid a turnaround delay can be controllable to airlines. Efforts at improving ground handling efficiency would be a good way to solve this problem. Similarly, different delay causes might have different effects on flight delays. Therefore, it is essential for airlines to differentiate controllable delays from uncontrollable ones. Even for those delays resulting from uncontrollable causes, airlines can still improve operational disruptions by applying appropriate management skills, e.g. a careful review of standard operating procedures to obtain ideal performance.

When an aircraft is delayed, the airline suffers delay costs and passengers may also lose their loyalties towards the airline. Directly increasing buffers to schedule is a common method used to stabilize schedule punctuality by airlines.

Nevertheless, there seems a lack of good tools to measure the effects of delay improvement schemes. This research uses survival analysis to examine the probability of each flight delay surviving to a specific value of time and the associated expected delay costs and buffer costs. The effects of flight delay propagation are addressed in the departure and arrival delay models.

Though buffer time may save some delays, it is found that it may not be cost effective for airlines when the costs of buffer minutes are taken into account. Alternatively, airlines can improve ground handling efficiency to indirectly increase turnaround buffer by adding more resources (e.g. staff and equipment) or simply using appropriate management skills without extra resources invested, depending on the circumstances permitted. However, as found in the delay models, departure and arrival delays are not greatly improved though turnaround and block operations include built-in buffer time. Nevertheless, insufficient buffers are only one aspect of flight delays. The reasons behind the delays may be the real issues that must be tackled by airlines. Besides, scheduling of buffer time will reduce aircraft productivity due to the resulted lower utilization of aircraft. Therefore, the benefits of adding buffer time to schedule need to be further investigated.

The management of flight schedule, dealing with flight delays and buffer time, may be much more of a compromise. Though the costs of flight delays and buffer time, treated as a trade-off relationship, may be optimized, this may not be the first priority of the various tasks that airlines should take. In fact, a flight schedule can be disturbed by many contributing factors as aforementioned. Therefore, airlines may improve the controllable delays or apply management skills to lessen the degree of the impact of the uncontrollable delays. This can be an essential prerequisite for airlines to improve schedule punctuality before jumping into some sophisticated measures.

In addition, buffers can also be considered as ‘opportunity costs’ to airlines because they can be used to make revenues if the accumulated buffer minutes saved are long enough to operate an additional flight. A few studies in literature explored the ‘opportunity costs’ of buffer minutes to assess the effect of the loss to airlines. However, to complete an operation of a revenue-generating flight, there should be engough buffer minutes saved for both turnaround and block operations. Lack of one of them will not be possible for ailines to operate any additional flight. Moreover, the maket may not support the demands of additional flights. Under this circumstance, it may cause losses instead to airlines for those more flights scheduled. It is also not unusual that airlines may not be able to have the slots for the intended additional flights. There are, on occasion, constraints to operate these flights at the next destination airports as well. Nevertheless, buffers should not be totally eliminated from schedule due to the important role played.

5.2 Suggestions

Although this research has taken a step forward in the direction of examing the problem of flight delay propagation and evaluating the effectiveness of delay improvement schemes by considering the stochastic characteristics of turnaround and block operations, some limitations should be noticed and some further studies are worth exploring.

1. This research is a new attempt to apply survival analysis as a tool for delay analysis. Though this approach is suitable for evaluating flight delay propagation for the airline operating in busy and short distant city-pairs, the findings are subject to change when flight data involves more than one airline. The results may also be different if international routes are analyzed. Especially, the problem of flight delays can be more complicated at hub airports, where flights may be delayed due to the required connections of passengers and baggage. Therefore, the proposed approach can be applied in other datasets in future studies.
2. Some important information is not available in the dataset collected. For example, the information of actual turnaround and block buffer time and the detailed financial information of system costs are not available in the dataset and are calculated approximately for the purpose of demonstration.

Though they can be revised by potential users to ensure values are appropriate to the circumstances in which they are to be used, more precise outcomes can be obtained if detailed information can be collected.

3. The hazard ratios obtained enable airlines to examine the chances of recovering from flight delays. These are calculated by comparing the delays caused by one cause to the delays caused by 'base type'; therefore, the results indicate the 'relative risk' between different delay causes and may be further investigated to find out more interesting information of delays.
4. Comparisons between survival analysis and other methodologies would be very interesting. However, it is necessary to have a very careful design to conduct these comparisons; particularly, the nature of survival analysis is quite different from those of other methodologies.
5. The operations of international flight networks are quite different from those of short distant routes as analyzed in this research, e.g. the number of flights in a day, aircraft dispatching for recovery of flight delays, and connections of passengers and baggage. Therefore, the delay costs incurred may be different between international and domestic routes and need to be estimated carefully.
6. In this research, crew costs are counted in all minutes of flight delays. However, the crew payment schemes vary greatly among airlines. Airlines could suffer no additional cost for flight delays in some cases. In addition, passenger delay costs can also be estimated through the 'value of time' of passengers, which is considered as the opportunity costs to passengers. Though this estimation is not addressed in this research, it is noted that passengers may not divide their losses in flight delays into two parts (i.e. departure and arrival parts). Instead, passengers may consider their losses as those in a 'trip'. These issues are worth investigating.

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APPENDIX 1

Glossary of Terms

Scheduled turnaround time	The time needed to service an aircraft from the ‘on-chock’ time at an airport gate to the ‘off-chock’ time for next flight, including scheduled required ground handling time and scheduled turnaround buffer time.
Scheduled block time	The time needed to complete the activities of taxi-out, airborne operation, and taxi-in, including scheduled required block operation time and scheduled block buffer time.
Scheduled turnaround buffer time	The extra time scheduled beyond the time required for ground handling.
Scheduled block buffer time	The extra time scheduled beyond the time required for block operation.
Survival time of a flight delay	The number of minutes from the beginning of a flight delay until an event occurs.
Event of a flight delay	The delay of a flight has come to an end.
System cost of a flight delay	The cost incurred in a flight delay, including delay cost and buffer cost.

APPENDIX 2

Notations and Symbols

STD	scheduled time of departure of flight f_i
STA	scheduled time of arrival of flight f_i
ATD	actual time of departure of flight f_i
ATA	actual time of arrival of flight f_i
STA_{-1}	scheduled time of arrival of previous flight f_{i-1}
ATA_{-1}	actual time of arrival of previous flight f_{i-1}
T^S	scheduled turnaround time of flight f_i
g^S	scheduled required ground handling time of flight f_i
b^{sg}	scheduled turnaround buffer time of flight f_i
G^d	ground delay of flight f_i
D^d	departure delay of flight f_i
A_{-1}^d	arrival delay of previous flight f_{i-1}
F^s	scheduled block time of flight f_i
f^S	scheduled required block operation time of flight f_i
b^{sr}	scheduled block buffer time of flight f_i
R^d	block delay of flight f_i
A^d	arrival delay of flight f_i
$S(t)$	survival function
$h(t)$	hazard function
$h_0(t)$	baseline hazard
$S_0(t)$	baseline survival function
$H_0(t)$	cumulative baseline hazard function

$D(t_j)$	the individuals that die at time t_j
$R(t_j)$	the individuals at risk at time t_j
$\hat{\Pr}(T=t_{j+1})$	the probability of a flight delay surviving to time t_{j+1}
$e^{\hat{\beta}_k}$	the hazard ratio associated with one-unit increase in the k^{th} covariate x_k
$\hat{\beta}_k$	the log hazard ratio (or the increase in log hazard) with one-unit increase in x_k
$e^{\hat{\beta}_k}-1$	the percentage change (increase or decrease) in the hazard of flight delay with a one-unit increase in x_k
C^D	delay costs of departure flight *i*
C^D_{AC}	aircraft delay costs of departure flight *i*
C^D_P	passenger delay costs to airlines of departure flight *i*
C^A	delay costs of arrival flight *i*
C^A_{AC}	aircraft delay costs of arrival flight *i*
C^A_P	passenger delay costs to airlines of arrival flight *i*
${}^eC^D$	expected delay costs of departure flight *i*
${}^eC^A$	expected delay costs of arrival flight *i*
B^D	cost function of adding turnaround buffer for departure flight *i*
B^A	cost function of adding block buffer for arrival flight *i*
$C^{SD}_{f_i}$	system costs of departure flight *i*
$C^{SA}_{f_i}$	system costs of arrival flight *i*
C_f	total system costs of all segments
NB^{SD}_g	the net benefit of shortening required ground handling time
θ	decreased ground handling time
G(θ)	costs of additional ground handling resources

NB_b^{SD} the net benefit of increasing turnaround buffer time

λ increased turnaround buffer time

NB_b^{SA} the net benefit of increasing block buffer time

α increased block buffer time

$NB_{\mathrm{gb}}^{\mathrm{S}}$ the net benefit of shortening required ground handling time and increasing block buffer time for all segments

$NB_{\mathrm{bb}}^{\mathrm{S}}$ the net benefit of increasing turnaround and block buffer time for all segments

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