

Flight Delay-Cost Simulation Analysis and Airline Schedule Optimization

A thesis submitted in fulfillment of requirement for the
degree of Doctor of Philosophy

Duojia Yuan

B. Eng.

School of Aerospace, Mechanical and Manufacturing Engineering

Faculty of Science, Engineering and Technology

RMIT University, Victoria, Australia

February 2007

Declaration

I certify that except where due acknowledgement has been made, the work is that of the author alone; the work has not been submitted previously, in whole or in part, to qualify for any other academic award; the content of the thesis is the result of work which has been carried out since the official commencement date of the approved research program; and any editorial work, paid or unpaid, carried out by a third party is acknowledged.

Duojia Yuan

February 2007

To My Son Runxing Yuan

Abstract

Flight Delay-Cost Simulation Analysis and Airline Schedule Optimization

By

Duojia YUAN

In order to meet the fast-growing demand, airlines have applied much more compact air-fleet operation schedules which directly lead to airport congestion. One result is the flight delay, which appears more frequently and seriously; the flight delay can also significantly damage airline's profitability and reputation

The aim of this project is to enhance the dispatch reliability of Australian X Airline's fleet through a newly developed approach to reliability modeling, which employs computer-aided numerical simulation of the departure delay distribution and related cost to achieve the flight schedule optimization.

The reliability modeling approach developed in this project is based on the probability distributions and Monte Carlo Simulation (MCS) techniques. Initial (type I) delay and propagated (type II) delay are adopted as the criterion for data classification and analysis. The randomness of type I delay occurrence and the internal relationship between type II delay and changed flight schedule are considered as the core factors in this new approach of reliability modeling, which compared to the conventional assessment methodologies, is proved to be more accurate on the

departure delay and cost evaluation modeling.

The Flight Delay and Cost Simulation Program (FDCSP) has been developed (using Visual Basic 6.0) to perform the complicated numerical calculations through significant amount of pseudo-samples. FDCSP is also designed to provide convenience for varied applications in dispatch reliability modeling. The end-users can be airlines, airports and aviation authorities, etc.

As a result, through this project, a 16.87% reduction in departure delay is estimated to be achieved by Australian X Airline. The air-fleet dispatch reliability has been enhanced to a higher level – 78.94% compared to initial 65.25%. Thus, 13.35% of system cost can be saved.

At last, this project also achieves to set a more practical guideline for air-fleet database and management upon overall dispatch reliability optimization.

Acknowledgement

As for anyone else, a dissertation is a milestone as well as a journey in my life full of challenges. Without the help and support from many people, the completion of this work would have been impossible. Although a few words do not justice to their contribution I would like to thank the following people for making this dissertation possible.

I would like to express my gratitude to my supervisor, **Dr. He Ren**. I thank him for leading me into the research field. His generous encouragement, continuing support and guidance throughout the course of the research work have made this dissertation possible.

I would also like to thank Mrs. **Xiaoyang Sun**, **Jo Connolly**, Mr. **Tianlun Yuan**, **Erjiang Fu**, **Richard Zhou**, and Miss **Xiaojie Bai** for their data providing, comments and suggestions during the process of this thesis.

My thanks also go to other friends who work or study in RMIT, Thanks for the various help I got from them and the precious time we spent together.

Finally, and most importantly, I wish to thank my family members, especially my parents, **Ding Yuan** and **Dafeng Zhang**, for their endless patience and support. Thank you for sharing both my enjoyment and endurance.

Table of Contents

ABSTRACT	I
ACKNOWLEDGEMENT	III
TABLE OF CONTENTS	IV
LIST OF FIGURES	VII
LIST OF TABLES	VIII
CHAPTER 1 INTRODUCTION	1
1.1 COMMERCIAL AVIATION INDUSTRY BACKGROUND FACT	1
1.2 BASIC PRINCIPLES.....	3
1.2.1 <i>Flight Delay & Delay Propagation</i>	3
1.2.2 <i>Simulation Methodology</i>	5
1.2.3 <i>Cost Model Analysis</i>	7
1.3 PROJECT SCOPE & OBJECTIVES.....	7
1.4 THESIS STRUCTURE.....	9
CHAPTER 2 LITERATURE REVIEW	11
2.1 RELIABILITY ENGINEERING EVOLUTION	11
2.1.1 <i>Basic Concepts</i>	12
2.1.2 <i>The Development History of Reliability</i>	14
2.2 THE CONVENTIONAL RELIABILITY METHODOLOGIES DEVELOPMENT	17
2.3 DEVELOPMENT OF FUZZY RELIABILITY	24
2.4 MONTE CARLO SIMULATION METHODOLOGY	28
2.5 DISPATCH RELIABILITY & DELAY COST	32
2.6 SCHEDULING ISSUES IN AIRLINES OPERATION MANAGEMENT	38
2.7 AIRPORT OPERATION MANAGEMENT, RELATED RUNWAY CONGESTION AND FLIGHT DELAY ..	41
2.8 USA HISTORICAL DATA COLLECTION & ANALYSIS.....	48
CHAPTER 3 BASIC CONCEPTIONS & RELEVANT DEFINITIONS	52
3.1 DEFINITION OF RELEVANT CONCEPTIONS	52
3.2 DEPARTURE PROCESS ANALYSIS	59
3.3 DELAY CLASSIFICATION & CRITERIA	62
3.4 CREW/AIRCRAFT TURNAROUND PROCESS AND RELEVANT REGULATIONS.....	65
3.4.1 <i>Crewmember Turnaround Process & Availability Regulation</i>	65
3.4.2 <i>Regulation Related to Aircraft Availability</i>	69
CHAPTER 4 TYPE I DELAY ANALYSIS AND MODELING	72
4.1 INTRODUCTION	72
4.2 TYPE I DELAY CAUSES.....	73
4.3 DATA COLLECTION.....	74
4.4 AUSTRALIAN DATA ANALYSIS.....	75

Table of Contents

4.5	DISPATCH RELIABILITY MODELING.....	79
4.5.1	<i>Assumptions</i>	79
4.5.2	<i>Dispatch Reliability Model</i>	80
4.6	TYPE I DELAY MODELING SUMMARY	83
CHAPTER 5 DELAY COST MODELING		85
5.1	INTRODUCTION	85
5.2	ANALYSIS OF THE PROBLEM.....	86
5.3	AIRPORTS FEE STRUCTURE	88
5.3.1	<i>Landing Fee</i>	89
5.3.2	<i>Aircraft Parking and Hanger Fee</i>	89
5.3.3	<i>The Passengers Fee</i>	90
5.3.4	<i>Other Aeronautical Fee</i>	91
5.3.5	<i>Airport Price Regulation in Australia</i>	91
5.4	PASSENGER DELAY COST	94
5.5	AIRCRAFT SCHEDULED TIME COST.....	95
5.6	OTHER RELEVANT DELAY COST.....	97
5.7	THE FACTORS OF DELAY COST.....	98
5.8	DATA COLLECTION & ANALYSIS	102
5.8.1	<i>Data Collection</i>	102
5.8.2	<i>Analysis</i>	102
5.9	ASSUMPTIONS.....	104
5.10	DEPARTURE DELAY COST MODELING	104
5.10.1	<i>Parking Cost</i>	104
5.10.2	<i>Airline Crewmember/Staff Cost</i>	105
5.10.3	<i>Passenger Cost</i>	105
5.10.4	<i>Other Aeronautical cost</i>	106
5.10.5	<i>The Sum of Delay Cost</i>	106
5.11	SAMPLE CALCULATION	107
5.12	SUMMARY	111
CHAPTER 6 TYPE II DELAY MODELING AND MONTE CARLO SIMULATION		113
6.1	INTRODUCTION	113
6.2	TYPE II DELAY MODELING METHODOLOGY	115
6.3	MODELING WITH MONTE CARLO SIMULATION	118
6.3.1	<i>Radom Number Definition</i>	118
6.3.2	<i>Arithmetic Model and Simulation Logic</i>	119
6.3.3	<i>The Model of Cost Computing</i>	121
6.4	SOFTWARE DEVELOPMENT.....	123
6.4.1	<i>Software Flow Chart</i>	123
6.4.2	<i>Software Language and Interface</i>	124
6.4.3	<i>Process of Simulation</i>	126
6.4.4	<i>Software Function</i>	127
6.5	AUSTRALIAN X AIRLINE DELAY PROPAGATION SIMULATION.....	129
6.5.1	<i>Assumptions and Data Processing</i>	129

Table of Contents

6.5.2	<i>Program Running Environment</i>	130
6.5.3	<i>Simulation</i>	130
6.5.4	<i>Error Analysis</i>	131
6.6	SUMMARY	132
CHAPTER 7 AUSTRALIAN X AIRLINE FLIGHT SCHEDULE OPTIMIZATION.....		133
7.1	INTRODUCTION	133
7.2	CURRENT AIR-FLEET OPERATION ANALYSIS	134
7.3	OVERALL SYSTEM COST MODELING.....	136
7.4	FLIGHT SCHEDULE OPTIMIZATION	138
7.4.1	<i>Data Collection</i>	138
7.4.2	<i>Current Airlines Delay Situation Analysis</i>	138
7.4.3	<i>Flight Schedule Optimization</i>	142
7.4.4	<i>Sensitivity Test and Analysis</i>	145
7.5	SUMMARY	154
CHAPTER 8 CONCLUSION		156
REFERENCE.....		161
APPENDIX A LIST OF U.S. AIRPORTS USED IN THE RESEARCH		170
APPENDIX B AIRPORT SLOT DEMAND MANAGEMENT TECHNIQUES.....		174
APPENDIX C SAMPLE OF X AIRLINE DEPARTURE DELAY DATA		178
APPENDIX D RANDOM NUMBER DEFINITION SHEET.....		182
APPENDIX E OUTPUT FORM OF FDCSP		183

List of Figures

FIGURE 1.1-1 WORLD-WIDE GROWTH BY DOMICILED AIRLINES.....	1
FIGURE 2.8-1 DEPARTURE AND DELAY INCREASE RATE.....	50
FIGURE 2.8-2 RATIO OF DELAY IN TOTAL DEPARTURE & THE INCREASED RATE OF DEPARTURE	51
FIGURE 4.4-1 PROPORTION OF DELAY	75
FIGURE 4.4-2 DELAY NUMBERS BY CAUSES.....	76
FIGURE 4.4-3 DEPARTURE DELAY TIME BY CAUSES.....	77
FIGURE 4.4-4 RATIO OF DELAY NUMBERS DISTRIBUTION.....	77
FIGURE 4.4-5 RATIO OF DEPARTURE DELAY DISTRIBUTION.....	78
FIGURE 4.4-6 FLIGHT DAILY PEAKS.....	78
FIGURE 4.5-1 DELAY DENSITY FUNCTION.....	82
FIGURE 5.11-1 DELAY COST PROPORTION BY FACTORS.....	109
FIGURE 5.11-2 COST DISTRIBUTION BY DELAY TIME.....	109
FIGURE 5.11-3 TOTAL DELAY COST DISTRIBUTION.....	110
FIGURE 5.11-4 TOTAL DELAY COST PROPORTION BY DELAY TIME SEGMENT.....	111
FIGURE 6.4-1 SOFTWARE FLOW CHART.....	123
FIGURE 6.4-2 AIRPORT INFORMATION INPUT INTERFACE.....	124
FIGURE 6.4-3 SCHEDULE INFORMATION INPUT INTERFACE.....	125
FIGURE 6.4-4 ITERATION TIMES SET INTERFACE.....	126
FIGURE 7.4-1 PROPORTION OF DELAYED FLIGHTS BY DIFFERENT DELAY LENGTH.....	140
FIGURE 7.4-2 PROPORTION OF TOTAL DELAY TIME BY DIFFERENT DELAY LENGTH.....	140
FIGURE 7.4-3 PROPORTION OF DELAY COST BY DIFFERENT DELAY LENGTH.....	141
FIGURE 7.4-4 STRUCTURE OF DELAY COST BY DIFFERENT DELAY LENGTH.....	142
FIGURE 7.4-5 OPTIMIZATION CURVE.....	144
FIGURE 7.4-6 OPTIMIZATION CURVE WITH -2% DEPARTURE DELAY.....	146
FIGURE 7.4-7 OPTIMIZATION CURVE WITH -5% DEPARTURE DELAY.....	147
FIGURE 7.4-8 OPTIMIZATION CURVE WITH -10% DEPARTURE DELAY.....	148
FIGURE 7.4-9 OPTIMIZATION CURVE WITH -20% DEPARTURE DELAY.....	149
FIGURE 7.4-10 OPTIMIZATION CURVE WITH +2% DEPARTURE DELAY.....	150
FIGURE 7.4-11 OPTIMIZATION CURVE WITH +5% DEPARTURE DELAY.....	151
FIGURE 7.4-12 OPTIMIZATION CURVE WITH +10% DEPARTURE DELAY.....	152
FIGURE 7.4-13 OPTIMIZATION CURVE WITH +20% DEPARTURE DELAY.....	153

List of Tables

TABLE 2.8-1 STATISTICS OF DEPARTURE DELAY IN USA	49
TABLE 4.4-1 CAUSE OF DELAY	76
TABLE 5.2-1 AIRLINES INFRASTRUCTURE AND COST RATE	87
TABLE 5.3-1 PARKING & LANDING FEE RATES	90
TABLE 5.3-2 AIRPORT CHARGES RATES IN AUSTRALIA	92
TABLE 5.7-1 DELAY COST FACTORS	98
TABLE 5.11-1 RELATIVE PARAMETERS IN MODELING.....	107
TABLE 5.11-2 CALCULATION RESULTS	108
TABLE 6.5-1 RESULTS OF 100 ITERATION TIMES SIMULATION	130
TABLE 6.5-2 RESULTS OF 500 ITERATION TIMES SIMULATION	131
TABLE 6.5-3 RESULTS OF 1000 ITERATION TIMES SIMULATION	131
TABLE 6.5-4 ERROR ANALYSIS DATA	132
TABLE 7.4-1 COMPUTING RESULT OF CURRENT SCHEDULE	139
TABLE 7.4-2 ADDITIONAL GROUND BUFFER TIME OF DIFFERENT SCHEME	143
TABLE 7.4-3 OPTIMIZATION CALCULATION RESULT.....	144
TABLE 7.4-4 SCHEME COMPARISON	145
TABLE 7.4-5 OPTIMIZATION WITH -2% DELAY	146
TABLE 7.4-6 OPTIMIZATION RESULT WITH -5% DELAY.....	147
TABLE 7.4-7 OPTIMIZATION RESULT WITH -10% DELAY.....	148
TABLE 7.4-8 OPTIMIZATION RESULT WITH -20% DELAY.....	149
TABLE 7.4-9 OPTIMIZATION RESULT WITH +2% DELAY.....	150
TABLE 7.4-10 OPTIMIZATION RESULT WITH +5% DELAY	151
TABLE 7.4-11 OPTIMIZATION RESULT WITH +10% DELAY	152
TABLE 7.4-12 OPTIMIZATION RESULT WITH +20% DELAY.....	153

Chapter 1 Introduction

1.1 Commercial Aviation Industry Background Fact

Based on the models of major traffic flow around the world, Airbus has done an all-sided research (www.Airbus.com, 2004) on econometric modelling techniques, integrate various analysis of the regional and structural changes that are expected to influence the dynamics and development of the current and future air transport system, in addition, the growing importance of the LCCs (Low Cost Carriers) around the world, as well as the Asia-Pacific region.

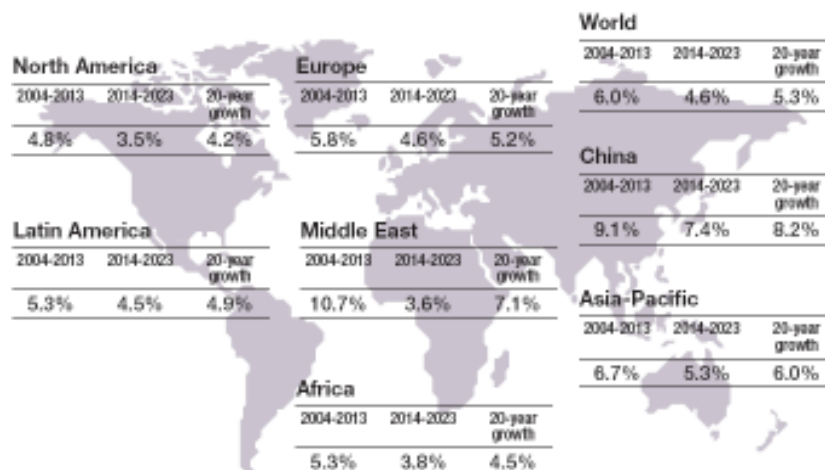


Figure 1.1-1 World-wide Growth by Domiciled Airlines

The results of careful analysis in these areas show that the average annual world traffic growth to 2023 is 5.3% per year.

As a matter of fact, since 11/9 disaster, the aviation industry and even the world economic have once touched down to the bottom. Recently, the economic recovery, the return of business confidence and corporate investment, the sustained trade in commodities and a pent-up demand in world-wide air travel, have all resulted in a

much stronger rebound in air traffic than previous anticipated.

One solution to this changing air-traffic environment is to employ more aircrafts. For example, very large aircrafts (e.g. Airbus A380, Boeing 747) will need to be acquired to enhance those hub-to-hub services; meanwhile more compact aircrafts (e.g. Airbus A350, Boeing 787) will replace a significant amount of existing aircraft models in those point-to-point services.

On the other hand, the problems are raised at the same time. Because of the limitation of the operation resources, the load factors have been in excess of 75% on the current aviation market; the increasing amount of air vehicles and their flight frequency has also forced the airlines apply even more demanding operation schedules, which directly results in serious airport congestion and more frequent flight delays. As one vital factor in air-fleet management, the dispatch reliability and schedule punctuality can not only significantly damage airlines' profitability and their reputation, and also becomes hindrance which would slow down the overall industry growing.

In this chapter, some basic principles related to this project will be introduced. Some analysis will be carried out on flight delay and its propagation. Furthermore, the methodology, project scope and objective will also be specified in the following sections.

1.2 Basic Principles

High demand of air transport demands and the limitation of the resources (such as available aircrafts, pilots, on-board attendants, airport gate space, ground service and staff, etc.) becomes a contradiction to be faced by the operators. In this bottle-neck like situation, airlines have to make the flight schedules even more compact and demanding, which leads to a higher probability of the occurrence of flight delays. It also brings huge impact on airline economy. For instance, research has indicated that there were 22.5 million minutes airlines scheduled delays in 1999, which cost over 3.2 billion dollars in U.S. This represents a 27% drain on financial resources, comparing to roughly 7.85 billion dollars in net profit for all airlines (Mueller & Chatterji, cited in Office of Inspector General, 2000). Delay due to air traffic alone cost the nation \$5 billion annually (Air Transport Assn., 2000). “The FAA estimates that airlines lose as much as \$1,600 for every hour an airliner sits delayed on a runway” (David Field of Insight on the News explains, 1995, p. 39).

1.2.1 Flight Delay & Delay Propagation

A complex chain of events occurs before aircraft departure and any of them may cause unexpected delay. Delay factors or causes are varied as aircraft mechanical failure, unscheduled maintenance, passenger or crewmember absence, weather, terrorism, airport capacity, Air Traffic Control (ATC), embarkation, administration, human factors and delay propagation, etc. Sometimes a delay results from a single reason, but the most come with multiple causes. It is vital to model all those dynamic

factors in a practical queue-resource simulation framework, which has been done at later stages in this project.

Upon airport operation and management, the operators are always trying to spread the flights uniformly over the entire day to minimize the congestion. However, differing from other transportation enterprises, airports are usually subject to peak demands. For example, the air-service provided by airlines is mostly concentrated in some specific time period simply because consumers wouldn't like to travel too early in the morning or very late in the night. Especially exacerbating in those hub airports, the uneven distribution of aircraft movement brings on the concentration of departures and arrivals in narrow time-band through daily operation, which induces more serious congestion, lower airport circulation efficiency, higher cost penalties and higher probability in flight delays.

When airlines establish the turnaround schedules for aircrafts and crewmembers, in order to absorb statistically foreseeable delays, a buffer is assigned to scheduled ground and airborne segment of a flight. However, the scheduled operation would not be as smooth as expected if there occurs a serious delay which exceeds the buffer. In addition, the accumulation of a series flight delays could also generate the same problem which would disrupt the initial schedule. In both cases, one important characteristic of flight delay has been explicated, that is delay propagation.

Numerous literatures have been found describing the methodologies of analysing and evaluating dispatch reliability, delay, delay propagation and delay cost. However,

few of them has distinguished the difference of mathematic characteristics between the original/initial delay (Type I) and the propagated delay (Type II), which have always been studied together by employing statistics method only. Meanwhile the characteristics of delay propagation and its effects on operation schedules have been ignored during the research process.

Generally, it is capable to enable the delay reduction by identifying the factors of Type I delay, which therefore can be studied by statistics method. At the same time, Type II delay can only decrease by cutting down the effect of previous delay or being managed by embedding enough buffer time into schedule; it is not suitable to be analysed by approach of statistics alone, since it is related to various and complicated factors such as human factor and time factor, etc.

1.2.2 Simulation Methodology

In this project, Monte Carlo Simulation (MCS) has been employed to model the airline schedule system with a high level complexity and randomness. MCS model is developed by producing a series of pseudo-samples to simulate the integrated delay scenarios according to airline's historical data and schedule. This newly proposed approach takes on solid ability of managing with complicated system as well as recognizing the randomness embedded. Meanwhile, the MCS model also enables the observation of the system behaviour with the interactions between fix flight schedules and stochastic disrupting events occurring in operation (Wu, 2005).

In order to study the trend of air transport demand/development and its

relationship with departure delay. The data collected in this project is based on U.S. historical departure data, which has been chosen as a representative research object. The data is abstracted from 9 million departures which occurred at 88 principal U.S. airports from 1995 to 2002 via the official record of Bureau of Transportation Statistics (BTS). The yearly increasing rates of departure and departure delay have been computed and compared respectively. In order to enable the universality of this project for Australian X Airline, the USA data has been chosen as a comparable sample as it is representative for the most airlines in the world.

Airlines historical departure delay data and correlative information was collected from websites of some major airports and airlines or by direct interview. 2002 yearly departure data (as a specific representative) has been collected from one of main airlines in Australia. Delay has been sorted into type I and type II respectively. Statistics method was employed to study type I delay; the distribution of the record has been determined into several different candidate families; the goodness-of-fit parameters have also been found. Moreover, MCS technique has been applied to build up a model to simulation type II delay and work over departure delay as a whole.

The Flight Delay & Cost Simulation Program (FDCSP) has been developed using Visual Basic 6.0 to perform the complicated numerical evaluation. As an important factor to the accuracy of the result, the iteration times input of simulation has been set to a relatively high level of 2,000.

1.2.3 Cost Model Analysis

It is true that airlines dispatch reliability can be improved simply by introducing longer buffer. However, it will whilst cause the increase of cost to airlines and airports. The trade-off between the desirable dispatch reliability and relatively low cost becomes fairly necessary and important. This trade-off has been done through the overall cost evaluation in this project. The cost has been considered as one major factor in the final optimization of ground buffer time and airline flight schedule.

A simulation model for computing delay cost is built up through FDCSP. Airport service charge rates were collected from Melbourne International Airport and Sydney International Airport. In order to make research result more universal and representative, the information related to airlines operation cost has been collected from Singapore Airlines, China Airlines, and Vietnam Airlines. A specific case study was carried out to demonstrate validity of the simulation using true data of cost rates, airline flight schedule, aircraft and crew turnaround schedule which operated between Sydney and Melbourne.

1.3 Project Scope & Objectives

The boundary of this project is limited in Civil Aviation operation. The main focus will be departure delay (especially gate delay and relevant propagation) and its impact on aviation economy. The simulation modeling is based on the data source of Australian and U.S.A airlines. The analysis is aided by computer programming simulation, known as FDCSP. The final result can be used in airport and airlines'

dispatch reliability assessment, air-fleet operation management and flight schedule optimization. Accordingly, the cost induced from delay can also be estimated as well.

The main purposes to conduct this project are to investigate the departure delay, delay propagation and its effect on overall schedule operation; establish a mathematic simulation model for further study and analysis; develop an integrated method to accurately assess flight delays and relevant cost; providing operators or decision makers a practical tool in optimization of operation schedules; improve the utilization of aviation resources and enhance the overall dispatch reliability and schedule punctuality.

In order to achieve the goals as mentioned above, this project is to accomplish the following objectives:

1. Collect relevant data and information to identify some major problems in air-fleet management;
2. Review existing literature to classify the delay and define the reasons;
3. Establish delay model and exam the delay time distribution;
4. Collaborate with airlines to construct delay and cost model (Australia based);
5. Use computer programming to accurately simulate dispatch reliability and relevant cost;
6. Investigate the impact of delay propagation on overall cost and optimize the airline operation schedule.

The dynamic approach used in this project is found to be more precise in analysing the internal relationships among initial delay, propagated delay, air-fleet operation schedules and other related aspects, which is the area that still remains ambiguous in today's commercial aviation management field.

1.4 Thesis Structure

This thesis is to be written in 8 Chapters:

Chapter 1 is a comprehensive introduction of the project, including the research background, current commercial aviation industry status, the basic principles of the research process, the scope and the main objectives.

Chapter 2 has discussed some major related aspects such as reliability development history, simulation methodologies, departure delay and delay propagation, system cost of airline operation, airline and airport management, and schedule optimization techniques. The author will summarize and synthesize those conventional methodologies from different researcher and approach.

Chapter 3 has introduced all the relevant conceptions and terminologies in this paper. The criterion of delay classification has also been discussed. Some relevant hypotheses, airline aircraft and crewmember turnaround principle, airport management rule, and information of delay cost factors and rates are given in this chapter as well.

Chapter 4 will analyse and model the Type I delay in detail. A comprehensive

study will be conducted. A real case study will also be included.

Chapter 5 will discuss all the issues of delay cost and airline operation cost. The various cost factors are described and analysed. The advantages and disadvantages of different models are listed and compared. Model of delay cost calculation will be revealed in this chapter. The calculation is presented based on Australian X Airline historical data.

Chapter 6 is one vital part of the core in this project. The focus has been put on delay propagation. A software has been developed based on Monte Carlo Simulation Methodology, which is proved to be a practical tool in future flight dispatch reliability management.

Chapter 7 is done especially for Australian X Airline flight schedule optimization. This can be regarded as a successful example in using the outcome of this project in airline fleet management.

Chapter 8 concludes the whole research project, some recommendations are also included. Additionally, some important results from this project are presented.

Chapter 2 Literature Review

This literature review is based on the theory and background of the concept – reliability. The author has paid special attention to some major related aspects such as reliability development history, simulation methodologies, departure delay and delay propagation, system cost of airline operation, airline and airport management, and schedule optimization techniques.

There are a few conventional research studies being achieved in this area. The author will summarize and synthesize the methodologies from different researcher and approach. The purpose of this literature review is to get an overview of current academic/professional environment and provide a background for the further investigation. In addition, this piece of work also helps the author to further define the project research and objectives.

2.1 Reliability Engineering Evolution

The real world is not perfect and not always runs as people expected. Human beings have experienced various kinds of failures and accidents all along, some of which could be disasters, such as space shuttle explosion (Challenger space shuttle, 1986), nuclear reaction accident (Chernobyl, 1986), airplane crash, chemical plant leak, bridge break, electrical network collapse. The causes of failures could be various under diverse circumstances, the research on various failures become essential and vital when the failure effects tend to be critical (Patrick & O'Connor, 1988).

2.1.1 Basic Concepts

Through the investigation upon failure characteristics of products and systems, the discipline of reliability has been paid specific attention and finally been established and well-developed. Igor Bazovsky (1961) had expressed the concept of reliability in his book as: “reliability is the probability of a device performing its purpose adequately for the period of time intended under the operating conditions encountered”. Meanwhile, the failure could be defined as: the inability of a system, subsystem, or component to perform its required function (Dhillon, 2005). The reason of a product failure could be the insufficiency of system concept, design, or operation standard, and also is the deviation between the design and actual operating environment (Frankel, 1988). The failure factors of the system are also varied a lot; they could be design deficiencies, poor system compatible, improper manufacture and materials selection, incorrect operation and maintenance, human factor and communication and coordination problem, and such on (Aggarwal, 1993).

Another concept needs to be discussed here is the ‘quality’. John P. Bentley (1993) had discussed the relationship between quality and reliability; the definition of quality was given in his book: “the totality of features and characteristics of a product, process or service that bear on its ability to satisfy stated or implied needs”. Quality and reliability are two different concepts which also interrelate. Generally, the quality is static without the considering of time variable, it can be measured quantitatively according to performance characteristics. Meanwhile the reliability of a product is dynamic, should be considered and measured over a period of time

(Bentley 1993). Igor Bazovsky (1961) also described the reliability as: a yardstick of the capability of equipment to operate without failures when put into service. Reliability predicts the behaviors of equipment mathematically under expected operating conditions. Comparing with quality, reliability is strictly defined with the time factor and operation environment. Reliability expresses in numbers the chance of equipment to operate without failure for a given length of time in an environment for which it was designed (Bazovsky 1961).

As one important concept in reliability discipline, availability can be defined as: the probability or degree to which an equipment will be ready to start a mission when needed (Frankel, 1988). Reliability can measure the likelihood of a product or system operating without failure during a specific period, whilst availability can measure the likelihood of a product or system can operate or not at all points of time into future (Billinton & Allan, 1992). Availability is usually divided into three types; they are up-time availability, steady state availability, and instant availability (Frankel, 1988).

Additionally, 'safety' has also been concerned a lot; it can be considered as a freedom degree from hazardous condition of specific product or system. It is a relative term that implies a level of risk that is measurable and acceptable. The objective of system safety is mishap risk management through hazard identification and control techniques (Ericson II, 2005). Safety margins should be based on risk factors, the reliability is a major factor in the establishment of safety margins (Frankel, 1988). The concept of reliability and availability illustrate that no one measure is universally

applicable, and other measures are also important, including reparability and maintainability (Billinton & Allan, 1992).

2.1.2 The Development History of Reliability

The development of reliability theory has suffered several stages. At the early of industrial age, reliability issue had be considered and confined to mechanical equipment. The various failures related aspects were almost studied and practiced respectively. With the great advances in technology and growing in complexity of system, various failures related aspects have been becoming more and more important and closely connected. The occurrence of the terminology “system failure engineering” is accompanying this trend (Cai, 1996). Till 20th century, reliability entered a new era with the advent of the electronic age. As the rapidly growing of electronic technology, the occurring of complex equipment and system with mass-produced component parts led to the need of higher degree of variability in the parameters and dimensions. Shooman (1968) had pointed that the fields of communication and transportation had gained rapidly in complexity when reliability engineering became identified as a separate discipline in the late 1940’s and early 1950’s.

The concept of reliability was only intuitive, subjective, and qualitative before Second World War, probability opens the door to the investigation of complex product and system (Page, 1989). The concept of quantitative reliability appears during the Second World War, and continues today, required by the size and complexity of modern system (Dhillon & Singh 1981). In December 1950, the Air

Force formed an ad hoc Group on Reliability of Electronic Equipment to study the whole reliability situation and recommend measures that would increase the reliability of equipment and reduce maintenance. By the 1950s the Department of Defense had established the Advisory Group on Reliability of Electronic Equipment (AGREE). AGREE published its first report on reliability in June of 1957 (AGREE 1957). This report included minimum acceptability limits, requirement for reliability tests, effect of storage on reliability etc. (Barlow & Proschan, 1969).

In 1951 Epstein and Sobel began work in the field of life-testing which was to result in a long stream of important and extremely influential papers. This work marked the beginning of the widespread assumption of the exponential distribution in life-testing research (Barlow & Proschan 1969). This development may be viewed as an outgrowth from the field of quality control since certain aspects such as “life testing” may be shown to be special applications of quality control procedures according to Duncan (1974).

Having recognized the significance of failure history data on failure characters studying, failure rate data banks were created in the mid-1960s as a result of work at such organizations as UKAEA (UK Atomic Energy Authority) and RRE (Royal Radar Establishment, UK) and RADC (Rome Air Development Corporation US). During the Second World War, US Air Force lost 21000 set aircraft due to various sort of failures, it is 1.5 times as more as the amount of aircraft which was shot down. It made US army study more formal methods of reliability engineering (Smith 2001).

The abstract conception of reliability might mean different things to different

people. Borrowed the concept from the original hardware and mechanical reliability, the new concepts had been developed in the new disciplines, such as software reliability and human reliability. The areas of application such as computer system, power system, and transit systems have also developed their own definitions, concepts, and techniques of reliability (Dhillon & Singh 1981).

In engineering and in mathematical statistics, reliability not only can be exactly defined and also difficult to be calculated, objectively evaluated, measured, tested, and even designed into a piece of engineering equipment (Bazovsky 1961). The modern reliability discipline is distinguished from the old one by quantitative evaluation versus the old qualitative evaluation. When reliability is defined quantitatively, it is specified, analyzed, and measured quantitatively, and becomes a parameter of design that can be traded off against other parameters such as cost and performance (Singh & Kankam 1979). Reliability could affect system specification, design, operation, maintenance, spare part stocking, and, in fact, all aspects of a system. The consequences of unreliability in engineering could be extremely costly and often tragic (Frankel 1988). Billinton (1992) had pointed that analyzing reliability quantitatively has two practical purposes: the first is assessment of past performance and the second is for prediction of future performance.

The conventional reliability theory is based on statistics and probability. Generally it is assumed that component and system have only two abrupt states: good or bad. Even in research of multi-state system, the failure or success criterion is also assumed to be binary. It is obvious that this assumption is valid in extensive

cases (Cai 1996). However, it may be natural that the system is a multiple states and that the transition from one state to the other is not abrupt. The system state is divided into several states not clearly but fuzzily, thus the fuzzy set is introduced into modern reliability concept. This unique approach will be further discussed in later section.

Reliability engineering today can be identified into four main branches, which is system reliability, structure reliability, human reliability, and software reliability (Volta, 1986). It is believed that all of these four subdivisions are contained in the complicated aviation reliability discipline.

2.2 The Conventional Reliability Methodologies Development

The reliability theory and relevant methodologies have been developed via several phases. There were three main technical areas evolved during the growth process: (1) reliability engineering, which includes system reliability analysis, design review, and related task; (2) operation analysis, includes failure investigation and corrective action; (3) reliability mathematics, which includes statistics and related mathematical knowledge (Amstadter, 1971).

Since no equipment is failure free, the risk against the benefit of activities and the cost of further risk reduction need to be considered with tradeoff. Reliability engineering is a discipline which seeks a better way to balance the cost of failure reduction against the value of the enhancement. To achieve this, accurately assessing failure rate of a system is necessary. The quantified reliability-assessment is one

basic technique (Smith, 2001).

In the earlier times, the reliability was focused on mechanical equipment and hardware area. A technology with reliability is a result of lessons learnt from failure. “Test and correct” principle was used before the formal data collection and analysis procedure development. During the design phase, to maximize the rate of reliability, the feedback principle was required through the formal data collection technique. And this is very useful to improve the inherent reliability. The failure data is the base of reliability research. Failure data was manipulated and calculated to get the failure rate.

Applications of renewal theory to replacement problems were discussed in 1939 by A.J.Lotks. N.R. Campbell in 1941 also approached replacement problems using renewal theory techniques. W. Feller is generally credited with developing renewal theory as a mathematical discipline (Feller, 1941, 1949). K.K.Aggarwal (1993) had described the methods to approach the reliability problem in the early days by using:

- (1) Very high safety factors which tremendously added to the cost and weight off the equipment;*
- (2) By extensive use of redundancy which again added to the overall cost and weight.*
- (3) By learning from the failures and breakdowns of previous designs when designing new equipment and system of a similar configuration.*

During 1940's the major statistical effect on reliability problem was in the area

of quality control. As the equipments and systems becoming bigger, more complex and expensive, the traditional approaches became impractical in front of new complex objects. Very little experience could be gained from previous failure in most case since the extremely growth of complexity and cost of whole system of product, such as jet aircraft or nuclear power plant system. (Frankel, 1988).

Estimates of the reliability of equipment or complex system depend heavily on the field of mathematics known as statistics and probability (Page, 1989). Even at a fairly elementary level, probability opens the door to the investigation of complex systems and situations. The language of probability is adapted to answer such questions as “What is the chance of that happening?” or “How much do we expect to gain if we make the decision?” (Page, 1989). However, it was not till the Korean War that quantitative reliability became widely used and statistics method were applied to its measurement (Amstadter, 1971).

In the early 1950's, some research result had been done on area of life testing, electronic and missile reliability problems. Some earliest procedures in life testing, and the use of the exponential distribution were developed by Epstein and Sobel (1953). Weibull (1951) first proposed an important distribution, which was named Weibull distribution late. Facing up seriously to the problem of tube reliability, the airlines set up an organization called Aeronautical Radio, Inc. (ARINC) which collected and analyzed defective tubes and returned then to the tube manufacturer. ARINC achieved significant success in improving the reliability of a number off tube types. The ARINC program has been focused on military reliability problems

since 1950 (Leitch, 1995).

Igor Bazovsky (1961) addressed three characteristic sorts of failures, which are called as “early failure”, “wear out failure”, and “chance failure”. The different of these types of failure follows a specific statistic distribution and requires different mathematical method to treat, and different methods must be used for their estimate. For example, wear out failures usually cluster around the mean wear out life of components, so the probability of component wear out failure occurrence at any operation period can be mathematically calculated according to their failure distribution. Meanwhile, the early and chance failure usually occur at random intervals, they obey different characteristic distribution from wear out failure, and the probability of their occurrence in a given operation period can also be mathematically calculated (Igor, 1961).

Since the statistics approach were engaged in the safety and reliability field during the period of World War II, the reliability theories and methodologies have been developed deeply (Cox & Tait 1991). As the coming of mass production age, cost of reliability is too expensive to afford for industry. The balance had to been sought between the reliability and benefit. It led to the higher demand of quantified reliability-assessment techniques. Reliability prediction modeling techniques is produced by using valid repeatable failure rate of standard component to calculate and estimate the reliability of equipment or system. The development of computer technology makes it is easier to sort the data and analyze the failure into failure mode.

In electric engineering area, redundancy system design and environmental screening/stress test techniques, Fault Tree Analysis (FTA), and Failure Mode Effect and Catastrophic Analysis (FMECA) techniques were applied widely. In structure engineering, the first order reliability methods (FORM) and second order reliability methods (SORM) were approaching mature. However, the common weakness of conventional methods is failure to describe the nature of malfunction in micro-process.

In addition, the Failure Mode and Effect Analysis (FMEA) is an intelligent response surface method based on simplified model; it is a successful tool for system reliability analysis (Ditlevsen & Johannesen, 1999). Monte Carlo Simulation (MCS) is versatile tool to analyze and estimate the reliability and maintainability for complex system. Fault Tree Analysis (FTA) is another widely used tool for system risk assessment. The Fault Tree Analysis by the fuzzy failure probability has the advantages as follow: it is not necessary to know crisp values of the failure and error probabilities of basic events in a fault tree (Kerre et al, 1998). People will find Fuzzy theory can be a useful tool to complement probability theory (Sundararajan, 1995).

The faulty tree and three-state devices are the widely used tools of reliability engineers to study complex system (Dhillon & Singh, 1981). Patrick D. T. and O'Connor (1988) had discussed the quality control technique of the manufacturing process and quality costs.

The classic index used to assess reliability is “probability” as its definition.

However many other indices are also frequently used. Typical additional indices include (Billinton & Allan, 1992):

- *the expected number of failures that will occur in a specified period of time (λ);*
- *the average time between failures (MTBF);*
- *the average duration or down time of a system or a device(MDT);*
- *the expected loss in revenue due to failure;*
- *the expected loss of output due to failure;*

The reliability is statistically computed from the mean time between failures (MTBF) frequently, which obtained from normal failure of operating period (Frankel, 1988). MTBF (Mean Time Between Faults) or MTTF (Mean Time To Failure). The average time between successive failures, estimated by the total measured operating time of a population of items divided by the total number of failures within the population during the measured time period. Alternatively, MTBF of a repairable item is estimated as the ratio of the total operating time to the total number of failures.

$$MTBF = \frac{1}{\lambda} \quad 2.1$$

$$\lambda = \frac{N_s(t_i) - N_s(t_{i+1})}{N_s(t_i)(t_{i+1} - t_i)} \quad 2.2$$

λ is Failure Rate, which is the rate at which failures occur in a specified time interval. So MTBF is the mean time of satisfactory performance of a system or

product between failures for a given period. It is also a main parameter to indicate the reliability for given productions or systems.

The conventional reliability theories have two basic assumptions: One is “binary assumption”, which assume the system only has two states: success and failure (good and bad), and the two states are exclusive each other. Another is “probability assumption”. We know probability has four presuppositions. First: the samples must be independence and defined clearly. Second: there are enough quantity samples. Third: samples have repeat regular. Fourth: samples should not be affected by human factors. Unfortunately, in many cases, the situation doesn't satisfy all those assumptions. For example, Classical reliability models must deal with extremely small probabilities, e.g., 10^{-7} or 10^{-8} . It is to be desired that these probabilities should be estimated from a large amount of data. In practice, it is quite obvious that it is almost impossible to determine these probabilities adequately for each component of complex system (such as aircraft) due to financial and time restrictions (Kerre et al, 1998).

Nowadays, the subject of reliability prediction, based on the concept of validly repeatable component failure rates, has become controversial. The failure rates of complex products or system do not always simply follow from component failure rates which are generally identified under some supposed identical environmental and operating conditions. The factors influenced the reliability of complex system are widely various, it could including software elements, human factors or operating documentation, and even continuously changed environmental factors. The system

reliability model and the relationship among contribution factors are also becoming more complicated. The hypotheses of conventional reliability theory are also the limitation of their application. So the theory and methodologies with the fuzzy set and Monte Carlo Simulation have been developed to supplement the conventional reliability theory.

2.3 Development of Fuzzy Reliability

As already being discussed, the conventional reliability is built on two fundamental hypotheses:

- the probability assumption (PRO); and
- The binary-state assumption (BIST).

The assumptions imply that the system failure behavior is fully measured by probability indices, since the system can be demonstrated only two absolute states: completely functional or completely failed. So the conventional reliability theory is also categorized as PROBIST reliability theory. Although the two hypotheses of conventional reliability theory can satisfy most PROBIST system reliability analysis, fuzzy concept can be also used to PROBIST system. For example, the probability of occurrence of a precisely defined system failure may be fuzzy.

It may be natural that the system is a multiple states and that the transition from one state to the other is not abrupt. The system state is divided into several states not clearly but fuzzily (Kerre et al 1998). It is seem that the fuzzy information should be

treated as fuzzy sets. An extension of the number of states by fuzzy sets is addressed with PROFUST reliability, which is based on the following two hypotheses:

- The probability assumption (PRO); and
- The fuzzy-state assumption (FUST).

The fuzzy-state assumption implies that there is not a clear circumscription between the system functional and failure. In other words, the state of system should be characterized by fuzzy states. For example, at any given time a system can be viewed as being in one of the two fuzzy states: fuzzy functioning or fuzzy failed. Each state is defined in a vague manner.

Although probability theory is very effective and well established, it is not almighty. Probability can be abused, just as can most tools. The best mathematical model can't produce true answers if incorrect or naïve assumptions are fed into it (Page 1989). Probability can not deal with all the possible events in extremely complex situation. It is this disadvantage that prompted the introduction of possibility theory. Possibility and reliability concepts are combined by Cai in 1990, and extended to formulate a theory named POSBIST reliability. POSBIST reliability is based on the following assumptions:

- The possibility assumption (POS); and
- The binary-state assumption (BIST).

These assumptions imply that the system failure behavior is fully characterized

by possibility indices, while the system is in either of the binary states at any given time. Till to Utkin and Gurov (1996), a real fuzzy reliability concept - POSFUST is delivered. POSFUST reliability theory is based on the following two assumptions:

- The possibility assumption (POS); and
- The fuzzy-state assumption (FUST).

These assumptions imply that the system failure behavior is fully characterized by possibility indices, and the system demonstrates success and failure as characterized by fuzzy states.

Most times, aviation system is complicated. It contains huge amounts of uncertain information, vague processes, and almost all kinds of reliability problems. How to estimate and improve the safety and reliability of aviation systems is one of the major tasks of whole industry. Although conventional reliability based on probability and binary hypotheses have been used in aircraft structural risk assessment, system reliability analysis and design, and fault diagnosis frequently, there is some limitations on the projects or events with some uncertain information and fuzzy processes, especially within the aspect of dispatch reliability and cost trade off analysis, and aviation risk management (Page, 1989). The classic deterministic and probability theories is suitable for the analysis of large samples and clear stat, however, fuzzy set theories in conjunction with possibility concept are likely the best way to deal with the integrative trade off analysis. That undoubtedly is the developing direction of reliability engineering.

In order to consummate the conventional reliability theories, fuzzy reliability theories gave other two assumptions, which are: Fuzzy-state assumption and Possibility assumption (Page, 1989). In fact, the theory of fuzzy sets has been widely developed especially in recently, nevertheless, at present the number of practical applications based on fuzzy model is rather scarce (Epstein & Sobel, 1953).

With fuzzy reliability theories, it will be possible to analyse and estimate the detailed process exist between the success and failure states. Also fuzzy reliability can be used for making quantitative judgments in a highly complex case. Although the conventional deterministic and probability theories are suited for the analysis of quantitative information, fuzzy set theory is best suited for the analysis of qualitative information (Cai, 1996).

Currently, the fuzzy reliability theories and methodology have not been developed maturely enough to be applied widely in air safety (Ren, 1997). Because the membership functions are hardly to be found for some particularly cases. The possibility conception should be introduced to some factors that affect air safety and reliability instead of probability one. Fuzzy reliability theories for air safety and reliability should be further developed.

2.4 Monte Carlo Simulation Methodology

Generally, there are two kinds of solution can be derived from mathematical model of a problem. First one is an analytic solution which is usually obtained directly from its mathematical representation in form of equations. The other solution is numerical, which is generally an approximate solution obtained as a substitution of numerical value for the variables and parameters of the model (Rubinstein, 1981). Monte Carlo Simulation is a type of numerical solution methods. Naylor et al (1966) gave a definition of simulation as follows: *Simulation is a numerical technique for conducting experiments on a digital computer, which involves certain types of mathematical and logical models that describe the behavior of business or economic system (or some component thereof) over extended periods of real time.* But it is obviously that simulation method can also be used to solve many complex problems which is not related to business and economic system, such as aircraft tunnel test or other engineering problems.

Naylor et al (1966) had described the situations where simulation can be successful used:

1. Firstly, it may be either impossible or extremely expensive to obtain data from certain processes in the real world. Such as the performance of large-scale rocket engines. In this case, the simulation data are necessary to formulate hypotheses about the system.
2. Secondly, the observed system may be so complex that it cannot be described in

terms of a set of mathematical equations for which analytic solutions are obtainable. For example, most economic system and large-scale queuing are belonged to this category.

3. Thirdly, even through a mathematical model can be formulated to describe some system of interest, it may not be possible to obtain a solution to the model by straightforward analytic techniques.
4. Fourthly, it may be either impossible or very costly to perform validating experiments on the mathematical models describing the system

Reuven Y. Rubinstein (1981) had discussed in his book: the simulation is not a precise technique, it provides only statistical estimates rather than exact results, and compare alternatives rather than generating the optimal one. The general definition is often called simulation in a wide sense, whereas simulation in a narrow sense, or stochastic simulation, is defined as experimenting with the model over time; it includes sampling stochastic variates from probability distribution (Kleinen, 1974). Therefore stochastic simulation is actually a statistical sampling experiment with the model. This model involves all the problem of statistical design analysis. The stochastic simulation is sometimes called Monte Carlo simulation, since random numbers are used to sampling from a particular distribution. Historically, the Monte Carlo simulation was considered to be a technique, sampling from a particular distribution involves the use of random numbers, for solution of a model.

Monte Carlo Simulation techniques have been developed for a long time. In the

19th century, “statistical sampling” method was applied in physics area frequently until it was coined as “Monte Carlo” by Nicolas Metropolis in 1949 (Newman, 1999). In the beginning of the 20th century, the Monte Carlo method was used to examine the Boltzmann equation. In 1908 the famous statistician Student used this method to estimate the correlation coefficient in his t-distribution. The term “Monte Carlo” was introduced by von Neumann and Ulam during World War II, as a code word for the secret work at Los Angeles, it was suggested by the gambling casinos at the city of Monte Carlo in Monaco (Rubinstein, 1981). The development is attributed to work of Von Neumann and Ulam is considered to be historically significant. The Monte Carlo method was applied to solve some problems related to the atomic bomb.

Reuven Y. Rubinstein (1981) had mentioned some differences between the Monte Carlo method and simulation:

- 1. In the Monte Carlo method time does not play as substantial a role as it does in stochastic simulation.*
- 2. The observations in the Monte Carlo method, as a result, are independent. In simulation, however, we experiment with the model over time so, as a rule, the observations are serially correlated.*
- 3. In the Monte Carlo method it is possible to express the response as a rather simple function of the stochastic input variates. In simulation the response is usually a very complicated one and can be expressed explicitly only by the computer*

program itself.

There are two problems to be faced when using Monte Carlo technique, the first one is how to generate random number. After the random numbers have been generated, the other problem is how to transform it to a variate based on the history data and the distribution. There are three main methods have been found to generate random number. Initially, manual methods were used, such as coin flipping, dice rolling, card shuffling, and roulette wheels. It is believed that only mechanical or electronic devices can generate “truly” random number. The disadvantage of these methods is too slow for general use, and sequence can not be reproduced. After the advent of computer, one method with computer’s aid is preparing a table and storing the table in computer’s memory. In 1955, the RAND Corporation published a well known table of a million random digits that can be used to form such a table (Page, 1959). Although the random generated by this method is reproducibility, it has the risk of exhausting the table, and is lack of speed. Then John von Neumann proposed a new method named mid-square method (Neumann, 1951). The idea is to take the square of the preceding random number and extract the middle digits. In fact the number is produced by this method are not real random, but they can be referred to as pseudorandom or quasi-random. Currently, the most common method used to yield pseudorandom number is one that produces a nonrandom sequence of numbers according to some recursive formula. Generally a method is considered as a good one if they are uniformly distributed, statistically independent, and reproducible (Rubinstein, 1981).

Monte Carlo method can be used not only for solution of stochastic problem and also for the solution of deterministic problem. Monte Carlo Simulation (MCS) has also become more accurate as a result of the invention of new algorithms (Newman, 1999). Although it is versatile, the cost of the analysis is prohibitively high, especially if very low probabilities are involved. In the early stage, numerical calculations were performed by hand using pencil and paper and perhaps slide-rule. The development of computer techniques has also brought down the cost of computing (Cai, 1996). Monte Carlo Simulation (MCS) is a very powerful tool to analyse and estimate the reliability and risk for complex system. Particularly in the last twenty years, many new ideas have been put forward. This methodology has been enhanced significantly and applied to solve a wide range complex problem. The model developed in this project is based on this method.

2.5 Dispatch Reliability & Delay Cost

Departure delay is main contributing factor which affect dispatch reliability. Departure delay has increased significant in past decade since the increasing demand of air transport. It had become a main obstacle of airline to achieve high profitability. Many papers and reports have presented these effects, and some conventional models and methodologies have also been developed to analyze and estimate the delay and delay cost. However, they are not precise and practical enough to solve the problem.

The aims to study on the delay are varied, and the different criteria also had

been employed on the delay definition and statistic. In U.S, there are two main agencies belong to government, The Bureau of Transportation Statistics (BTS) and Federal Aviation Administration (FAA), record the statistic of the air traffic delay data of whole nation. The BTS defined the departure delay as an aircraft fails to release its parking brake less than 15 minutes after the schedule departure time; when FAA defined it as when a flight requires 15 minutes or longer time over the standard taxi-in or taxi-out time. The BTS consider more about the passengers' benefits comparing to FAA seems more interested in aircraft inefficient movement (Mueller & Chatterji 2002). FAA also classifies the delay into several aspects such as gate delay, taxi-out delay, en route delay, terminal delay and taxi-in delay. The different air carriers also use different criteria to record flight delay. For business reason, some airlines report the gate arrive when parking brake is applied, and others report when the passengers door is opening.

The increase of flight schedule delay leads to more demand of flight punctuality predictions. Many methods and tools have been employed by related organizations to study and predict flight punctuality. Such as the Collaborative Routing Coordination Tools (CRCT) program was developed and used by FAA and CAASD; the Future ATM Concepts Evaluation Tool (FACET) by NASA; and the Center TRACON Automation System (CTAS) based on Traffic Flow Automation System (TFAS) by NASA and FAA (Clayton & Murphy 2001; Bilimoria et al 2001; Wanke 2000).

Eric R. Mueller and Gano B. Chatterji (2002) used 12 variables to describe the

distribution of delay. These variables are showed as table 2.1.

Table 2.1 Variables of Delay Distribution

Variable	Definition
f_1	Avg. number of aircraft that departed/arrived in a single day
f_2	Avg. minutes of delay for a single aircraft
f_3	Pcnt. of aircraft departing/arriving after the schedule time
f_4	Avg. minutes of delay for aircraft defined by f_3
f_5	Avg. minutes of delay for aircraft not defined by f_3
f_6	Avg. minutes of delay for aircraft that are later than 15 minutes
f_7	Avg. minute early of the earliest aircraft on a given day
f_8	Avg. minutes late of the latest aircraft on a given day
f_9	Pcnt. of aircraft departing/arriving later than 15 minute
f_{10}	Pcnt. of aircraft departing/arriving later than 45 minutes
f_{11}	Mean of the delay distribution
f_{12}	Standard deviation of the delay distribution

The Normal and Poisson distribution had been used to compare with raw data, and the Least Squares method has also been employed to good-fit the parameters. But this kind of method is not able to consider the delay propagation in micro-process; it can not be used to analyze the interrelation between the delay propagation and flight schedule.

For most air carriers, the delay would propagate through airline schedule because of the limitation of the operation resources such as aircraft, crews and passengers. Along with the development of air transportation, it is becoming more difficult to improve the accuracy of flight schedule punctuality prediction, especially

without a good understanding of the relationship between delay propagation and flight schedule. In order to study the delay propagation and the effects on airline flight schedule, Roger Beatty (1998) proposed a concept of Delay Multiplier (DM), DM was defined as:

$$DM = (I+D)/D \quad 2.3$$

Where the time of 'I' is initial delay and 'D' is the initial delay time, 'I' is sum of all downline delay time; all values of delay are in minutes. The initial delay with larger DM value shows the significance of the effect on delay propagation. Generally, the delay, which occurs earlier and last longer time, would have a larger value since it is easier to cause delay propagation. The research also demonstrated that even small amounts of decrease in initial delay would significantly reduce the effect upon overall schedule (Beatty et al 1998). Even so, the DM just gives a qualitative analysis and evaluation of initial delay effect on delay propagation. It could not be used to calculate the delay, delay propagation and delay cost base on different airline flight schedule.

Cheng-Lung Wu and Robert E. Caves (2000) developed a mathematical model to quantitatively study the relationship between the flight schedule punctuality and aircraft turnaround efficiency. This model was used to help airline optimizing the ground buffer time of aircraft turnaround via simulating the aircraft turnaround operation with different schedule and minimum of total cost (Wu 2005; Wu & Caves 2002; Wu & Caves 2000; Beatty et al 1998). In the model which was presented by

Wu, he connected the delay and aircraft turnaround schedule successfully by simulation method. But it was failed to find the dynamic interaction between propagation delay and airline schedule changing, which can't be traced and quantitatively assessed.

Khaled F. Abdelghany and Sharmila S. Shah (2004) had also tried to use the classic shortest path algorithm to model and predict the flight schedule delay for United Airlines of U.S. The model used a directed acyclic graph containing a series of nodes, which were sorted topologically in a liner time, to represent and simulate the process of scheduled flights operation and delay propagation. In his method, the node was used to represent the four main scheduled events of each flight: departure, wheels-off, wheels-on, and arrival; the arcs represent taxing-out, fly, and taxing-in respectively. Each resource was represented using a set of nodes and arcs standing for different events and activities scheduled for this resource (Abdelghany et al 2004). The model had been used at United Airlines' Operation Control Center (OCC) to monitor the daily schedule operation. After input the information of resources (including aircraft and crewmembers etc.), flight schedule and Ground Delay Program (GDP) which is issued by FAA, the model is able to monitor and predict the schedule flight delay based on future 12 hours horizon. And the controller could take some recovery actions such as replacing aircraft or trip-pairs (pilot and flight attendant) to avoid or reduce the schedule disruptions based on the delay prediction mentioned above. This model hasn't got the function of optimizing the slack time between flights and the flights schedule in advance, even it can computer how much

slack time have between two connective flights.

Civil aviation operation is becoming more complex since it has to be operated safely and economized. Besides the estimation of dispatch reliability and departure delay, how to evaluate the airlines operation cost and delay cost accurately is one important problem which the airlines have to face. Till now, the method of using average delay cost and total delay time has been applied most frequently to analyze and calculate the delay cost by relevant agencies, such as International Civil Aviation Organization (ICAO). Although the methods which use the simulation method to analyse quantitatively the relationship between flight delay and airlines operation schedule have been developed successfully (Wu & Caves 2000), there are still some debates on the method of cost evaluation including the operation cost and delay cost. Most existing methods and models use average cost rate or simplified method of cost computing. Although these methods can significantly reduce the computing process and satisfy some special purposes, such as roughly estimate the sum of delay cost. The calculation results provided by these simplified methods are not accurate enough to optimize the flight schedule because of the following reasons:

- The cost factors and cost rates are extremely various according to different airlines and different airports.
- The average schedule opportunity cost of aircraft or crewmember is much different between international flight and domestic flight, since the domestic flights generally have much down time during night time.

How to identify cost factors and rates? How to build up a model which can calculate the delay cost more accurately? These are the problems to be solved in this research. The issue of airlines operation cost and flights delay cost are discussed in detail in chapter 5.

Mathematical model can be classified in many ways: static and dynamic model, or deterministic and stochastic model. Static models are those that do not explicitly take time-variation into account, where dynamic models deal explicitly with time-variation interaction. In a deterministic model all mathematical and logical relationship between the elements are fixed. As a consequence, these relationships completely determine the solutions. In a stochastic model at least one variable is random (Rubinstein 1981). The models which only explore the delay distribution are belonged to static model; when others are dynamic which use simulation method to study schedule issue. The model developed in this research is dynamic and stochastic model, which is based on Monte Carlo Simulation method.

2.6 Scheduling Issues in Airlines Operation Management

The deregulation, happened at the end of the 20th Century, has created new opportunities and brought challenges for commercial aviation industry. The amount of people traveling on scheduled airlines jumped from 9 million in 1945 to about 1.25 billion of mid-1990. Air-cargo market has also robustly grown from 1.3 million tone miles in 1970 to 7.8 million in 1994 (Dempsey & Gesell, 1997). Struggling to achieve profitability, more than 100 airlines have fallen into the abyss of bankruptcy

since 1978. Till early 21st century, more than 1,000 scheduled airlines operate more than 15,000 aircraft. The strategy of prudent management is a main contribution factor making airline survival in the fiercely competitive environment.

In order to develop strategic vision for an airline, management must evaluate the internal and external factors affecting revenue achievement. Route structure and flight operation schedule are internal factors which influence whether airlines are able to accomplish desired objectives.

Schedule planning is a complex issue since the demand of the market is highly cyclical which could depend on varied (time) factors. For example, business traffic peaks usually appear from 7:00 a.m. to 9:00 a.m. and 4:00 p.m. to 6:00 p.m. during weekdays. Whilst leisure traffic peaks arises during holidays and weekends. Additionally, according to the “S-Curve” phenomenon identified by economist William Fruhan in 1972 which illustrated the effect of flight frequency on demand and revenue, the connecting points added to hub networks can be able to bring a geometric increase in product lines, which stimulates passenger and revenue growth (Dempsey & Gesell, 1997). Tretheway & Oum (1992) indicated a carrier with 60% of the flights may receive 80% of the passengers, and even more of the revenue. Passenger flow is the major consideration of airline scheduling.

Generally, development of a schedule, especially at a major hub with capacity problem, is an extreme complicated problem. Airline should also consider a series of important factors as following:

- (1) Aircraft utilization and load factors;

- (2) Reliability and schedule punctuality;
- (3) Runway slot, airport pricing policies, and terminal constraints;
- (4) Crewmember availability;
- (5) Aircraft availability; For example, a B747 might be limited to 120 hours of continuous operation. After this, 8 hours of maintenance is required, including terminal and towing times, which could mean 12 hours downtime. A further 24-hour maintenance break is required every three weeks, and at three-month intervals a major maintenance check is necessary. This might be 2.5 days, 5 days, or even a month depending on the aircraft's position in its 20,000-hour maintenance cycle.
- (6) Long-haul scheduling windows and short-haul convenience
- (7) Marketability; and
- (8) Season variations.

The survey also indicated that the schedule is a secondary issue for discretionary travelers and the primary reason for high-yield business passenger on choosing airlines (Aviation Daily, Oct. 1991). The S-Curve phenomenon carries out a practical simulation for carriers to possibly offer more capacity in important markets. Airlines have relatively low variable cost, accounting for less than 25% of full allocated cost, Once aircraft is purchased, crew is trained, and flights are scheduled, almost all cost are fixed. High cost of airline capacity results in the trade-off between excessive capacity/schedule frequency and operation cost. However excessive capacity and schedule frequency can also incur geometric

increase in passengers and revenue. As a result, airline schedule optimization should be not only based on the cost and also on the revenue.

Unlike the fixed cost, airlines variable costs are extremely difficult to estimate and manage. The borderline between fixed and variable cost is not always clear. Load rate also have a significant impact on airline profitability (Dempsey & Gesell, 1997).

In this project, a model of variable operation cost assessment is established to accurately evaluate the direct or hidden factors in cost analysis.

2.7 Airport Operation Management, Related Runway Congestion and Flight Delay

Airport insufficient capacity is another main factor affected flight delay. The rapidly growing of passenger and cargo demand for air transportation has made airports become serious congested worldwide. There is complex interrelationship among the passenger, airport, and airlines. The strategies of the airlines and airports to deal with the 'peaks' are not coincide. Airlines always try to maximize fleet utilization and improve load factors by offering services in the most attractive time slot. On the other hand, the airport operators would like to decrease the need for services during the peak segment. Additionally, passengers only concern if they can safely arrive the destination on time. Several indices can be used to measure airport peaking: United Kingdom and elsewhere in Europe use SBR (Standard Busy Rate); BHR (Busy Hour Rate); FAA uses TPHP (Typical Peak Hour Passengers); and BTH

(Busiest Timetable Hour).

Another problem is runway congestion, which can be defined as: congestion arising when the demand for access to a runway, in order to execute an aircraft landing or take-off, exceeds the capacity of a runway. According to the definition of runway capacity, a slot is to schedule either a landing or take-off within a particular period, and has specific time dimensions which define the exact duration within a day, within a week, and within a year. It is ruled by government policy that the capacity at Sydney's Kingsford Smith airport is capped at 80 aircraft movements per hour, and this cap will be achieved by implementing a system of slot rights for airport access (Elderton, S., 1996).

There are essentially two approaches to eliminate or reduce runway congestion. The first is by expanding existing runway capacity or by building new airports. In order to add new runways and build related facilities (e.g. paving more aircraft apron parking area, expanding the terminal, concourses, or number of gates), enormous economic resources are needed. According to the data of airline industry's International Air Transport Association (IATA) and the U.N. International Civil Aviation Organization (ICAO), US\$250 billion will be spent for airports project in the worldwide by the year 2010. Even if the financial resources are available, the airport development projects are often constrained by land, environment and politic considerations.

The second approach is using administration, which classified into demand management method and traffic management method.

The demand management technique is a long-term strategy which can control runway congestion by better allocating existing runway capacity. This technique is divided into two terms: administrative techniques; and price techniques. Administrative techniques involve an executive body making decisions on the order of aircraft to get access to the runway, it includes: restrictions on aircraft operations (quotas and bans); use of schedule committees; and allocation of slots by lottery. The most famous administrative techniques application worldwide is the “schedule coordination approach” of IATA. Schedule coordination is carried out at Schedule Coordination Conference (SCCs) organized by the IATA every November and June and attended by numerous representatives of airports, airlines and civil aviation organizations around the world (Neufville & Odoni, 2003).

Pricing techniques rely on whether or not aircraft operators shall pay the access fee to use a runway during a specific period in a day; it includes peak period pricing and auctioning of airport slots. The relevant definitions and detailed information about demand management techniques are attached in appendix B.

For example, slot allocation is an issue at Vancouver and Toronto in Canada, as the other Canadian airports operate well below capacity. In Vancouver, under the chairmanship of Airport Authority, a scheduling committee consisting of airlines allocates slot times on a quarterly basis. The “grandfather” is the only rule used by them. Slots are allocated by day of week and time of day. If a carrier drops a flight, it loses its original slot. The number of hourly slots is capped at Toronto airport. Slots are also allocated by a scheduling committee, which works much like

Vancouver's. At congested Heathrow and Gatwick airports of the United Kingdom, scheduling committees comprising resident airlines are responsible for allocating slots. The process was implemented by a coordinator supported by specialists. In the United States of America, slot quotas were introduced in some main airports in 1968, and were allocated on a six-month basis by scheduling committees. User classes for quota purposes are certified air carriers, scheduled air taxi/ commuter services, and other. Trading of slots as well as other forms of explicit bargaining are prohibited. Unlike other countries, the scheduling committees did not operate using IATA principle, on the other hand, slot allocation was discussed within the scheduling committee and has to be agreed upon unanimously. If there were disagreements and a deadlock could not be resolved, the FAA has to choose a method for slot allocation according to its priority rules. The FAA performs an important role as a threat for the committee to reach agreement. Some methods used by the FAA were: first-come-first-served; arbitrary administrative allocation; lotteries; auctions and grandfathering of slot rights.

In Australia, the capacity cap of Sydney Kingsford Smith Airport is designated as a maximum of 80 aircraft movements per hour (Sydney Airport Demand Management Act 1997). Details of system for allocating slot are set out in the Slot Management Scheme 1998 (made under the Airport Act), including "grandfather" rights to slot, the "use it or lose it" principle. Swapping slot among airlines is permitted. Another feature of this scheme is the "regional ring fence" which produces a separate slot pool for regional service operator. The slots are allocated

and administered by the Slot Manager, Airport Coordination Australia (Banks, Snape & Byron, 2002). The advantages and disadvantages of pricing slot is discussed ardently since airport deregulation and privatization of 2002. The pricing rule is believed to be able to generate more efficient outcomes of airport operation and become a trend in the future.

The traffic management technique is short-term which generally executed by ATC or relevant government agencies to compulsively decrease the requirement of airport service during peak segment. For example, FAA has several tools to handle this problem. Ground Delay Programs (GDPs) and Ground Stops (GSes) are traffic management initiatives used to strategically manage arrivals at an airport by controlling the departure times of flights going to that airport (www.fly.faa.gov/Products/ July 2006). The programs delay departures in a manner so that the arrivals can be handled by the destination airport and airspace. A GDP is run in two cases: when the capacity of an airport is reduced, e.g., due to weather, and cannot handle the normal demand; or when the demand at an airport becomes unusually high, (e.g., due to a local convention), and exceeds the normal capacity.

Airspace Flow Programs (AFPs) are similar to GDPs in that they attempt to meet a desired arrival rate by controlling departure times. However, AFPs control flights arriving at a Flow Constrained Area (FCA) rather than an airport. An AFP might be used, for example, to reduce the flow rate of flights through a center when that center has reduced en route capacity due to severe weather.

There are two primary tools used to issue and manage GDPs, GSes, and AFPs:

- Flight Schedule Monitor (FSM) – FSM is the used to monitor airport or airspace demand, model GDPs, GSeS, and AFPs in certain functions, and initiate the sending of the program.
- Enhanced Traffic Management System (ETMS) – ETMS is the underlying database and communications system for traffic management. ETMS produces demand data, applies control times to the data, processes user substitutions, and generates user reports.

Generally, the dynamic characteristics of airfield delay are difficult to be accurately predicted. Airport delay generally has features below (Neufville & Odoni, 2003):

- May occur during period when the demand rate is lower than capacity.
- Depend in a nonlinear way on changes in demand and capacity, become very sensitive to even small changes when demand is close to or greater than capacity.
- Present a complex dynamic behavior over any time span when the runway system is utilized heavily.

Gallihier and Wheeler (1958) contributed the earliest attempts at using numerical solution to help describe the transient of airport landing queue. They provided assumes that the entry into the queuing system is a Poisson process. Rue and Rosenshine (1979) used a Semi-Markov decision process to show the advantages of using the social optimum to control aircraft arrival access to an airport. Gross and Miller (1984) presented a method to achieve a transient solution to discrete state space, continuous time Markov processes. Odoni et al (1987) offered a general

discussion of airport capacity estimation and aircraft delay optimization. One primary conclusion from him is that “optimization tends to favor large aircraft (biases) and long flights”. Shumsky (1993) delivered a research for FAA to help agency to predict flights take-off time. He tried to identify the causes for delay in take-off time, which includes delay propagation and airports capacity limitation. Gilbo (1993) also provided an approach of estimating an airport’s operation capacity. His method involves analyzing the observed number of departures and arrivals over a fixed time period. Gilbo explained that peak operating capacity might periodically surge beyond rates which are sustainable so that his estimates were determined after rejecting extreme outlier observations.

In addition, aircraft ramp service is one main portion contributing to round time. Inefficient ramp service can also incur gate delay. These ramp services may include: fault service; fueling; wheels and tires visual check; ground power supply; deicing and washing, cooling/heating; cleaning; catering and so forth. Unless the ramp service procedure can be performed efficiently with many services being carried out synchronously, the aircraft will have to experience long turnaround times so that no productive revenue is earned. Inefficient ramp servicing can lead to low level of aircraft and staff utilization and airline productivity. Aircraft delay generates significant negative financial effects upon the airlines management. The impact of delay in terms of extra cost and lost revenue can be very serious. To control ground handling efficiency, monthly complaint report and monthly punctuality report are required by most airlines.

Simulation technique is also used to study the Taxi and ramp delay. Ottman, Ford and Reinhardt (1999) used simulation technique to deliver The Taxi Simulation Model (TSM) for The Louisville International Airport and United Parcel Service (UPS). The information of flight schedule, Parking positions, direction of takeoff and other variables based on aircraft type and airport regulations can be take into account. The result of simulation can assist airport management staff make decision on parking planning and departure schedule for flights.

It is necessary to discuss the effect of airports operation capacity on departure delay. Furthermore, it is necessary to develop an integrated method connecting delay problem with flight schedule as a whole, which has been done through this project.

2.8 USA Historical Data Collection & Analysis

In order to investigate civil aviation departure delay development trend, a large numbers of data in a long-term time framework need to be collected. United States of America has the most mature aviation market. In U.S. the annual schedule delay reached 22.5 million minutes in 1999, the cost of delay was over 3.2 billion dollars, while the net profit of all airlines is roughly 7.85 billion U.S. dollars. Therefore the U.S. civil aviation historical data is chosen and collected to study, as the most representative and typical sample.

Since 1995, historical departure delay data of U.S airports had been published by Bureau of Transportation Statistics (BTS). From 1995 to 2002, eight years historical delay summary drawing from a total of about 9 million departures at 88 main U.S

airports has been collected via the BTS website. These 88 candidates are chosen from 278 U.S. airports. The airports' names and codes have been collected and listed in appendix A.

The data collected from BTS include: the total numbers of departure, departure delay, cancelled and diverted flights which occurred at the 88 main U.S. airports (names are showed in Appendix A) during 1995-2002. These detailed data is showed in table 2.8-1. The yearly increasing rates of departure and departure delay are computed and compared respectively.

	Departure	Delay	Proportion	Cancelled	Proportion	Diverted	Proportion
1995	4,734,850	946,904	20.00%	80,456	1.70%	9,137	0.19%
1996	4,765,073	1,106,941	23.23%	113,926	2.39%	12,488	0.26%
1997	4,837,304	979,444	20.25%	85,706	1.77%	10,643	0.22%
1998	4,817,574	976,125	20.26%	128,191	2.66%	11,658	0.24%
1999	4,967,058	1,058,175	21.30%	139,488	2.81%	12,103	0.24%
2000	5,129,655	1,247,895	24.33%	171,635	3.35%	12,870	0.25%
2001	5,302,441	1,001,461	18.89%	205,490	3.88%	11,384	0.21%
2002	4,706,521	779,617	16.56%	53,876	1.14%	7,193	0.15%
Total	39,260,476	8,096,562	20.62%	898,312	2.29%	87,476	0.22%

Table 2.8-1 Statistics of Departure Delay in USA

The summary table illustrates that departure delay occupied 20.62%, the cancelled flight carried 2.29%, and the diverted flight taken 0.22% in the totally 39,260,476 departures at 88 main US airports from 1995 to 2002. That apparently indicates flight departure failure is a significant problem to aviation industries. Here the departure delay was defined as a flight that fails to release its parking brake within 15 minutes after the scheduled departure time.

The annual increase rates of departure and its delay numbers from 1995 to 2002 are shown in figure 2.8-1. The comparison between the ratio of departure delay and the annual departure increased rate is shown as in figure 2.8-2. Generally, the total departure number has stably increased by a ratio of 12% from 1995 to 2001, while the increase ratio of annual delay is greatly varied during same period. However, the proportion of departure delay in total departure numbers keep relative stable except 1995. In some way, the increase of departure delay is relational to the increasing of the total departure numbers. It also demonstrates the increasing of air transport demand will cause the increasing of departure delay.

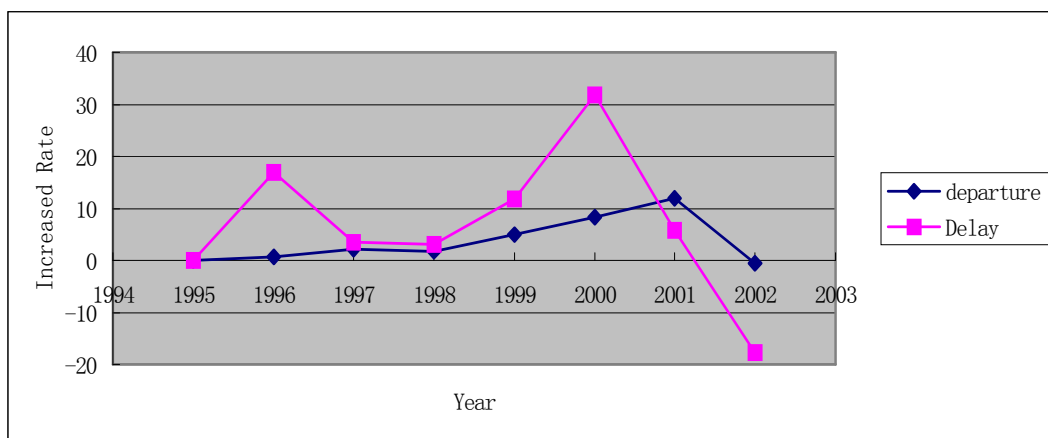


Figure 2.8-1 Departure and Delay Increase Rate

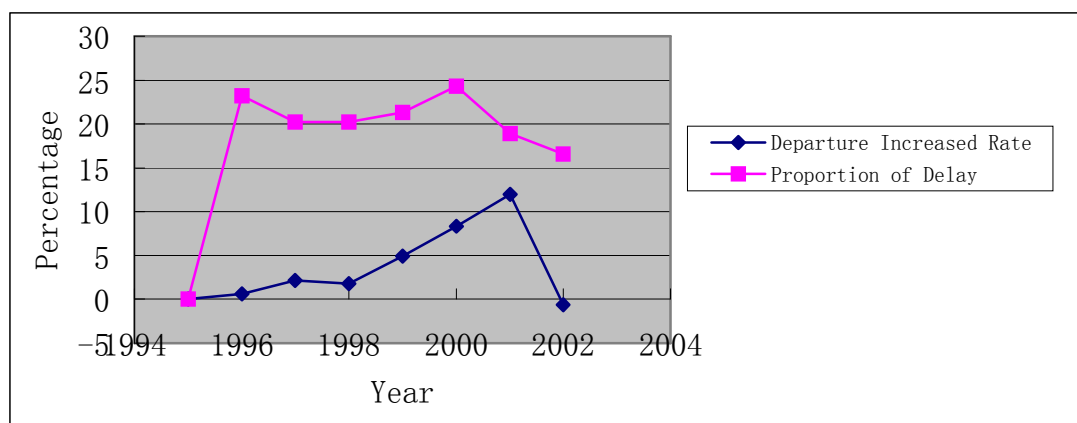


Figure 2.8-2 Ratio of Delay in Total Departure & the Increased Rate of Departure

The departure delay had a significant decline starting from 2001, there was 24.4% departure delay occurred in 2000, but only 18.9% in 2001 and 16.6% in 2002. Till 2001, both of cancelled and diverted flights had a steady rise. But in 2002, all number showed in table had a significant decrease. It illustrates U.S. aviation transportation demand is seriously affected by the 11/9 attack, which demonstrates that the airport capacity and air service demand are not the only factors which can affect departure delay. Although infrastructure expansion and new airports building are the efficient solutions for airports congestion and departure delay in the long term, it is very costly and causing many environmental problems. Therefore it is proved to be a better way to reduce the departure delay by using technical and managerial methods till the service demand is highly excess the airport capacity.

The purpose to collect and analyze the historical data from USA is to show the importance of this project as the delay becomes a serious problem in the current commercial airline industry. Furthermore, the data trends in the last decade also indicated that the situation will become even worse.

Chapter 3 Basic Conceptions & Relevant Definitions

In this chapter, firstly, some basic concepts, terminologies and criteria will be defined, including dispatch reliability, departure failure, and delay classification, etc. Secondly, some details in aircraft/crew turnaround process and relevant airworthiness regulations will be described.

3.1 Definition of Relevant Conceptions

Some terminologies that referred in this thesis are defined in details as below:

Reliability

It can be simply defined as the probability that a system or product would perform in a satisfactory manner for a given period of time when used under specified operating condition. Reliability can be measured in term of mean time between failure (MTBF), mean time to failure (MTTF), or mean time between maintenance (MTBM). Thus, the aspect of time is the critical in reliability measurement (Smith, 2001).

Dispatch Reliability

Dispatch reliability is normally defined as the probability that an aircraft can departure in a satisfactory manner during a given period of time at the specified airport or area. Satisfactory departure means a successful takeoff without failure.

Failure

It is the termination of the ability of an item to perform its specified function. Or, Non-conformance to some defined performance criteria (Smith, 2001).

Failure Rate

A value expressing the frequency of failure occurrence over any specified time interval or cycles of operation.

Failure Mode

It means the various manner or ways in which failures occur and the resulting operating condition of item at the time of failure.

Departure failure

It can be defined as an aircraft fails to take off successfully or departure delay more than 15 minutes comparing to scheduled departure time due to any accidents and incidents happen in departure period, but except the unexpected factors and scheduled human actions, such as strikes and wars. Departure failure can be expressed as a distribution function $[F(t)]$, which is related to various risk factors. For the civil aviation, the departure failure includes: flights cancellation, flight divert and flight departure delay.

Pushback

The point in time when an aircraft is pushed away from the departure gates so that it may commence taxi-out. This is also known as the gate departure time.

R (t) – It is reliability function, over the time.

F (t) – It is failure distribution function, or the unreliability function. If the random variable t has a density function of $f(t)$, then

$$R(t) = 1 - F(t) = \int_t^{\infty} f(t)dt \quad (3-1)$$

Assuming that the time to failure is described by an exponential density function, then

$$f(t) = \frac{1}{\theta} e^{-t/\theta} \quad (3-2)$$

where θ is the mean life, it is the arithmetic average of the lifetimes of all items considered, the mean life θ for the exponential function is equivalent to mean time between failures (MTBF). t is the time period of interest, e is the natural logarithm base (2.7183). The reliability at time t is

$$R(t) = \int_t^{\infty} \frac{1}{\theta} e^{-t/\theta} dt = e^{-t/\theta} = e^{-t/M} = e^{-\lambda t} \quad (3-3)$$

Where $\lambda = \frac{1}{\theta}$, λ is instantaneous failure rate, M is the MTBF, which is Mean Lifetime (ET).

$$f(t) = \lambda e^{-\lambda t} = \int_0^{\infty} tf(t)dt = \int_0^{\infty} R(t)dt = \lambda R(t) \quad (3-4)$$

Out Time

It refers to the time of pushback, especially when the parking brake is released and may commence to taxi-out. It is also known as the gate departure time.

Off Time

It refers to the takeoff time at which the aircraft weight is no longer borne on the landing gear.

On time

It is associated with the touchdown time, it is the time that aircraft's weight is borne on the landing gear again.

In time

It is related to the moment the parking brake is applied at the gate. These times are recorded and reported by the respective airlines.

Departure Queue

It refers to the line consisting of aircraft waiting for their turn to take off.

Demand for service

It is the time when an aircraft is ready to be granted access to the runway. This does not imply that the runway is available for this aircraft to use. If other aircraft are already waiting for the service, then the occurrence of a demand for service means that an aircraft has entered the end of the departure queue to wait its turn for take off.

Roll-out

It is the time interval between pushback and the start of the aircraft take-off. This time includes taxi-out time and time spent waiting in the queue.

Taxi-out

It is the time interval between pushback and demand for service.

Taxi-in

It is the time interval between touchdown and the aircraft parking brake is applied at the gate.

Down time

Also called outage, it is the period during which equipment is in the failed state.

Availability (A)

It is the probability that an item, when used under stated conditions in an ideal support environment (i.e., ideal spare parts, personnel, diagnosis equipment, procedures, etc.), will be operational at a given time (Modarres, 1993). or degree to which an equipment will be ready to start a mission when needed. Availability is divided into up-time availability, steady state availability, and instant availability.

When u is uptime during total time T , and d is downtime during total time T , the availability A can be expressed by:

$$A = \frac{UpTime}{TotalTime} = \frac{u}{u + d} \quad (3-5)$$

Maintainability

A characteristic of design and installation which is expressed as the probability that a failed item will be restored to operational effectiveness within a given period of time when the repair action is performed in accordance with prescribed procedures and resources. This, in turn, can be paraphrased as “the probability of repair in a given time”.

Dependability

It is the probability or degree to which an equipment will continue to work until a mission is completed.

Mean time between failures (MTBF)

For a stated period in the life of an item the mean value of the length of time between consecutive failures, computed as the ratio of the total cumulative observed time to the total number of failures.

Mean time to failure (MTTF)

For a stated period in the life of an item, it is the ratio of cumulative time to the total number of failures.

Mean life

It is the mean of the times to failure where each item is allowed to failure.

Fault tree

It is a graphical method of describing the combinations of events leading to a defined system failure. In fault tree terminology the system failure mode is known as the top event. The fault tree involves essentially three logical possibilities and hence two main symbols. The three types are: The OR gate whereby any input causes the output to occur; The AND gate whereby all inputs need to occur for the output to occur; The Voted gate, similar to the AND gate, whereby two or more inputs are needed for the output to occur. Two symbols are for the AND and OR gates.

RAMS

It is the abbreviation of Reliability, Availability, Maintainability and Safety-integrity.

Type I delay

Also named original delay, it can be defined as the flight delay occur due to the factors of a specific flight itself – not related to any previous flight delay. The delay factors can be mechanism, weather, airport operation, passenger, crew human factor, maintenance.

Type II delay

Also named propagated delay, it can be defined as the flight delay occurs due to the delay of its previous flight. the delay propagated through airlines schedule, since the operation resources, such as aircraft, crew operation schedule, and passengers or luggage are limited. In the other word, this sort of delay happens due to delay

multiplication.

Runway capacity

It can be defined as the number of ‘slots’ available at an airport in a given period (often one hour). A slot is the right to schedule either a landing or take-off within a particular period, and has specific time dimensions which define where occurs within a day, within a week, and with in a year.

Turnaround time

For a short-haul flight, it is defined as the time for an aircraft to complete full off-loading, loading and where required, catering and cabin cleaning procedures; For long-haul flights, the time including comprehensive technical and cabin services should be considered instead (international Air Transport Association, 1997). The scheduled ground time of a turnaround aircraft is defined as consisting of two portions, namely the standard ground service time and schedule buffer time (if applicable)

3.2 Departure Process Analysis

In order to accurately determine departure delay, it is important to understand the departure processes. Generally, flight pilot is allowed to release parking brakes and leave the gate for taxi-out when receives the departure permit from ATC of the airport. The time prior to the aircraft’s parking brake released is called out time, and is also reported as flight gate departure time. After arrived at the end of runway, the flight pilot needs to send ATC the request of service so as to get the permit to use the

runway before access and start to take off. The time interval between sending request of service and receiving take-off clearance is called queue time. After got the take-off clearance from airport ATC, the aircraft is granted to access the runway and start to take-off. The time for aircraft take-off is recorded as off time.

The out time, off time, on time, and in time are usually recorded as OOOI (out, off, on, in time) data, which indicates four important time check points of whole flight phase. The whole phase of departure runs through from out time to off time. The departure process can be divided into 2 stages: gating, and roll-out. Gating includes the aircraft sending and receiving the departure permit from airport ATC, then releasing the parking brake and leaving the gate. The roll-out also can be broken into two stages: the first stage is pushback from gate to runway or departure queue, second stage is runway or from departure queue to take-off. It is showed as in Figure 3.1.

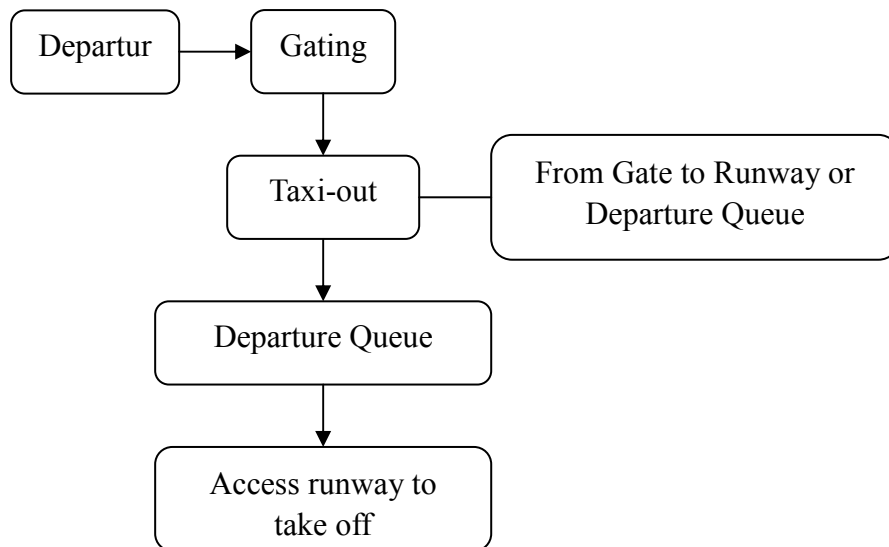


Figure 3-1 Departure Process Illustration

According to the period of departure during which delay happened, the departure

delay includes gate delay and taxi-out delay. The gating delay occupies significant proportion of departure delay since there are many factors can cause flight departure delay before it leaves the gate. This issue will be discussed in detail in later sections. But there should be paid specific attention that some departure queues happen at gate because of the airport ATC instruction.

Currently, as the application of those compact schedules, airline flight schedule are especially sensitive to individual flight delays as a result of the manner in which operating resources are linked together. Basically, there is a buffer involved in the planned flight time on published airline schedules in order to absorb statistically foreseeable delays. The buffer can be assigned to scheduled ground and airborne segment of a flight. Arrival delays would occur once accumulated delays exceed the buffer. When the duration of arrival delay exceeds followed flight ground buffer, departure delay of later flight occurs, then delay is propagated.

It needs to be noticed that many taxi-delays and en route delays are hidden in departure delay. It is because the ability of absorbing delay of airborne buffer is limited and costly. Different from automobile, rail and ship traffic, airplane can not stop and wait unlimited amount of time in the middle of its journey. So the delay necessary for buffering can be spread out over a large scope, or taken on the ground before departure. Modeling these dynamics in a standard queue-resource simulation framework becomes difficult due to airplanes limited capacity of delay absorption (Boesel, 2003).

3.3 Delay Classification & Criteria

There is not any standard definition or measurement for delay used industry-wide. According to the flight process discussed in section 3.2, there are standard and precisely defined events that can be used: Out-time, Off-time, On-time, and In-time (OOOI). Therefore the Federal Aviation Administration (FAA) categorizes delay into gate delay, taxi-out delay, en route (in flight) delay, and taxi-in delay (or terminal delay). Gate delay is judged by comparing out-time and airlines published schedule departure time. Taxi-out delay is estimated by comparing the standard taxi-out time and actual flight taxi-out time. Through the analysis of the data which come from Department of transportation (DOT), the contribution of the delay occurrence according to flight phases can be computed, and is shown as blow.

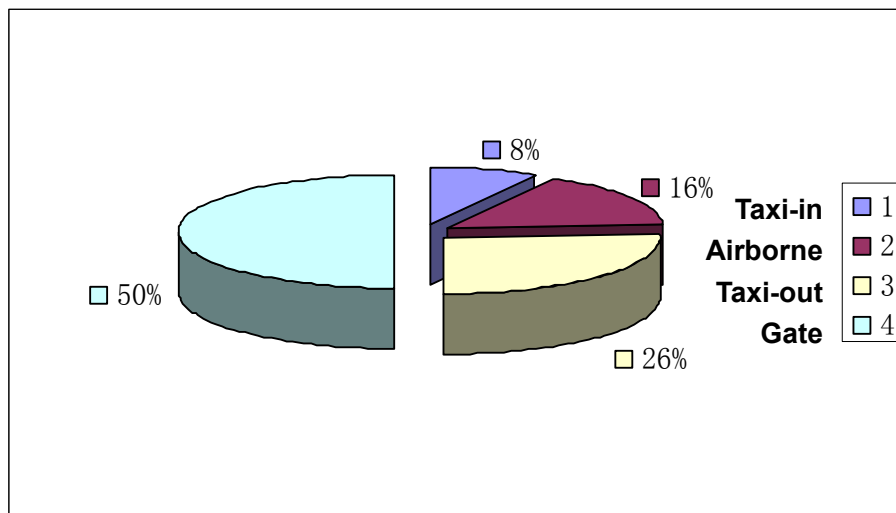


Figure 3-2 Contribution of delay Occurrence

It is obvious that the Off-time can directly affect the flight arrive time (On-time or In-time) rather than Out-time, without considering en route delay. From academic view, we trend to consider that the take off time should be used as the measure

criterion of departure delay. Generally, the passengers' real concern is if they can arrive at their destination on time. The en route buffer can absorb very limited departure delay, so it is the Off-time that affects arrival time in most situations, despite the departure delay happened at gate or during roll out.

From figure 3.2, we can find 76% delay occurred during departure phase, while gate delay and taxi-out delay contributed 50% and 26% respectively. And many occurrences of arrival delay are directly caused by departure delay.

For airlines practical operation, gate delay seems more significant than others. Because there are total 50% delay happened at gate and taxi-out delay, en route delay, and taxi-in delay are out of airlines operation control in most circumstance (controlled by ATC). Therefore the term – ‘departure delay’, mentioned in later part of this dissertation, is mostly related to ‘gate delay’ except those with specific illustration.

Generally, serious delay propagation would incur huge impact on flight schedule. Airlines published schedules incorporate buffer time which is added to the planned flight time and ground time to absorb foreseeable delays. So the time of arriving delay D_{Arr} can be calculated by blow equation:

$$D_{Arr} = D_{Dep} + D_{TO} + D_{Enr} + D_{TI} - T_{Buf} \quad (3-6)$$

Where the D_{Dep} is departure delay time, D_{TO} is Taxi-out delay time, D_{Enr} is en route delay time, D_{TI} is Taxi-in delay time, and T_{Buf} is buffer time which include en route buffer time and ground buffer time.

According to the delay propagation phenomena, the departure delay could also be classified into ‘Type I delay’ (original delay) and ‘Type II delay’ (propagated delay). Type II delay occurs due to the delay of previous flight, despite the delay happened at gate, taxi-out, en route, or Taxi-in period. The delay propagated through aircraft, crewmember, passengers, luggage, and even airport ground services. Unlike the Type I delay, Type II delay can not be eliminated or reduced directly by improving the operation and delay factors of a specific flight. To reduce and eliminate delay, we should focus on study of type I delay factors and optimize airlines operation schedules.

The conventional methods have limitation on studying of delay propagation issue. Because of the type II delay is not independent event. Propagated delay comes from previous delay and also relates to airlines schedules. According to the research report of Beatty et al (1998), large type I delay which occurred in the early time of operating day has more serious effect on delay propagation, while the short delays which occurred at later time in operating day have little or no propagation through the schedule. Delay propagation is not a stochastic problem. All of these features contravene the hypotheses of statistics. An alternative method is need at this stage, which has been studied and developed in this project.

3.4 Crew/Aircraft Turnaround Process and Relevant Regulations

3.4.1 Crewmember Turnaround Process & Availability Regulation

To optimize the aircraft and crewmember turnaround schedule, the process of turnaround, the relevant regulations about aircraft and crew down time are the issues to be understood. Generally, crewmember's down time and their work schedules are the result of negotiation which held between the company and union, since the civil aviation industry is heavily unionized.

The trip-pair is known as the type of crewmember schedule design, which means a pilot and flight attendants would form a work group and is assigned a specific flight duty. The duration of a trip-pair is usually in the range of 1-5 days. Each day is generally a duty period for domestic assignment. A trip-pair should start from one base station and finish at the same base station. A rest period as known as layover is given to trip-pair member between the periods of their two successive duties. Similarly, between two successive flight duties, the crewmember is given a reasonable connection time that is enough to let them connect from the previous arrival gate to next departure gate.

A typical operation process of two-way trip-pair is showed as figure 3.3 (Abdelghany et al, 2004). 'A' is crewmember's domicile, there are three flights in duty # 1, the first one is from 'A' to 'B', then from 'B' to 'S', after that is 'S' to 'H', the time between two flights is connection time, and they have away-from-home layover at station 'H'. After layover, trip-pair perform other three flights for duty #2,

which is ‘H’ to ‘L’, ‘L’ to ‘H’, and from ‘H’ back to ‘A’ finally.

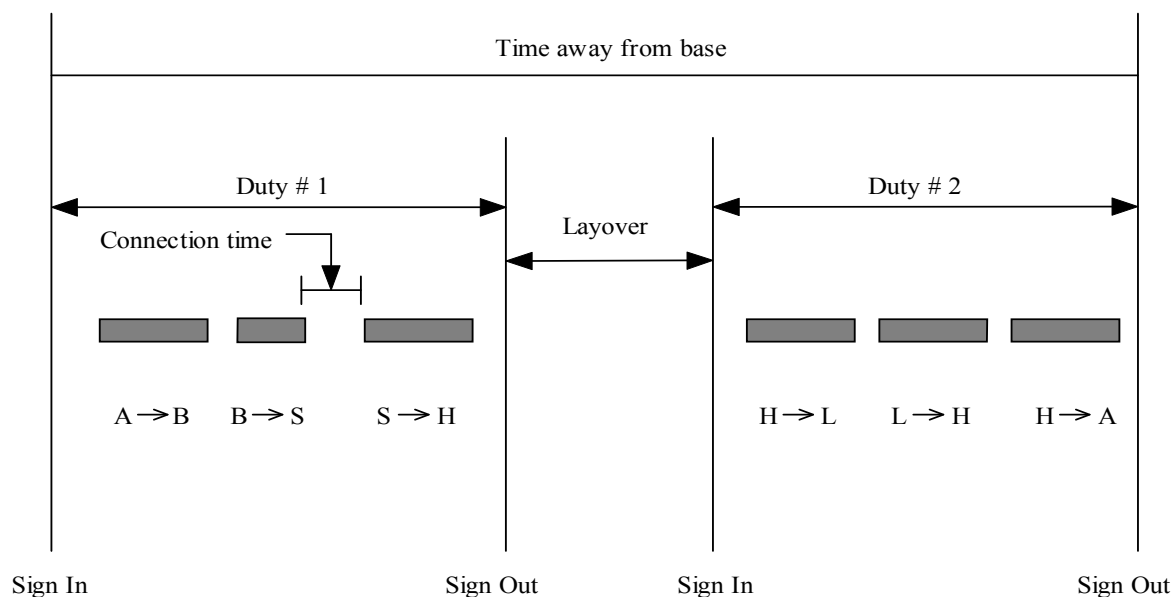


Figure 3-3 The Process of Crewmember Turnaround

According to airworthiness and other relevant government regulations, crewmembers are required to have enough rest between two duty periods. The length of duty period, and the rest time between layovers, are determined based on a series of rules specified by the related air traffic administration agency (which usually belongs to the national government) regulations and labor agreements. Government regulations are generally designed to ensure airlines operate safely. Similarly, aircrafts need maintenance after a running period and airlines companies usually suffer severe fines if they fail to adhere to these regulations. These regulations usually make delay propagation become more serious, and airlines managements to feel more difficulty in rearranging available resources, especially for those airlines that are operated with more compact schedules.

According to a set of rules that are specified in the relevant government

regulations and labor agreements, the length of duty periods and layovers are determined. For example, in the United States, the FAA mandates a list of regulations, which are designed mainly to ensure safe operations. Airlines companies who disobey these regulations are subjected to severe fines. In addition, airlines companies and labor unions set agreements to regulate the relation between the two sides, since the airlines industry is heavily unionized. From the labor prospective, these contracts are set to ensure that crews are receiving the right compensation, training, and good quality life. From the companies' aspect, these contracts obligate each employee to fulfill the assigned work load based on the rules in the negotiated agreements.

There are two main rules affect the day-to-day operations, which are:

(1) Legal rest: Each crewmember must be given the adequate rest between any two successive duties. The length of the rest depends on a combination of several factors, which may include:

- Flying time in the last 24 hours or length of the previous duty.
- Rest location (crewmembers are at their base or not).
- Crewmember work status (reserve or line-holder).
- Market of the trip (domestic/international).

Rest periods increase as flying time in last 24h increases or the length of previous duty increases. Layovers at the crew base station are usually longer than whose

which is away from base. Also, reserve crewmembers have longer layovers than line-holder crewmembers. In addition, crewmembers who execute duty of international trips usually have longer rest period than those who execute duty of domestic trips.

(2) Legal duty: Each crewmember can not exceed a certain number of working hours in one duty. Factors affecting the length of the duty are:

- The scheduled departure time for the first flight in the duty.
- The last time when the crewmember received a rest.
- Existence of augmented crew on the flight.

Crewmember duty period started early in the morning (around 2 or 3 A.M.) is usually shorter than those started later (such as 7 or 8 A.M.). The last time of crewmember having a rest also affects the length of their next duty period. For example, the FAA mandates a rule that any crewmember has to receive unbroken rest of eight hours in any consecutive 24 hours period for any domestic trip-pair (<http://www.alpa.org>). As a result, any domestic duty period cannot exceed more than 16 hours. However, if a flight is scheduled to have augmented crew, on board crewmembers are expected to have longer duty periods.

Various operation breaks could happen under irregular operations conditions. These breaks are defined as follows (Abdelghany et al, 2004):

(1) Misconnect break: It occurs when a connecting crewmember is projected to

arrive late such that she/he is unable to timely connect to the next flight.

(2) Rest break: This break is similar to the misconnect break. It occurs when a crewmember gets a rest period (layover) that is less than the minimum required (legal) rest period because of late arrival at the end of the previous duty period. In this case, the crewmember would be unable to fly the first flight segment in the next duty period on time.

(3) Duty break: is occurs when the actual duty period exceeds the duty period limit due to delaying one or more flights in the duty period cannot be flown by their original crewmember. Under this situation, a substitute crewmember is needed at this departure station to fulfill the flight duty as its originally assigned crewmember cannot beyond her or his duty period limit.

Aircraft down time and schedule should abide relevant regulations of airworthiness. Aircraft maintenances is usually required based on cyclic basis, which could be scheduled based on time, number of flown hours, number of landing/take-offs, etc. Aircraft route are designed to ensure that all maintenance activities are conducted at the base airport which has the maintenance stations in the required dates.

3.4.2 Regulation Related to Aircraft Availability

Each aircraft must undergo a comprehensive check at a maintenance and engineering base. According to FAA regulation, the designated number of flight hours and pressurization cycles is various by aircraft type. Maintenance checks are

of four types:

- A-Check: required about 125-150 flight hours. It consists of a visual examination of airframe, power plant, avionics, and accessories to ascertain the general condition of aircraft. The A-Check requires about 8 hours of ground hours, and about 60 hours of labor.
- B-Check: required about every 700 hours flight hours. It includes an A-check, plus selected operational checks, fluid servicing, and lubrication, as well as an open inspection of the panels and cowling during which preventive maintenance is performed. The B-check requires about 8 hours of ground time and 200 hours labour.
- C-Check: required about 3000 flight hours. It includes an A-Check and a B-Check, and consists of a detailed inspection of the airframe, engines and accessories, heavy controls are calibrated, major internal mechanisms are tested, and FAA service Bulletin requirements are fulfilled. The C-Check requires about 72 hours of ground time and 3000 hours of labor.
- D-Check: required about every 20, 000 flight hours. It includes removal of cabin interiors to allow careful structure inspection, in effect, stripping the aircraft to its shell and rebuilding the interior.

A and B Checks are considered “line maintenance”, C and D Checks are considered “heavy maintenance”.

Similar to crew, aircraft routes are designed to cover a list of consecutive flights.

Ground time, which is the time interval between two successive flights in the same route, is scheduled to finish the aircraft service or maintenance activities. Ground slack/buffer time is always added into ground time to absorb foreseeable flight delay. Aircraft service includes fueling, cleaning, baggage handling, and catering. A similar set of breaks for the aircraft could also occur just like what happened on crewmember during a state of irregular operation. For example, a misconnect break (short turn) can occur when an aircraft arrives late and its projected ready time is beyond the scheduled departure time of the next flight after adding service or maintenance time. Furthermore, similar to crew duty break, a substitute aircraft is needed to perform the next flight duty when the original aircraft is going to violate its due maintenance.

Chapter 4 Type I Delay Analysis and Modeling

4.1 Introduction

The availability of the aircraft comprises of many factors, such as scheduled and unscheduled maintenance, logistic and administration, security and departure delay, etc. Any down time, will be translated into a significant cost for the operators (Yuan & Ren, 2004).

The growth rate in commercial aviation had been forecasted at 37% by FAA from 1999 to 2007. As the rapid growth of air transport demand and vigorous market competition, airlines and airports are becoming more concerned with schedule punctuality as which heavily influences flight safety, the airlines' profitability and the enterprise reputation.

As described in previous chapters, departure delay can be classified into two types – Type I & Type II.

Type I delay occurs due to the outside factors such as administration, unscheduled maintenance, weather, airport operation, human factors, etc. The occurrence of this sort of delay has no relationship to its previous flight and aircraft/crew operation schedule. Type I delay is independent and random. Therefore, the probability functions can be applied to analyze and estimate this type of delay.

In this chapter, a statistic model will be established to analyse the Type I delay. The type I delay causes, related historical data and historical performance of

Australian X Airline will also be discussed. The statistic model conducted in this chapter can also be used to estimate relevant delay cost. Additionally, the probability distribution of the historical delay for Australian X Airline will be found.

4.2 Type I Delay Causes

As mentioned before, the occurrence of Type I delay is independent and random.

The causes can be greatly varied as listed below:

- Weather
- Aircraft mechanical failure
- Maintenance issue
- Absence of passengers/crewmembers
- Airport capacity and ATC management
- The change of operation procedure
- Terrorism
- Administration
- Human factors
- Delay propagation

4.3 Data Collection

For analysis of distribution of the delay, random flight samples were abstracted from the Australian X airlines' database in the period of 2003-2004. (For the commercial confidential reason, the name of the airline is ignored here.)

The original delay and propagated delay data are classified and studied respectively. Additionally the original delay factors are also analyzed and identified according to the original delay data.

As required, the probability distribution of Type I departure delay can be gained based on the historical data. To fulfill above objects, the blow information is necessary to be collected from airlines:

- (a) The number of flights for each day;
- (b) Flight date;
- (c) The type of aircraft;
- (d) The scheduled departure time of flight;
- (e) The actual departure time of flight;
- (f) The reasons of flight departure delay/delay code;
- (g) Airlines flight schedule
- (h) Other relative background information if applied.

4.4 Australian Data Analysis

A certain number of flights have been randomly taken from the data record of Australian X airlines in the period of 2003~2004, (sample data has been listed in Appendix) the analysis results show that there were 7 % of flights took off right on scheduled time; 58% flights delay 1~14 minutes; and 35% of flights delayed more than 15 minutes. The proportion of delay according to time is showed as figure 4.4.2-1. The longest delay was 548 minutes. As a matter of fact, there are hundred reasons can cause departure delay in practice.

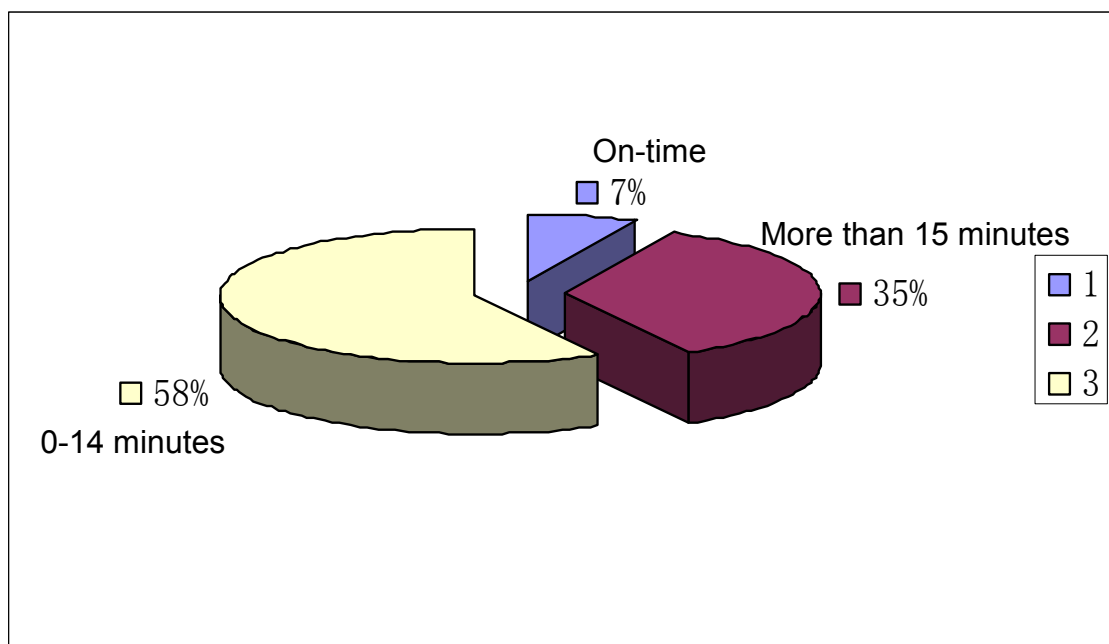


Figure 4.4-1 Proportion of Delay

For further study on the causes of delays, all information was collected into categories such as: aircraft, maintenance, operation management, etc. The detailed definitions are listed in table 4.4-1.

Category	Aircraft Technical Problem & Maintenance	Operational Procedures	Others
Contents	Any technique problem due to aircraft design and manufacture including delay due to scheduled and unscheduled maintenance	Any delay due to operational or management procedures	Such as accidents and weather factors etc.

Table 4.4-1 Cause of Delay

Normally the departure delay is generally defined and recorded as the aircraft fails to release its parking brake less than 15 minutes after the scheduled departure time. However the additional delay cost could be brought by any excess minutes to scheduled departure time. All departure delay including those less than 15 minutes should be also taken into account when studying delay cost.

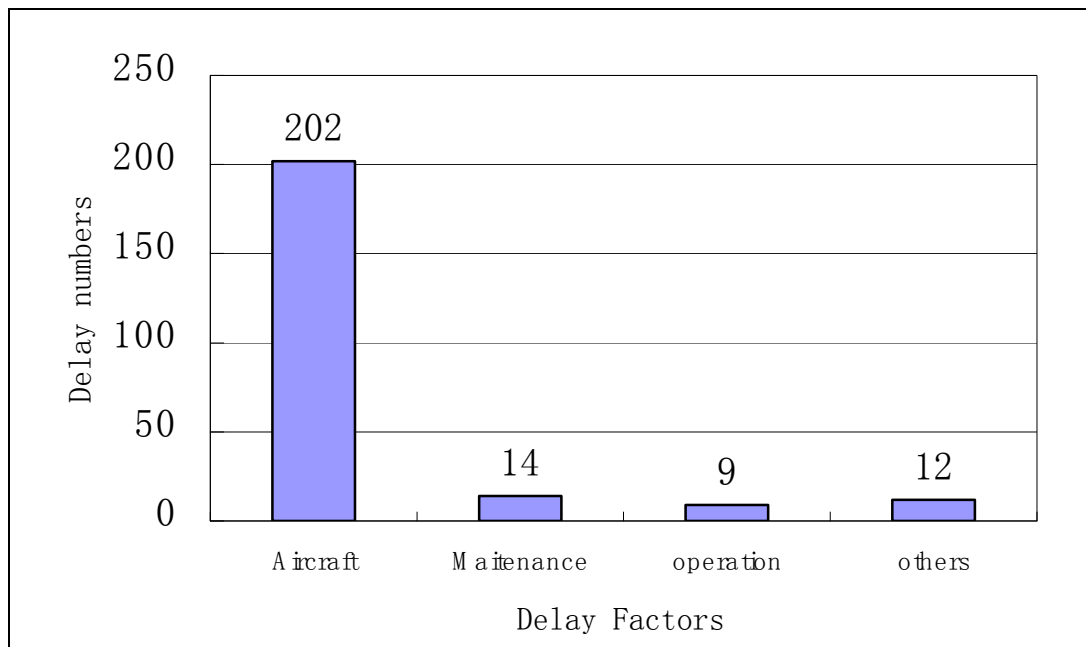


Figure 4.4-2 Delay Numbers by Causes

The causes of departure delay are categorized and statistically plotted in figure

4.4-2, and the cumulative delay time (minutes) of each reason is illustrated in figure 4.4-3 accordingly. Additionally, the proportions are also indicated.

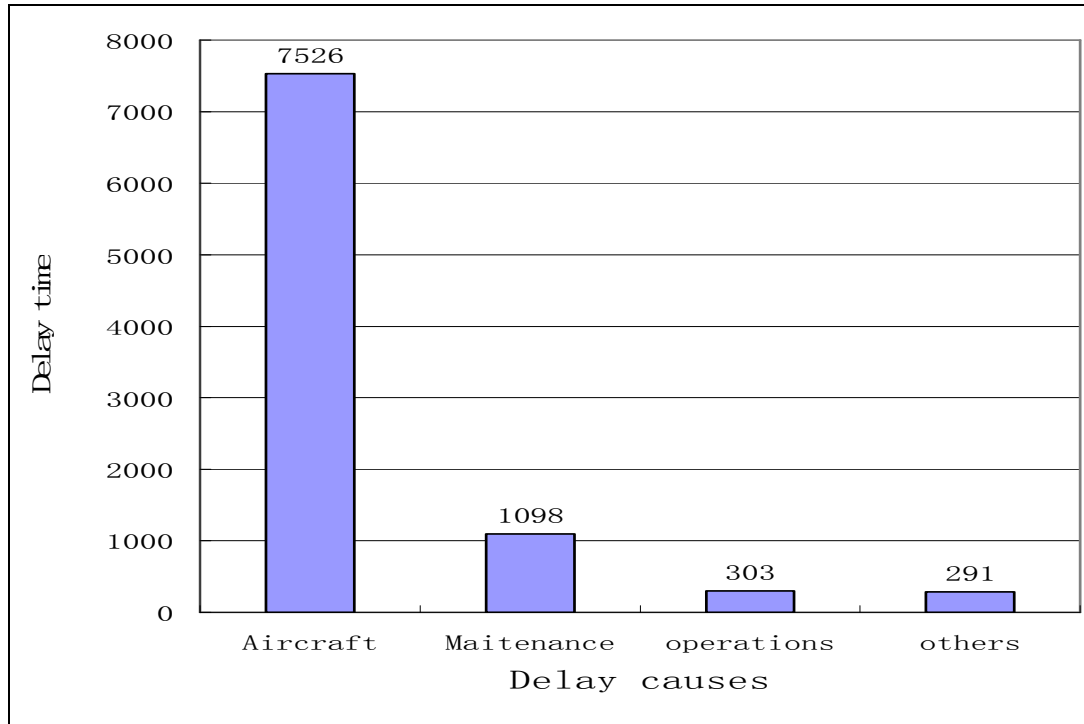


Figure 4.4-3 Departure Delay Time by Causes

The ratio of departure delay numbers distribution is shown as in figure 4.4-4.

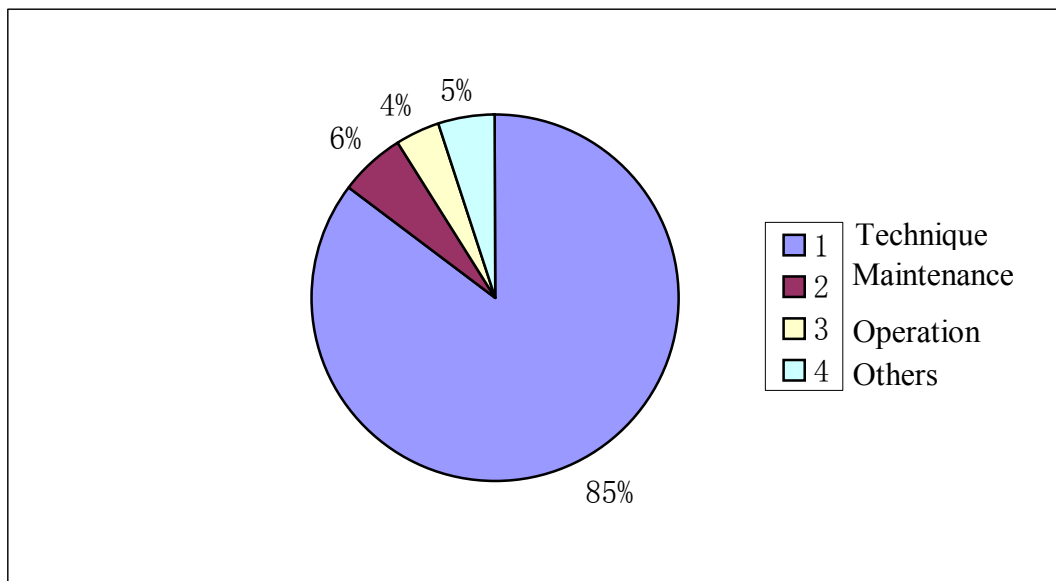


Figure 4.4-4 Ratio of Delay Numbers Distribution

The percentage of departure delay by causes is shown below.

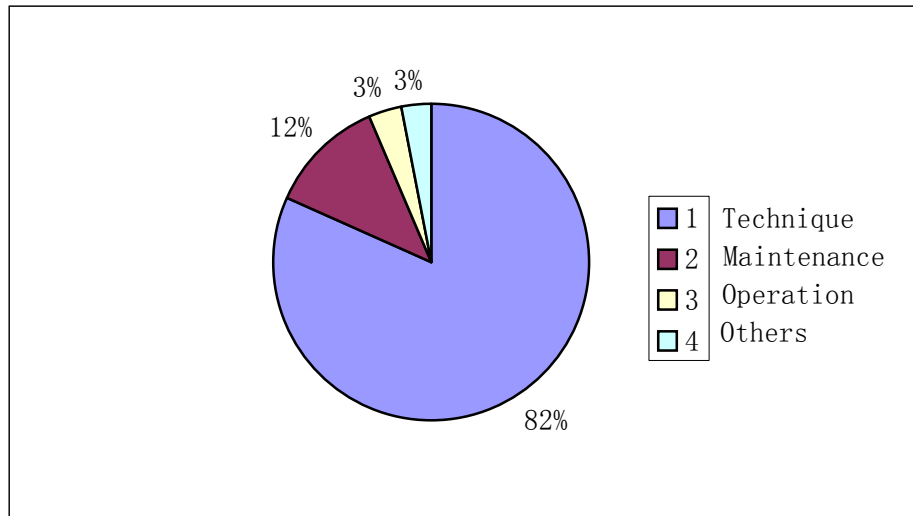


Figure 4.4-5 Ratio of Departure Delay Distribution

According to the illustrations above, the delay due to technical problems and maintenance factor occupies 94% of total departure delay time whilst it occupies 91% in total delay number. Obviously, in order to decrease airlines’ delay time/cost, technical aspect is the key point and solution.

In addition, research shows that there are two daily delay peaks as shown in the diagram below, which is corresponding to the peak time of business travelling.

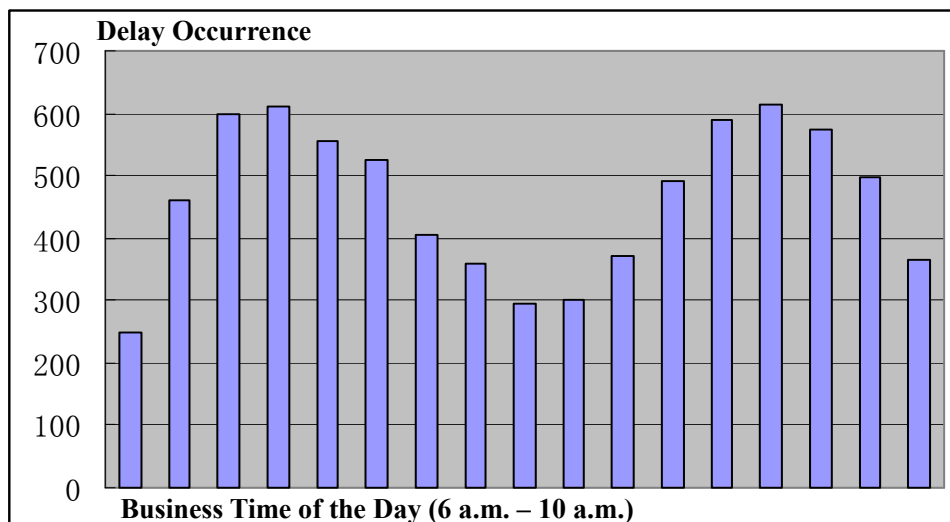


Figure 4.4-6 Flight Daily Peaks

4.5 Dispatch Reliability Modeling

4.5.1 Assumptions

(1) Only gate delay is considered as departure delay, taxi-out delay is ignored in this model.

(2) All factors of type 'I' delay is independent, and the occurrence of delay is random.

Base on above assumptions, the dispatch reliability (DR) can be defined as equations:

$$DR = 1 - F(t) = 1 - \int_{15}^t f(t)dt \quad (4-1)$$

$$F(t) = \int_{15}^t f(t)dt \quad (4-2)$$

$F(t)$ is departure failure distribution function, while $f(t)$ is density function, t is delay time. The probability of a flight will departure at t minute later than scheduled departure time $P_i(t)$ is:

$$P_i(t) = \int_t^{t+\Delta t} f(t)dt \quad (-\infty < t \leq +\infty, 0 < \Delta t \leq 1) \quad (4-3)$$

Then the probability of a flight will departure at t minute later than schedule time due to i th contribution factor $P_{ii}(t)$ can be calculated by equation 4-4:

$$P_{ii}(t) = \int_t^{t+\Delta t} f_i(t)dt \quad (0 < t \leq +\infty, 0 < \Delta t \leq 1) \quad (4-4)$$

$f_i(t)$ is the distribution which is related with i th contribution factor. These factors could be technique, maintenance, weather and so on.

4.5.2 Dispatch Reliability Model

In order to build up the reliability model of the flight dispatching, the estimation method applied is to identify the distribution and parameters. Here, Exponential, normal, lognormal and Weibull distribution have been chosen respectively to find out the characteristics of the flight delays for Australian X Airline.

1730 departure delay data of 2002 have been abstracted from Australian X airlines historical departure database. The mean value of data equals to 38.97, while variance is 17431.2. The process and results of calculation are presented as blow.

Case A: When exponential distribution is considered, mean life equals to 38.97, standard deviation is 38.97, failure rate p_1 is .2566E-01, and initial time p_2 is 0. Using chi-square test, degree of freedom equals to 11, then rejected region $x^2 > 19.68$ when level of significance is 5%, and $x^2 > 17.28$ when level of significance is 10%. x^2 equals to 21.56 > 19.68 (the value of x^2 when significance is 5%). the level of significance for accepting is 2.80%, so this distribution is rejected.

Case B: When delay is assumed to follow normal distribution, mean life equals to 38.97, standard deviation is 41.75. Using chi-square test, degree of freedom is 10, the rejected region $x^2 > 18.31$ when level of significance is 5%, and $x^2 > 15.99$ when level of significance is 10%. x^2 equals to 120.3 > 18.31 (the value of x^2 when significance is 5%). So normal distribution is rejected.

Case C: When lognormal distribution is considered, mean life equals to 39.54, standard deviation is 44.27, log average equals to 3.271, and log standard deviation is 0.9254. Using chi-square test, degree of freedom equals to 10, then rejected region $x^2 > 18.31$ when level of significance is 5%, and $x^2 > 15.99$ when level of significance is 10%. x^2 equals to 5.215 < 15.99 (the value of x^2 when significance is 10%). the level of significance for accepting is 95%, so this distribution is accepted.

Case D: When Weibull distribution is considered, mean life equals to 39.22, standard deviation is 34.59, scale parameter equals to 41.07, and shape parameter is 1.136. Using chi-square test, degree of freedom equals to 10, then rejected region $x^2 > 18.31$ when level of significance is 5%, and $x^2 > 15.99$ when level of significance is 10%. x^2 equals to 15.82 < 15.99 (the value of x^2 when significance is 10%). the level of significance for accepting is 10.48%, so this distribution can be also accepted but with lower significance level comparing with lognormal distribution.

As a result, It was found that X airline departure delay time variation most likely follows the lognormal distribution, (Case C) which formula is:

$$f(t) = \frac{1}{\sigma\sqrt{2\pi}} e^{\left[-\frac{(\ln t - \mu)^2}{2\sigma^2}\right]} \quad t > 0 \quad (4-5)$$

Where μ and σ^2 are the mean and variance respectively. The parameters result as $\mu = 3.271$, $\sigma = 0.9254$, $\sigma^2 = 0.8564$, with significance level 95%. Thus the

density function of departure delay can be expressed as:

$$f(t) = 2.3196e^{-0.5838(\ln t - 3.271)^2} \quad t > 0 \quad (4-6)$$

And the curve of the density function has been plotted as in figure 4.5.2-1,

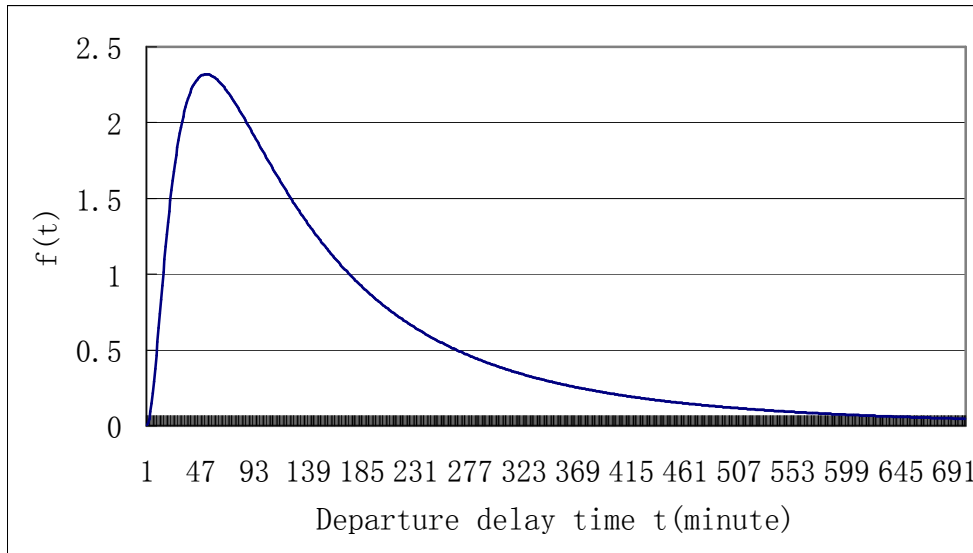


Figure 4.5-1 Delay Density Function

Then the dispatch reliability (DR) of this airline's fleet would be:

$$\begin{aligned}
 DR(t) &= 1 - \int_{15}^t 2.3196e^{-0.5838(\ln t - 3.271)^2} dt \\
 &= 1.2709 - \Phi\left(\frac{\ln t - 3.271}{0.9254}\right) \quad t > 15 \text{ minutes} \quad (4-8)
 \end{aligned}$$

However, for most airports in Australia, any delay after the scheduled departure time will be charged by airport, which means any excess time need to be accounted for the cost estimation. Thus, it is necessary to consider the probability of any delay excess the scheduled departure time, rather than only determine the time after 15 minutes behind the schedule. In that case, the departure failure probability function $P_t(t)$ is shown as equation 4-9, $P_{0-t}(t)$ represents the probability of a flight which delays 0-t minutes:

$$\begin{aligned}
 P_{0-t}(t) &= \int_0^t 2.3196e^{-0.5838(\ln t - 3.271)^2} dt && t > 0 \\
 &= \Phi\left(\frac{\ln t - 3.271}{0.9254}\right) && (4-9)
 \end{aligned}$$

4.6 Type I Delay Modeling Summary

In this chapter, a statistic model has been applied for Type I delay and related cost analysis. This model has also been used to describe and analyse the dispatch reliability for the whole airline fleet based on the historical data.

The result has indicated that the delay of Australian X Airline obeys the lognormal distribution; meanwhile the good-fitness parameters have been identified. Thus, the probability of future flight delay can be predicted through the model developed in this chapter which has provided a practical tool to estimate the impact of specific factor on delay and related cost.

As being illustrated, there were about 93% flights leaving gate later than scheduled time; 35% of them left later than 15 minutes, which is normally the critical time to record a delayed flight. However, the airports will charge the operators/airlines for every minute after the scheduled departure time. Therefore, all those 93% flights delay need to be taken into consideration for the economy estimation purpose. (The detailed discussion and analysis of cost related issues will be in the following chapter.)

Additionally, the main reason of those departure delays is subject to aircraft technical and maintenance problems, which lead to even more cost.

On the other hand, there are still limitations at this stage.

With this modeling method, all relevant factors (such as the distribution of type I delay occurrence and operation schedules) are not variable. Thus, this method can not be employed to analyse delay propagation and optimize the schedule.

Furthermore, when the operation conditions have been changed, this model can not be used to predict flight delay any more.

But this modeling method can always be effective to calculate the dispatch reliability not only for Australian X Airline and also for most airlines in the world.

In order to reduce and eliminate departure delay, rather than a comprehensive investigation on the Type I, even more attention should be paid on the research in Type II delay, which is often ignored by some conventional studies. The method of type II delay estimation will be presented in chapter 6.

Chapter 5 Delay Cost Modeling

5.1 Introduction

The cost induced by departure delay is tremendous. As mentioned in Section 1.2, in 1999, there are more than 3.2 billion dollars drained out due to flight delay in U.S. This compares to roughly 7.85 billion dollars in net profit for all airlines, representing a 27% drain on financial resources (Mueller & Chatterji, cited in Office of Inspector General 2000). “FAA estimates that airlines lose as much as \$1,600 for every hour an airliner sits delayed on a runway” (David Field of Insight on the News explains, 1995, p. 39).

As one main objective of this project, optimizing the flight schedule may significantly affect the profitability of airlines, especially those principle ones, who use more compact schedules. Basically, the process of the schedule optimization is a trade-off among profit, cost and reliability.

Departure delay incurs four main group substantial costs: aircraft operators, airline passengers, airports and local communities. Despite people have already realized the negative impacts due to departure delays, there is still not an effective way to solve the problem, which even became worse.

- In Western Europe, the proportion of flights delayed doubled to 24 percent between 1986 and 1989, resulting in an estimated congestion cost of US\$1.5 billion per year

(SRI international 1990) ;

- In the United States, during 1986, the direct cost of congestion to aircraft operators was estimated at US\$2 billion (Hong and Harker 1992) ; and
- In Australia, the Price Surveillance Authority, in 1993, estimated that congestion at Kingsford Smith airport was costing airlines and passengers at least Aus\$40 million per year.

In this chapter, it will start from the analysis of the current problems in the areas related to cost. The airport fee structure will be introduced as a supplementary background analysis. All the delay cost will also be identified and sorted as to raise the accuracy of the result. The focus will be put on Australia X Airline. A practical departure delay cost model will be established, which can also be used for any potential end-users.

5.2 Analysis of the Problem

Currently, one of most common methods of computing delay cost is using average delay cost of unit time (hourly or minutely) multiply by the total delay time of the whole fleet. It is almost the easiest way of computing delay cost, however it is found that this 'easy approach' wouldn't be accurate or practical enough in real scenarios. Thus, the main problem in delay cost modeling is to find an effective method.

As been investigated, it is really difficult to set up a standard average value in

terms of hourly or minutely delay cost. In fact, it is hardly possible to get such a standard value for different airlines in different countries; because the factors and their rates contributing to the delay cost are great varied even the airlines are belonged or operating in the same country.

	Heavy Jet	Large Jet	Medium Jet	Operation Cost
Lufthansa	8%	16%	76%	\$3407/h
United Airlines	9%	15%	76%	\$2736/h
British Airways	32%	42%	26%	\$4498/h
British Midland	0	0	100%	\$2822/h
KLM	10%	33%	57%	\$4757/h
American Airlines	0	19%	81%	\$2207/h

Table 5.2-1 Airlines Infrastructure and Cost Rate

One reason could be the different infrastructure of their fleet. And the other reason could be the airlines purchase products or services from the suppliers with different price. So most of airlines have the different hourly operation cost. The statistic data from IACO showed as table 5.2-1 could demonstrate the difference (Wu & Caves 2000).

Some literatures have revealed the aircraft delay cost on ground. The cost rates for European airlines are \$1330, \$2007 and \$3022 per hour for medium, large and heavy jets respectively (Janic, 1997), meanwhile the values are \$430, \$1300, and \$2225 with respect to small, medium and large aircraft in the US (Richetta and Odoni,

1993). But, even for those airlines, which have similar fleet structure, could also have different operation cost. For instance, Lufthansa and United Airlines have very similar fleet structure but the average operation costs are still various as \$3407 and \$2736 per hour respectively (Wu & Caves 2000).

Even for the same airlines, the result of fleet total delay cost which is calculated through the average delay cost of unit time may be also not accurate. As discussed before, the airlines' total delay cost usually is not a simple linear function of the total delay time of the whole fleet. For example, the cost of total 1000 minutes delay would be greatly different if the corresponding flight number is different. According to the analysis on several main delay cost factors, the payment for the crew is more likely to be linear with the delay time; airport charge could be also considered to be linear with delay time based on some assumptions. However, the compensation of passengers when flight delay happens is definitely not ratable to delay time. Till now, there is not any published standard delay cost of unit time is accurate and credible enough to be applied by all airlines.

Different calculation models can be chosen according to the result accuracy requirement. In order to have a better understanding of the delay cost estimation basis in this project, it is necessary to have an overview on the airport fee structures.

5.3 Airports Fee Structure

Airlines are facing a number of airport charges for commercial aircrafts. Some of charges are the causation which incur additional cost for the flight delays. And these

charges are the main contribution to the total airline delay cost. It is necessary to well understand the structure of airports charges before identifying some critical delay cost factors.

5.3.1 Landing Fee

In the majority of airports all over the world, the landing fee is paid on arrival per landing and has covered the departure fee of the aircraft itself. Generally, the landing fee is based on the weight of aircraft, which normally defined by the Maximum Take-Off Weight (MTOW) or the Maximum Authorized Weight (MAW). Landing fee may also cover 2-6 hours free-parking which according to how busy the airport is. Usually, the busier airport would provide shorter free-parking period.

5.3.2 Aircraft Parking and Hanger Fee

Beyond the free-parking period, aircraft must be charged if it parked on the gate, airport apron, taxiways ramps or hangars. The parking fee may vary between different areas of the airports. For example, a position closer to the terminals would surely be more expensive. The parking charge is calculated usually on the basis of the aircraft's weight or the time staying on its area. Another way is to charge the parking fee as a percentage of the landing fee that is weight based.

Parking fee rates are various as the different areas, countries or airports. Generally, more parking fee would be charged in busier airports.

Another important parameter is time. For most airports, the aircrafts parking time would be calculated start from the In-time (the moment the parking brake turns into

operation at the gate) or the schedule arriving time, and end at Out-time. The payable time equal to the margin between the parking time and the free parking time

The following example is to indicate how the departure delay would increase the airlines' expenditure. The main charges level of Melbourne international airport and Sydney airport of Australia is shown as in table 5.3.2-1.

Airports	Passenger Fee	Parking Fee	Landing Fee
Melbourne	\$11.00/person	\$27.50/per 15 Minutes	\$3.81/per 1000 kg MTOW
Sydney	\$22.63/person	\$38.50/per 15 Minutes	\$6.60/per 1000 kg MTOW

Table 5.3-1 Parking & Landing Fee Rates

For both airports above, the landing Fee is applied for freight aircraft only, free parking hours is 6 hour at Melbourne airport, and generally parking fee is not charged when airport is not busy, free parking hours is 2 hours at Sydney airport. If an aircraft delay 4 hours, the airline would lose AUS\$440 at Melbourne airport, or AUS\$616 at Sydney airport for additional parking time.

5.3.3 The Passengers Fee

The passenger fee is normally charged by the number of departing passenger only. The arrivals are not taken into account. Many countries levy a lower or even exempt the charges on domestic passengers, because international passengers are more costly to handle in terms of facilities and staff. The rates shown in the table 5.3.5-1 are only applied for the passengers taking international flights.

5.3.4 Other Aeronautical Fee

The other aeronautical fee includes: terminal navaid charge; fuel throughput charge; fee for airbridges, buses, mobile lounges, or terminal facilities include counter fee; fee for handling passengers, baggage, or freight; security fees and other ground handling fee.

5.3.5 Airport Price Regulation in Australia

In late 1990's, most Australian airports started to be privatized as a reformation of the industry structure. In 1997, the Commonwealth Government granted the long-term leases of 50 years to private sector operators at Brisbane, Melbourne and Perth airport (phase 1). And further sell the leases of even more airports in 1998 (Adelaide, Alice Springs, Canberra, Coolangatta, Darwin, Hobart, Launceston, Townsville, Mount Isa, Tennant Creek, Archerfield, Jandakot, Moorabbin and Parafield airport).

Core-regulated airports: leased airports designated as such under the airport Act 1996. 12 of 22 leased airports were designated as 'core-regulated' airports which comprised Adelaide, Alice Spring, Brisbane, Canberra, Coolangatta, Darwin, Hobart, Launceston, Melbourne, Perth, Sydney and Townsville airports. These 12 airports include Sydney airport and 11 privatized airports were subject to price regulation under the prices Surveillance Act 1983 (PS Act)..

Price regulation of core-regulated airport included prices notification, price monitoring, price-cap arrangements and special provisions for necessary new

investment at airports. A range of service provided by core-regulated airports was subject to price notification or monitoring under the PS Act for the period following the granting of leases until October 2001. The ASA (Airservices Australia) charges and charges subject to the price cap at core-regulated airports are shown as table 5-3 (Price Regulation of Airport Services, 2002). ASA charges here include terminal navigation, aviation rescue, and firefighting charges. All charges included GST.

Airport in Australia	Runway Fee (A\$/t MTOW)	International Terminal Fee (A\$/t MTOW)	Aircraft Parking Fee (A\$/aircraft)	ASA (A\$/t MTOW)
Adelaide	4.72	1.05	11/day	10.39
Alice Spring	5.55	N/A	0	12.14
Brisbane	5.30	2.43	11/day	5.67
Canberra	(2.27) ^a	N/A	0	10.83
Coolangatta	5.32	N/A	0	11.99
Darwin	5.55	1.02	0	8.89
Hobart	5.55	1.05	11/day	13.79
Launceston	5.61	N/A	0	14.53
Melbourne	5.34	3.80	50/day	4.06
Perth	5.06	2.48	10/day	8.19
Sydney (2000)	2.92	7.92	11/day	4.65
Sydney (2001)	(6.88) ^b	(35.10) ^c	35/per 15 Min	4.65
Townsville	5.75	1.05	0	4.33

Table 5.3-2 Airport Charges Rates in Australia

- a** - Per passenger charge.
- b** - Based on a runway charge of \$3.44/t MTOW, which is levied at landing and take-off. Other core-regulated airports charge for landing only.
- c** - Based on a per passenger charge of \$17.55, which is levied on each arriving and departing passenger, and cover runway, passenger, and security screening services.

From October 2001, the changes were made by Commonwealth Government as following:

- Melbourne, Brisbane and Perth airports were allowed a once-only price increase, as a pass-through in the price cap, of up to 6.2, 6.7 and 7.2 per cent of starting point price at privatization respectively. In all other respects, price regulation at these airports remained unchanged.
- Price caps on aeronautical services at Adelaide, Canberra and Darwin airports were replaced by price monitoring under the PS Act.
- Coolangatta, Alic Springs, Hobart, Launceston and Townsville airports are no long subject to any price regulation. Both of the price caps and price monitoring have been removed.
- Sydney Airport remained unchanged on price regulation, which included price notification of aeronautical service and price monitoring of aeronautical-related services.

In order to effectively improve the airport operation quality, nowadays, the

deregulation and privatization of airport have been a trend in the worldwide (Ashford, 1997).

5.4 Passenger Delay Cost

The compensation for passengers is another main factor of airlines' flight delay cost. As the civil aviation industry's convention, when the delay happened to passenger, the airlines should provide passenger with certain compensation according to the delay duration. For example, when delay time is less than 2 hours, the airline don't need provide compensation; if delay lasts between 2-6 hours, airline need to provide least additional refreshment; if delay time last more than 6 hours, the meal and accommodation (if it is needed) should be provided.

To use passenger's average salary as the standard (conventional approach) to calculate passenger delay cost has several disadvantages. First of all, the airlines rarely compensate passengers according to their salary standard when flight delay occurs. This method will enlarge the passenger delay cost comparing to airlines' actual passenger delay compensation. Additionally, how to calculate the passenger average salary accurately is another problem since the passengers' salary is great varied according to their occupations.

Furthermore, to analyse passenger delay cost from the point of view of society is also not accurate enough to calculate passenger time value. Because in real cases, this value would not be as same as the exact amount of passengers' salary. A coefficient may be necessary to be applied on passengers' time value calculation according to

relevant economic increase rate. However it would be another problem to specify the coefficient value and it would not be discussed in detailed in this dissertation. To optimizing aircraft and crewmember turnaround schedule, and flight schedule, providing the support to airlines operation planning, airlines actual payment to delay passengers is proposed to be used on passenger delay cost computing.

5.5 Aircraft Scheduled Time Cost

Aircraft scheduled time cost can be another component of delay cost. The fee of aircraft purchase or renting and its maintenance determine the using aircraft will incur cost.

The aircraft ground time comprises of three sections: the scheduled ground service time, schedule buffer time and unscheduled delay time (if applicable). Meanwhile the airborne block time could also contain three sections: standard flight time, airborne buffer time, and airborne delay time (if applicable). It should not be simply deemed that ground time would incur the schedule time-opportunity cost. Since the scheduled ground service time is necessary part of airlines normal flights operation and revenue generation. So the aircraft scheduled ground service time and standard flight time should be both considered as aircraft available operation time, and aircraft available operation time can also be optimized to improve the aircraft utilization efficiency during its life period. Meanwhile the buffer time and the delay time could be considered as aircraft unavailable operation time. The airlines ideal aircraft turnaround and flights operation schedule can be defined as ‘the operation

schedule without considering any aircraft unavailable operation time impact'.

Furthermore, the aircraft schedule time cost should not be simply counted in for all flight delays. A hypothesis has been applied that the total cost of a single aircraft during its life cycle is invariable or not related to the flight delay; the delay can only reduce the profit of the aircraft employment by cutting the scheduled flight amount that the aircraft can perform. It is obvious that not all delay will affect an aircraft to perform its scheduled flight, especially for those aircraft which fly domestic route.

Based on analysis above, it is assumed that the standard ground service time of a specific aircraft at the same airport is fixed. It is proposed that the policy of whether aircraft schedule time cost should be applied is: during an aircraft specific operation schedule period between maintenance intervals (day, week or others), an aircraft schedule time cost should be applied when this aircraft unavailable operation time increase significant enough to reduce the aircraft available operation time; otherwise aircraft schedule time-opportunity cost should not be counted in. In other words, to decide whether the schedule time cost should be applied, the criterion is to check-up if the aircraft actual available operation time (in a specific time framework) has been cut or not.

For example, most domestic flights don't operate 24 hours circularly. If the occurrence of delay and the increase of buffer time are not really serious, the operation time (number of flights) of the aircraft wouldn't be reduced, it would only shorten the night halt intervals. Other operation cost would happen in this case, but

there is no schedule time cost. On the other hand, if the aircraft could not fulfil the planned amount of daily flight tasks due to some serious delay or disruption, which could affect the aircraft operation service for the next day, then both of the cost should be taken into account, which includes the schedule time cost.

5.6 Other Relevant Delay Cost

Other operation cost may include: crew cost; ground staff cost; petrol and oil cost; ATC service cost etc.

The crew cost feature is similar with aircraft schedule cost one. And they also operate according to the schedules. But the difference is, even the crew schedule time cost is not applicable, airlines still need to pay more allowance to crew when delay happened because they need work longer than usual. For example, about additional \$15/hr averagely need to pay to each crew personnel due to delay in some airline.

Some departure delay won't incur ground staff cost, such as the delay due to airport ATC; meanwhile some will, such as the delay due to the passenger late arriving or unscheduled maintenance. In some situation, when the delay occurred, the check-in counter using also needs to be extended. It would be charged more of the counter and staffs. The level of charges is also varied by different airlines or service companies.

5.7 The Factors of Delay Cost

In order to accurately assess the delay cost, a cost computing model has been developed based on cost factor analysis. The factors contributed to delay cost are identified as below based on social aspect and airlines finance respectively.

	(a) Social Aspects		(b) Airlines Finance	
	Engine-off	Engine-on	Engine-off	Engine-on
¹ Passenger (Time) Cost	✈	✈	✈	✈
² Airport Ground Staff Cost	✈		✈	
³ A/C Utilization Time-Opp. Cost	✈	✈	✈	✈
⁴ Airline Abroad Staff Cost	✈	✈	✈	✈
⁵ Airport Facility Utilization Cost	✈	✈	✈	
⁶ Airport Energy/Resources Cost	✈			
⁷ ATC Operation Cost	✈	✈	✈	✈
⁸ Petrol & Oil Utilization Cost		✈		✈
⁹ Exhaust & Noise Pollution Cost		✈		✈
¹⁰ Reputation & Passenger Loss			✈	✈

Table 5.7-1 Delay Cost Factors

(a) From the point of view of whole society, delay cost is very difficult to be estimated quantitatively. But we still can identify some factors and evaluate them qualitatively in a way. Here when delay occurs on the gate or ground, it has been taken as ‘Engine-off’, while it has been taken as ‘Engine-on’ when the delayed

aircraft was taxi-in or taxi-out.

(b) Comparing to delay social cost, it becomes easier to estimate delay cost quantitatively when we consider it from airline finance aspect, which will be analyzed in later sections.

1. For Social Aspect: Passenger time cost equal to the total social value could be created by each specific passenger during the flight delay time;

For Airline Finance: Passenger cost is equal to actual additional cost the airline spent on each specific passenger due to the flight delay;

2. For Social Aspect: Airport ground staff time cost is equal to the total social value could be created by each specific staff during the flight delay time;

For Airline Finance: Airport ground staff cost is equal to actual additional payment the airline spent on each specific staff due to the flight delay;

3. Aircraft Utilization Time-Opportunity Cost

For Social Aspect: it is equal to the social value which this specific aircraft can create during the delay time;

For Airline Finance: if applicable, it is equal to the airlines business value which this specific aircraft can create during the delay time;

4. For Social Aspect: Airline aboard staff (pilots and crew) cost is equal to the social value could be created by each specific aboard staff during the flight delay time;

For Airline Finance: Airline aboard staff (pilots and crew) cost is equal to actual

additional payment the airline spent on each specific aboard staff;

5. For Social Aspect: Airport facility utilization (time-opportunity) cost is equal to the social value could be created by these specific facility during the flight delay time;

For Airline Finance: Airport facility utilization (time-opportunity) cost is equal to airlines actual additional payment spent on these specific facility due to the flight delay;

6. For Social Aspect: Airport energy and other resources cost is equal to the social value could be created by these specific amount energy or other resources that have been used on this flight due to its delay;

7. For Social Aspect: ATC operation cost is equal to the social value could be created by the specific ATC service resource that had been wasted due to the flight delay;

For Airline Finance: ATC operation cost, if applicable, it is equal to actual additional payment the airline spent on ATC service due to the flight delay;

8. For Social Aspect: Petrol & oil utilization cost is equal to the social value could be created by these specific amount petrol and oil that had been used on this flight due to its delay;

For Airline Finance: Petrol & oil utilization cost is equal to additional cost the airline spent on these specific amount petrol and oil due to the flight delay;

9. For Social Aspect: Exhaust gas and noise pollution cost is equal to the social

value that is lost due to these additional exhaust gas and noise pollution;

For Airline Finance: Exhaust gas and noise pollution cost, if applicable, is equal to the actual additional payment the airline spent on these additional exhaust gas and noise pollution due to the flight delay;

10. Airlines negative impact on reputation and potential passenger loss.

Most social costs of flight delay, the airlines' reputation and potential passenger loss are very hard to accurately estimate, and these parts are also not belonged to the core of this project. To provide a trade-off tools for airlines operation schedule optimization, this research will focus on the analysis and estimation delay cost based on airline finance. So airlines delay cost can be mainly classified into: aircraft using cost; crew cost; passenger cost; airport using cost and other operation cost etc. The model of cost calculation is presented in detailed in section 5.8.

5.8 Data Collection & Analysis

5.8.1 Data Collection

Besides of the collected data of airlines delay history which mentioned in chapter 4, to quantitatively evaluate delay cost, relevant airport service charge items and rates are collected from Melbourne International Airport and Sydney International Airport. To deliver a more universal and representative delay cost estimation method, even more airports are involved; Singapore Airline; Air China; Southern Airline of China; Qantas Airline; Vietnam Airline have also been interviewed for the data collection related to delay cost. Historical data from Australian previous second biggest airline - Ansett has also been collected. The cost factors and cost rates which can be used for this research have been analyzed and identified. The collected information is including the data as listed below:

- (1) The structure of airport charge
- (2) The rate of airport charges
- (4) The passenger's compensation
- (5) The allowance rate of crewmembers
- (6) Other relative background information if applied.

5.8.2 Analysis

As mentioned before, the main factor which affects dispatch reliability is departure delay. According to the analysis of data collected, it can be known that the

departure delay occur 20.6%, the cancelled flight occur 2.5%, 0.22% diverted in the totally 39,259,682 departures happened at 88 main US airports from 1995 to 2002. The actual number of delay flights and minutes has been shown in table 4-1.

It has been indicated that the departure delay will surely increase the airlines cost. The main charges level of Melbourne international airport and Sydney airport of Australia is showed as table 5.3-1.

As previously discussed, enormous economic resources are needed to expand the current airport capacities to meet the fast growing demands. International Air Transport Association (IATA) and the U.N. International Civil Aviation Organization (ICAO) indicated that US\$250 billion will be spent for airports project by the year 2010 worldwide. Even so, the airport development projects are often constrained by land, environmental and political problems. This project is to provide a solution that is both affordable and practical in today's commercial aviation industry. In the following sections, a delay cost modeling methodology will be established as an important criterion of the overall airline flight schedule optimization. This methodology can be applied to most of the current airlines as a tool which can be able to assist in air-fleet management and decision making process.

5.9 Assumptions

- The delay referred in the following modeling represents the gate delay only. Taxi-way and en route delay is excluded from data.
- Actual delay time has been taken to estimate the cost of delay instead of the delay report criteria of D+15.
- The following model has been developed only counting the cost factors based on airline. As some of the other factors are difficult to estimate, such as the social cost.
- The maximum delay time is set to a reasonable value. Since a delayed flight could be cancelled or standby when disruption is serious enough.
- Petrol fee is not counted when delay occurred at gate.

5.10 Departure Delay Cost Modeling

5.10.1 Parking Cost

The excess airport parking fee rate p_a can be defined as equation 5-1:

$$p_a = \frac{A_p}{T_p} \quad (5-1)$$

A_p is the charge of an excess parking, T_p is the time of excess parking. For example, at Melbourne International Airport, the excess parking fee is \$27.5 per 15 minutes, so A_p is \$27.5, T_p equals 15min, then $P_a=1.83$. The increase airport parking cost due to departure delay C_a can be defined as equation 5-2:

$$C_a = \sum_{t=1}^N n_a p_a t P_t(t) = n_a p_a \sum_{t=1}^N t P_t(t) \quad (5-2)$$

n_a is the total amount of flights. Any departure delay may incur the excess cost, even it only delays 1 minute. So the t should start from 1, but not 15 or any others. $P_t(t)$ is the probability of flight delay t minutes which can be computed by equation 4-3.

5.10.2 Airline Crewmember/Staff Cost

The increased airline crew cost due to delay C_c can be defined as equation 5-3:

$$C_c = \sum_{t=1}^N n_c p_c t P_t(t) = n_c p_c \sum_{t=1}^N t P_t(t) \quad (5-3)$$

n_c is the total number of airline crew on duty, p_c is the crew payment rate. The model is also applicable to ground staff worked overtime due to delay.

5.10.3 Passenger Cost

Then the increased passenger cost C_p is defined as equation 3.4:

$$C_p = \sum_{t=1}^N n_p p_{p\Delta t} P_t(t) = n_p p_{p\Delta t} \sum_{t=1}^N P_t(t) \quad (5-4)$$

n_p is the total number of passenger, $p_{p\Delta t}$ is the passengers cost rate when delay time is during Δt period. Since the cost spent on the delayed passenger by airline is not simply direct ratio relation to flight delay time, it keeps constantly during a delay interval. For example, when $\Delta t=1$ means the flight will delay 0-2 hours, and airlines might cost almost nothing for delay passengers; if a flight delayed 2-6 hours, $\Delta t=2$, the airlines need provided passengers refreshment or meal, the cost rate is \$15/person;

when flight delay more than 6 hours, $\Delta t = 3$, the airline need provide accommodation and more meal, so the cost rate might be \$60/person. $P_t(t)$ is the probability of flight will delay during Δt period.

5.10.4 Other Aeronautical cost

C_o is other increased aeronautical fee due to departure delay if applicable. It can be calculated by equation 5-5:

$$C_o = \sum_{t=1}^N n_a p_o t P_t(t) = n_a p_o \sum_{t=1}^N t P_t(t) \quad (5-5)$$

Where p_o is the charge rate for other aeronautical service due to delay. p_o would be variable when multi-service is applicable.

5.10.5 The Sum of Delay Cost

So the total delay cost C_D due to departure delay is defined as:

$$C_D = C_a + C_c + C_p + C_o \quad (5-6)$$

If we study the delay cost by some specified (*ith*) factor, the equations is defined as:

$$C_{ai} = n_{ai} p_a \sum_{t=1}^N t P_{ti}(t) \quad (5-7)$$

$$C_{ci} = n_{ci} p_c \sum_{t=1}^N t P_{ti}(t) \quad (5-8)$$

$$C_{pi} = n_{pi} p_{p\Delta t} \sum_{t=1}^N P_{ti}(t) \quad (5-9)$$

$$C_{oi} = \sum_{t=1}^N n_a p_o P_{ti}(t) \quad (5-10)$$

$$C_{Di} = C_{ai} + C_{ci} + C_{pi} + C_{oi} \quad (5-11)$$

$P_{ii}(t)$ is the probability of flight t minutes caused by i^{th} factor.

5.11 Sample Calculation

In this sample calculation, the Australian X airlines' delay historical data and some results calculated in chapter 4 are used to calculate overall airline delay cost. According to the computing result of last chapter, departure delay follows lognormal distribution, and the parameters are: $\mu = 3.271$, $\sigma = 0.9254$, $\sigma^2 = 0.8564$. It is assumed that the airline has 1000 flights will departure late than schedule time from Melbourne airport during a specific period. the aircrafts type is Boeing 737 series which contain 130 seats, the load factor is 70%, there are 6 crew staff for each flight averagely, the average crew payment rate is \$15/hr, the airport excess parking fee is \$27.5 per 15 minutes, the passengers payment rate is \$15/person if flight delay 2-6 hours or \$70/person if flight delay more than 6hours, and there are not any other aeronautical fee will be charged due to departure delay. The relative parameters are showed in table 5.11-1:

Items	n_a	P_a	n_c	P_c	n_p	P_{p1}	P_{p2}	P_o
Data	1000	\$1.83/min	6000p	\$0.25/min	91000p	\$14/p	\$70/p	0

Table 5.11-1 Relative Parameters in Modeling

Therefore the increased delay cost of example airlines due to technique factor can be calculated by bellowed equations:

$$C_{at} = n_a p_a \sum_{t=1}^N t \Phi\left(\frac{\ln t - 3.271}{0.9254}\right) \quad (5-12)$$

$$C_{ct} = n_{ct} p_c \sum_{t=1}^N t \Phi\left(\frac{\ln t - 3.271}{0.9254}\right) \quad (5-13)$$

$$C_{pt} = n_p p_{pt} \sum_{\Delta t=1}^j \Phi\left(\frac{\ln t - 3.271}{0.9254}\right) \quad (5-14)$$

$$C_{ot} = n_{ot} p_o \sum_{t=1}^N t \Phi\left(\frac{\ln t - 3.271}{0.9254}\right) \quad (5-15)$$

$$C_t = C_{at} + C_{ct} + C_{pt} + C_{ot} \quad (5-16)$$

And the calculation result is showed in table 5.11-2:

Items	C_{at}	C_{ct}	C_{pt}	C_{ot}	C_t
Data	\$80390.4	\$60292.8	\$140683.2	0	\$281366.4

Table 5.11-2 Calculation results

The delay cost proportion by factors is showed in figure 5.11-1. It indicates passenger delay cost occupies 50%, parking cost is following by 29% contribution, and crewmember cost is 21% of total delay cost.

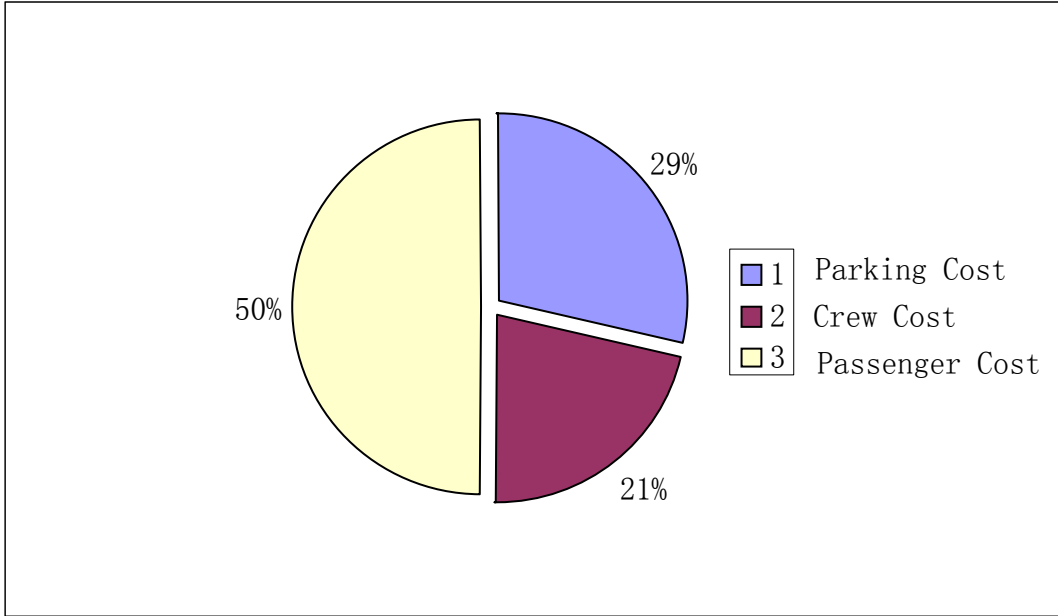


Figure 5.11-1 Delay Cost Proportion by Factors

Cost distribution by delay time is showed by figure 5.11-2, the sudden increasing of cost value occur at 120th minutes and 360th minutes, because of payment rate to delayed passengers start to change from these two time points.

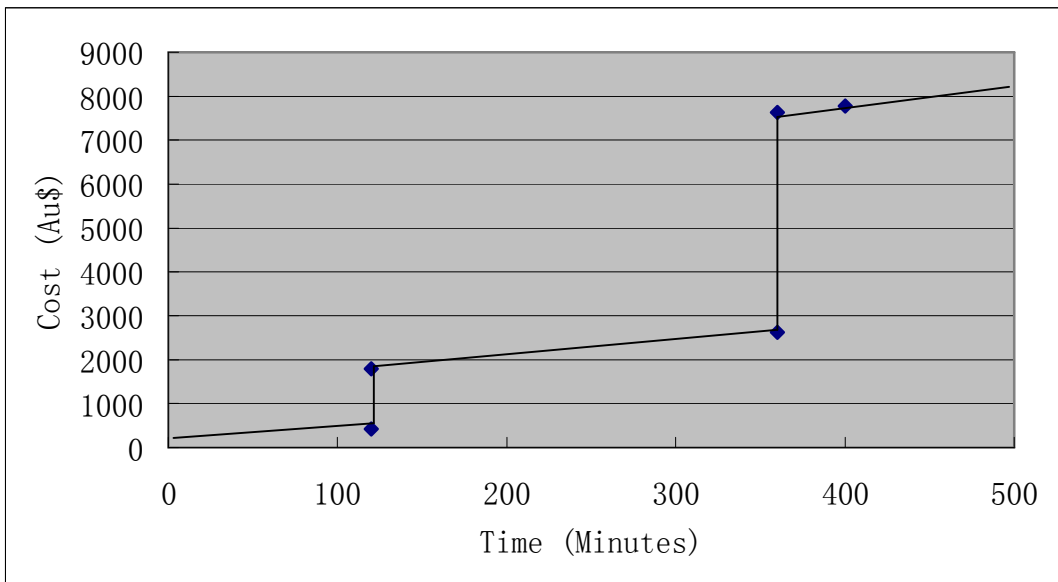


Figure 5.11-2 Cost Distribution by Delay Time

Figure 5.11-3 presents the total delay cost according to flight delay distribution. It indicates that most delay cost comes from those delay which last 10 to 100 minutes, which is Aus\$94264.8, contributes 34% in Aus\$281366.4 of total delay increased cost; meanwhile Aus\$62475.7 cost come from flights which delay last 120 to 180 minutes, it occupies 22% of total delay cost, it is due to the passenger cost occurred from 120 minutes and longer delay.

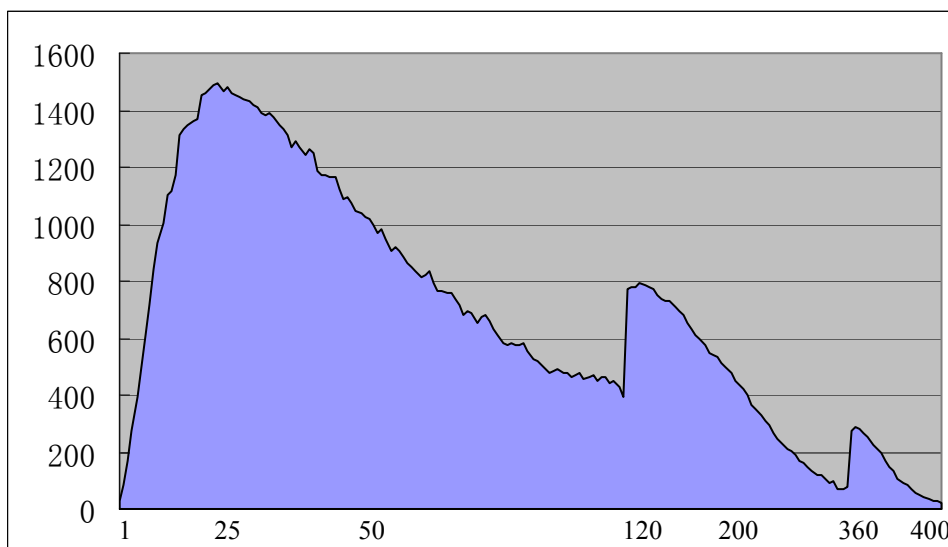


Figure 5.11-3 Total Delay Cost Distribution

The total delay cost proportion by different delay time segment is showed in figure 5.11-4. From the figure 5.11-3 and 5.11-4, it is demonstrated delay cost is not a simple linearity function of the delay time, the delay cost of unit time vary with delay time is showed as figure 5.11-2. These curves also demonstrate that calculation method of delay cost by using average unit delay cost is simplified and roughly.

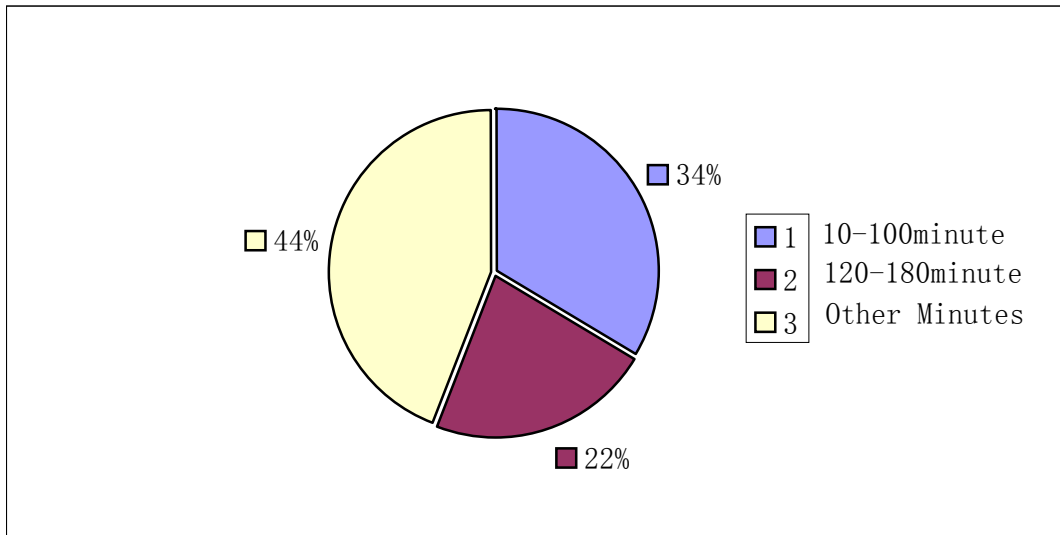


Figure 5.11-4 Total Delay Cost Proportion by Delay Time Segment

5.12 Summary

As one main factor affecting departure reliability, departure delay significantly cuts down the profitability of the growing commercial air transport industry. The flight delay causes cost increase in four main aspects: aircraft operators, airline passengers, airports and communities. Furthermore, from the point view of society aspect, delay results in even more social cost which is hardly to be estimated.

The parking cost, crew cost and passenger cost are three main contributions to the overall delay cost and the passenger cost occupies 50% of them, which is the largest portion among those three aspects.

According to the sample delay cost model of Australian X Airlines, the company will have to pay an additional cost of AUD\$281,366 for the occurrence of 1000 delayed flights at Melbourne airport. The passenger cost occupies 50% of total increased cost. In order to cut down this unexpected expenditure dramatically, the

airline should manage to reduce the delay in the majority proportion within all delay time segments as shown in figure 5.11-4. Approximately 56% of the total delay cost would be saved if those delays during 10-180minutes are eliminated.

Being different from the conventional approaches which using average cost in delay cost estimation, the modeling method demonstrated in this project can compute and model the delay cost more accurately, since the analysis is subject to all the factors which result in flight delays.

Through this newly developed modeling, firstly, the delay distribution can be found and the factors of delay cost can also be clearly identified. Some mathematical equations are used to calculate the cost corresponding to the factors respectively.

On the other hand, the delay distribution used in this model is only based on Type I Delay data which comes from the result in Chapter 4. Therefore, the outcome can only represent the Type I Delay cost. However, the modeling methodology developed in this chapter is also effective for the cost estimation of whole delay when all delay data is included.

Chapter 6 Type II Delay Modeling and Monte Carlo Simulation

6.1 Introduction

Flight delay can be categorised into Type I and Type II. Distinguished from Type I delay (original delay/initial delay), Type II delay is not independent and stochastic.. It is related to the factors such as the length of the original delays, standard operation time, the specific time of the delay occurrence, the scheduled buffer time and the compactibility of the airline schedules, etc. Due to the high complexity of the Type II delay, it is even more difficult to be eliminated compared to Type I. Under the same operation condition, in order to reduce the propagation of the delay, Type I delay has to be decreased or shortened and airlines' operation schedule has to be changed by providing more slack time.

In early years, Type I and Type II delay were not studied separately. The result was still acceptable since the delay propagation was not really serious and did not start to significantly influence airlines' operation and revenue. With the fast growing of air transportation in the last decade, more compact flight schedules are applied by many carriers and airports, especially those airlines that have more market share. Departure delay and its propagation is becoming into one major problem. Because the delay cost significantly impacts the airlines' finance meanwhile affects airlines' reputation as well. Commercial aviation industry has now fully realized the negative effect of delay propagation and the importance to optimize the operation schedules.

As discussed in previous chapters, for the mathematical modeling, the conventional statistics method is not valid for the analysis of Type II delay at this stage. An alternative way has been developed in this dissertation; it is a dynamic method which uses numerical simulation to analysis. Usually, dynamic methods can be much more concentrated on time-related variables. Therefore, it is used to study the dynamic relationship among the flight delays, airlines operation schedules, airlines schedule punctuality prediction and schedule optimization, which are the core factors of the delay propagation analysis.

Airlines flight schedule punctuality is particularly sensitive to individual flight delays and their propagation. Initial delay can be propagated by various turnaround schedules and airports service queue. The effect brought from original delays on delay propagations is definitely different according to its duration and the occurrence time of the day. That explains why evaluating result of statistics approach is quite inaccurate with using only total delay time for the analysis. Combined with statistics methodology and Monte Carlo Simulation (MCS), an integrated method has been established in this project. This newly developed approach is proved to be able to quantitatively evaluate the delay (including original delay and propagated delay synthetically) and relevant cost as a whole.

6.2 Type II Delay Modeling Methodology

Beatty (1998) proposed a numerical definition of ‘delay multiplier’ (DM) in developing a ‘generic’ total value of both the original delay and its continuing consequences on the airlines schedule. DM is calculated based on the length of the initial delay and the time of day it occurred. DM is not used to predict the actual downline flight delay, but it can estimate a specific initial delay’s influence on downline flights through a specific schedule.

The research indicated that under a same schedule operation condition, reducing a 60 minutes delay to 30 minutes or reducing a serious disruption in the early time of day is much more valuable than reducing a 30 minutes delay to zero or reducing a serious delay in late time of day. It is obvious that airlines’ delay propagation is more serious with a high frequency, short turn time operation schedule.

Type I delay occurred due to its own factors of a specific flight. The factors of type I delay are random and independent; therefore type I delay can be studied by using statistic methodology. Besides the randomness, Type II delay is tightly related to the time of day when Type I delay occurs, the length of Type I delay last, and the airlines’ aircraft and crew operation schedule. In fact, Type II delay can be controlled by human action in some way. Hence type II delay is not independent event. In order to accurately analyze issues mixed by Type I delay and II delay together, Monte Carlo numerical simulation has been chosen by its advantage, together with the aid of computer technique.

Generally, most statistic models have to make many assumptions that would limit the method application and reduce errors of estimating results. On the other hand, Monte Carlo Simulation has proved its advantage on solving complicated problems.

In this chapter, some models and tools with MCS is constructed to analyze the tradeoff between the delay propagation and the airline schedule optimization.

Monte Carlo Simulation offers an alternative to analytical mathematics for understanding a statistic's sampling distribution and evaluating its behavior in random samples. Monte Carlo simulation does this empirically by using random samples from known populations of simulated data to track a statistic's behavior (Mooney, 1997). Monte Carlo simulation is very simple in concept. Simulation is using random number technique to conduct stochastic experiment, which involves certain types of mathematical and logical models that describe the behavior of aimed system. Monte Carlo is one of these techniques of providing such random numbers.

The general procedure of Monte Carlo Simulation method is as follow (Mooney, 1997):

- (1) Specify the pseudo-population in symbolic terms in such a way that it can be used to generate samples. This usually means developing a computer algorithm to data in a specified manner.*
- (2) Sample from the pseudo-population (a pseudo-sample) in ways reflective of the statistical situation of interest, for example, with the same sampling strategy, sample size, and so forth.*

- (3) Calculate aimed variable in the pseudo-sample and store it in a vector;
- (4) Repeat step 2 and 3 t times, where t is the number of trials.
- (5) Construct a relative frequency distribution of the t times trials result, which is the Monte Carlo estimate of the sampling distribution of aimed variable under the conditions specified by the pseudo-population and the sampling procedures.

The modeling procedure which is applied in this chapter is showed as follow:

- (a) According to history data, give definition to random;
- (b) Build up arithmetic model;
- (c) Set up computer algorithm and Program Flow Diagram;
- (d) Develop software of trial;
- (e) Running software with case data to text built model;
- (f) Analyse results.

6.3 Modeling with Monte Carlo Simulation

6.3.1 Radom Number Definition

The delay time of each flight needs to be calculated first so as to determine the relevant delay cost. Here, it is assumed that Type I can be able to estimated according to historical data. Delay propagation is determined by when and where Type I delay occurs, as well as the time duration it lasts.

As calculated through airlines' historical data, Type I delay distribution function (i.e. the percentage of delay flights number by delay length) is applied to define the random numbers. The level of accuracy is set by the digit of random number, which has been fixed at the very beginning. 4 digits number has been applied in this simulation process, which means that the applicable random numbers are from 0 to 9999. (10,000 numbers in all)

Each random number represents one time occurrence of delay. The duration of each delay is defined from 0 to n minutes, where 0 means the flight departs on time (no delay), and n is the maximum value of the delay time. The distribution of the value (duration of the delay) for each random number (each delay) has been defined as same as the probability distribution of Type I delay occurrence according to the historical data. For example, assume there are 5.3% of Type I delays whose duration are 10 minutes; in other words, the occurrence probability of 10 minutes Type I delay is 5.3%. Thus, for 10,000 times of delay (random numbers), 530 of them would have a 10-minute duration of delay, which is the value for each one of those 530 random

numbers. An example of Random Number Definition Sheet is given in Appendix D.

In this chapter, the delay during taxi-out, airborne or taxi-in is ignored. Based on airlines operation schedule, the model is developed to estimate type II delay by focusing on gate delays. The en route and schedule ground buffer time has been taken into consideration where applicable.

The inputs for the simulation are:

- (a) Random number definition sheet (as showed as appendix D). It is compiled according to airlines' departure history statistic data and percentage of type I delay by delay duration (minute is used as delay length unit);
- (b) Flight schedule
- (c) Airlines aircraft operation schedule
- (d) Airlines crew operation schedule
- (e) Delay cost rates to airport, crew, passengers and other items when applicable.

6.3.2 Arithmetic Model and Simulation Logic

In the simulation process, the flights have been classified into two types. One type of flights is not interrelated to any previous flights so that its actual departure time would not be affected by other previous flights. Only type I delay would influence its departure. The simulator starts from calculating delay from this type of flights following the daily schedule sequence. A random number is generated and assigned to each flight to define the time of duration it will delay. The flights actual departure

time T_{AD} and actual arrival time T_{AA} can be calculated by formulas below:

$$T_{ID} = T_R \quad (6-1)$$

$$T_{AD} = T_{SD} + T_{ID} \quad (6-2)$$

$$T_{AA} = T_{AD} + T_{AB} \quad (6-3)$$

T_{ID} is the duration of flight type I delay, T_R is delay duration defined according to the random number given by the simulator, T_{SD} is scheduled departure time, T_{AB} is flight en route time.

To the opposite, the other type of flights is interrelated to the previous flights. Besides type I delay, the actual departure time T_{AD} for this type of flights could be also affected by the actual arrival time of previous flights. From then on, the simulator starts to compute flight delays following the sequence of their previous flights actual arrive time T_{AAA} . In other words, the simulator has taken the propagated delay time into consideration. In this case, the actual departure time of a flight is calculated by formulas below:

$$T_{AD} = T_{SD} + T_D \quad (6-4)$$

$$T_D = \max\{T_{ID}, T_{IID}\} \quad (6-5)$$

$$T_{IID} = \max\{T_{AAA} + T_{AP}, T_{ACA} + T_{CP}\} - T_{SD} \quad (6-6)$$

T_D is the duration of departure delay, T_{IID} is flight II delay duration, which is determined by previous flight delay and operation schedule; T_{AAA} is aircraft actual arrive time of previous flight, T_{AP} is turnaround aircraft ground preparing time at a specific airport for next flight; T_{ACA} is the turnaround crewmember actual arrive

time of previous flight, T_{CP} is turnaround crewmember ground preparing time at a specific airport for next flight.

The integrated result of delay can be produced by above model. The actual delay duration T_D includes Type I delay and Type II delay. Together with the cost model presented in chapter 5, the gross of delay cost can be computed as shown in the next section. And dispatch reliability DR can be computed as below:

$$DR = \frac{N_O}{N_T} \quad (6-7)$$

N_T is the total amount of departure flights as schedule, N_O is the total amount of flights which depart not late 15 minutes comparing to schedule departure time.

6.3.3 The Model of Cost Computing

Different from the cost model presented in chapter 5, here, the value of delay duration of each specific flight can be calculated via simulation modeling. Therefore the delay cost model can be modified as blow. The flight i delay cost C_i is defined as equation 6-8:

$$C_i = C_{ai} + C_{ci} + C_{pi} + C_{oi} \quad (6-8)$$

The increase of airport parking cost of flight i C_a can be defined as equation 6-9:

$$C_{ai} = T_{Di} p_a = T_{Di} \frac{A_a}{T_a} \quad (6-9)$$

p_a is the excess parking fee rate of airport a, A_p is the charge for an excess airport parking per calculation unit, T_p is minutes of per charge calculation unit. The

increased airline crew cost due to delay C_c can be computed as equation 6-10:

$$C_{ci} = T_{Di} p_{ci} \quad (6-10)$$

p_{ci} is the crew payment rate of flight i. Then the increased passenger cost C_{pi} can be calculated according to equation 6-11:

$$C_{pi} = N_i p_{pn} \quad n=1, 2, 3 \dots \quad (6-11)$$

N_i is the passenger number of flight i, p_{pn} is the payment rate to the passengers when T_{Di} is in different period, because the increased passenger cost is same during a period. C_o is other increased aeronautical fee due to departure delay. It can be calculated by equation 6-12:

$$C_{oi} = T_{Di} p_{oi} \quad (6-12)$$

p_{oi} is the aeronautical charge rate on flight i. So the total delay related cost of airlines fleet is computed as:

$$C_D = \sum_{i=1}^n C_i \quad (6-13)$$

6.4 Software Development

6.4.1 Software Flow Chart

Based on previous analysis, computer programming is illustrated in Fig 6.4-1.

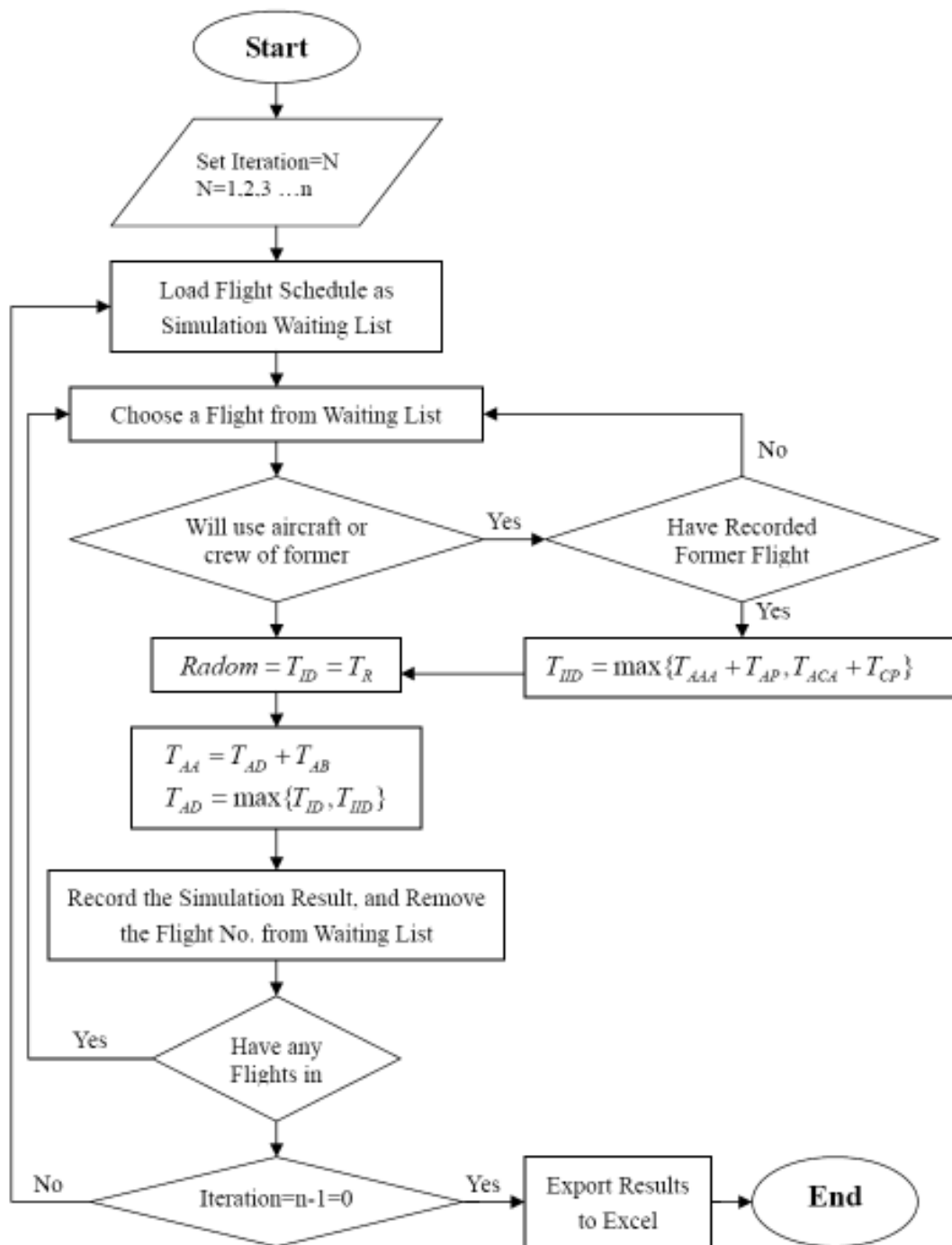


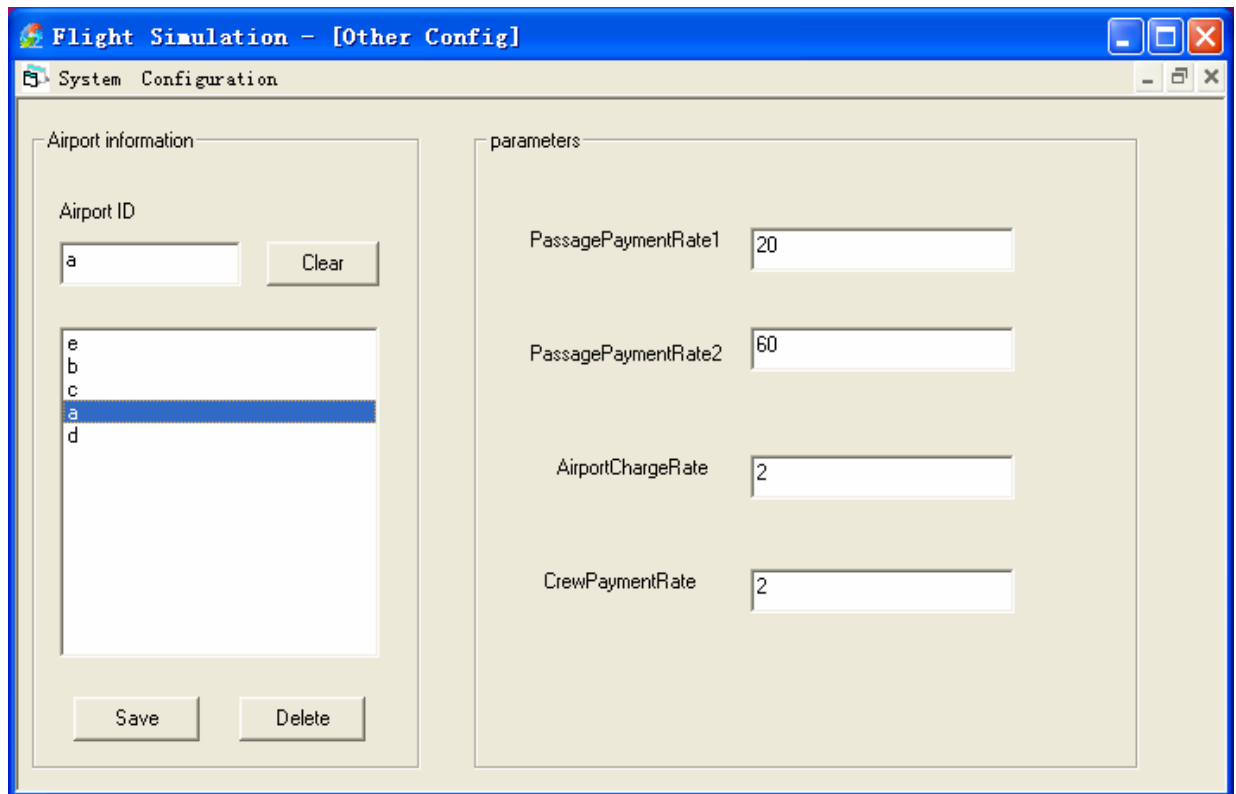
Figure 6.4-1 Software Flow Chart

6.4.2 Software Language and Interface

The simulation was programming in language VB 6.0, and can be operated in window 2000 or later version environment. The system user interface is windows based and requiring visual operation. A SQL Server database is used to store all relevant information.

6.4.2.1 Airport Input Interface

The interface of airport information input is showed as figure 6-2.



The screenshot shows a Windows application window titled "Flight Simulation - [Other Config]". Inside, there is a "System Configuration" dialog box. The dialog is divided into two main sections: "Airport information" on the left and "parameters" on the right. In the "Airport information" section, there is a text box for "Airport ID" containing the letter "a", a "Clear" button, a list box containing the letters "e", "b", "c", "a", and "d" (with "a" selected), and "Save" and "Delete" buttons at the bottom. The "parameters" section contains four text boxes: "PassagePaymentRate1" with the value "20", "PassagePaymentRate2" with the value "60", "AirportChargeRate" with the value "2", and "CrewPaymentRate" with the value "2".

Figure 6.4-2 Airport Information Input Interface

An exclusive ID should be input to denote a specific airport. The passenger delay compensation rates, airport charge rate, and crewmember payment rate, associated to this specific airport, can be input from right column. Passenger cost rates are

Australian dollar, and the unit of airport charge rate and crew payment rate are AU\$/per minute.

6.4.2.2 Schedules Parameters Input Interface

Schedule information input interface is showed as figure 6.4-3.

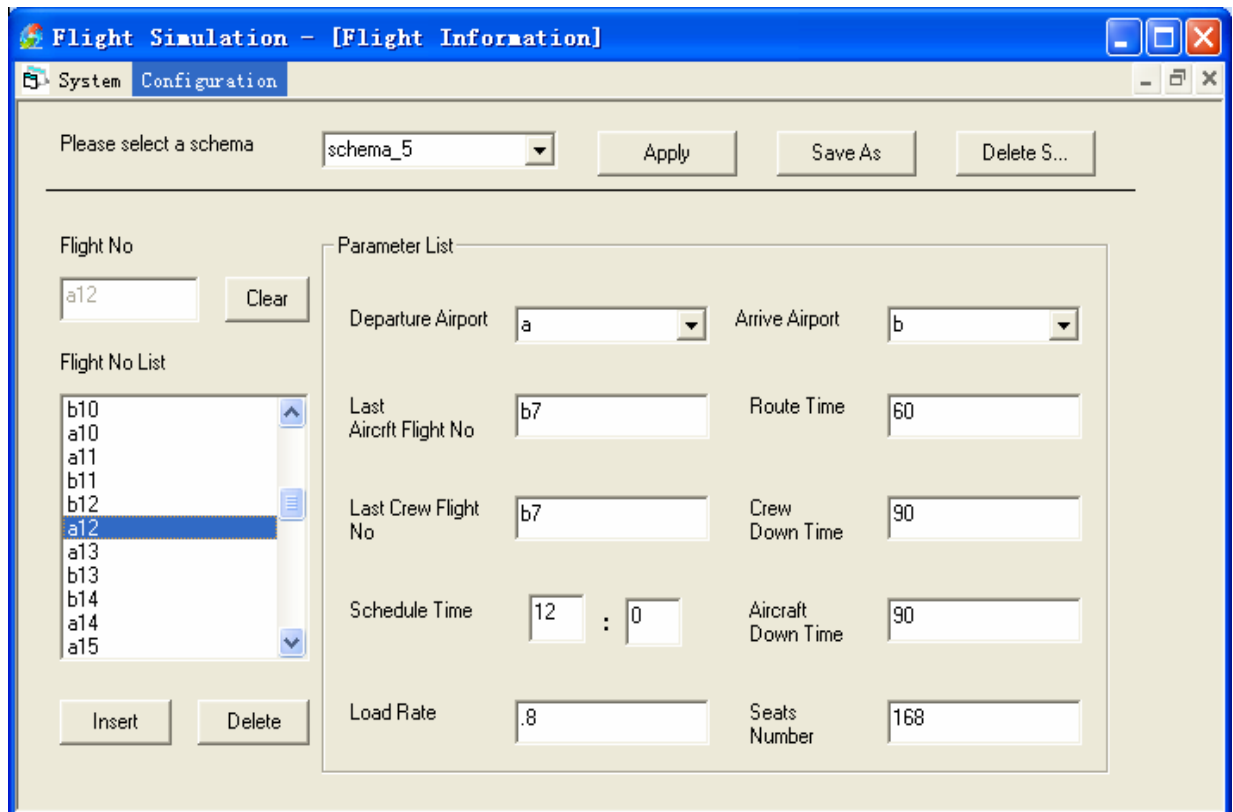


Figure 6.4-3 Schedule Information Input Interface

After a schema is selected, its flight information can be input or amended. The parameters of a flight includes: flight number, departure Airport, arrival airport, scheduled departure time, previous flight number of aircraft, previous flight number of crewmember, standard en route time, standard crew ground preparing time, standard aircraft ground preparing time, number of aircraft seats, and load rate. The unit of en route time, aircraft and crew ground time are minute. Iteration times set interface is showed as figure 6.4-4.



Figure 6.4-4 Iteration Times Set Interface

6.4.2.3 Output Interface

The results of program running are output to database of Access application firstly. The data can be further exported from database to the sheets of excel application as required. An example of Output Form of FDCSP is given in Appendix E.

6.4.3 Process of Simulation

To calculate the flight actual delay time, the simulation starts from the flight departed earliest on schedule. A random number is generated by computer to determine this flight type I delay duration T_{ID} according to the value of random number, random number definition sheet, and formula 6-1. Because the actual departure time of this flight would not be affected by any other flight, so the actual depart time T_{AD} and actual arrival time T_{AA} can be computed by equations 6-2, 6-3 respectively. T_{ID} will be recorded as actual delay time T_D of this flight, and type I will be recorded as delay classification as well. Furthermore, the delay cost can be computed according to the formulas 6-8.

The following flights will be simulated one by one for calculating their delay

duration according to the sequence of scheduled departure time till the occurrence of the first flight which will use aircraft or/and crewmembers of previous flight. After then, the same computing process as above is used to calculate the flight type I delay duration. The type II delay duration is computed by equation 6-6,. So the actual delay duration T_D of this sort of flights is calculated by equation 6-5. The actual departure time and arrival time can be gained by equations 6-4, and 6-3 respectively. When $T_D > 0$ and $T_{ID} \geq T_{IID}$, the delay is recorded as type I delay; when $T_{ID} < T_{IID}$, it will be recorded as type II delay. And the sequence of following flights simulation is according to the actual arrival time of their previous flight.

It is recorded as iteration once when all flights on schedule have been calculated once. The simulation computing will keep iterating till the setting numbers of iteration have been fulfilled and enough pseudo-population has been gained.

6.4.4 Software Function

In the simulation, each scheduled flight is corresponding to a random number which is generated by computer. According to the flight schedule, aircraft and crewmember turnaround schedule, standard ground time, scheduled buffer time, actual delay time, and standard en route time, the flight actual arriving time can be calculated. Then the computer will determine whether the delay is propagated to the next flight. A new random number is produced and given to the following flight to determine its type I delay length. Actual departure time of this following flight can be obtained by combining its type I delay length and the delay propagated

previously. In the end, the flight actual arriving time, final delay time, and delay cost can be computed. After all scheduled flights have been simulated and computed, the computer will record it as one time of iteration. The software will keep running till the required iteration times have been performed.

The input of the parameter and information includes: airport name and code, airport charge rate, flight number, scheduled departure and arriving airports, scheduled departure time, standard airborne route time, the former flight number of aircraft and crew, aircraft and crew ground preparing time, aircraft capability and load rate. Ground slack time is contained in flight schedule information.

The output data includes: flights number, scheduled departure and arriving time, actual departure and arriving time, aircraft and crewmember turnaround time, departure delay time, airport delay charge, crew and passengers delay cost, and total delay cost. Delay classification is given by comparing which delay (type I or type II) determined the final actual departure time. Data can be output to excel and access sheet. The sample excel sheet of output is presented in Appendix E.

6.5 Australian X Airline Delay Propagation Simulation

6.5.1 Assumptions and Data Processing

To test the program and analyze computing result, Australian X Airline's 2002 departure delay data is applied as sample. The airline's actual dispatch reliability can be calculated from Airline's 2002 departure data. The dispatch reliability estimated by the program is used to test the validity and efficiency of the software by comparing with the actual value. Data is analyzed first and type I delay data are abstracted to build Radom Definition Sheet. The following assumptions are made for this simulation program testing:

- The flight standard aircraft and crew ground time in same airport is same
- Only gate delay is considered for this simulation implement, taxi-out, en route, taxi-in delay is ignored.
- Maximum delay duration is bounded

To process, firstly, open the Airport Information window, showed as figure 6.4-2, from configuration menu. Input the airport ID, then passenger, crewmember, and airport cost rates based on various airports respectively. Click "Save" button to save this data into program database. Secondly, open Flight Information window presented in figure 6.4-3 from configuration menu also. Choose a schema first, input flight number. Infill flight departure and arrival airport ID; last flight number of aircraft and crewmember if applicable; schedule departing time; schedule en route

time; aircraft and crewmember schedule ground preparing time; the number of aircraft seats and load rates. These information is also saved into database.

Set iteration times as 100; 500; and 1000 and compute airline fleet dispatch reliability three times respectively. Compare computing result with history data and analyze the error.

6.5.2 Program Running Environment

The computer hardware environment is Pentium(R) 4 CUP with 3.00 GHz frequency, and 512 MB memory. Computer operation system is Microsoft Windows XP Professional 2002, and Visual Basic 6.0 compiler is also needed to run this program.

6.5.3 Simulation

The computing result of 100, 500, 1000 iteration times are presented in table 6.5-1, 6.5-2, 6.5-3 respectively.

	Total flights	0-15mins Delay	15mins more delay	Dispatch Reliability
1 th run	6200	4145	2055	0.6685
2 th run	6200	4170	2030	0.6726
3 th run	6200	3990	2210	0.6435

Table 6.5-1 Results of 100 Iteration Times Simulation

	Total flights	0-15mins Delay	15mins more delay	Dispatch Reliability
1 th run	31000	20801	10199	0.6710
2 th run	31000	20750	10250	0.6694
3 th run	31000	19980	11020	0.6445

Table 6.5-2 Results of 500 Iteration Times Simulation

	Total flights	0-15mins Delay	15mins more delay	Dispatch Reliability
1 th run	31000	20801	10199	0.6710
2 th run	31000	20750	10250	0.6694
3 th run	31000	19980	11020	0.6445

Table 6.5-3 Results of 1000 Iteration Times Simulation

6.5.4 Error Analysis

It is assumed that the deviation between the simulation result and true value obey normal distribution. When iteration times equal to 100, based on the data of table 6-1, average value of predicted DR (dispatch reliability) is 66.16%, $\sigma = 0.012$, and $n = 3$. The significance level of simulation result can be estimated based on blow equations:

$$|\bar{x} - \mu_0| = k \tag{6-12}$$

$$z_{\sigma/2} = \frac{k}{\sigma / \sqrt{n}} \tag{6-13}$$

According to Australian X airline 2002 departure data, the actual value of dispatch reliability can be calculated as 65.1%, so $\mu_0 = 65.1\%$. Then $z_{\alpha/2} = 1.53$, $\frac{\alpha}{2} = 0.063$, and significance level is 87%.

Similarly, when iteration times is 500, $\bar{x} = 66.16\%$, $\sigma = 0.011$, $n = 3$, we can get $z_{\alpha/2} = 1.67$, $\frac{\alpha}{2} = 0.0475$, and significance level is 90%; when iteration times equal to 1000, $\bar{x} = 64.97\%$, $\sigma = 0.001$, so $z_{\alpha/2}$ is 1.88, $\frac{\alpha}{2} = 0.03$ and significance level is 94%. The data of error analysis with different iteration times is

presented in table 6.5-4.

Iteration Times	\bar{x}	μ_0	n	σ	$z_{\alpha/2}$	$\frac{\alpha}{2}$	Significance Level
100	66.16%	65.1%	3	0.012	1.53	0.063	87%
500	66.16%	65.1%	3	0.011	1.67	0.048	90%
1000	64.97%	65.1%	3	0.001	1.88	0.030	94%

Table 6.5-4 Error Analysis Data

6.6 Summary

The estimation model and computer program are based on MCS technique. They have been developed in this project to accurately assess the Type II delay, when the operation condition and flight schedules are dynamic.

Australian X Airline 2002 departure data and the value of dispatch reliability are applied to test the efficiency of the program. With the computer (introduced in 6.5.2), 190 minutes are needed for per 1000 times simulation iteration. The estimated significance level of simulation result is 87%, 90%, and 94% when iteration times are 100, 500, and 1000 respectively. To save computing time and get higher significance level result, 2000 iteration is proposed for practical application of this program.

Chapter 7 Australian X Airline Flight Schedule Optimization

7.1 Introduction

Australian X airline has been experiencing unsatisfactory flight punctuality performance in the past several years. The dispatch reliability has been remaining at a relatively low level due to the increase of air transportation market.

The negative impacts include serious airline profitability damaging and reputation loss. Compared to the acquisition of more new aircrafts, schedule optimizing is believed to be a more economical approach in enhancing airline punctuality performance and profitability in a way.

The accuracy of the assessment for the flight delay distribution and relevant cost is vital in the flight schedule optimization. Unusually, the influence of the delay propagation has been solved using the MCS techniques developed in previous chapters.

In this chapter, the schedule optimization scheme of Australian X Airline will be conducted. The target will be on the flight schedule optimization by minimizing the system cost for Australian X Airline.

7.2 Current Air-fleet Operation Analysis

Good schedule punctuality performance can maintain or improve customers' satisfaction and loyalty, meanwhile enhance airlines' profitability. These business require airline to have an efficient management of their aircrafts, pilots, and flight attendants turnaround schedule. The objectives are aimed:

- (1) Minimizing operating cost;
- (2) Maximizing profits;
- (3) Maintain a satisfactory level of safety.

Aircraft using cost usually points at the fee of aircraft purchase or hiring and the related maintenance. Wu (2000) named this sort of cost as aircraft schedule time-opportunity cost or schedule time cost to calculate the airline delay cost and optimize the aircraft and crew operation schedule. It is assumed that the aircraft scheduled ground time can be alternatively used as revenue-generation airborne block hours. Generally aircraft ground time contains three sections:

- (1) Scheduled ground service time, which is necessary aircraft preparing time for next flight duty. Generally, this segment time can't be shorten or eliminated unless the standard or process of ground service is changed.
- (2) Schedule buffer time, which is set to absorb unscheduled delay. The length of this segment time can be adjusted according to schedule delay situation or

financial condition by airlines' management staff.

(3) Unscheduled delay time (if applicable). It occurs when the delay, is longer than ground buffer time.

Similarly, airborne block time could also contain three sections: standard en route time, airborne buffer time, and airborne delay time (if applicable). As same as standard en route time, the scheduled ground service time is also part of the process for flights operation. Hence both of the aircraft scheduled ground service time and standard en route time should be considered as aircraft available operation time and also can be optimized to improve the aircraft utilization efficiency during its life cycle. It is obvious that aircraft ground time can not be simply used for schedule time-opportunity cost calculation. To the opposite, even the aircraft available time has been accounted in; airborne buffer time should still be considered as unavailable time of aircraft since it may also decrease airline revenue.

As a result, both of the buffer time and the delay time should be considered as aircraft unavailable operation time. Furthermore, if it is assumed that there is not any delay occurrence and buffer time applicable, then the ideal aircraft turnaround and flights operation schedule can be defined as: the operation schedule without any impact from aircraft unavailable operation time. For example, assume that aircraft A should fulfill 6 flight-duties as scheduled, when some delay occurred, if it still can accomplish these 6 scheduled flights without influencing the scheduled tasks for the next day, there only occurs operation cost instead of aircraft schedule using cost. If

this aircraft can't complete this 6 flight duties or delay is propagated to next day's scheduled flight mission, the aircraft schedule using cost should be taken into account. In fact, most domestic flights schedules don't employ aircrafts continually operating 24 hours per day. There are stand-by intervals between their daily operations. In many cases, the increased buffer time or delay time only reduce aircraft night leisure interval instead of reducing aircraft available operation time.

Based on the above, the criteria to decide whether the additional aircraft using cost should be applied is proposed as: during an aircraft specific operation schedule period (day, week or others), an aircraft schedule time cost should be applied when its unavailable operation time increases enough to reduce the aircraft available operation time comparing with its ideal operation schedule of the same period; or it won't incur the schedule time-opportunity cost.

7.3 Overall System Cost Modeling

Airlines' flight overall system cost C_S is used to trade off dispatch reliability and airlines' operation cost. System Cost consists of flight delay cost C_D and additional flight operation cost C_{OP} which is caused by the change of initial operation schedule. C_S can be calculated by the following formulas:

$$C_S = C_D + C_{OP} \quad (7-1)$$

C_D is flight delay cost, which can be calculated by formula 5-6, C_D consists of additional parking cost against delay C_a , additional crew cost C_c , delayed passenger cost C_p and other delay aeronautic cost C_o . These delay cost can be also

computed respectively by formulas 5-2, 5-3, 5-4 and 5-5. Additional flight operation cost C_{OP} can be computed by equation 7-2.

$$C_{OP} = C_{PK} + C_{CW} + C_{AC} + C_{OA} \quad (7-2)$$

Where C_{PK} is the additional parking cost due to schedule change, C_{CW} is additional crewmember cost, C_{AC} is aircraft schedule time cost if applicable, and C_{OA} is other applicable aeronautic cost due to schedule change. They can be calculated by following equations:

$$C_{PK} = p_a T_{PK} \quad (7-3)$$

$$C_{CW} = n_c p_c T_{CW} \quad (7-4)$$

$$C_{AC} = p_{AC} T_{AC} \quad (7-5)$$

$$C_{OA} = p_{OA} T_{OA} \quad (7-6)$$

p_a is airport parking charge rate, it can be computed by formula 5-1, T_{PK} is aircraft additional parking time (computing unit is minute) of new operation schedule; n_c is total number of on board crew, p_c is the crew payment rate, T_{CW} is additional crew labor time (computing unit is minute) of new schedule; p_{AC} is aircraft schedule time cost rate, $p_{AC} =$ the cost of aircraft whole life cycle/ aircraft total schedule available time, this parameter is generally provided by airlines, T_{AC} is aircraft available operation reduced by new schedule; p_{OA} is other applicable aeronautic charge rate, and T_{OA} is additional applicable charged time.

7.4 Flight Schedule Optimization

7.4.1 Data Collection

Flight schedule and aircraft turnaround schedule are provided by this Australian X Airline. Because of commercial confidential agreement, flights number and airports names are replaced by assigned codes.

Several assumptions are made as following:

- A single type of aircraft is used for shuttle flight;
- Average loading rate is assumed at 75%;
- The value of T_{PK} , T_{CW} , T_{AC} , T_{OA} are set as constant variable under same operation environment.
- The other aeronautic cost is ignored here.

7.4.2 Current Airlines Delay Situation Analysis

Currently, the schedule employed by X Airline is very compact. As a result, the delay and delay propagation occur more frequently in recent year.

Relevant delay parameters with current operation schedule are calculated by using simulation software which is described in earlier chapters.

In order to get a higher level of accuracy in this real-world case, computing

iteration times is set as 2000, and total 124000 flights are calculated as pseudo-samples. Some computing results are shown as in table 7.4-1:

Delay Sort	flight Amount	Total delay time	Parking cost	Crew cost	Passenger cost	Total cost
0 minute (No delay)	8770	0	0	0	0	0
1-15 mins (Total)	72150	708200	1594675	49590	0	3011075
15+ mins (Total)	43080	2152110	4831115	4304220	10090200	19225335
1-15 mins (Type I)	28650	259800	583555	519600	0	1103155
1-15 mins (Type II)	43500	448400	1011120	896800	0	1907920
15+ mins (Type I)	12280	607850	1351960	1215700	2934600	5502260
15+ mins (Type II)	30800	1544260	3479155	3088520	7155600	13723275
Total Sum	124000	2860310	6425790	4353810	10090200	22236410

Table 7.4-1 Computing Result of Current Schedule

In table 7.4-1, minute is applied as the unit of time, and Australian Dollar is the unit of cost. Figures from 7.4-1 to 7.4-4 present the distribution of delayed flights, totally delay time and delay cost by delay length and delay classification.

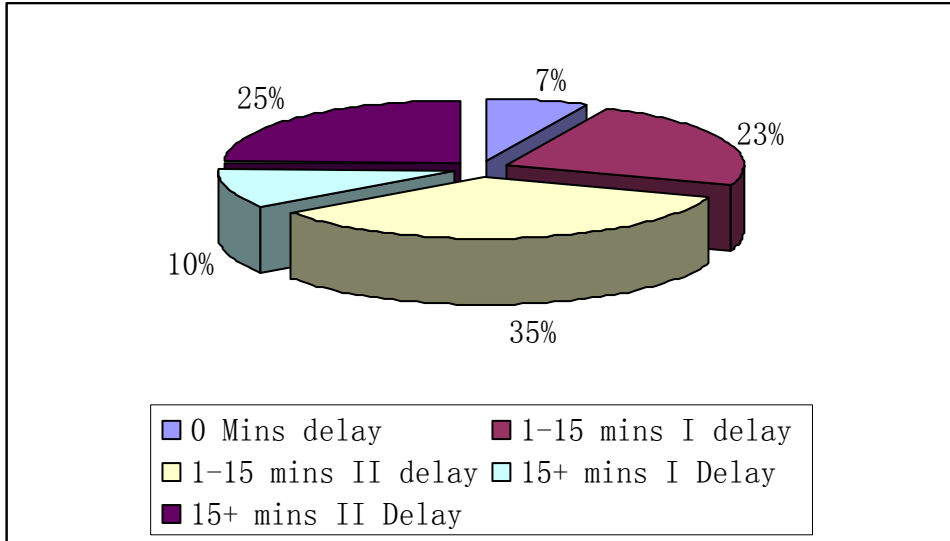


Figure 7.4-1 Proportion of Delayed Flights by Different Delay Length

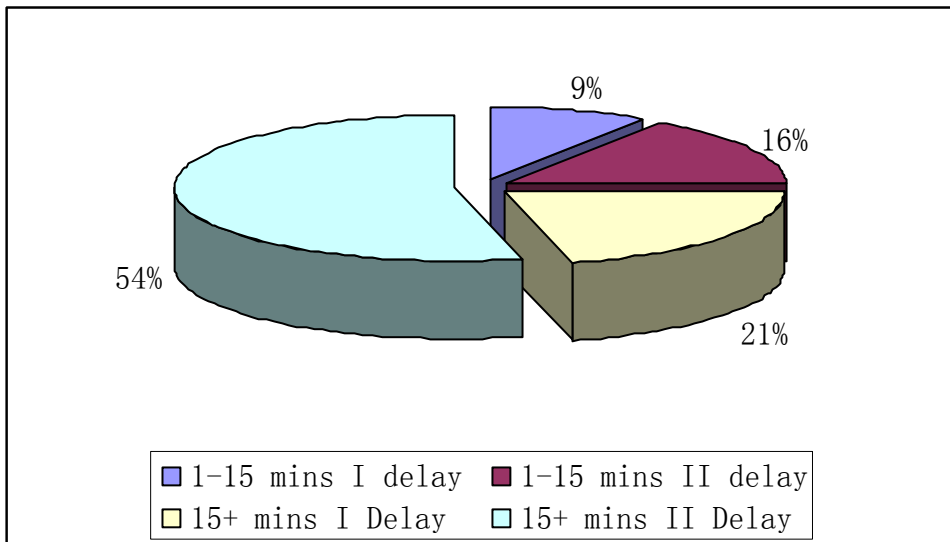


Figure 7.4-2 Proportion of Total Delay Time by Different Delay Length

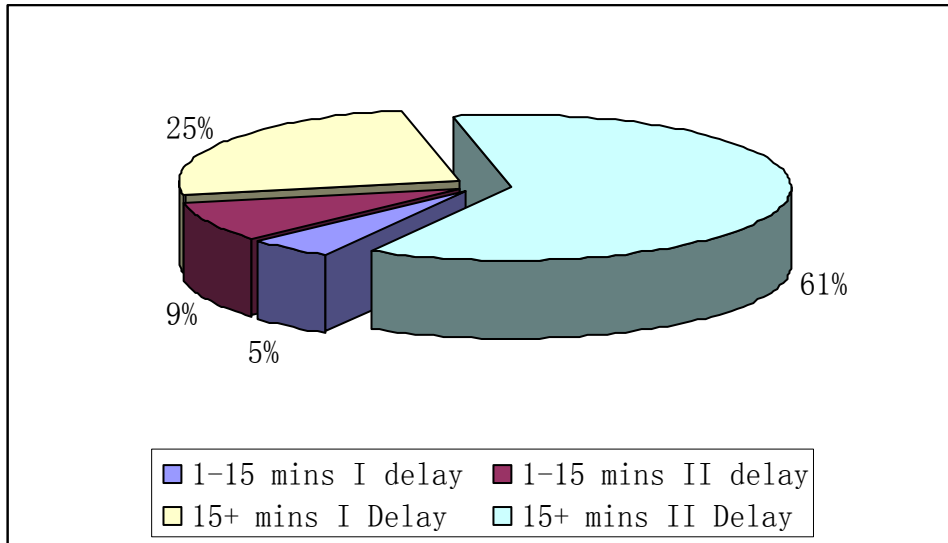


Figure 7.4-3 Proportion of Delay Cost by Different Delay Length

There are only 8770 flights depart on time in total 124000 pseudo samples. 72150 flights delay 1-15 minutes, occupies 58.19% of total flights, while contributes 24.76% of total delay time, and about 13.54% delay cost. Its average delay cost is Au\$4.25/min. Meanwhile there are 34.74% delay lasted longer than 15 minutes, which contributes 75.24% of total delay time and 86.46% of total delay cost. Type II delay contributes more delay time and cost than type I delay. Its average delay cost is Au\$8.93/min. The difference of average delay cost between varied delay length demonstrates that the method of delay cost calculation with average cost rate is difficult to provide accurate result. And the passenger cost is the main reason incurred this difference.

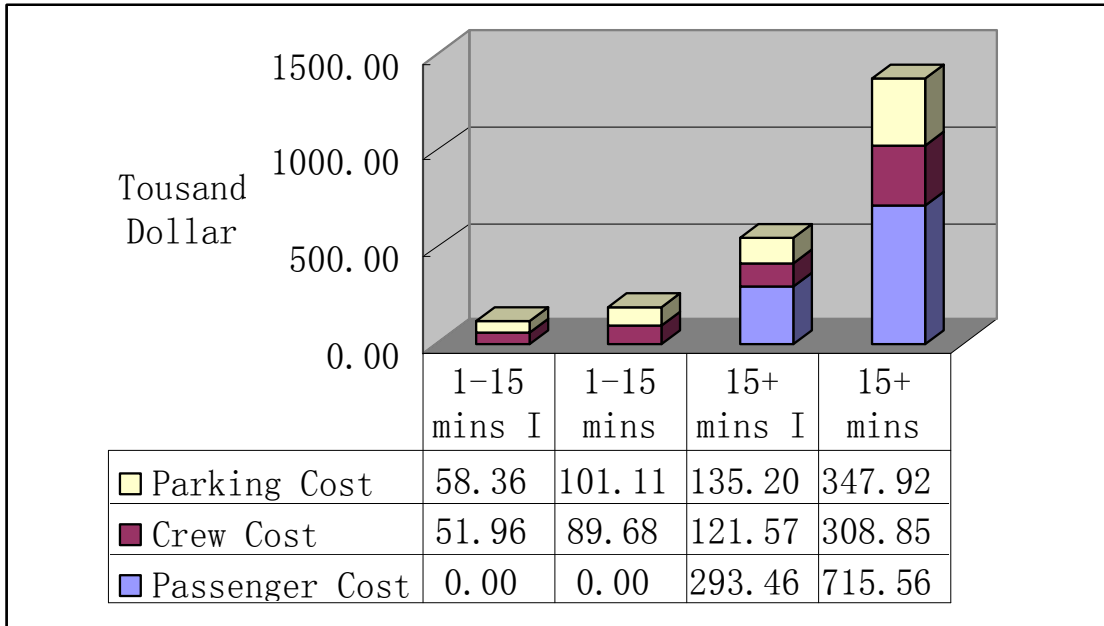


Figure 7.4-4 Structure of Delay cost by Different Delay Length

7.4.3 Flight Schedule Optimization

Buffer time is generally embedded into flight schedule to absorb probably occurred flight delays. The basic principle of the airline flight schedule optimizing is to determine an appropriate buffer segment to minimize the system cost of the schedule execution.

The system cost C_s can be calculated according to equation 7-1. To gain the value of delay cost C_D and operation cost C_{OP} , FDCSP runs with the different flight schedules. Original actual schedule is set as scheme 1, and an additional 5 minutes segment of buffer time is added to next scheme till to scheme 9 which would have 40 minutes more buffer time than the original scheme. According to formula 7-2, 40 minutes buffer time will incur more than 21 million dollars additional operation cost, which has approached to the total delay cost when actual schedule is applied. This indicates that the longer buffer time would not give a lower

system cost.

With the using of a series of gradually increasing buffer time, a group of C_s can be generated after running FDCSP and calculation. The optimizing curve can be drawn according to values of C_s . The scheme with the minimal system cost is identified as optimal schedule. The different buffer time values of each scheme are presented in table 7.4-2. Iteration parameter is set as 2000 times, that means there are 124000 flights is simulated as pseudo-samples. Optimization calculation result and optimization curve are showed as table 7.4-3 and figure 7.4-5.

Scheme No.	Scheme 1	scheme 2	Scheme 3	Scheme 4	Scheme 5	Scheme 6	Scheme 7	Scheme 8	Scheme 9
Ground Buffer time	Current applied	5 Mins more	10 mins more	15 mins more	20 mins more	25 mins more	30 mins more	35 mins more	40 mins more

Table 7.4-2 Additional Ground Buffer Time of Different Scheme

Australian X Airline Flight Schedule Optimization

	Additional Buffer Time	Totally Delay Time	Totally Delay Cost	Additional Operation Cost	System Cost Sum
Scheme 1		2, 860, 310	22, 236, 410	0	22, 236, 410
Scheme 2	5	2, 116, 190	17, 433, 000	2, 635, 000	20, 068, 000
Scheme 3	10	2, 036, 250	13, 997, 370	5, 270, 000	19, 267, 370
Scheme 4	15	1, 892, 480	13, 173, 430	7, 905, 000	21, 078, 430
Scheme 5	20	1, 763, 880	12, 902, 120	10, 540, 000	23, 442, 120
Scheme 6	25	1, 601, 960	12, 368, 320	13, 175, 000	25, 543, 320
Scheme 7	30	1, 598, 160	11, 720, 180	15, 810, 000	27, 530, 180
Scheme 8	35	1, 474, 760	10, 867, 850	18, 445, 000	29, 312, 850
Scheme 9	45	1, 409, 180	10, 054, 240	21, 080, 000	31, 134, 240

Table 7.4-3 Optimization Calculation Result

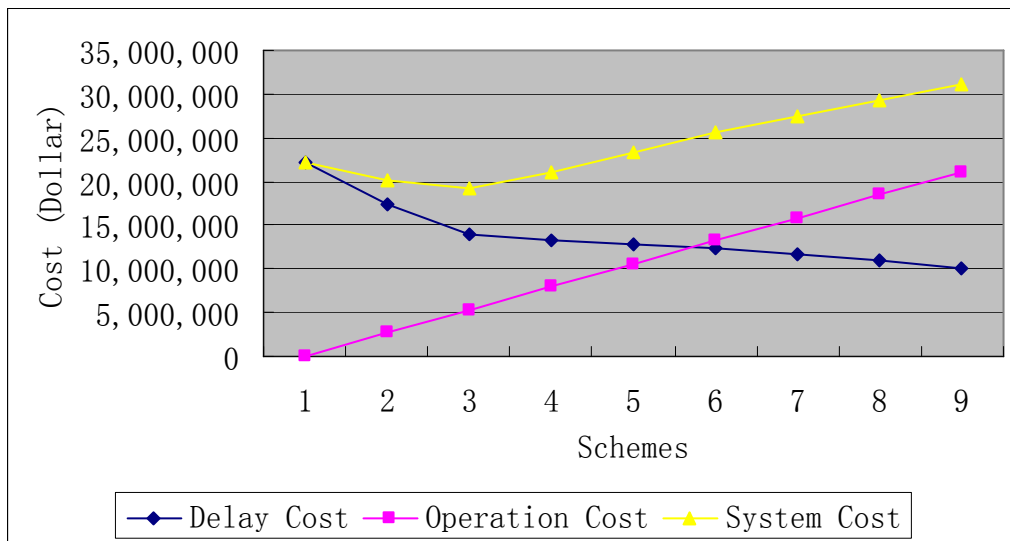


Figure 7.4-5 Optimization Curve

According to computing result, scheme 3, which embedded additional 10 minutes buffer time into schedule, is the optimal scheme with lowest system cost. The related parameters of scheme 1 and scheme 3 are listed in table 7.4-4.

	Amount of 0 Mins Delay	Amount of 1-15 mins delay	Amount of 15 +Mins Delay	Dispatch Reliability	Delay Cost	System Cost
Scheme 1	8,770	72,150	43,089	65.25%	22,236,410	22,236,410
Scheme 3	28,200	69,690	26,110	78.94%	13,997,370	19,267,370

Table 7.4-4 Scheme Comparison

Comparing with original schedule, optimal schedule will reduce 16.87% departure delay, dispatch reliability can be increased by 20.98%, and reduce delay cost 37.05%, save 13.35% system cost.

7.4.4 Sensitivity Test and Analysis

A test is done to analyze and assess the sensitivity of the models and FDCSP to the changing of departure delay. The test assumes additional 8 group data of departure delay, which has -20%, -10%, -5%, -2%, +2%, +5%, +10%, and +20% delays respectively comparing with original history delay data. The calculation results are listed in table 7.4-5, 7.4-6, 7.4-7, 7.4-8, 7.4-9, 7.4-10, 7.4-11, and 7.4-12, the schedule optimizing curves are presented as figure 7.4-6, 7.4-7, 7.4-8, 7.4-9, 7.4-10, 7.4-11, 7.4-12, and 7.4-13. Simulation iteration is also set as 2000 times.

Australian X Airline Flight Schedule Optimization

	Additional Buffer Time	Totally Delay Time	Totally Delay Cost	Additional Operation Cost	System Cost Sum
Scheme 1	0	2, 783, 620	21, 543, 620	0	21, 543, 620
Scheme 2	5	2, 121, 740	17, 326, 670	2, 635, 000	19, 961, 670
Scheme 3	10	1, 800, 900	13, 442, 860	5, 270, 000	18, 712, 860
Scheme 4	15	1, 661, 340	12, 950, 500	7, 905, 000	20, 855, 500
Scheme 5	20	1, 507, 960	11, 885, 420	10, 540, 000	22, 425, 420
Scheme 6	25	1, 498, 240	10, 170, 410	13, 175, 000	23, 345, 410
Scheme 7	30	1, 398, 320	9, 689, 520	15, 810, 000	25, 499, 520
Scheme 8	35	1, 226, 520	9, 309, 700	18, 445, 000	27, 754, 700
Scheme 9	45	1, 182, 280	8, 760, 770	21, 080, 000	29, 840, 770

Table 7.4-5 Optimization with -2% Delay

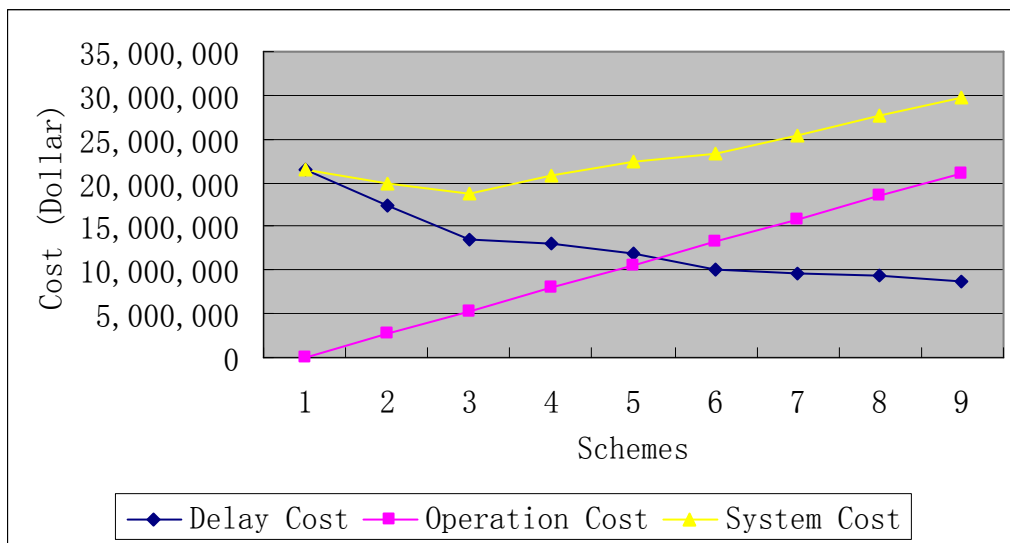


Figure 7.4-6 Optimization Curve with -2% Departure Delay

Australian X Airline Flight Schedule Optimization

	Additional Buffer Time	Totally Delay Time	Totally Delay Cost	Additional Operation Cost	System Cost Sum
Scheme 1	0	2, 578, 320	20, 430, 680	0	20, 430, 680
Scheme 2	5	2, 089, 880	16, 885, 730	2, 635, 000	19, 520, 730
Scheme 3	10	1, 852, 820	15, 534, 820	5, 270, 000	20, 804, 820
Scheme 4	15	1, 680, 980	14, 040, 120	7, 905, 000	21, 945, 120
Scheme 5	20	1, 588, 480	12, 077, 480	10, 540, 000	22, 617, 480
Scheme 6	25	1, 575, 160	11, 755, 100	13, 175, 000	24, 930, 100
Scheme 7	30	1, 478, 620	10, 615, 860	15, 810, 000	26, 425, 860
Scheme 8	35	1, 420, 300	9, 222, 200	18, 445, 000	27, 667, 200
Scheme 9	45	1, 328, 760	8, 681, 320	21, 080, 000	29, 761, 320

Table 7.4-6 Optimization Result with -5% Delay

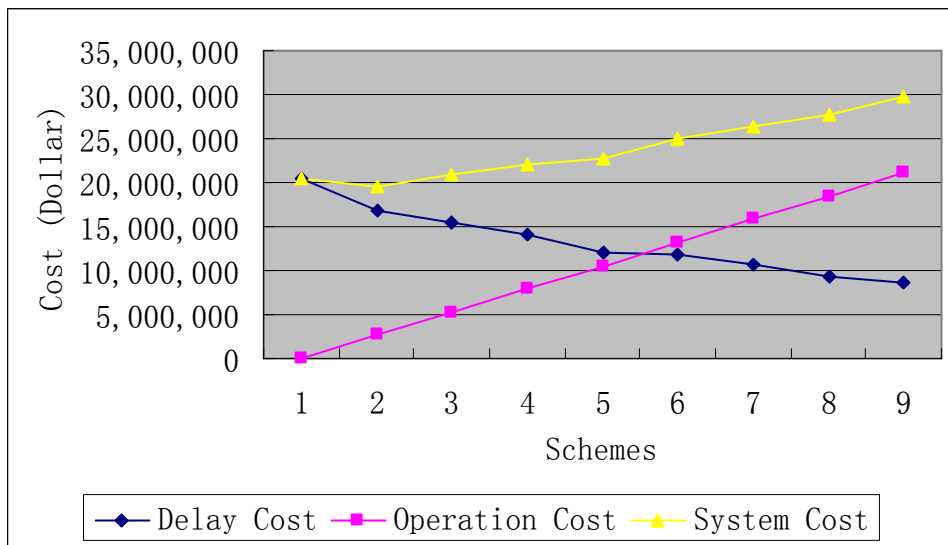


Figure 7.4-7 Optimization Curve with -5% Departure Delay

Australian X Airline Flight Schedule Optimization

	Additional Buffer Time	Totally Delay Time	Totally Delay Cost	Additional Operation Cost	System Cost Sum
Scheme 1	0	2, 487, 260	17, 703, 320	0	17, 703, 320
Scheme 2	5	1, 963, 700	13, 604, 880	2, 635, 000	16, 239, 880
Scheme 3	10	1, 652, 500	12, 919, 500	5, 270, 000	18, 189, 500
Scheme 4	15	1, 500, 200	11, 619, 100	7, 905, 000	19, 524, 100
Scheme 5	20	1, 470, 200	10, 698, 280	10, 540, 000	21, 238, 280
Scheme 6	25	1, 405, 500	10, 073, 050	13, 175, 000	23, 248, 050
Scheme 7	30	1, 350, 800	9, 842, 780	15, 810, 000	25, 652, 780
Scheme 8	35	1, 311, 000	8, 887, 700	18, 445, 000	27, 332, 700
Scheme 9	45	1, 284, 300	8, 065, 900	21, 080, 000	29, 145, 900

Table 7.4-7 Optimization Result with -10% Delay

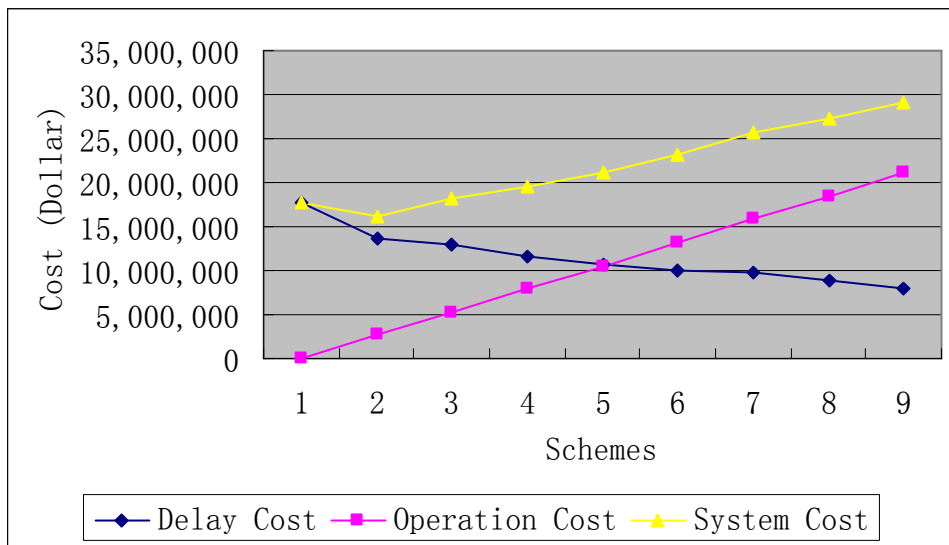


Figure 7.4-8 Optimization Curve with -10% Departure Delay

Australian X Airline Flight Schedule Optimization

	Additional Buffer Time	Totally Delay Time	Totally Delay Cost	Additional Operation Cost	System Cost Sum
Scheme 1	0	2,302,060	15,724,390	0	15,724,390
Scheme 2	5	1,871,450	14,031,390	2,635,000	16,666,390
Scheme 3	10	1,764,300	13,411,000	5,270,000	18,681,000
Scheme 4	15	1,622,500	12,062,100	7,905,000	19,967,100
Scheme 5	20	1,467,000	11,888,000	10,540,000	22,428,000
Scheme 6	25	1,345,700	10,240,450	13,175,000	23,415,450
Scheme 7	30	1,205,500	9,832,100	15,810,000	25,642,100
Scheme 8	35	1,093,500	8,100,950	18,445,000	26,545,950
Scheme 9	45	925,200	7,857,000	21,080,000	28,937,000

Table 7.4-8 Optimization Result with -20% Delay

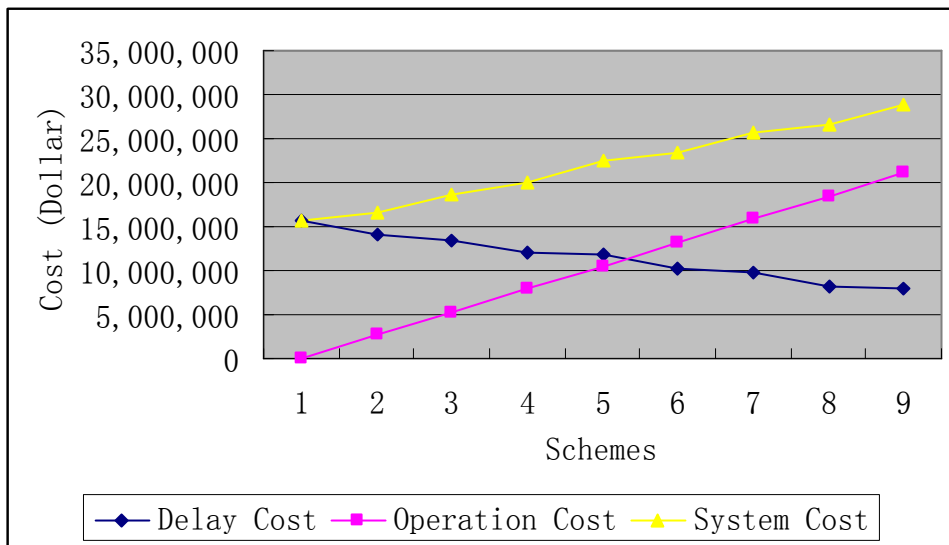


Figure 7.4-9 Optimization Curve with -20% Departure Delay

Australian X Airline Flight Schedule Optimization

	Additional Buffer Time	Totally Delay Time	Totally Delay Cost	Additional Operation Cost	System Cost Sum
Scheme 1	0	2, 852, 600	22, 272, 350	0	22, 272, 350
Scheme 2	5	2, 273, 300	19, 435, 800	2, 635, 000	22, 070, 800
Scheme 3	10	1, 907, 300	16, 021, 100	5, 270, 000	21, 291, 100
Scheme 4	15	1, 758, 200	14, 364, 100	7, 905, 000	22, 269, 100
Scheme 5	20	1, 659, 700	13, 738, 300	10, 540, 000	24, 278, 300
Scheme 6	25	1, 559, 000	12, 796, 600	13, 175, 000	25, 971, 600
Scheme 7	30	1, 335, 500	11, 945, 850	15, 810, 000	27, 755, 850
Scheme 8	35	1, 221, 000	11, 030, 900	18, 445, 000	29, 475, 900
Scheme 9	45	1, 126, 200	10, 190, 700	21, 080, 000	31, 270, 700

Table 7.4-9 Optimization Result with +2% Delay

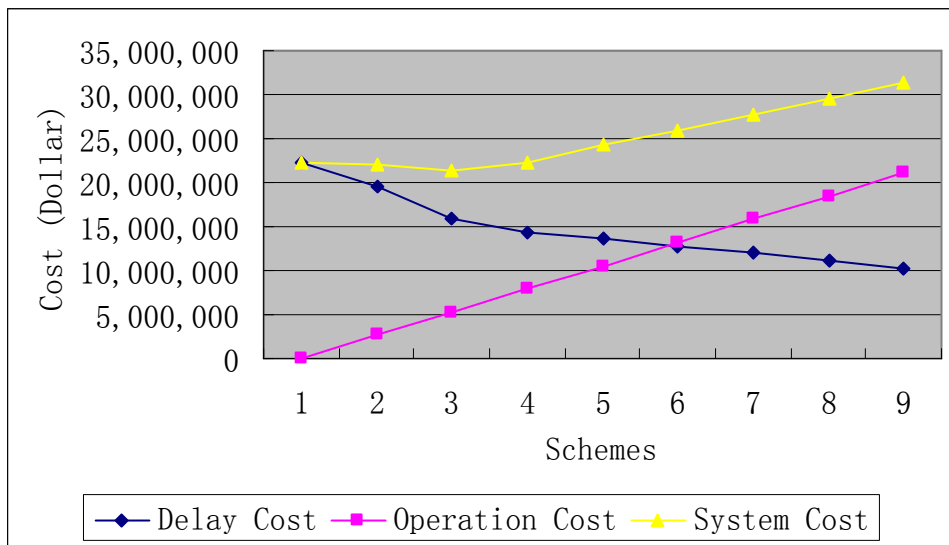


Figure 7.4-10 Optimization Curve with +2% Departure Delay

Australian X Airline Flight Schedule Optimization

	Additional Buffer Time	Totally Delay Time	Totally Delay Cost	Additional Operation Cost	System Cost Sum
Scheme 1	0	2, 895, 710	24, 614, 240	0	24, 614, 240
Scheme 2	5	2, 577, 600	21, 425, 000	2, 635, 000	24, 060, 000
Scheme 3	10	2, 199, 100	18, 225, 390	5, 270, 000	23, 495, 390
Scheme 4	15	1, 952, 300	15, 774, 500	7, 905, 000	23, 679, 500
Scheme 5	20	1, 804, 000	14, 630, 900	10, 540, 000	25, 170, 900
Scheme 6	25	1, 702, 100	13, 588, 120	13, 175, 000	26, 763, 120
Scheme 7	30	1, 624, 700	12, 442, 600	15, 810, 000	28, 252, 600
Scheme 8	35	1, 490, 200	11, 365, 700	18, 445, 000	29, 810, 700
Scheme 9	45	1, 270, 850	10, 261, 660	21, 080, 000	31, 341, 660

Table 7.4-10 Optimization Result with +5% Delay

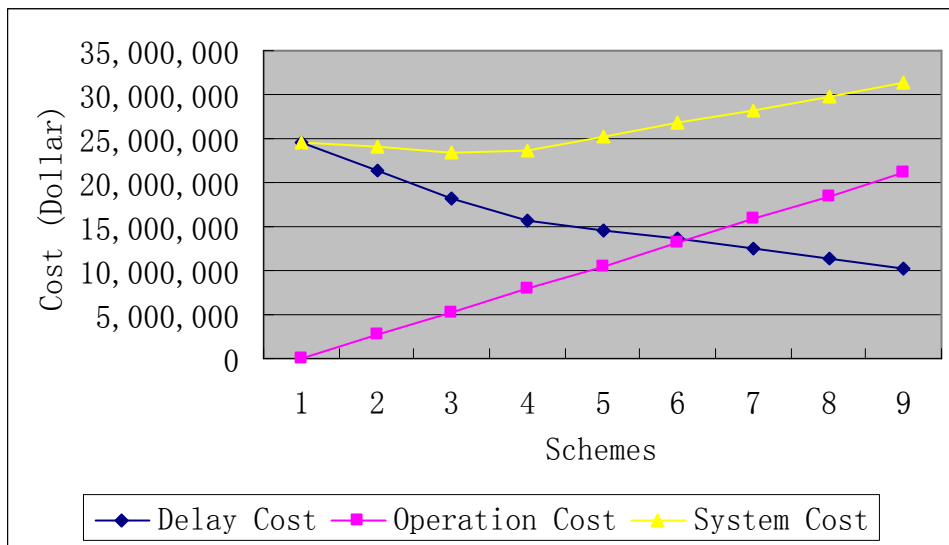


Figure 7.4-11 Optimization Curve with +5% Departure Delay

Australian X Airline Flight Schedule Optimization

	Additional Buffer Time	Totally Delay Time	Totally Delay Cost	Additional Operation Cost	System Cost Sum
Scheme 1	0	2,960,200	25,889,700	0	25,889,700
Scheme 2	5	2,600,100	22,002,500	2,635,000	24,637,500
Scheme 3	10	2,294,400	18,616,290	5,270,000	23,886,290
Scheme 4	15	2,118,000	15,052,200	7,905,000	22,957,200
Scheme 5	20	1,904,600	14,505,100	10,540,000	25,045,100
Scheme 6	25	1,755,510	14,019,100	13,175,000	27,194,100
Scheme 7	30	1,708,500	13,543,900	15,810,000	29,353,900
Scheme 8	35	1,628,640	12,792,400	18,445,000	31,237,400
Scheme 9	45	1,553,200	11,895,790	21,080,000	32,975,790

Table 7.4-11 Optimization Result with +10% Delay

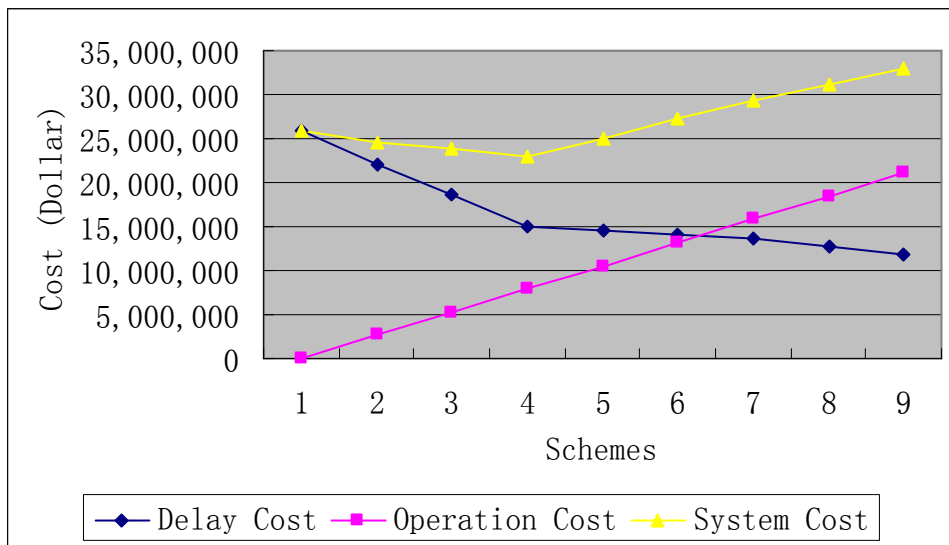


Figure 7.4-12 Optimization Curve with +10% Departure Delay

Australian X Airline Flight Schedule Optimization

	Additional Buffer Time	Totally Delay Time	Totally Delay Cost	Additional Operation Cost	System Cost Sum
Scheme 1	0	3, 243, 970	27, 895, 500	0	27, 895, 500
Scheme 2	5	2, 909, 400	25, 012, 800	2, 635, 000	27, 647, 800
Scheme 3	10	2, 705, 850	21, 712, 600	5, 270, 000	26, 982, 600
Scheme 4	15	2, 254, 900	18, 106, 700	7, 905, 000	26, 011, 700
Scheme 5	20	2, 054, 100	15, 118, 000	10, 540, 000	25, 658, 000
Scheme 6	25	1, 887, 550	14, 321, 300	13, 175, 000	27, 496, 300
Scheme 7	30	1, 774, 600	13, 789, 710	15, 810, 000	29, 599, 710
Scheme 8	35	1, 709, 360	13, 002, 200	18, 445, 000	31, 447, 200
Scheme 9	45	1, 618, 840	12, 370, 140	21, 080, 000	33, 450, 140

Table 7.4-12 Optimization Result with +20% Delay

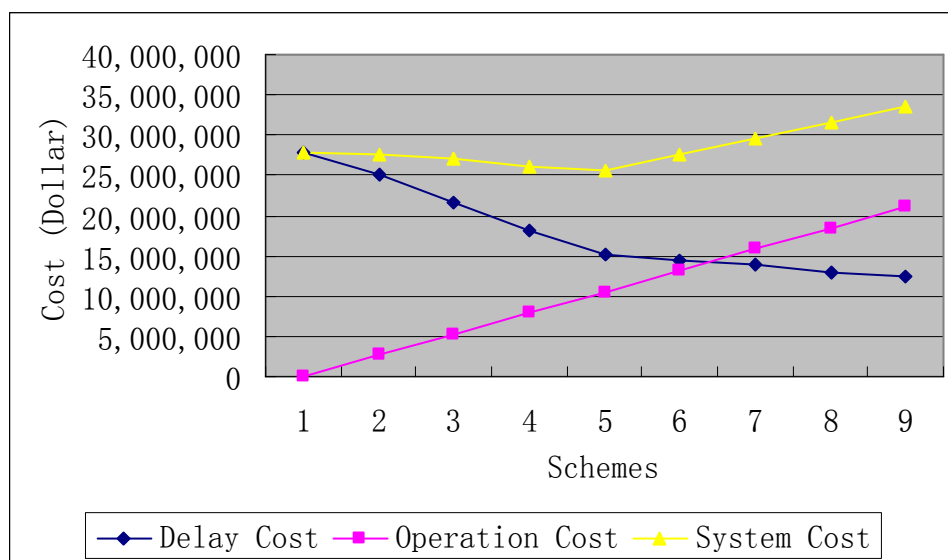


Figure 7.4-13 Optimization Curve with +20% Departure Delay

It is shown that the buffer time required by optimal schedule is declined accompanying with the reducing of departure delay. When departure delay is reduced by 5% to 10%, Scheme 2 becomes optimal schedule which embedded additional 5 minutes buffer only. The current actual schedule become optimal one when delay is declined 20%. By contraries, the buffer time of optimal schedule is required to extend as departure delay increasing. 15 minutes buffer is needed when delay increased 10%, and 20 minutes is required as 20% increasing of delay. The result of schedule optimization is stable when departure delay changes between -2% to +5%. It demonstrates the model and software developed in this project is a stable approach to optimize flight schedule by embedding various buffer time.

7.5 Summary

In this chapter, it has been introduced and proved that the enhancement of the airline dispatch reliability can be achieved through flight schedule optimization. The MCS technique is employed to simulate the air-fleet operation of Australian X Airline. Compared to the conventional literatures or studies, the accuracy has been raised to a higher level, which can enable the modeling results to be more reliable. The key innovation at this stage is to classify the type of the delay into a logical and rational way. Type I is the initial/original delay, while Type II is the propagated delay.

As analysed before, the impact brought by the delay propagation is much more serious than Type I delay. Thus, the assessment of Type II delay has performed as

the core of the flight delay simulation. The usual statistics method has been shown as invalid in such cases. Therefore FDCSP software has been developed to accurately estimate the departure delay and related cost for Australian X Airline.

As a result, the schedule with additional 10 minutes buffer is verified to be optimal. The application of new optimal schedule can be able to improve the dispatch reliability of X Airline from current 65.25% to 78.94%, meanwhile reduce 16.8% of departure delay and 13.35% system cost.

Sensitivity test has also been done to analyze the impact of the probability of type I delay occurrence on schedule optimization. The results have been demonstrated as being stable when departure delay changes from -2% to +5%. Along with the operation in the future, it will be necessary to revise the schedule optimization process periodically, especially when the probability of type I delay occurrence has obviously changed. Continuing the approach of this project, Australian X Airline need to adjust the parameters to ensure the whole air-fleet has been managed in the most cost-effective way.

Chapter 8 Conclusion

The significance of this project is to enhance the dispatch reliability of Australian X Airline's fleet through a newly developed approach to reliability modeling, which employs computer-aided numerical simulation of the delay distribution and related cost to achieve the flight schedule optimization. Additionally, airlines, airports, aviation authorities and other related organizations can also adopt the methodology and the outcome of this project in varied applications.

Flight delays have both randomness and inevitability. It is hardly possible to predict exactly when or where a delay would occur. Meanwhile, it is practical for the operators to minimize the impact from unexpected flight delays through management techniques. The main achievement of this project is to develop a unique modeling system that can assist in estimating the delay and relevant cost with high accuracy.

In this project, the different mathematical characteristics of type I and type II have been distinguished and analysed in depth, more advanced and suitable approaches have been used respectively to build the models to gain the more accurate estimating results. Based on previous research works, delay cost factors have been examined and identified again, and new delay cost assessment model has been developed by factors analysis. These various models and approaches are integrated by a computer-aid program developed in this project to evaluate departure delay and related cost as a whole.

However, to optimize the air-fleet operation schedule can only solve the partial

problem in the current air-transportation market environment. On the other hand, the excess of the capacity is the substantial cause of the increase of flight delays and delay propagation. In some cases, this problem can only be solved through a costly way, which is to purchase or hire more aircrafts and employ aircrafts with larger capacity (e.g. Airbus A380). At this stage, an integrated model needs to be developed to take both of aspects into consideration. Because the air-fleet management technique and the airline financial strategy usually supplement each other. In other words, it is always indispensable to conduct the tradeoff among the cost, revenue, reliability, safety, spend and profit during the airline business management.

Through this project, Australian X Airline's fleet dispatch reliability has been estimated. The main delay factors have been identified. The flight schedule has been optimized which improves airline's dispatch reliability and significantly reduces the operational cost.

The distribution of Australian X Airline's flight delay occurrence has been found as lognormal. A series of model have been built up including the FDCSP, which is a software programming through Monte Carlo Simulation methodology.

In this project, Monte Carlo Simulation methodology has been proved to be a useful tool and a practical modeling method in flight dispatching optimization. In fact, the approach of MCS in this project can be a successful example for the application of this methodology in even more scenarios and areas in aviation industry. Because the MCS method can be established to consider factors such as reliability and maintainability (R&M) characteristics of the aircraft, weather conditions,

management, number of aircraft, route structure, maintenance level, personnel skills, spare parts supply, and so forth. The analysis results through MCS can provide the decision-making basis to improve an aircraft's R&M and to adjust flight, dispatch procedure, logistic supports, etc., rationally for airlines

The accuracy of the results has been raised to a high level as the unique delay classification employed in this project. Distinguished from those conventional studies, the delay has been classified into Type I (Initial/Original Delay) and Type II (Propagated Delay). The MCS simulation technique has also provided an effective assessment model which can catch the randomness of type I delay and the internal relationship between type II delay and operation schedule.

In this project, the taxi-out and en route delay has not been taken into consideration due to the absence of data. The current database established by the operators and relevant agencies hasn't included such catalogue which is an essential contribution to the accuracy of the assessment.

The lack of available data is always a major obstacle of air safety and reliability research. Motivation of staff to provide field reports with sufficient relevant detail is a current management problem. Besides non-punishment policies, the incentive could be provided by airline to encourage more completed and accurate information collection. Official departure and arrival punctuality data, aircraft delay factors and other published finding should be organized and published by government agencies on a regular basis with more detailed catalogue classification. Through the research of this project, it is also found that the current category of delay from those operators and

authorities are not practical enough. As previously discussed, delay should be classified into Type I and Type II, which can be set as a standard classification criteria. Thus, the current procedure and format of data collection need to be modified in a proper way to provide convenience for any future study.

In recent years, Australian X Airline has been suffering from frequent occurrence of delay. Delay propagation has been shown as the core factor resulting in this low reliability performance. Additionally, based on the calculation in the previous chapter, Type II delay has also occupied the larger portion of the overall delay cost at around 70%, which is significant to the business management of this Australian carrier. With the further increase of the market demand in the future, the situation would come to even worse.

As a result, through this project, the additional 10 minutes buffer has been verified to be optimal. The application of new optimal schedule can be able to improve the dispatch reliability of X Airline from current 65.25% to 78.94%, meanwhile reduce 16.8% of departure delay and 13.35% system cost.

At last but not least, this project also has achieved to set a more practical standard and guideline for air-fleet delay management upon overall dispatch reliability optimization. The modeling system and the FDCSP developed in this project can be applied for varied applications in dispatch reliability investigations. The end-users can be airlines, airports and aviation authorities, etc. The software program established in this project can be further developed to be accessed through

Conclusion

internet as a real-time remote application. Using VB.NET, the FDCSP can be used remotely with the installation of .NET run time on the Windows based web server. User interface will be web based. This application can enable the FDSCP as a practical and universal tool in the air-fleet (dispatch reliability) management which could benefit most of the airlines in the world.

Reference

- Abdelghany, K. F., Shah, S. S., Raina, S., & Abdelghany, A. F. 2004, *A Model for Projecting Flight Delay During Irregular Operation Conditions*, Journal of Air Transport Management 10 (2004) 385-394.
- Advisory Group on Reliability of Electronic Equipment [AGREE], 1957, *Reliability of Military Electronic Equipment*, Washington, D.C. U.S.
- Aggarwal, K.K. 1993, *Reliability Engineering*, Kluwer Academic Publishers.
- Amstadter, B. L. 1971, *Reliability Mathematics*, McGraw-Hill, Inc.
- Ascher, H. & Feingold, H. 1984, *Repairable System Reliability*, Marcel Dekker, Inc. New York.
- Ashford, N. J. 1997, *Airport Operations*, McGraw Hill, New York.
- Aven, T. 1992, *Reliability, and Risk analysis*, Elsevier applied science.
- Bachner, R. Burke, J. Manczak, M. Runde, C. 2001, *Modeling Airline economics: Airline Decision Making in A Hub and Spoke Environment*, 2001 System Engineering Capstone Conference • University of Virginia.
- Beatty, R., Hsu, R., Lee, B., & Rome, J. 1th - 4th December 1998, *Preliminary Evaluation of Flight Delay Propagation through an Airline Schedule*, 2nd USA/EUROPE AIR TRAFFIC MANAGEMENT R&D SEMINAR, Orlando,.
- Beyer, M. 2003, *Sky Marshals*, Rosen Book Works, Inc.
- Bilimoria K. D., Sridhar B., Chatterji G. B., Sheth K. S., & Grabbe S. R. 2001, *FACET: Future AT Concepts Evaluation Tool*, Air Traffic Control Quarterly, Vol. 9,

No.1,.

- Bachner, R., Burke, J., Manczak, M. & Runde, C. 2001, *Modeling Airline economics: Airline Decision Making in A Hub and Spoke Environment*, 2001 System Engineering Capstone Conference • University of Virginia.
- Banks, G. Snape, R. Byron, N. 2002, *Price Regulation of Airport Services*, Productivity Commission, report no. 19, AusInfo, Canberra.
- Barlow, R. E. & Proschan, F. 1969, *Mathematical Theory of Reliability*, John Wiley & Sons, Inc.
- Barlow, R. E. & Proschan, F. 1975, *Statistical Theory of Reliability and Life Testing*, Holt, Rinehart and Winston, Inc.
- Bazovsky, I. 1961, *Reliability Theory and Practice*, Prentice-Hall, Inc. Englewood Cliffs, New Jersey.
- Beatty, R., Hsu, R., Lee, B. & Rome, J. 1st-4th December 1998, *Preliminary Evaluation of Flight Delay Propagation Through An Airline Schedule*; 2nd USA/Europe Air Traffic Management R&D Seminar, Orlando.
- Bentley, J. P. 1993, *Reliability & Quality Engineering*, Longman Scientific & Technical, Longman Group UK Limited.
- Billinton, R. & Allan, R. N. 1992, *Reliability Evaluation of Engineering Systems*, 2nd Ed, Plenum Press and Pitman Publishing Limited, New York.
- Blanchard, B. S. 1998, *Logistics Engineering and management*, Upper Saddle River, N.J. Prentice Hall.
- Boesel, J. 2003, *Simulation Aircraft Delay Absorption*, Proceedings of the 2003 Winter

Simulation Conference.

Cai, K. Y. 1990, *Study on Fuzzy Reliability*, Ph.D dissertation of Beijing University of Aeronautics and Astronautics.

Cai, K.Y., 1996, *Introduction to Fuzzy Reliability*, Kluwer Academic Publishers.

Chambers, R.P., Feb.1961, *Random Number Generation on Digital Computers*”, IEEE Spectrum, 4, pp48-56.

Clayton J. & Murphy J. 2001, *Preliminary Analysis of TFAS Prediction Performance*, Metron Inc., 11911 Freedom Drive, Suite 800, Reston, VA 20190, Sep.

Clinton, V., Oster, JR., Strong, J. S. & Zorn, C. K. 2000, *Improving Air Safety: Long-Term Challenges*, Issues in Science and Technology, v17, i2, p77.

Cox, S. J. & Tait, N. R. S. 1991, *Reliability, Safety, and Risk Management, an integrated approach*, Butterworth-Heinemann Ltd.

Croxton, F. E., Cowden, D. J. & Klein, S. 1967, *Applied General Statistics*, Sir Isaac Pitman Sons Ltd. London.

Decker, B. D. 2001, *Measuring Reliability and Availability*, Conklin & de Decker Associates, Inc.

Dempsey, P. S, 2000, *Airport Planning and Development Handbook: A Global Survey*, McGraw-Hill Companies, Inc.

Dempsey, P. S. & Gesell, L. 1997, *Airline Management: Strategies for 21st Century*, Coast Aire Publication.

Dhillon, B. S. 2005, *Reliability, Quality and Safety for Engineers*, CRC Press.

Dhillon, B. S. & Singh, C. 1981, *Engineering Reliability*, John Wiley & Sons, Inc.

- Ditlevsen, O. & Johannes, M. 1999, *System reliability analysis by model correction factor method*, ICASP 8, Application of statistics and probability, Volume 2, pp623-628.
- Doganis, R. 1992, *The Airport business*, Routledge, Chapman and Hall, Inc.
- Duncan, & Acheson, J. 1974, *Quality Control and Industrial Statistics*, 4th ed. Richard D. Irwin, Inc.,.
- Elderton, S., 1996, *Techniques For Managing Airport Runway Congestion*, Bureau of Transport and Communication Economics working paper.
- Epstein, B. & Sobel, M. 1953, *life Testing*, JASA, 48, pp486-502.
- Ericson, II. C. A. 2005, *Hazard Analysis Techniques for System Safety*, A John Wiley & Sons, Inc..
- Fabian, V. & Hannan, J. 1985, *Introduction to Probability and Mathematical Statistics*, John Wiley & Sons.
- Frankel, E. G. 1988, *System Reliability and Risk Analysis*, Kluwer Academic Publishers Group.
- Gallihier, H. P. & Wheeler R. C. January 1958, *Nonstationary Queuing Probabilities for Landing Congestion of Aircraft*, Operation Research Vol. 6, No. 3: 264-275.
- Gertman, D. I. 1994, *Human Reliability & Safety Analysis Data Handbook*, New York: Wiley.
- Gilbo, E. P. September 1993, *Airport Capacity: Representation, Estimation, Optimization*, IEEE Transactions on Control System Technology, Vol. 1, No. 3: 144-154.
- Gross, D. & Miller D. R. 1984, *The Randomization Technique as a Modeling Tool and*

- Solution Procedure for Transient Markov Processes, Operations Research, Vol. 32, No. 2: 343-361.
- Haugen, E. B. 1968, *Probabilistic Approaches to Design*, John Wiley & Sons, Inc., New York.
- Henley, E. J. & Kumamoto, H. 1992, Probabilistic Risk Assessment, IEEE Press.
- Hignett, K. C. 1996, *Practical Safety and Reliability Assessment*, E & FN Spon.
- Jendo, S. & Niczyj, J. 1999, *Reliability-based polyoptimization of structural system using fuzzy logic*, ICASP 8, Application of statistics and probability, Volume 2, pp629-636.
- Juan, A. & Vila, A. March 2002, *SREMS: System Reliability Using Monte Carlo Simulation With VBA and Excel*; Quality Engineering, Vol.15, No. 2, pp. 333-340,
- Kerre, E., Onisawa, T., Cappelle, B. & Gazdik, I. 1998, *Fuzzy sets in decision analysis, operation research and statistics*, Chapter 12, Kluwer Academic Publishers, pp 391-420,
- Kleinen, J. P. C. 1974, *Statistical Techniques in Simulation*, Part 1, Marcel Decker, New York.
- Kumamoto, H. & Henley, E. J. 1996, *Probability Risk Assessment and Management for Engineers and Scientists*, the Institute of Electrical and Electronic Engineering (IEEE) PRESS, New York.
- Leitch Bsc, R.D. 1988, *Basic Reliability Engineering Analysis*, Butterworth & Co. Ltd.
- Mengali, G. September 2001, *Fuzzy modelling for aircraft dynamics identification*, The

- Aeronautical Journal, , pp 551-555.
- Modarres, M, 1993, *What Every Engineer Should Know About-Reliability abd Risk Analysis*, Marcel Dekker, Inc. New York.
- Mooney, C.Z. 1997, *Monte Carlo Simulation*, Sage Publications, Inc. California, U.S.
- Moubray, J. 1997, *Reliability-Centred Maintenance*, 2nd Ed, Butterworth-Heinemann, Linacre House, Jordan Hill, Oxford OX2 8DP,
- Mueller, E. R. & Chatterji, G. B. 2002, *Analysis of Aircraft Arrival and Departure Delay Characteristics*, AIAA 2002-5866, NASA Ames Research Center, Moffett Field, CA 94035-1000
- Naylor, T.J., Balintfy, J.L., Burdick, D.S. & Chu, K. 1966, *Computer Simulation Techniques*, Wiley, New York.
- Neufville, R. D. & Odoni, A. R. 2003, *Airport System: Planning, Design, and Management*, McGraw-Hill.
- Noland, R.B., Small, K.A., Koskenoja, P.M., & Chu, X. 1998, *Simulating Travel reliability*; Elsevier Regional Science and Urban Economics. 28. 1998. 535-564.
- Odoni, A. R. et al, 1987, *Flow Control of Congested Networks*, Heidelberg, Germany: Springer-Verlag.
- Office of Inspector General, July 2000, *Air Carrier Flight Delays and Cancellations*, Audit Report: CR-2000-112, U.S. Department of Transportation, Washington, DC.
- Office of Inspector General, Sep. 2000, *Flight Delay and Cancellations*, Report:

- CR-2000-112, U.S. Department of Transportation, Washington, DC.
- Ostle, B. & Malone, L. C. 1988, *Statistics in Research*, fourth edition, Iowa State University Press/Ames.
- Page, L. B. 1989, *Probability for Engineering with Applications to reliability*, Computer Science Press, Inc..
- Patrick, D. T. & O'Connor, 1988, *Practical Reliability Engineering*, John Wiley & Sons Ltd.
- Ren, H. 1997, *Study on Fuzzy- Random Reliability of Aircraft Mechanism Wear and Structure Corrosion*, Northwest Polytechnic University (China).
- Ren, H. 2002, *Aircraft Maintainability Design and Maintenance Management*, AV732/AE831 Course Note, RMIT.
- Rubinstein, R. Y. 1981, *Simulation and the Monte Carlo Method*, John Wiley & Sons, Inc. New York.
- Rue, R. C. & Rosenshine, M. May 1985, *The Application of Semi-Markov Decision Processes to Queueing of Aircraft for Landing at an Airport*, Transportation Science, 19:154-172.
- Schaefer, L. & Miller, D. 2001, *Flight Delay Propagation Analysis with The Detailed Policy Assessment Tool*, Proceedings of the 2001 IEEE System, Man, and Cybernetics Conference.
- Shooman, M. 1968, *Probability Reliability: An Engineering Approach*, McGraw-Hill.
- Shumsky, R. 1993, *Dynamic Models for the prediction of Take-Off Times: An Exploratory Data Analysis*, Cambridge MA: Massachusetts Institute of

Technology Operations Research Center.

Singh, C. & Kankam, M.D. 1979, *Failure Data Analysis for Transit Vehicles*, Proceedings of the 1979 Annual Reliability and Maintainability Symposium, IEEE, New York.

Smith, D. J. 2001, *Reliability Maintainability and Risk*, Butterworth-Heinemann, A division of Reed Educational and Professional Publishing Ltd.

Sundararajan, C. 1995, *Probabilistic Structural Mechanics Handbook*,

Taylor, L. 1997, *Air travel: how safe is it?* Blackwell science.

Utkin, L.V. & Gurov, S. V. Oct. 1996, *A General Formal Approach for Fuzzy Reliability Analysis in the Possible Context*, Fuzzy Set and System, Volume 83, Issue 2, Pages 203-213.

Vose, D. 1996, *Quantitative Risk Analysis: A Guide to Monte Carlo Simulation Modelling*, John Wiley & Sons.

Volta, G. 1986, *Reliability Engineering in Europe*, Proceedings of the 5th Euredata Conference, Heidelberg, Germany, April 9-11, 1986.

Wanke C. November 2000, *Collaborative Routing Coordination Tools (CRCT): Developing Traffic Flow Management Decision Support Concepts*, Proc. Of 2000 Air Traffic Control Association Conference.

Weibull, W. 1951, *A Statistical Distribution Function of Wide Application*, J. Appl. Mech., 18, pp293-297.

Wells, Alexander, 2004, *Airport Planning & management*, New York: McGraw-Hill.

Wu, C. & Caves, R. E. 2000, *Aircraft Operational Costs and Turnaround Efficiency at*

Airports, Journal of Air Transport Management 6 (2000) 201-208.

Wu, C. & Caves, R. E. 2002, *Towards the Optimisation of the Schedule Reliability of Aircraft Rotations*, Journal of Air Transport Management 8 (2002) 419-426.

Wu, C. 2005, *Inherent Delays and Operational Reliability of Airline Schedules*, Journal of Air Transport Management 11 (2005) 273-282.

Yen, J. W. & Birge, J. R., *A Stochastic Programming Approach to the Airline Crew Scheduling Problem*, Industrial Engineering University of Washington Seattle, Washington, USA.

www.airbus.com/store/mm_repository/pdf/att00003033/media_object_file_GMF2004_fu11_issue.pdf

www.airdisaster.com

www.alpa.org

www.boeing.com/commercial/777family/777technical.html

www.bts.gov/ontime/statistics/

http://www.faa.gov/aboutfaa/working_delays.cfm

www.fly.faa.gov/Products/NASDOCS/ICD_%20for_Substitutions_during_GDPs_and_AFPs_v3.0.doc

<http://www.melair.com.au/index.asp>

<http://www.melbourneairport.com>

<http://www.sydneyairport.com.au>

www.Safe-skies.com

Appendix A
List of U.S. Airports Used in the Research

Appendix A

List of U.S. Airports Used in the Research

No.	Name	Code
1	Albany, NY – Albany County	ALB
2	Albuquerque, NM – Albuquerque International	ABQ
3	Atlanta, GA – Hartsfield International	ATL
4	Austin, TX – Austin – Bergstrom International	AUS
5	Baltimore, MD – Baltimore/Washington International	BWI
6	Birmingham, AL – Birmingham International	BHM
7	Boston, MA – Logan International	BOS
8	Buffalo, NY – Buffalo Niagra International	BUF
9	Burbank, CA – Burbank – Glendale - Pasadena	BUR
10	Charlotte, NC – Charlotte Douglas International	CLT
11	Chicago, IL – Chicago O’Hare International	ORD
12	Cleveland, OH – Cleveland – Hopkins International	CLE
13	Colorado Springs, CO – Colorado Springs	COS
14	Columbus, OH – Port Columbus International	CMH
15	Dayton, OH – James M Cox/Dayton International	DAY
16	Dallas/Ft. Worth, TX – Dallas/Ft. Worth International	DFW
17	Des Moines, IA – Des Moines International	DSM
18	Denver, CO – Denver International	DEN
19	Detroit, MI – Detroit Metropolitan Wayne County	DTW
20	Eagle, CO – Eagle County Regional	EGE
21	EI Paso, TX – EI Paso International	ELP
22	Fresno, CA – Fresno Air Terminal	FAT
23	Ft. Lauderdale, FL – Ft Lauderdale – Hollywood International	FLL
24	Ft. Myers, FL – Southwest Florida International	RSW

Appendix A
List of U.S. Airports Used in the Research

25	Greensboro/High Point, NC – Piedmont Triad International	GSO
26	Gunnison, CO – Gunnison County	GUC
27	Harrisburg, PA – Harrisburg International	MDT
28	Hartford, CT – Bradley International	BDL
29	Honolulu, Oahu, HI – Honolulu International	HNL
30	Houston, TX – George Bush International	IAH
31	Huntsville/Decatur, AL – Huntsville International	HSV
32	Indianapolis, IN – Indianapolis International	IND
33	Indio/Palm Springs, CA – Palm Springs International	PSP
34	Islip/Long Island, NY – Long Island - MacArthur	ISP
35	Jackson, WY – Jackson Hole	JAC
36	Jacksonville, FL – Jacksonville International	JAX
37	Kahului, HI - Kahului	OGG
38	Kansas City, MO – Kansas City International	MCI
39	Las Vegas, NV – McCarran International	LAS
40	Little Rock, AR – Adams Field	LIT
41	Los Angeles, CA – Los Angeles International	LAX
42	Louisville, KY – Standiford Field	SDF
43	Memphis, TN – Memphis International	MEM
44	Miami, FL – Miami International	MIA
45	Minneapolis/St Paul, MN – Minneapolis – St Paul International	MSP
46	Mission/McAllen, TX – McAllen Miller International	MFE
47	Nashville, TN – Nashville International	BNA
48	New York, NY – John F Kennedy International	JFK
49	New York, NY - LaGuardia	LGA
50	Newark, NJ – Newark International	EWR
51	Newburgh, NY – Stewart International	SWF
52	Norfolk/Virginia Beach, VA – Norfolk International	ORF
53	Oakland, CA – Oakland International	OAK

Appendix A
List of U.S. Airports Used in the Research

54	Oklahoma City, OK – Will Rogers World	OKC
55	Omaha, NE – Eppley Airfield	OMA
56	Ontario, CA – Ontario International	ONT
57	Orange County, CA – John Wayne/Orange County	SNA
58	Orlando, FL – Orlando International	MCO
59	Philadelphia, PA – Philadelphia International	PHL
60	Phoenix, AZ – Phoenix Sky Harbor International	PHX
61	Pittsburgh, PA – Pittsburgh International	PIT
62	Portland, OR – Portland International	PDX
63	Providence, RI – T.F. Green International	PDV
64	Raleigh/Durham, NC – Raleigh – Durham International	RDU
65	Reno, NV – Reno Cannon International	RNO
66	Richmond, VA – Richmond International	RIC
67	Rochester, MN – Rochester International	RST
68	Rochester, NY – Rochester International	ROC
69	Sacramento, CA – Sacramento Executive	SMF
70	Salt Lake City, UT – Salt Lake City International	SLC
71	San Antonio, TX – San Antonio International	SAT
72	San Diego, CA – San Diego International	SAN
73	San Francisco, CA – San Francisco International	SFO
74	San Jose, CA – San Jose International	SJC
75	San Juan, PR _ Luis Munoz Marin International	SJU
76	Seattle, WA – Seattle Tacoma International	SEA
77	St. Croix, VI – Henry E. Rholsen	STX
78	St. Louis, MO – Lambert – St Louis International	STL
79	St. Thomas, VI – Cyril E. King	STT
80	Steamboat Springs, CO – Yampa Valley	HDN
81	Syracuse, NY – Syracuse Hancock International	SYR
82	Tampa, FL – Tampa International	TPA

Appendix A
List of U.S. Airports Used in the Research

83	Tucson, AZ – Tucson International	TUS
84	Tulsa, OK – Tulsa International	TUL
85	Washington, DC – Ronald Reagan Washington National	DCA
86	Washington, DC – Washington Dulles International	IAD
87	West Palm Beach, FL – Palm Beach International	PBI
88	White Plains, NY – Westchester County	HPN

Appendix B

Airport Slot Demand Management Techniques

1. Administrative Techniques

Quotas are usually applied to the number of movements allowed per hour by an aircraft category, such as international scheduled regular public transport (RPT). For example, if the hourly capacity of a runway system is 80 movements, 30 of these movement slots might be reserved for international RPT flights. Quotas system is a simple way to treat congestion problem and are attractive to airport authorities because they can strictly relate the volume of access rights to the technical capacity of the airport. It is important as movement delays begin to increase exponentially when demand approaches airport – a small reduction in the volume of traffic at an airport approaching congestion can result in a relatively large decrease in overall traffic delay.

Bans can be used to exclude particular types of aircraft movements during congested periods. These would most commonly be movements which airport authorities feel are of less value than other types of movement, or perhaps are of less cost to the community if they are excluded, For example, an airport might ban freight aircraft from congested peak hours, allowing only passenger aircraft movements.

A disadvantage of both quotas and bans is that, in individual instances of aircraft movements, they may result in an economically inefficient allocation of access rights.

Schedule committees are usually made up of airline representatives, and in some cases airport operators, and meet at regular intervals for the purpose of allocating scarce airport access rights among competing demands. These access rights are in the form of airport slots. They operate at two levels. At the first level, biannual meetings of the International Air Transport Association (IATA) coordinate worldwide international airline schedules. At the second level, local scheduling committees provide schedule and access

Appendix B

Airport Slot Demand Management Techniques

coordination at their own airports. The main principles can be summarized as follows:

- Airline are entitled to keep slots granted to them previously (grandfather rights)
- Services (flights) which operate for a long duration have preference (for example, a year round service has priority over a summer peak service); and
- Services which are operated on more days of the week have priority (a daily service has priority over a service operated five days a week)

The advantage and disadvantage of schedule committee:

- Scheduling committees, in allocating slots according to the principle of grandfather rights, appear to encourage certainty in airline route planning, and encourage continuity in services by rewarding the investments made by airlines in developing new routes;
- However, scheduling committees are also viewed as having anti-competitive effects, and by biasing slot allocation towards incumbent airlines are suspected of reducing the contestability of the aviation industry.
- In not using price signals to determine who obtains slot rights, the potential exists for scheduling committees to make inefficient slot allocations; and
- While scheduling committees have been used extensively around the world to allocate scarce access rights, airport congestion is generally on the rise, and scheduling committees tend to become less and less workable as the gap between airport access demand and supply widens.

Allocating airport slots by lottery. Lotteries may only form a small part of a slot allocation system. Its feature is showed as blow:

- Lotteries can be used as part of an overall system of slot allocation to circumvent the bias that scheduling committees tend to give towards incumbent airlines, and can thus be used as a means to foster the entry of new airlines and in crease the contestability of airline markets,
- Lotteries can result in inefficient allocations of slots and may require secondary market trading in slots so airlines can untangle unusable allocations- a corollary of

Appendix B
Airport Slot Demand Management Techniques

this is that lotteries can generate windfall gains to airlines, in particular if the buying and selling of slots in secondary market trading is allowed;

- Lotteries can result in slot allocation that do not fit in with airline schedules and can thus be a cause of uncertainty in airline scheduling and planning- but this might be remedied by establishing a secondary market for trading in slot rights;
- The many disadvantage of lotteries mean that they are not a suitable means of allocating all airport slots, but could have a minor role in increasing competitiveness as a subsidiary part of a more efficient and workable slot allocation system.

2. Pricing Techniques

There are 2 main demand management methods which rely on prices. One, which is used in practice at airports around the world, is peak period pricing. The other, which doesn't seem to have been used in practice, is airport slot auctions.

Peak period pricing typically takes the form of a surcharge levied on the use of an airport during busy hours with the aim of encouraging some aircraft operators to shift flights out of the most congested periods to other less busy times.

- The method is easy to implement and does not inherently discriminate against any user group; that is, if charges are “set correctly” the method can help alleviate congestion problems, and the revenue raised can be used for airport expansion;
- Even if the intention of peak period charge is to remove certain type of movements from the peak, it is still difficult to determine the appropriate charge to do this, other than through a process of trial and error;
- Further, once determined, the peak period charge is not likely to be static for very long as underlying demand for peak period access will continue to change – regular adjustments to the charge may be needed;
- It may be difficult to use peak period pricing as a peak demand spreading technique due to the low cross elasticity of demand between peak and off-peak periods for some categories of users, such as domestic RPT airlines who have flight schedules tightly tied to daily business cycles and network requirements;
- Some critics of peak period pricing argue that it is inequitable, favouring large RPT airlines who can spread the access charge across a large passenger revenue base.

Appendix B
Airport Slot Demand Management Techniques

Auctioning airport slots

- There is no practical illustration yet that slot auctions can be successfully implemented, in theory such a system of demand management would allow airlines to freely bid for one or more of a predetermined number of access rights within a given time period, with the rights going to the bidder prepared to pay the highest;
- This approach should ensure slots are obtained by the users who value them the most, and the auction would help establish the 'true' market price of a slot and thus provide a guide for future airport investment.
- It is also suggested that allocating slots by this method would increase the contestability of the aviation industry.
- However, there are also some concerns expressed about a system which auctions airport slots. The main one concerns the difficulty of successfully implementing auctions, given that there is no tried and tested system. The secondary concerns are equity or social issue, such as: the potential for large airlines to exclude entry by weaker rivals and those that are capital poor; and the inherent inequity of a method that favours large RPT airlines who can spread the slot price across a large revenue base.

Europe: 1993 the European Council Regulation on common rules for the allocation of slots at community airports took effect. The main provisions were:

- Confirmation of the principle of grandfather rights;
- Creation of slot pools comprising newly created, unused and returned slots, of which 50 percent would be made available to "new entrants" – a new entrant was defined by the number, and proportion of slots held by the airline at the airport or airport system;
- Slots would be lost if they were not used for at least 80% of the time for which they were allocated;
- Slots may be freely exchanged between airlines or transferred between routes and types of service;

Slots for domestic services may be protected by government action in certain circumstances.

Appendix C
Sample of X Airline Departure Delay Data

Appendix C

Sample of X Airline Departure Delay Data

<i>Date</i>	<i>SVR</i>	<i>VH</i>	<i>Service</i>	<i>Dep</i>	<i>Arr</i>	<i>Cod</i>	<i>Hrs</i>	<i>Mi</i>
30/11/2002	105	TJD	XXXX	SYD	MEL	521	0	17
30/11/2002	110	TJD	XXXX	SYD	ADL	510	0	14
30/11/2002	128	THE	XXXX	SYD	ADL	020	0	50
30/11/2002	131	ZXD	XXXX	SYD	MEL	430	0	40
30/11/2002	134	EAN	XXXX	SYD	MEL	461	0	35
30/11/2002	135	EAN	XXXX	SYD	MEL	4X2	0	0
30/11/2002	173	EAO	XXXX	MEL	SYD	020	0	42
30/11/2002	186	TJG	XXXX	MEL	ADL	4X2	0	0
30/11/2002	206	EAN	XXXX	MEL	SYD	4X2	0	0
05/10/2002	1	OJH	XXXX	MEL	SYD	431	0	4
05/10/2002	181	OGB	XXXX	MEL	SYD	0	0	0
05/10/2002	224	NOA	XXXX	MEL	SYD	0	0	0
15/09/2002	5	OJK	XXXX	SYD	MEL	010	0	15
15/09/2002	7	OJM	XXXX	SYD	MEL	020	1	0
15/09/2002	19	OGH	XXXX	SYD	MEL	440	1	8
15/09/2002	66	TJX	XXXX	SYD	MEL	400	0	8
15/09/2002	83	OGS	XXXX	SYD	MEL	410	0	4
15/09/2002	113	NOA	XXXX	SYD	MEL	410	0	8
15/09/2002	114	OGS	XXXX	MEL	SYD	460	0	8
15/09/2002	119	ZXE	XXXX	MEL	SYD	410	0	6
15/09/2002	121	TJE	XXXX	MEL	ADL	410	0	31

Appendix C
Sample of X Airline Departure Delay Data

<i>Date</i>	<i>SVR</i>	<i>VH</i>	<i>Service</i>	<i>Dep</i>	<i>Arr</i>	<i>Cod</i>	<i>Hrs</i>	<i>Mi</i>
15/09/2002	123	OGS	XXXX	MEL	SYD	410	0	42
15/09/2002	125	VXM	XXXX	MEL	BNE	460	0	4
15/09/2002	126	TJX	XXXX	MEL	SYD	020	0	28
15/09/2002	129	ZXD	XXXX	MEL	SYD	410	0	5
15/09/2002	132	ZXG	XXXX	MEL	ADL	020	0	7
15/09/2002	148	TJS	XXXX	MEL	CBR	460	0	23
15/09/2002	178	TAB	XXXX	ADL	SYD	401	0	10
15/09/2002	200	OGP	XXXX	PER	MEL	431	0	3
21/08/2002	1	OJK	XXXX	MEL	SYD	410	0	20
21/08/2002	64	NOA	XXXX	SYD	CNS	410	0	10
21/08/2002	71	ZXG	XXXX	SYD	MEL	460	0	21
21/08/2002	94	ZXA	XXXX	MEL	SYD	020	0	19
21/08/2002	97	ZXG	XXXX	MEL	SYD	0	0	0
21/08/2002	123	OGL	XXXX	MEL	SYD	410	0	38
21/07/2002	22	OGT	XXXX	SYD	MEL	410	0	5
21/07/2002	111	ZXG	XXXX	SYD	MEL	410	0	6
21/07/2002	120	TJT	XXXX	SYD	MEL	0	0	0
21/07/2002	122	VXK	XXXX	SYD	ADL	430	0	11
21/07/2002	152	EAJ	XXXX	MEL	SYD	410	0	5
21/07/2002	170	TJT	XXXX	MEL	SYD	0	0	0
21/07/2002	172	OGH	XXXX	MEL	PER	410	0	5
09/06/2002	19	OJO	XXXX	SYD	MEL	460	2	37
09/06/2002	62	TJD	XXXX	SYD	MEL	400	0	5
09/06/2002	69	TJR	XXXX	SYD	MEL	510	0	7
09/06/2002	80	ZXE	XXXX	SYD	PER	420	0	16

Appendix C
Sample of X Airline Departure Delay Data

<i>Date</i>	<i>SVR</i>	<i>VH</i>	<i>Service</i>	<i>Dep</i>	<i>Arr</i>	<i>Cod</i>	<i>Hrs</i>	<i>Mi</i>
10/05/2002	67	ZXB	XXXX	SYD	MEL	0	0	0
10/05/2002	80	EAM	XXXX	SYD	MEL	440	0	3
10/05/2002	87	OGL	XXXX	SYD	MEL	410	0	23
10/05/2002	93	TJG	XXXX	SYD	PER	461	0	24
10/05/2002	129	ZXA	XXXX	MEL	SYD	430	0	7
10/05/2002	138	ZXB	XXXX	MEL	SYD	0	0	0
10/05/2002	210	TAJ	XXXX	ADL	MEL	410	0	30
09/06/2002	87	OGV	XXXX	SYD	MEL	410	0	33
09/06/2002	90	TAK	XXXX	SYD	MEL	460	0	27
11/04/2002	147	VXA	XXXX	MEL	ADL	410	0	8
11/04/2002	150	OGM	XXXX	MEL	SYD	431	0	41
11/04/2002	160	OGG	XXXX	MEL	SYD	410	0	6
11/04/2002	166	VXD	XXXX	MEL	BNE	410	0	6
26/03/2002	104	ZXC	XXXX	SYD	MEL	461	0	36
26/03/2002	107	ZXB	XXXX	SYD	MEL	461	0	48
26/03/2002	109	ZXC	XXXX	SYD	MEL	461	0	48
26/03/2002	111	ZXC	XXXX	SYD	MEL	461	0	11
26/03/2002	113	ZXB	XXXX	SYD	MEL	461	1	21
26/03/2002	115	ZXC	XXXX	SYD	BNE	461	2	11
26/03/2002	118	ZXB	XXXX	SYD	MEL	461	1	12
26/03/2002	119	ZXB	XXXX	SYD	MEL	410	0	59
26/03/2002	123	ZXB	XXXX	SYD	MEL	461	1	2
26/03/2002	131	EAO	XXXX	SYD	MEL	461	1	37
26/03/2002	133	EAO	XXXX	SYD	MEL	461	1	14

Appendix C
Sample of X Airline Departure Delay Data

<i>Date</i>	<i>SVR</i>	<i>VH</i>	<i>Service</i>	<i>Dep</i>	<i>Arr</i>	<i>Cod</i>	<i>Hrs</i>	<i>Mi</i>
26/03/2002	148	TAZ	XXXX	MEL	ADL	420	0	41
26/03/2002	171	TJF	XXXX	MEL	ADL	410	0	24
26/03/2002	180	ZXC	XXXX	MEL	SYD	411	0	10
06/02/2002	72	ZXF	XXXX	SYD	MEL	410	0	4
06/02/2002	95	EAQ	XXXX	SYD	MEL	461	0	32
06/02/2002	97	EAQ	XXXX	SYD	MEL	410	0	8
06/02/2002	100	TJV	XXXX	SYD	ADL	461	2	2
06/02/2002	153	EAQ	XXXX	MEL	ADL	460	1	28
06/02/2002	157	EAL	XXXX	MEL	SYD	410	0	7
16/01/2002	67	TJG	XXXX	SYD	MEL	410	0	48
16/01/2002	77	EAM	XXXX	SYD	MEL	020	0	56
16/01/2002	103	TAJ	XXXX	SYD	ADL	420	1	58
16/01/2002	142	TJQ	XXXX	MEL	ADL	480	0	5
16/01/2002	143	TJP	XXXX	MEL	SYD	430	0	9
16/01/2002	144	EAL	XXXX	MEL	SYD	430	0	15
16/01/2002	161	OGK	XXXX	MEL	SYD	410	0	5
16/01/2002	173	TJM	XXXX	MEL	SYD	520	0	15
16/01/2002	180	ZXB	XXXX	MEL	SYD	650	0	6

Appendix D

Random Number Definition Sheet

Delay Time (Minutes)	Random number
0	0-3391
1	3392-3460
2	3461-3631
3	3632-3927
4	3928-4329
5	4330-4867
...	...
71	9846-9848
72	9849-9851
73	9852-9854
74	9855-9857
75	9858-9860
...	...
101	9906-9907
102	9908-9909
104	9910-9911
105	9912-9913
106	9914-9915
...	...
320	9991-9992
340	9993-9994
360	9995-9996
380	9997-9998
400	9999-9999

Appendix E

Output Form of FDCSP

No	Run Time	Flight No	Schedule Departure Time	Actual Departure Time	Schedule Arrive Time	Actual Arrive Time	Aircraft Down Time	Cre w Time	Random Time	Delay Time	Airport Charge	Cre w Pay ment	Passage Payme nt	Total Cost	Delay Sort
1	1	a1	6:00	6:08	7:00	7:08	90	90	8	8	16	16	0	32	I
2	1	b1	6:00	6:30	7:00	7:30	90	90	30	30	75	60	0	135	I
3	1	b2	6:30	7:10	7:30	8:10	90	90	40	40	100	80	0	180	I
4	1	a2	6:30	7:24	7:30	8:24	90	90	54	54	108	108	0	216	I
5	1	a3	7:00	7:26	8:00	8:26	90	90	26	26	52	52	0	104	I
6	1	b3	7:00	7:00	8:00	8:00	90	90	0	0	0	0	0	0	No delay
7	1	b4	7:30	8:00	8:30	9:00	90	90	30	30	75	60	0	135	I
8	1	a4	7:30	7:35	8:30	8:35	90	90	5	5	10	10	0	20	I
9	1	a5	8:00	8:00	9:00	9:00	90	90	0	0	0	0	0	0	No delay
10	1	b5	8:00	10:01	9:00	11:01	90	90	121	121	302.5	242	2680	3224.5	I
11	1	b6	8:30	8:58	9:30	9:58	90	90	28	28	70	56	0	126	I
12	1	a6	8:30	8:30	9:30	9:30	90	90	0	0	0	0	0	0	No delay
13	1	a7	9:00	10:51	10:00	11:51	90	90	111	111	222	222	0	444	I
14	1	b7	9:00	9:32	10:00	10:32	90	90	32	32	80	64	0	144	I
15	1	b8	9:30	9:54	10:30	10:54	90	90	0	24	60	48	0	108	II
16	1	a8	9:30	9:40	10:30	10:40	90	90	2	10	20	20	0	40	II
17	1	a9	10:00	11:07	11:00	12:07	90	90	67	67	134	134	0	268	I