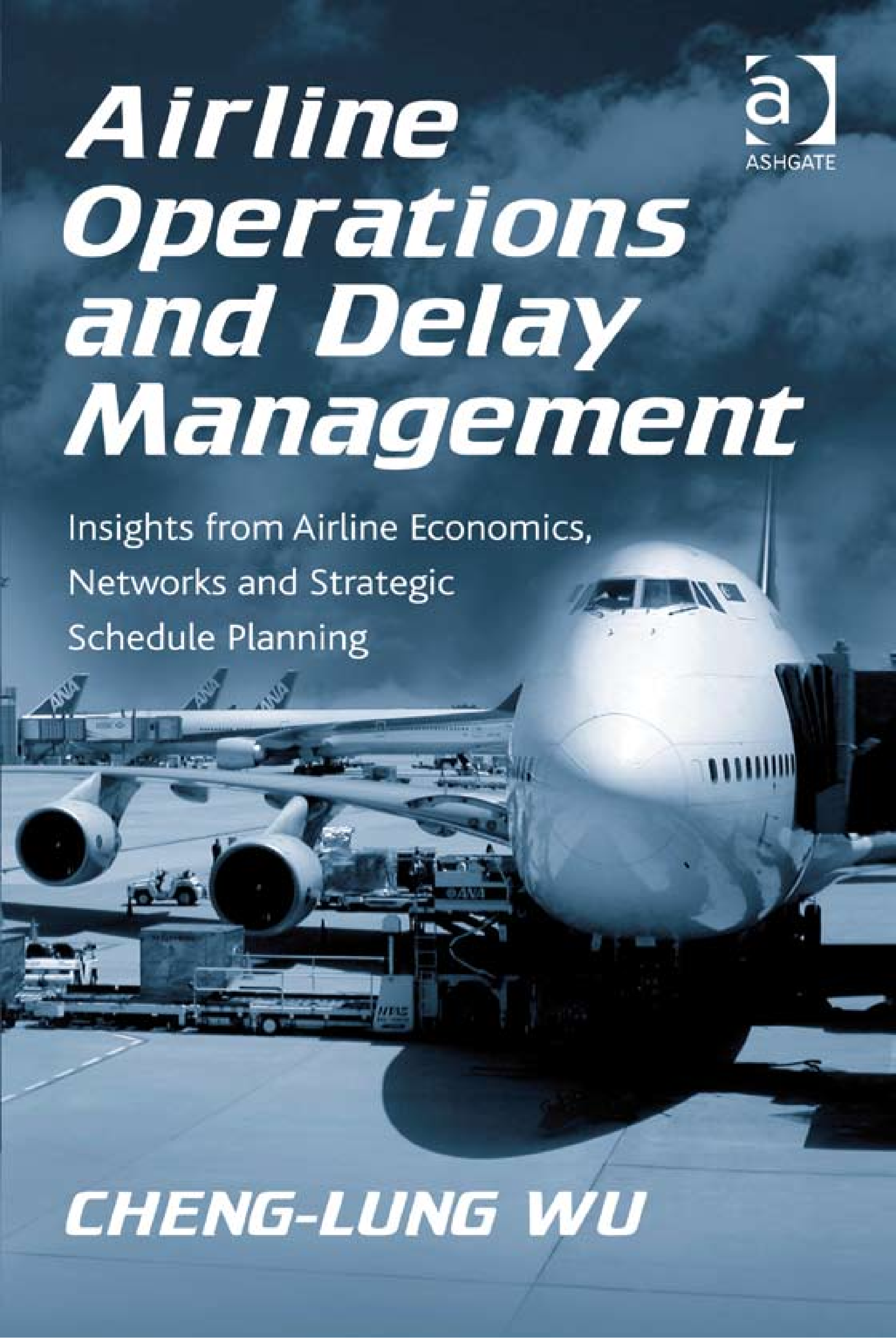

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# Airline Operations and Delay Management

## Insights from Airline Economics, Networks and Strategic Schedule Planning

CHENG-LUNG WU

# AIRLINE OPERATIONS AND DELAY MANAGEMENT

*To my parents, my wife, Po-Wen, and my daughter, Annie.*

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## Insights from Airline Economics, Networks and Strategic Schedule Planning

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Published by
Ashgate Publishing Limited
Wey Court East
Union Road
Farnham
Surrey, GU9 7PT
England

Ashgate Publishing Company
Suite 420
101 Cherry Street
Burlington
VT 05401-4405
USA

www.ashgate.com

**British Library Cataloguing in Publication Data**
Wu, Cheng-Lung.
Airline operations and delay management : insights from
airline economics, networks and strategic schedule planning.
1. Airlines--Management. 2. Airlines--Cost of operation.
I. Title
387.7'068-dc22

ISBN: 978-0-7546-7293-7 (hbk)
ISBN: 978-0-7546-9190-7 (ebk.V)

**Library of Congress Cataloging-in-Publication Data**
Wu, Cheng-Lung.
Airline operations and delay management : insights from airline economics, networks, and strategic schedule planning / by Cheng-Lung Wu.
p. cm.
Includes bibliographical references and index.
ISBN 978-0-7546-7293-7 (hardback) -- ISBN 978-0-7546-9190-7 (ebook) 1. Airlines--Management. 2. Business logistics. 3. Scheduling. 4. Operations research. 5. Airlines--Timetables. 6. Aeronautics, Commercial--Passenger traffic. 7. Strategic planning. I. Title.
HE9780.W82 2009
387.7068'5--dc22

2009032357

Printed and bound in Great Britain by
MPG Books Group, UK

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# Preface

If one has a chance to visit the Operations Control Centre of an airline and talk to a senior controller about the "ideal" airline schedule, they will surely describe some attributes of an ideal schedule that they would like to see in operations. If one is lucky enough to speak to a senior scheduler in an airline and ask the same question, they will definitely sketch a schedule which often looks different in many ways to that of an operations controller. After researching and consulting in airline operations for ten years, I have observed such internal conflicts in nearly every airline I have worked with in the past, regardless of the size of the company. Such conflicts are still seen in the industry now and they often result in operational losses to an airline in the forms of delays, schedule disruptions (and recovery), and un-satisfied passengers. The goal of this book is to bring these two diverging functions of an airline back together and work for the company's goal, i.e. profitability.

This book aims to provide readers with knowledge of both the practical and theoretical aspects of airline operations and delay management, as well as offering mathematical models for solving operational and schedule planning issues. The subject, *airline operations and delay management*, is explored extensively from a wide range of perspectives including: airline economics, airline business models, network development strategies, scheduling practices, and difficulties in actual airline operations. There is a strong need to address airline operations in the context of these wider views because many operational issues and problems are "inherent" in strategic airline schedule planning, and are inevitably encountered in actual operations, although operational issues are mostly manageable (with extra operating costs). This book adopts a different approach from conventional scheduling practices and explores the area of airline operations by addressing the inter-dependency between network development, economic/commercial driving forces in strategic airline scheduling, uncertain flight demands, and operational complexity of a modern airline network.

I have written this book in such a structure that it can serve as an introductory text for studying airline operations in a senior undergraduate course in a University. This book is also intended for those readers who would like to have a deeper understanding of contemporary schedule planning, airline operations, and delay management practices in the industry. Most of the contents of this book are written in a style such that concepts can easily be followed by professional analysts and aviation students even with limited aviation knowledge; some sections, in particular those developing mathematical models in various chapters, are intended more for those who pursue technical modelling knowledge and analytical tools for solving industrial problems such as aviation analysts, consultants, and postgraduate students in a University.

This book has been organised to allow individual chapters to independently address certain aspects of airline operations and scheduling, while as a whole the chapters provide a steady development when read from the beginning to the end. This book starts by introducing the operating environment of airlines, the evolution of airline networks, the driving economic forces behind airline scheduling, and the general practices of airline schedule planning procedures. Airline operations at airports are discussed in detail in Chapter 2, including activities by airlines at airports, the uncertainties involved in daily operations, and the impact of uncertain disruptions on the management of airline operations. Chapter 3 explores the issues in managing daily aircraft turnaround operations, combining industry practices and mathematical models for managing airline ground operations at airports.

The network effects of airline operations in Chapter 4 outline the impact of stochastic disruptions on a network scale, followed by the operational management of complex airline networks and on-time performance of a schedule in Chapter 5. Chapter 6 begins by introducing the emerging concept of robust airline scheduling and operational reliability of airline networks. Recent advances in modelling and optimising airline operations and schedules are discussed and examples are given in the book from real-world cases, wherever possible.

Preparing this book has occupied most Thursdays and Fridays of my work schedule since late 2007. Along the journey of writing, Prof. Jason Middleton at the Department of Aviation (UNSW) has provided me with the much-needed resources for book writing, in particular time and encouragement. I would also like to thank those graduate students in my research group, who have shown understanding to the fact that their research supervisor was working on his "second PhD thesis". Among my students, Dr. Theo Koo contributed to an earlier version of Section 3.5 of Chapter 3 on passenger flow management and passenger consumption behaviour at airport terminals. Prof. Jinn-Tsai Wong (NCTU Taiwan) contributed to the discussion on the modelling framework of delay propagation in Chapter 4 during his sabbatical visit in Sydney in 2006. Special thanks go to Miss Miriam Fewtrell who assisted in model development for Chapter 4 and editing the English of early drafts of this book. Just like cycling in the *Tour de France*, I would not have been able to finish this work and enjoy the journey of book writing without the excellent "team car" trailing behind me with the company of my family aboard: my lovely wife, Po-Wen and my sweet little daughter, Annie. Thank you and I love you.

Dr. Cheng-Lung (Richard) Wu
UNSW Aviation, Sydney Australia

# Chapter 1

# Introduction to Airline Operations and the Operating Environment

This chapter provides a brief introduction to airline network design issues, the economic and regulatory forces driving airline network evolution, airline schedule planning procedures, airline operation issues, the greater environment in which airlines operate, and the complexity of managing an airline network. Section 1.1 briefly discusses different types of airline networks, and the driving economic forces that have changed airline scheduling and networking in the past two decades. Section 1.2 examines common airline schedule planning processes and some shortcomings in airline operational management that result from this scheduling paradigm. Also introduced in this section is the concept of the "complex network" that makes airline scheduling, resources allocation and operational management challenging.

Section 1.3 covers airline operations both on the ground at airports and en-route in airspace. Various activities and procedures are required during airline ground operations and the success or efficiency of executing ground operational plans largely determines the schedule execution results, i.e. flight on-time performance (OTP) and profitability. Section 1.4 discusses the greater environment in which airlines operate, including airports and airspace. This section follows earlier sections and provides links between airline operations, schedule planning, complex network design, and delicate schedule synchronisation. The last section, Section 1.5 summarises this chapter and sets up the context for the remainder of this book. Section 1.5 explores airline operations, airline scheduling philosophy, and some management issues by addressing internal and external factors (with respect to an airline) that significantly influence tactical airline operations and strategic airline planning. The outline of the remaining chapters of this book is provided in this section as well.

## 1.1 Airline Networks and Airline Economics

### *1.1.1 Airline Network Types*

Broadly speaking, the term "airline network" has two meanings. First, an airline network means the network that is formed by those airports that are serviced directly or indirectly by an airline. This definition places an emphasis on network coverage (the "spatial" coverage) and the seamless services that an airline and its partner airlines can provide customers. The second meaning of an airline network focuses on the more “temporal” attributes of an airline network. The temporal attributes of an airline network are characterised by the frequency of services between two airports and the extent an airport is connected with other airports in the network via various service types (direct flights or transfer services) and service frequency. The strong focus and competition, both on the temporal and spatial attributes, gives rise to various airline network models. Among these, some focus more on the temporal attributes such as a hub-and-spoke network, and others focus more on the spatial attributes or market orientation such as a point-to-point network.

A hub-and-spoke network consists of at least one “hub airport” that plays the role of “collecting and distributing” passenger traffic among flights at an airport. Passengers fly to the hub airport and then either transit to another flight to reach their destination, or end their journey at the hub airport. To efficiently “exchange” transit passengers among flights at a hub, inbound flights come in “waves” (or “banks”), followed by waves of outbound flights. The role of a hub airport is to facilitate intensive and often dense aircraft ground operations during the time when passengers need to travel from one gate to another for a connecting flight. Since limited direct connections are available between spoke airports in a hubbing system, most spoke-to-spoke connections must be made via a hub, resulting in a longer travel time than a direct service between two spokes. In a large geographic region such as North America, there may be two or more hubs in a hubbing network to facilitate passenger connections.

A point-to-point network, on the other hand, focuses more on individual markets. Passengers are often able to travel directly between two airports which are serviced by an airline that operates a point-to-point network. Due to the nature of such a network system, it is not always possible for passengers at a city to travel to any other cities that are serviced in a point-to-point network, because the market between any two cities in the network may not sustain a direct flight. The emerging low-cost carriers (LCCs), pioneered by the Southwest Airlines in the U.S., take advantage of this type of network system, and this “low-cost” sector in the industry has expanded quickly around the world in different continents.

Naturally, the geographic location of the base airport of an airline has a profound influence on the network model that an airline adopts. This gives rise to the “mixed network” model that adopts both attributes from the hubbing system as well as from the point-to-point system. In such a network, the intensity of hubbing is not as high as that in a hubbing system and the focus of hubbing is often *ad hoc* and aimed at providing flight connection opportunities between specific markets. Hence, inbound and outbound flights at such a mixed hub are usually highly synchronised and for most hubs, this operation is often “directional” in terms of traffic. For instance, Qantas and British Airways operate a hub at Singapore Airport where there is north bound traffic to Europe in the evening and south bound traffic to Australia in the early morning.

The growth of airline alliances has also changed the definition of an airline network. Through code-sharing agreements among partner airlines in an alliance, an airline is able to expand its network by including airports/flights that are not directly operated by itself. This "virtual" expansion of an airline network provides airlines with economic benefits due to the lower costs of operating some code-sharing markets, whilst providing passengers with better network coverage.

### *1.1.2 Economic Forces*

The "structure" of an airline network is the result of airline route planning, which is aimed at maximising network revenues by changing the structure, i.e. by adding and/or dropping airports or by changing service frequency between airports in a network. The driving force of airline route planning is deeply rooted in corporate revenue maximisation, although there are "flag carriers" that may operate certain routes more for political considerations than economical ones. In a highly regulated market such as the U.S. market in early 1970s, airlines operated certain routes for various considerations, e.g. national and community benefits, and there was usually limited competition in most markets. After deregulation in the U.S. market in 1978, market forces came into play and dramatically reshaped the network models of many American carriers. The most obvious change has been the emergence of the hub-and-spoke system after deregulation.

Due to geographic constraints and the nature of directional (east-west) traffic in North America, economic forces have driven the development of hub-and-spoke systems for decades. An airline that operates such a network can readily vary the frequency of services to a market, so as to easily extend flight supplies or to fend off new entrant carriers into the same market. The concentration of flights at certain hubs also creates the desirable "economies of density", meaning that the marginal cost of varying flight density (frequency) is relatively low in such a network structure, so an airline can easily generate more profits by increasing frequency (Button 2002). Pursuing this potential economic benefit, airlines started developing strong hubbing systems in the U.S. after deregulation.

Another emerging force in the deregulated market is to focus on origin-destination (OD) markets. This is the underlying economic rationale of most low-cost carriers: an OD market is added to the network if and only if the market is profitable and sustainable in the short run. In such a point-to-point network, the focus is less on the economies of density or the "network synergy", but more on the profitability of individual OD markets in the network. Potential connecting markets and network coverage are not the central issues of airline route planning. Hence, few connections ("on-line" connections in particular) are facilitated or available between markets, although passengers may still independently organise self-hubbing or self-connection at certain airports that serve more destinations in a region.

### 1.1.3 Complex Networks and Network Effects

Compared with other forms of network systems, an airline network is a "time-varying network", in which the "physical" links between nodes (i.e. airports) in such a network are formed by flights on a timetable. Since there are only a certain number of flights scheduled at specific times between a city pair in a network, the "physical structure" of an airline network depends on the times when flights are scheduled, hence being a time-varying network. Another unique attribute of an airline network, which is similar to many large complex network systems, is that most of elements in the network are subject to stochastic influence. For airports, the operation of an airport is subject to weather conditions, which influence the practical runway capacity and some ground operations. For airlines, ground operations are subject to uncertainties coming from external sources such as aircraft ground service delays and shortage of ground staff, and internal sources such as connecting crew delays. For airspace, uncertainties come from air traffic control loading in individual sectors, and congested terminal areas around large airports during peak hours.

The combined time-varying and stochastic nature of an airline network creates a set of "dynamics" that affect the way an airline operates and manages its operations. Like many other large complex networks, the operations at an airport may influence other parts of the network through traffic flows, e.g. aircraft routing and passenger connections. Constraints at a particular airport may cause partial network degradation. For instance, a thunderstorm around a major hub airport can cause delays to hundreds of flights and even flight cancellations across the network due to the capacity reduction of runways. Although economic forces drive airlines towards revenue maximisation and asset utilisation, operational issues arising in running a complex network may offset some of these financial gains. It is in the context of this conflict between potential financial gains and uncertainties in real-world operations that we will examine airline operations and scheduling issues. This will provide the overarching context of this book in general.

## 1.2 Airline Schedule Planning

### 1.2.1 Schedule Planning Stages

There are four major stages in airline schedule planning. First of all, *network planning* (also called route planning or schedule generation) is the fundamental step in schedule planning. The goal of network planning is to explore potential markets and forecast market demands for certain services, e.g. leisure demand or business demand. Hence, this stage of work involves demand modelling, market forecasting and initial schedule establishment. Airlines often start route planning well ahead of operations and often base this work on the existing network by adding/cutting services and optimising/changing frequency to capitalise on existing and new markets. The objective of airline network planning is to set up a preliminary timetable to generate maximum profits with limited resources such as aircraft fleets, capital investments and human resources.

The second stage of schedule planning is to conduct *fleet assignment* based on the outcome of route planning from stage one, i.e. the preliminary timetable. The goal of fleet assignment is to explore the best possible way to execute the timetable by assigning available fleets with the minimum operating costs. Since operating different types of aircraft would incur different levels of costs and provide different levels of seat capacities, individual demand forecasting on a market basis is essential at this stage, to match potential or expected market demand with the appropriate supply of seats (i.e. the right type of aircraft). Hence, the objective of fleet assignment is to "partition" the proposed timetable into a number of "flight sets" which are operated by different fleets in a way which minimises cost.

The third stage of scheduling is *aircraft routing*. For each "set" of flights obtained from fleet assignment, an aircraft routing plan is developed. Flights flown by a specific fleet are partitioned and "connected" in a chronological order to form a "route", such that an aircraft of this fleet can operate those flights in a route sequentially. The other objective of aircraft routing is to route each aircraft to specific maintenance stations according to aircraft maintenance requirements and schedules. The timely routing of an aircraft back to the maintenance station is essential for safety considerations.

The fourth stage of scheduling is *crew rostering*. Flight crew are specifically fleet type endorsed, so a pilot can only be rostered to fly a certain type of aircraft. Cabin crew are generally not constrained by this endorsement, but would require specific training for those aircraft types they will operate. Crew cost is usually the second largest cost item (after fuel cost) on the balance sheet of an airline, so crew rostering is a critical stage where an airline can potentially generate substantial savings. Hence, the goal of crew rostering is to utilise crew resources to execute the planned timetable at a minimal cost. Since the crew are humans and not like aircraft that can be on duty for extended hours, there are safety regulations on the workload of pilots by civil aviation authorities in different countries. In addition, crew unions often have enterprise bargain agreements with airlines that further limit the workload and conditions in which crew rosters can be designed. In a sense, crew rostering is similar to aircraft routing, but with additional restrictions on fleet types, working hours, and the location of crew bases in the network.

### *1.2.2 Resource Connections and Delicate Schedule Synchronisation*

In addition to being time-varying and subject to stochastic disruptions, the complexity of an airline network is deeply rooted in the high levels of synchronisation among the four "layers" of a network – the aircraft routing network, crewing network, passenger itinerary network, and cargo shipping network. The *aircraft routing network* is the "backbone" of an airline network system, with which other networks/sub-systems are synchronised accordingly. Aircraft are routed to conduct a specific flight at a specific time, and meet the frequency demands between destinations. An important task in aircraft routing is to route the aircraft back to a maintenance base in time for the required maintenance services.

Once a specific type of aircraft routing network has been decided upon, crew (cabin and cockpit crew) are assigned to operate a number of flights during a certain period of time (called *crew pairing* or a *tour of duty*). Since the endorsement of cockpit crew must match the aircraft type, a group of cockpit crew and cabin crew may follow an aircraft for a number of flights during a day before switching to another aircraft or ending the duty of the day. This creates the layer of the *crew rostering network* (also known as the *crew pairing network* in the industry), which is highly synchronised with the movement of aircraft in the aircraft routing network.

In addition to these two networks, passengers take flights that transport them from origin airports to destination airports. If a journey involves a transfer at an airport then the whole "itinerary" of a journey will span across a number of flights in the network. Since there are millions of passengers travelling between airports in a network, there is a high degree of itinerary overlapping among passengers, especially for hub-bound traffic; the individual itineraries of passengers on a flight vary and "overlap" with one another at least for this flight. This layer of the *passenger itinerary network* is driven by market demands in the network and follows the nature of airline networks in that it is both time-varying and subject to stochastic disruptions.

The fourth layer of an airline network is the *cargo shipping network*. This layer is not as critical as the other three, because most cargo/mail shipments can tolerate delays (for non-express shipments), or can be routed through a number of airports before reaching the destination (depending on the destination of shipments and the location of cargo hubs in a network). For "belly cargo" (i.e. those cargo that are carried by passenger flights), they form a similar type of network to the passenger itinerary network. Freighter flights form a separate sub-network which contains a separate aircraft routing sub-network (due to different fleets from passenger aircraft), and a crew rostering sub-network (due to different crewing requirements and no passenger charter).

We can see from the structure of an airline network that the high levels of schedule synchronisation between layers contributes significantly, both to the complexity of network planning and also to the complexity of daily operational management in such a network. If an aircraft is delayed, passengers, crew and cargo aboard are also delayed. Late passengers and crew may also delay other flights down the line at other airports that are supposed to receive connecting passengers and crew. For major disruptions such as the closure of an airport due to a thunderstorm, there may be numerous inbound and outbound flights at the affected airport that need to be cancelled or delayed. This causes a ripple effect throughout various layers of an airline network due to the resource connections and synchronisation among them.

In the grid of airports, this ripple effect also causes delays at some other airports because of airline operations in the airport network. A highly synchronised airline network runs well in normal operations and is able to cope with minor stochastic disruptions. However, the conventional approach we have introduced to airline schedule planning may be vulnerable to stochastic forces and major disruptions, which unfortunately occur during airline operations. We will explore this issue in depth and how the industry has been addressing it recently in Chapters 5 and 6 of this book.

## 1.3 Airline Operations

### *1.3.1 Airline Operations at Airports*

The goal of airline operations at airports is to facilitate the execution of airline schedules, movements of passengers, baggage, and cargo. Airline operations at airports can be generally categorised by activities on the landside and on the airside of an airport by an airline. On the landside, airline operations involve passenger check-in, baggage check-in, connecting passenger/baggage processing, cargo and goods handling (in a cargo processing facility adjacent to an airport), catering service preparation (usually in a facility nearby an airport and often next to the airside), and passenger boarding at the gates.

The area beyond the boarding gates belongs to the airside of an airport. Activities on the airside by airlines mainly include the tasks of turning around aircraft at the gates. This turnaround operation includes passenger handling (disembarkation and embarkation), cabin cleaning, crewing (crew change), routine visual maintenance checks, re-fuelling, cargo handling (unloading and loading), and catering services (unloading and loading). Some airlines have their own ground handling agents that carry out both airside and landside services, especially at their base or hub airports. Other airlines outsource ground handling services to independent service agents or to different airlines for cost-cutting purposes, especially at non-hub airports (also known as *out-stations* in the industry).

Airline operational activities at an airport, like those activities in some service and manufacturing industries, have unique characteristics including operating time constraints and a standardised operating procedure. The timeline of airline operations is based on the scheduled departure time of flights in the timetable. Passenger check-in starts around one and a half hours before departure for a domestic flight, and up to three hours for an international flight, depending on aircraft size. Aircraft turnaround operations are conducted within the scheduled turnaround time between two flights, which is fleet type and service requirement dependent. For a domestic low-cost service by a B737 or A320, the turnaround time can be as short as 15 to 20 minutes by some low-cost carriers. For a full-service by a B747 on an international route, the turnaround time can be between one and a half hours to two hours.

Aircraft turnaround activities are often standardised to a strict timeline, and most airlines follow their own standard operating procedures (SOPs) or the ones provided by aircraft manufacturers. For most activities, there are planned operating sequences in the SOP. For instance, check-in counters are open from two and a half hours before the scheduled departure time (for a wide body aircraft operation) and are closed thirty minutes before the departure time. For turnaround activities, on-board passengers disembark first, then followed by crew (if needed), cabin cleaning, crew changes (if needed), and passenger boarding.

Most workflows can run simultaneously with limited interference between them such as the passenger handling flow and the cargo/baggage handling flow. However, disruptions can occur to any activities in the workflows and delays to an activity may disrupt other activities and eventually delay a flight, due to the sequential nature of most workflows. In addition, workflow interference may occur among flights that are being turned around at the same airport at the same time, due to connections of passengers, crew and goods/baggage, i.e. synchronisation between flights. This type of connection can occur within flights operated by an airline or between flights by different airlines at the same airport.

### *1.3.2 Enroute Flight Operations in a Network*

Enroute operations consist of the procedures after aircraft push-back at the gate of the departure airport and before the arrival at the gate of the destination airport (also called *gate-to-gate operations* in Europe). Enroute airline operations mostly involve airborne flight operations and aircraft operations on the ground at airports. For airlines, "flight operations" often refers to the management of flights when airborne. These operations are carried out by cockpit crew and are facilitated by air traffic controllers in the various sectors through which an aircraft will fly. There is a certain level of flexibility such that an airline can choose the "optimum" flight path of an airborne aircraft between an origin and destination, depending on enroute weather conditions and estimated fuel consumption.

The flight path an aircraft takes is often planned a few days before departure and is also subject to updates on the day of departure by the airline. Considerations to flight path planning (a part of *flight dispatch*) include the estimated fuel consumption along the path, engine numbers and emergency needs (also known as "ETOPS"), weather forecast along the path (influencing fuel consumption and safety), and the estimated take-off weight (influencing the fuel carried aboard). Delays occurred during flight operations are mostly due to requested detour by air traffic controllers for various reasons such as: weather conditions on the path, and congested air traffic control (ATC) sectors. The congestion in the terminal manoeuvring area (TMA) around the destination airport may force an arriving aircraft to join a landing queue in an airborne holding pattern and await a landing slot.

Aircraft enroute operations are largely beyond an airlines' control, with the exception that airlines are able to alter their flight plans in advance subject to the current practice of the air traffic control and management. Some airlines may be able to request a shuffle of departure or landing slots at an airport under specific circumstances such as inclement weather, or if they are the dominant (hub) carriers at the airport. However, this scenario only happens during heavily disrupted periods, when airlines need to cancel, delay and prioritise some flights in order to minimise the impact due to the unexpected schedule disruptions.

Aircraft operations on the ground of an airport are procedural, and in most cases are facilitated by the air traffic control services provided by airport towers. This sequence of operations at the departure airport involves the captain requesting for push-back permission, ground staff pushing back the aircraft from a gate to the taxiway, the aircraft taxiing on the taxiway, waiting in the departure queue at the holding apron of the runway end (if necessary), and taking off (wheels off the runway). The operation at the arrival airport follows an opposite but similar procedure from landing (wheels on the runway), taxiing on the taxiway, to parking at the arrival gate. Congestions for arrival aircraft may occur on the taxiway or before parking at a gate, due to late gate clearance.

## 1.4 The Operating Environment of Airlines

### *1.4.1 The Nature of Airline Scheduling and the Greater Environment*

Airline operation is the execution of a complex airline schedule system which is designed to maximise corporate revenues in a specific market, which is formed by a network of airports. Schedule planning itself contains major strategic and tactical decisions made by an airline, with the aim of utilising available corporate resources and maximising revenues. Like other industries, the airline industry is a competitive market in which market forces such as supply, demand and pricing play a key role in airline strategic planning, scheduling and consequently schedule execution. The nature of an airline business is like any other businesses, but the operational side is more constrained by the "greater environment".

From an airline's perspective, an airline operates in a "man-made" environment, in which airports provide ground infrastructures, and air traffic control authorities provide air traffic management services (allocating limited capacity). Unlike the free market that most businesses or industries operate, this man-made environment imposes numerous constraints on airlines not only in terms of strategic planning, but also on daily operations. Strategically, the limited capacity of airports, bilateral air service accords between countries, and consequently limited air traffic services constrain the free growth of an airline in certain markets. Under such constraints, airlines cannot freely expand services to any markets that may have business potential.

Tactically speaking, airline operations are stochastic in nature when compared with the "fixed" schedule that an airline needs to operate. Some operations depend on weather conditions, while others may depend on workload that is often directly related to the actual number of passengers carried on the day of operation. Therefore, we need to have a good understanding of the "environment" in which airlines operate, before further elaborating on airline schedule planning and operational improvements. Interestingly, it is also the operating environment that influences or even enforces how airlines plan schedules and more importantly, how airline operations perform in such a highly constrained environment.

### *1.4.2 Complex Networks and Schedule Synchronisation*

An airline network involves layers of sub-networks which inter-connect with each other via resources (aircraft and crew) or passengers. An airline network also connects with the networks of other airlines, mostly via connecting passengers in code-share operations or reciprocal bilateral agreements. Given the unique attributes of the complex aviation system, as discussed earlier, airlines operate in a unique environment in which delicately synchronised connections among networks take place at many airports in the network. Airline operation is expected to adhere to the planned schedule, though stochastic disrupting events can occur to any elements of the complex system and in some cases, may cause serious network-wide impacts.

The "network effect" on an airline system is a double-edged sword: on the one hand, airlines take advantage of networks to utilise resources and assets in order to maximise corporate profits; on the other hand, the complex web of resource synchronisation inherently contains some degrees of operational uncertainty that often lead to extra operating costs. The driving force of utilising airline resources and assets has resulted in schedule plans that are over-optimistic on the drawing board, or are optimised only for normal operations. With such a plan, the well-synchronised network runs smoothly under normal operating conditions. However, when the plan is disrupted, more resources are needed to restore the system back to its normal status. This scheduling philosophy has dominated airline scheduling for more than a decade. It is not until recently that airlines started to look for solutions which create "robust" airline schedules that can improve operational reliability in the actual environment that airlines face. We will explore how this shift of scheduling paradigm has evolved recently in Chapter 6.

### *1.4.3 Stochastic Operations and Disruptions*

Stochastic forces affect airline scheduling and operations in two ways. First, many tasks in airline operations are naturally stochastic, in terms of the time required to finish those tasks. For instance, the time required to load baggage depends on the number of passengers on the day of operation, as well as on the actual weight of the baggage brought by all passengers aboard. Since the actual number of passengers aboard a flight is unknown until check-in is finished, the service time of a few tasks is always unknown until the last minute. Moreover, catering service time and fuel carriage also depend on the actual passenger number on the day of operation. This uncertainty brings a stochastic factor into airline operations.

Second, disrupting events in airline operations and in the operating environment (airports and airspace) occur in a stochastic nature, such that many of disruptions are not predictable. Major events such as aircraft technical issues and severe weather conditions are hard to prepare for and the consequences of major disruptions like these are always serious and expensive for airlines and the society. Minor disruptions such as delays and late inbound passengers/bags have less of an impact, but gradually, delays may accumulate and propagate across some parts of a network, due to the synchronisation in an airline network. The effect of delays in a network will be further modelled and discussed in detail in Chapters 4 and 5.

## 1.5 The Context and Outline of the Book

In this book, we will focus on airline operations and some management issues specifically pertaining to operations such as delay management, operating process optimisation, schedule optimisation, and schedule disruption management. Since airline operation is subject to stochastic forces and is a result of airline schedule planning, we will approach airline operations from the perspective of airline schedule planning and optimisation. Thus, we do not only address the "consequences" of airline operations in this book, we also explore the "root causes" resulting from airline scheduling that are often overlooked by airline management. Further up the scale, we shall bear in mind that the philosophy of airline schedule planning is deeply rooted in economic principles and market forces, some of which are imposed or constrained by the operating environment of this industry. Therefore, many operational issues, indeed are "created" by airlines themselves, because of the constraints from the environment (airports and airspace), the risk of pursuing potential economical benefits, and uncertainties naturally inherent in a complex system. It is in this overarching environment and unique context that we will examine airline schedule planning, airline operations, operational control, and the evolving schedule planning philosophy in this book.

The outline of the remaining book is to focus on airline operations on the ground in Chapters 2 and 3. Chapter 2 explores the influence of airport constraints on airline scheduling and operations on the ground. Apart from limited airport slots for departures and arrivals, airlines are subject to the time constraint imposed by their own planned schedules to conduct aircraft turnaround operations. An analytical model that considers uncertainties in airline operations is provided and we shall run a few scenario tests to explore the extent to which airline operations are subject to uncertainties and self-imposed scheduling considerations. Chapter 3 shifts the focus to some operational issues, in particular: delay management, delay data collection, managing aircraft turnaround operations and managing passenger flows in airport terminals. A micro-simulation model is developed as a tool that allows us to examine in detail how individual service processes of turning around an aircraft are synchronised with each other, and how collectively they can affect flight punctuality.

Having explored airline operations, the book moves on to discuss enroute flight operations by airlines in Chapter 4 and airline disruption management in Chapter 5. Chapter 4 focuses on the "network factor" in airline scheduling and operations, and extends the scope of this book from a "local perspective" (i.e. at an individual airport level) to a network and system perspective. This chapter starts by introducing aircraft routing, fleeting, crewing requirements, then crew scheduling. Next, an airline network is broken down into sub-networks with which we explain the delicacy of schedule synchronisation and resource connections in this complex system. Based on this network view, we return to the topic of delay management and explore the potential impacts of delays on a network scale, namely delay propagation.

Chapter 5 expands on this by addressing some issues in daily airline operational management such as disruption management, and on-time performance reporting. A case study based on a set of real data is provided to demonstrate a common approach by airlines to delay and operation diagnosis. Building upon the network view in Chapter 4, we introduce operational uncertainties in the network and the concept of "inherent delays" that results from airline scheduling philosophy/policies, network features, and constraints imposed by the operating environment, e.g. capacity limitations of airports. A schedule optimisation model is then presented to demonstrate the possibility of improving the robustness in airline operations by an emerging scheduling concept, namely robust airline scheduling.

Chapter 6 will firstly provide a brief review of past practices of scheduling in the industry. Subsequent to this review, this chapter introduces the concept of schedule robustness and how this concept is currently evolving in the airline industry. Some strategic and tactical methodologies are discussed in reference to improving schedule robustness in strategic schedule planning and tactical operations. Before finishing this chapter and concluding this book, we return back to the debate of airline schedule planning and its on-going struggle with the complexities of network synchronisation and market-driven economic forces in corporate finance. We lay out some potential scheduling philosophies for the future based on the emerging robust scheduling and integrated modelling concepts.

# Chapter 2

# Airline Operations at Airports[1]

Chapter 2 details the activities involved in airline operations at airports. Although for most activities of airline operations at airports there are "standard procedures", most airlines adopt these procedures with some in-house modifications, aiming at improving operational efficiency. Accordingly, details about these "in-house modified operational procedures" are often not available in the public domain and are treated as commercial in confidence by airlines. Hence, this chapter covers those standard procedures of airline operations at airports, while introducing some ad hoc operations of airlines wherever data are available from public sources. Operations at airports may also differ between network carriers and low-cost carriers. Differences will be identified and detailed where necessary and relevant. Mathematical models developed to improve the operational efficiency of airline ground operations are described in detail.

This chapter begins by introducing airline scheduling philosophy and its implications on airline operations for different types of airline networks, e.g. hubbing and point-to-point services. The impact of airline scheduling on the allocation and availability of airport slots and airport infrastructures is discussed in detail in Section 2.1. Section 2.2 further delineates operational activities involved in aircraft turnaround operations, including passenger processing and goods handling. Section 2.3 moves on to discuss the stochastic variations of service time of ground operations, limited turnaround time in schedules, and random flight delays.

Based on these discussions, Section 2.4 introduces an empirical method which is commonly used by airlines to deal with uncertain delays and pursue the optimal allocation of turnaround time. Section 2.5 continues this by developing an analytical method that provides sufficient modelling details to meet scheduling demand. The last section is a case study based on real airline data which demonstrates some key concepts regarding punctuality management and airline scheduling. Within these discussions, modelling concepts are introduced gradually as relevant to the content. The pursuit of efficient and effective allocation of turnaround time in airline scheduling is discussed with the presentation of mathematical models and applications in both real and hypothetical cases.

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[1] This chapter is partially based on the following publications: Wu and Caves (2000); (2002); (2003); (2004).

## 2.1 Airline Scheduling at Airports

The "philosophy" of airline scheduling differs between airlines and the development of the "philosophy" is strongly influenced by two key forces in scheduling, namely commercial interests and technical considerations. In the next two sections, we will explore how these two forces shape the philosophy of airline scheduling and how different scheduling philosophies influence airline business models and operations.

### *2.1.1 Hub Scheduling and Operations*

Commercial interests are driven by the desire to maximise revenues of airline products, i.e. the flights on airline timetables. Flights are the "intangible and perishable" products that airlines offer customers. The "intangibility" reflects the fact that the consumed product is those "services" provided by airlines aboard aircraft to transport passengers from an origin airport to a destination airport. The "perishability" reflects that once a flight departs according to a timetable, the "product" no longer exists in the market and has perished immediately. Hence, the "attributes" of airlines products, e.g. onboard/ground services and flight timetables, determine the saleability of these products as well as the revenue of sales.

Within these attributes, airline scheduling philosophy is strongly influenced by the "perishability" of products and the desire to maximise the saleability of products by scheduling flights at the most attractive times for passengers. Generally speaking, there are three broad airline scheduling models and each reflects different scheduling philosophies and airline business models including: the hub-and-spoke model, the mixed hubbing model, and the point-to-point model.

A hubbing schedule is driven by the desire to "exchange" passengers between an inbound and an outbound "wave" of flights at a hub airport after a short period of connection time. This type of hubbing networks creates numerous connection options among airports of a network and also creates the desired "economies of density" for hubbing airlines. A common hubbing schedule looks like the one in Figure 2.1 that has clear arrival peaks and departure peaks. This scheduling philosophy is ideal for a network in which there is regional and/or directional traffic, e.g. Munich for Lufthansa, Atlanta for United Airlines, Dallas-Fort Worth and Chicago O'Hare for American Airlines. A hub-and-spoke network is also ideal for domestic operations with a few "gateway airports" in the network serving as the hubs between domestic and international connections such as Los Angeles, New York JFK and Frankfurt. For other cases, the hub location may enjoy some geographical benefits for traffic exchanges, e.g. Singapore and London Heathrow Airport.

Hubbing schedules are not universally applicable for every airline. Those airlines which do not have enough destinations or demand in their networks to sustain frequent and dense wave structures will not enjoy the benefits of strong hubbing. However, the model of "weak hubbing" and "rolling hubs" provides an answer to this situation. Some carriers naturally adopt the "weak hubbing" model, mainly for directional and long-haul traffic with regional feeding traffic in a network, e.g. Qantas at Singapore, British Airways at London Heathrow Airport and Emirates at Dubai. Often, "weak hubbing" schedules comprise both hubbing functions and point-to-point services between spokes and hubs. In such a network, the hubbing function facilitates passenger interlining between flights and the point-to-point service provides a channel to feed regional/domestic traffic to hubs. The figure below (Figure 2.2) illustrates a possible traffic pattern by a "weak hubbing" carrier which operates hubbing flights in the early morning and in the evening. It is noted that flight frequency in a weak hubbing network is significantly lower and the number of waves is also less than a strong hubbing model, as seen earlier.

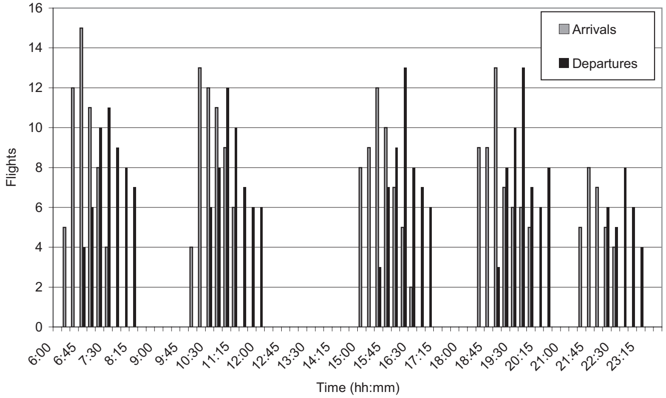

**Figure 2.1 A strong hubbing schedule (hypothetical data)**

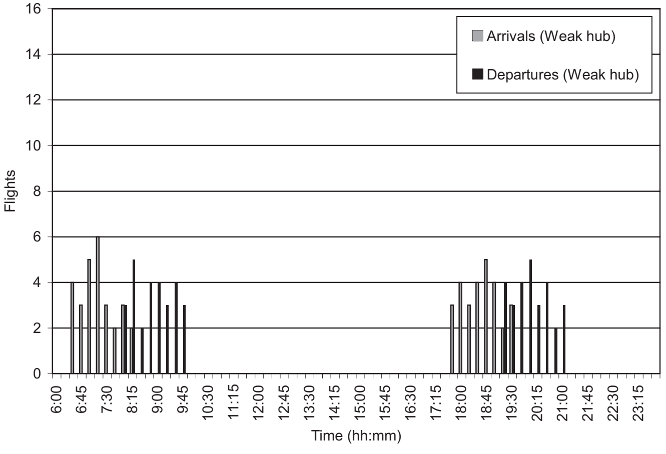

**Figure 2.2 A weak hubbing schedule (hypothetical data)**

The rolling hub model is a modified hubbing concept that came from the strong hubbing model. Although a strong hubbing network can create certain benefits, it also generates some hidden operating costs such as high delay costs in a network and low airport infrastructure utilistation (i.e. high asset costs). Since 2001, airlines have started reducing the intensity of flight hubbing by spreading the peak traffic of inbound and outbound waves more evenly during peak and off-peak hours of operations. As the peaks of inbound and outbound traffic are smoother, flight hubbing activities now do not only appear during the peak traffic period but more evenly spread out along the day, hence the name: *rolling hubs*. Rolling hubs still exhibit the structure of hubbing, but the hubbing "strength" is not as intense as the strong hubbing model. American Airlines and Lufthansa adjusted their networks and modified some hubbing airports to rolling hubs, e.g. O'Hare, Dallas-Fort Worth, and Frankfurt as shown in Figure 2.3, an example rolling hub structure. A noticeable difference between strong hubbing and a rolling hub is that a rolling hub has lower demand for peak slots and the duration of an inbound or outbound wave of flights is longer.

The point-to-point (P2P) scheduling philosophy is mostly aimed at origin/destination (OD) traffic and is often used on "trunk routes", i.e. those routes with high traffic volumes. Pure P2P networks are widely adopted by LCCs because of the traffic density on these trunk routes and the simplicity of LCC business models (Lawton 2002). P2P networks do not have the desirable "economies of density", but most LCCs still enjoy the "economies of scale" at the level of individual routes and the corporate business level by maintaining a low-cost business base. Since P2P services are aimed at OD markets, pure P2P networks often provide passengers with little or no connections (interlining services), except at those airports serving more destinations in a P2P network, e.g. Luton of easyJet and Dallas-Fort Worth of Southwest.

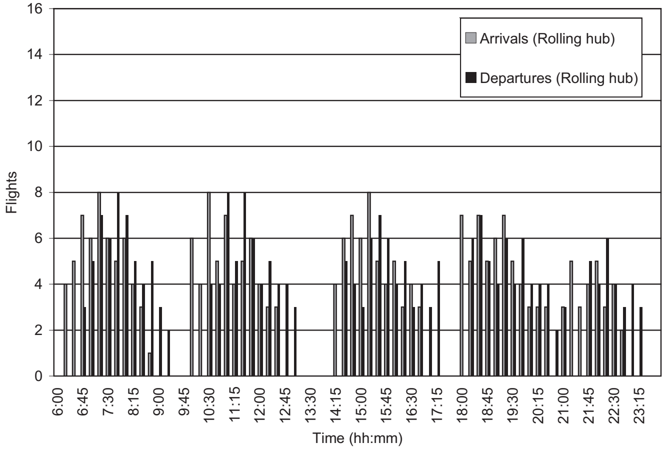

**Figure 2.3 A rolling hub schedule (hypothetical data)**

The desired attribute of limited connections of pure P2P schedules also limits the growth of this model, especially in two areas: limited inbound traffic from inter-continental operations and limited internal connecting traffic within their own network. Virgin Blue and JetBlue in the U.S. are the best examples where "low-cost interlining agreements" with inbound traffic have been utilised, often from non low-cost carriers or international partners. "Internal" connecting traffic in a P2P network can be facilitated by the "self-connection" of passengers (Malighetti et al. 2008), in which passengers buy two sectors and connect by themselves with no "through check-in or interlining services" provided by the carrier.

### *2.1.2 Airport Slots and Ground Service Infrastructures at Airports*

Regarding the technical considerations in airline scheduling philosophy, these are mostly driven by the requirements to service and maintain aircraft, as well as the physical and operational limits imposed by airports and air traffic control authorities. Among those technical considerations, the issues of landing/take-off slots and ground service infrastructures at airports are the most critical ones.

An airport slot refers to the "right to operate an aircraft (for landing or taking off) at a certain time" (IATA 2006). Slots are allocated to both departure and arrival flights and are limited by the "operating" or "regulated" capacity of an airport (Gilbo 1993). The implication of hubbing schedules is that flights arrive and depart in separate waves with a short period of separation time in between, allowing passenger connections among inbound and outbound flights. The gap between departure and arrival waves is longer than the declared "minimum connection time" at a specific airport. The intensity of arriving and departing flights reflects the strength of hubbing as well as the demand for runway slots. For strong hubbing operations, the demand for slots in the peak of a wave could be more than the capacity, while the demand in the non-peak hours is often significantly lower. The implication for airport capacity is that slot utilisation at a strong hubbing airport is often not efficient.

For rolling hub operations, the difference between peak and trough demand for slots is less than the case of strong hubbing. Accordingly, slot utilisation is more efficient throughout the day, although peaks and troughs may still exist. Flight connection times among high-demand flights are kept short in the case of a rolling hub, while the connection times for other flights could be longer due to the "spread and de-peaked" waves (Goedeking and Sala 2003). For weak hubbing operations, there is usually no clear difference between arrival and departure waves. Accordingly, connections are facilitated among those high-demand flights. For those connections with lower demand, the connection time in a weak hubbing schedule could be longer than the case in a strong hubbing scenario, but under a certain threshold, in order to make the connection commercially competitive in the market.

The high demand for airport slots also increases the demand for ground services and infrastructures at airports. In order to accommodate the arrival flights, airports need to provide enough gates, terminal spaces for connecting passengers, security screening facilities, and baggage/cargo sorting services. The hubbing operation implies that there is high demand for these infrastructures during the peaks of inbound waves and low demand during the off-peak hours. The highly fluctuating demand for airport facilities causes inefficient use of facilities, with low utilisation of facilities during off-peak hours. Since these infrastructures are expensive asset investments for airports, and in some cases, for airlines, low utilisation of airport assets translates into high fixed costs in airline businesses. Under the pressure of cost cutting in the era of post-9/11 terror attack in the U.S. in 2001, and growing competition from LCCs, many network carriers have started depeaking some hubs in the U.S. and in Europe, so as to cut operating costs.

The goal of de-peaking is to utilise more fully airport facilities and reduce "self-induced" delays due to congestion in peak-hour operations. The actual amounts saved moving from strong hubs to rolling hubs are not publicly reported in the industry. It is generally believed that in this scenario airlines lose some connection options, and hence, less products (or less attractive products due to increased connection time) can be offered in the market for connecting traffic. However, benefits are obtained through the higher utilisation of facilities and human resources at airports, as well as strengthening of key connecting markets (Goedeking and Sala 2003). There are significant implications of the scheduling philosophy of airline operations at airports. We have discussed some characteristics of the general scheduling philosophy and the potential impact on airline operations. We will now move on and explore those activities involved in airline operations on the ground at airports.

## 2.2 Aircraft Turnaround Operations

The goal of ground activities by airlines at airports is to facilitate the transport of passengers and goods under certain safety and security requirements. In addition, the operation of the aircraft itself requires certain engineering services on the ground to prepare an aircraft for a following flight. There are also logistic activities which occur on the ground at airports, providing those resources needed for on-board services such as passenger catering and aircraft fuelling. Aircraft turnaround operations, broadly speaking, cover all of these activities, in which some occur on the landside of an airport, e.g. passenger check-in, and others occur on the airside, e.g. goods loading on the ramp. Since passenger processing and goods handling involve operations on both the landside and airside of an airport, the context of this section covers both airside and landside activities and jointly discusses them from the perspective of airline operations including: aircraft turnaround operations, schedule planning and flight delays.

### *2.2.1 Passenger Processing*

The purpose of passenger processing is to facilitate the movement of passengers at airports, either departing or arriving. Passenger connection between flights involves a slightly different workflow and will be discussed in detail in later sections when we examine flight interlining services. For departing passengers, this process begins with checking in at counters (or on-line check-in as early as 48 hours before the departure time). From the perspective of airline operations, the subsequent processes that are after check-in and before passenger boarding at gates are facilitated by different authorities, including the immigration agency (for international flights), the security screening agency, and the airport authority. This is where airline operations can potentially be disrupted by non-airline processes, contributing to uncertainties in passenger processing.

Departing passengers arrive at boarding gates randomly and wait for the call from ground staff to board the aircraft. Passenger boarding starts from 15 minutes before the departure time for narrow-body aircraft operation such as B737s, to 40 minutes before for jumbo jet operations such as B747s. Depending on airline business models and ground operating procedures, airlines use different boarding methods. For instance, many LCCs adopt the “free-seating” policy for passenger boarding to encourage passengers to arrive at the gate and board the aircraft early, so as to choose preferred seats. This tactic also avoids the process of assigning seats to passengers, so LCCs can reduce operating costs. Other airlines may use the “random” boarding method or even the “back-to-front” method, which is preferred by some network carriers. More passenger boarding methods will be discussed in detail in Chapter 3.

For arriving passengers the processes are simpler, from passenger disembarkation, immigration checks (international flights only), baggage claim, custom checks (international flights only) to leaving the terminal. Little passenger processing by airlines is involved here, except baggage unloading and baggage services for missing bags.

### *2.2.2 Goods Handling*

Goods handling includes the handling of passenger bags and cargo (including mail). Passenger bags are checked in at counters and X-Rayed immediately after passenger check-in before baggage sorting and loading on to an aircraft. A simplified baggage flow at an airport from passenger check in to baggage loading is shown in Figure 2.4. Baggage sorting can be automatic (by RFID or barcodes), semi-automatic or fully manual for small airports, while baggage loading is often operated manually by baggage handlers with loading equipment such as trailers, mini trucks and conveyors. Even in an automatic baggage sorting system, it is often impossible for the scanning and sorting system to reach 100 per cent successful identification. Hence, manual scanning is often involved in an automatic baggage sorting system with a separate manual processing line as illustrated in Figure 2.4.

Depending on the type of an aircraft, baggage can be stored in Unit Load Devices (ULDs), on pallets, or even loosely stored in the belly space for smaller planes. Different ways of baggage processing, storage and loading require different operating times and are subject to different sources of operating disruptions.

For connecting passengers, if a change of plane is involved in a journey, then passenger bags need to be unloaded from the first plane and fed into the baggage sorting system during the connection time of a journey. This process is illustrated in Figure 2.4 in which there is a feeding conveyor that transports inbound connecting bags to the baggage sorting system. Sorted connecting bags are then loaded to the departing aircraft as locally checked-in baggage does. Due to these extra baggage transportation and sorting processes, the connection time between flights at an airport has a specified "minimum time" in order to ensure that connecting bags can be loaded on departure flights before the scheduled departure time. This baggage handling time often significantly influences the "minimum connection time" between flights that an airline can offer at a specific airport. In turn, this constrains airline competitiveness in the commercial world in terms of product offering and the competitiveness of these products. Regarding inbound passenger bags, the process is reversed as shown in Figure 2.5. Custom and quarantine authorities take over baggage screening after passengers have claimed their bags, especially for international inbound travellers.

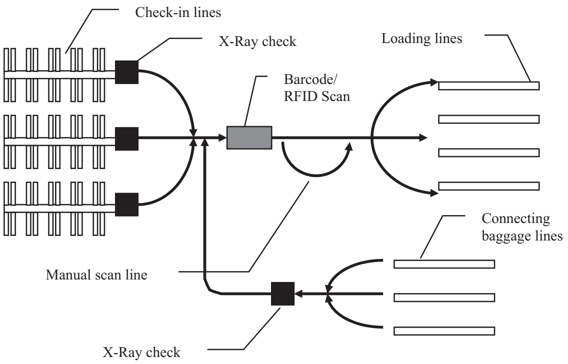

**Figure 2.4 Outbound and connecting baggage handling flows**

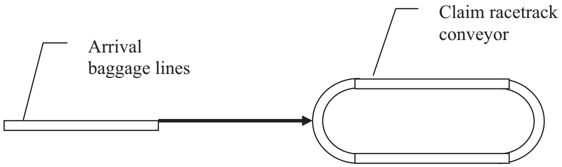

**Figure 2.5 Inbound baggage handling flows**

Outbound cargo is usually processed at cargo centres close to an airport. Since passenger bags enjoy priority in loading, cargo loading is often processed after the “weight and balance” calculation is finalised for passenger loading. Apart from freighters, passenger aircraft can carry only a certain amount of belly cargo, depending on the available weight of an aircraft after passenger and bags loading, and often more critically, depending on the space available. Belly cargo operation is a relatively small operation when compared with passenger chartering, although it can be significant for some international routes and even more financially significant when the passenger transport volume declines. Belly cargo operations may improve the financial bottom line of airlines during periods of global market downturn such as the one post the burst of the technology bubble and the 9/11 attack in the U.S. in 2001.

### *2.2.3 Interlining Services*

Connecting passengers are aided by “interlining services” between flights by different carriers or with the same carrier. This service simplifies passenger connection via “through check-in” for both passengers and bags between the origin and destination. At the connecting airport where passengers transfer between flights, baggage and cargo are also processed for transfer. The time required to process connecting passengers and baggage at an airport determines the “minimum connection time” of an airline at the airport, which in turn influences the available connections between inbound and outbound flights at hub airports. A shorter minimum connection time between flights creates more connection opportunities within the same connecting window, say 90 minutes. Accordingly, carriers will be able to offer more connections and be more competitive in the connection market via a specific hub. This is why it is so important for major hub airports to maintain efficient passenger and baggage handling in order to maintain the competitiveness of airport operations.

Connecting passengers may go through security screening again before boarding an outbound flight, especially for international flights. Since there is a distance between the arrival gate and the departure gate of an outbound flight (and for international connections, these gates are often located on different levels), connecting passengers need to travel to the departure lounge within a given connection time. This imposes some pressure on connecting passengers, especially when their inbound fight is late.

Connecting baggage and cargo both go through the unloading, sorting and loading processes for outbound flights within the same connection time. Depending on the sorting facilities of an airport, this operation may take less time for newer sorting facilities, e.g. Cathay Pacific at Hong Kong International Airport, and more time for other airports, e.g. two-hour connection from international to domestic flights at some U.S. airports. To ensure passenger and baggage connections, some ground handling agents at hub airports have special operating units whose duty is to ensure urgent connections, with short connection time, are made. For instance, a Quick Transfer Unit (QTU) was developed at Paris Charles de Gaulle (CDG) Airport, helping the hubbing operations of Skyteam, Star Alliance and Oneworld Alliance with up to 3,000 connection possibilities per day in 2006 including connecting bags of passengers (Goldnadel 2007). With the influence of airline alliances increasing, airlines in the same alliance often request to use gates near each other at the same terminal, in order to reduce the connection time for passengers, baggage and cargo. This is already seen at the new Terminal 5 of London Heathrow Airport where Oneworld Alliance will host most operations, and the Terminal 3 of Singapore Changyi Airport, which will be occupied by Star Alliance.

### *2.2.4 On-board Services*

A major part of the "product" that an airline offers to customers is the services that customers receive aboard an aircraft. Regardless of the "classes" of cabins on board, there are two types of services, namely catering services and entertainment services. Catering services provide passengers with snacks, light meals or main meals, depending on the duration of the flight, and the time within the flight the service is offered. Now passengers on some domestic flights are not provided with meals but only snacks and drinks. This is partly due to cost cutting by airlines and partly due to the realisation that not all passengers require meal services, especially for a short travel time aboard. For those passengers who need catering services, some airlines have successfully converted this service from a "cost" item to the airline business in the past to a "revenue" item by offering on-demand catering services on a user-pay basis. This is the tactic adopted by most low-cost carriers and gradually by full-service carriers around the world. On mid- to long-haul operations, this strategy has also been adopted by low-cost carriers, e.g. Jetstar Airways in Australia.

In aircraft turnaround operations, catering services are conducted independently with other turnaround activities, depending on the location of galleys on an aircraft. For narrow-body jets, galleys are often located at the rear of an aircraft, so catering unloading and loading can take place at the same time as passenger disembarkation and boarding. For larger wide-body jets, passenger disembarkation and boarding interfere with catering processing at the galleys aboard the plane, so there are usually separate catering workflows to facilitate passenger boarding, catering loading and cabin cleaning activities during aircraft turnaround operations. The reduction in complementary catering services on board also reduces the time required to finish catering unloading and loading; accordingly, this reduces the time required for aircraft turnaround operations. This has a profound impact on designing the procedures of aircraft turnaround operations and on increasing aircraft utilisation, due to less time spent on the ground for aircraft. More details on aircraft turnaround procedures will be examined in Chapter 3.

Entertainment services include newspapers, magazines and in-flight entertainment programmes. With the increased offering of on-demand in-flight entertainment programmes, airlines need to prepare these programmes during aircraft turnaround time, especially for long-haul international flights. Some programmes are pre-loaded on entertainment systems aboard an aircraft, while some programmes are uploaded for specific flights during turnaround. The uploading of video/audio programmes can take time, depending on the channel of uploading (wireless or wired) and the media used for loading. Live television programmes have gained popularity since JetBlue Airways introduced its DirectTV service across its fleets back in 2000 (Shifrin 2004). The DirectTV service utilises satellite communication channels, so avoids the need to upload entertainment programmes during aircraft turnaround.

### *2.2.5 Aircraft Services*

A major duty in the aircraft turnaround process is providing the required services to the aircraft itself such as: refuelling, routine visual engineering check, and auxiliary power unit (APU) services. Refuelling an aircraft is perhaps the most critical activity (service time-wise) for LCC short-haul operations, due to the very limited turnaround time for each flight. Some flights by Southwest, Ryanair and easyJet are reported to have a turnaround time for B737 as short as 15 minutes. Even a longer 20-minute turnaround time can put some pressure on aircraft refuelling, depending on whether a fuel truck or only a pump truck is needed on the ramp of an airport. The use of fuel trucks to transport fuels from depots to aircraft gates takes time and can be disrupted due to the logistic scheduling of fuel trucks on the tarmac.

Routine engineering checks are also conducted on the ramp and usually involves visually inspecting the aircraft body and engines. This service is to ensure that there is no visible damage to engines and aircraft body due to “foreign objects” (e.g. bird strikes), and the aircraft is suitable to conduct those following flights scheduled for the remaining day. In some scenarios, further inspection will be conducted beyond visual inspection if the monitoring systems on an aircraft indicate such a need. If prompt engineering service cannot resolve the issue, further aircraft down time is needed and may cause long delays and schedule disruption. Auxiliary Power Units (APUs) are used to provide an aircraft with external power when engines are switched off. This is usually the case when air conditioning is required for an aircraft, if the aircraft is parked at a remote airport stand for an extended period of time in cold or hot conditions. However, the use of APUs on the apron often causes air pollution issues because of the fuel burning by some APUs.

The activities involved in aircraft turnaround operations are best described by Figure 2.6. The figure shows the activities required to turn around a B737 for domestic operations by a carrier. There are two important messages to be taken from this chart. First, some activities are conducted sequentially on the time line, e.g. cabin cleaning starts after passenger disembarkation. Accordingly, delays to some services may cause delays to other services “down the line”. Second, the service time of activities determines the total required time for turning around an aircraft, meaning the shorter the individual service time of each activities, the shorter the total aircraft turnaround time is. This explains how LCCs can pursue short turnaround time and high daily aircraft utilisation. This chart will also play an important role when we discuss the allocation of aircraft ground time in a schedule in the next section and the modelling of aircraft turnaround operations in Chapter 3.

## 2.3 Schedule Constraints and Delays

### *2.3.1 Delays and Schedule Flexibility*

Schedule delays are common occurrences in airline operations, given the many operational tasks involved, the stochastic nature of operating time, and unexpected disruptions in operations. In addition, airlines operate in an environment in which airlines have limited control over the system constraints, including airport capacities and airspace capacities. The complex interaction between the planned (and fixed) airline schedules and stochastic disruptions may cause flight delays.

Flight delay refers to the time difference between the scheduled departure/arrival time and the actual departure/arrival time of a flight on the day of operation. By definition, it may occur that delays are "negative", meaning early departure or early arrival of a flight. Negative delays are often not an issue and occur when the schedule is running close to plans. However, early departures and arrivals can cause minor issues for airport operations, because early departure requests may disrupt the sequencing of departing flights and early arrivals may disrupt the allocation of gates, especially during peak hours at busy airports.

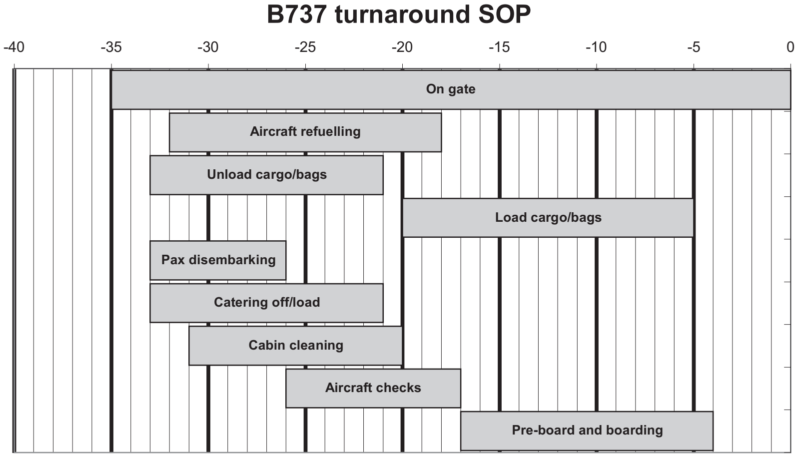

**Figure 2.6 B737 turnaround operations for domestic flights**

On the other hand, “positive” flight delays are often causes of concern for airlines and passengers. Flight delays are frequently cited by the industry and aviation research to be among the important factors which may significantly impact passenger satisfaction and re-purchase intention in the future (Doganis 2002; Holloway 2008), and even the market share and financial performance of an airline (Bhat 1995; Suzuki 2000). Analytically, the relationship between the planned schedule, arrival (inbound) delay, operational delay and departure (outbound) delay can be modelled by Figure 2.7. For the convenience of delay modelling in the remaining sections of this chapter, the notations used hereafter (including those in Figure 2.7) are summarised below and are also seen in the Appendix of this chapter.

| | |
|---|---|
| $f_{ij}$ | flight *i* of route *j* that departs Airport A and arrives at Airport B (as in Figure 2.7) |
| $f_{(i-1,j)}$ | the flight flown before $f_{ij}$ on route *j* operated by the same aircraft |
| $s^{A}_{ij}$ | the scheduled time of arrival of $f_{ij}$ |
| $t^{A}_{ij}$ | the actual time of arrival of $f_{ij}$ |
| $s^{A}_{(i-1,j)}$ | the scheduled time of arrival of $f_{(i-1,j)}$ |
| $t^{A}_{(i-1,j)}$ | the actual time of arrival of $f_{(i-1,j)}$ |
| $s^{D}_{ij}$ | the scheduled time of departure of $f_{ij}$ |
| $t^{D}_{ij}$ | the actual time of departure of $f_{ij}$ |
| $S^{TR}_{ij}$ | the scheduled turnaround time of $f_{ij}$ at Airport A |
| $S^{BX}_{ij}$ | the scheduled block time of $f_{ij}$ |
| $d^{A}_{(i-1,j)}$ | the arrival delay of $f_{(i-1,j)}$ and $d^{A}_{(i-1,j)} = t^{A}_{(i-1,j)} - s^{A}_{(i-1,j)}$ |
| $d^{D}_{ij}$ | the departure delay of $f_{ij}$ and $d^{D}_{ij} = t^{D}_{ij} - s^{D}_{ij}$ |
| $d^{A}_{ij}$ | the arrival delay of $f_{ij}$ and $d^{A}_{ij} = t^{A}_{ij} - s^{A}_{ij}$ |
| $d^{OP}_{ij}$ | the delays due to turnaround operations of $f_{ij}$ |
| ${}_{G}S^{b}_{ij}$ | the scheduled ground buffer time of $f_{ij}$ at Airport A |
| ${}_{A}S^{b}_{ij}$ | the scheduled airborne buffer time of $f_{ij}$ en-route Airport A and B |

| | |
|---|---|
| $\hat{h}_i$ | the realised (actual) turnaround time of $f_{ij}$ |
| $f_i(h)$ | the stochastic distribution of $\hat{h}_i$ with mean value, $\overline{h}_i$ |
| $\hat{k}_i$ | the realised (actual) flight time of $f_{ij}$ between Airport A and B |
| $f_i(k)$ | the stochastic distribution of $\hat{k}_i$ with mean value, $\overline{k}_i$ |
| $f_i(t)$ | the stochastic distribution of the actual arrival time of $f_{ij}$, i.e. $t_{ij}^A$ |
| $g_i(t)$ | the stochastic distribution of the actual departure time of $f_{ij}$, i.e. $t_{ij}^D$ |
| $g_i'(d_{ij}^D)$ | the function of departure delay; $g_i'(d_{ij}^D) = g_i(t_{ij}^D - s_{ij}^D) = g_i(t) - s_{ij}^D$ |
| $m_1$ | the efficiency of delay absorption by the scheduled buffer time of $f_{ij}$ |
| $m_2$ | the efficiency of turnaround operations at Airport A |
| $C_P(d_{ij}^D)$ | the passenger delay cost function with a marginal delay cost function, $\gamma_P^m(d_{ij}^D)$; a function of delay time $d_{ij}^D$ |
| $C_{AC}(d_{ij}^D)$ | the aircraft delay cost function with a marginal delay cost function, $\varphi_{AC}^m(d_{ij}^D)$; a function of delay time $d_{ij}^D$ |
| $C_{AL}({}_G S_{ij}^b)$ | the opportunity cost of aircraft time with a marginal schedule time cost function, $\delta_{AL}^m({}_G S_{ij}^b)$; a function of ground schedule buffer time, ${}_G S_{ij}^b$ |
| $C_T$ | the total cost of the schedule time optimisation model, including the cost of delays, $D_C$ and the cost of schedule time, $S_C$ |
| $D_C$ | the expected cost of delays including passenger delay cost, $C_P(d_{ij}^D)$ and aircraft delay cost, $C_{AC}(d_{ij}^D)$ |
| $S_C$ | the cost of schedule time calculated by $C_{AL}({}_G S_{ij}^b)$ |
| $\alpha$ | the weight factor, representing the trade-off between delay cost and schedule time cost |

In Figure 2.7, flight $f_{ij}$ originates from Airport A and is scheduled to leave for Airport B by the scheduled time of departure, $s_{ij}^{D}$. $f_{(i-1,j)}$ is the flight flown before $f_{ij}$ on "route" *j* that is operated by the same aircraft. A *route* is a series of flight legs that is assigned for operation by an aircraft within a period of time. For illustration purposes, we assume that flight $f_{(i-1,j)}$ arrives late at Airport A by an arrival delay of $d_{(i-1,j)}^{A}$ which is analytically defined by $d_{(i-1,j)}^{A} = t_{(i-1,j)}^{A} - s_{(i-1,j)}^{A}$. Since flight $f_{(i-1,j)}$ and $f_{ij}$ are operated by the same aircraft on the same route *j*, flight $f_{ij}$ incurs an inbound delay of the same amount, $d_{(i-1,j)}^{A}$ as shown in Figure 2.7.

The common methodology to design the scheduled turnaround time ($S_{ij}^{TR}$) for $f_{ij}$ is to combine two components in the turnaround time, namely the mean turnaround time to finish ground services and the ground buffer time, ${}_{G}S_{ij}^{b}$ to compensate arrival delays due to late inbound aircraft, i.e. $d_{(i-1,j)}^{A}$ or delays occurred in turnaround operations, $d_{ij}^{OP}$. In some cases, the scheduled turnaround time also needs to consider the time required for passenger connections from other inbound flights to $f_{ij}$, especially if a hubbing schedule is operated at Airport A.

If delays ($d_{ij}^{OP}$) due to disrupting events in turning around flight $f_{ij}$ at Airport A together with the inbound delay $d_{(i-1,j)}^{A}$ are higher than the scheduled ground buffer time ${}_{G}S_{ij}^{b}$, then flight $f_{ij}$ may incur departure (outbound) delay by $d_{ij}^{D}$, depending on the "realised" turnaround time of $f_{ij}$ on the day of operation. $d_{ij}^{D}$ is analytically defined by $d_{ij}^{D} = t_{ij}^{D} - s_{ij}^{D}$. Disrupting events in this context may come from aircraft turnaround operations as well as from connecting crew and passengers from other flights.

A certain amount of airborne buffer time, ${}_{A}S_{ij}^{b}$ is often embedded in the block time of flight $f_{ij}$ to absorb delays due to airport congestion at both ends of the flight. If flight $f_{ij}$ is further delayed en-route and this delay together with the outbound

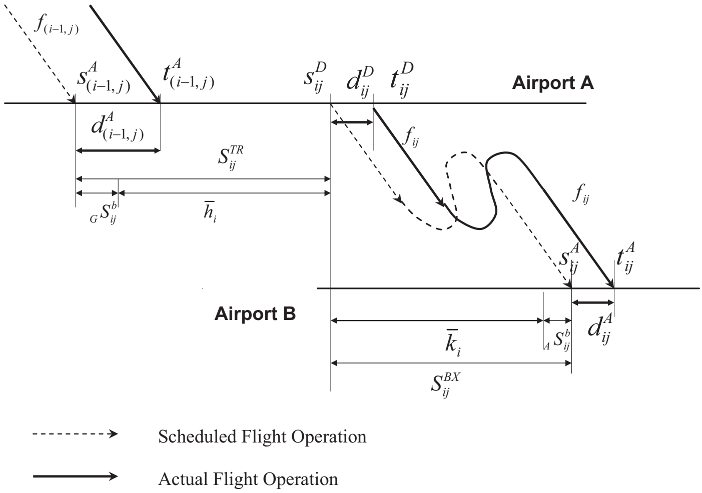

**Figure 2.7 The relationship between schedules, turnaround times and delays**

delay, $d_{ij}^{D}$ cannot be fully compensated for by the airborne buffer time, ${}_{A}S_{ij}^{b}$, then flight $f_{ij}$ would incur arrival (inbound) delay at the destination Airport B, i.e. $d_{ij}^{A}$ ($d_{ij}^{A} = t_{ij}^{A} - s_{ij}^{A}$). This example also demonstrates how inbound delays and ground operational delays to flight $f_{ij}$ at Airport A may cause the arrival delay of flight $f_{ij}$ at Airport B.

Delays due to disruptions of ground operations at Airport A may exacerbate the situation by cancelling out the function of the built-in ground buffer time of $f_{ij}$. The inbound delay at Airport B may further cause delays to other flights that receive inbound connecting passengers, crew or goods from $f_{ij}$ at Airport B, causing delay propagation within the network. The development of delays within a network will be further discussed in Chapter 4, when the concept of network operation is introduced.

### *2.3.2 Stochastic Service Time of Turnaround Activities*

Airline schedules and flight timetables are usually planned well ahead of the operation. The challenge of managing aircraft turnaround operations is to ensure that ground operations for turning around an aircraft finish within the planned turnaround time, as denoted by $S_{ij}^{TR}$ in Figure 2.7 earlier. The crux of this challenge is in the fact that the service time for most activities in turnaround operations is stochastic in nature. Passenger processing time is often proportional to the number of boarding and connecting passengers of a specific flight. Accordingly, some on-board services for passengers take longer to accomplish, when more passengers are boarding an aircraft, e.g. catering services and baggage processing. Aircraft re-fuelling may also take longer, as the take-off weight of an aircraft increases.

Due to the stochastic nature of operating times of ground services, one way to alleviate the impact of this uncertainty is to incorporate a buffer time in the scheduled turnaround time, e.g. the ${}_{G}S_{ij}^{b}$ in Figure 2.7. Hence, the actual (realised) turnaround time of $f_{ij}$ on the day of operation determines departure delays and can be modelled by (2.1):

$$d_{ij}^{D} = d_{(i-1,j)}^{A} + \hat{h}_{i} - S_{ij}^{TR} = d_{(i-1,j)}^{A} + \hat{h}_{i} - ({}_{G}S_{ij}^{b} + \bar{h}_{i}) \tag{2.1}$$

where $\hat{h}_{i}$ is the realised turnaround time of $f_{ij}$ and is a stochastic variable; the distribution of $\hat{h}_{i}$ is $f_{i}(h)$ and is a stochastic function with a mean value of $\bar{h}_{i}$, i.e. the "mean turnaround time" as shown in Figure 2.7. It can be seen from (2.1) that airline schedules form a "fixed boundary", i.e. $S_{ij}^{TR}$, while other variables in (2.1) are stochastic, causing the departure delay of $f_{ij}$, $d_{ij}^{D}$ a stochastic variable as well. The flexibility of airline schedule comes from the planned ground buffer time, i.e. ${}_{G}S_{ij}^{b}$ in (2.1), that is designed to compensate inbound delays to $f_{ij}$, $d_{(i-1,j)}^{A}$. There are chances that $S_{ij}^{TR}$ may over-compensate the total of inbound delay and actual turnaround time, $(d_{(i-1,j)}^{A} + \hat{h}_{i})$. For these cases, an early departure with a "negative" departure delay is possible.

### *2.3.3 Attributes of Turnaround Operations*

Since the service times of activities in aircraft turnaround operations are stochastic and may depend on passenger load, the time required to turn around an aircraft is stochastic as well. As discussed briefly in Section 2.2 earlier, there are two important attributes of airline ground operations. First, some activities need to be conducted sequentially on the timeline, while some can be conducted on parallel with other activities. The implication is that any disruptions to a component of ground operations can cause "knock-on" effects to other processes and can cause delays to departure flights. For instance, a delay of baggage unloading at the apron may cause a delay to baggage loading, which may also cause delays to connecting passengers and goods to other flights at the same airport.

Second, the total time required to turn around an aircraft has a profound impact on airline scheduling and airline operations. When various aircraft turnaround activities are treated aggregately as a "single" process, we will not observe the influence of individual processes on the whole operation. Instead, the turnaround operation is seen as a "black box" which receives an input delay (from an inbound flight) and generates an output delay (for an outbound flight). This approach provides us with a "macro" view of aircraft turnaround operations and simplifies the observation and modelling work needed to study airline schedules. Also, this approach provides us with the "standard" turnaround time needed for different types of fleets and sometimes for similar operations at different airports in a network.

With historical data of flight operations, one can plot the distribution curve, i.e. the probability density function (PDF) of the "realised" turnaround time, $f_i(h)$ for flight $f_{ij}$ over a period of time. These PDFs can reveal important information such as: (a) the mean departure and arrival delay of $f_{ij}$, i.e. $d_{ij}^D$ and $d_{ij}^A$; and (b) the variance of departure and arrival time of $f_{ij}$, i.e. the range of $t_{ij}^D$ and $t_{ij}^A$. Together with data of the actual turnaround time ($\hat{h}_i$), the PDFs of flight delays help airlines conduct post-operation delay analyses and design the optimal turnaround time for ground operations. Accordingly, this helps shape airline schedules, networks and aircraft utilisation and improve operational efficiency as well as financial bottom line.

## 2.4 The Optimal Turnaround Time – Empirical Methods

### *2.4.1 The Pursuit of Optimal Turnaround Time*

It can be seen from the discussions in previous sections that airline schedules impose constraints on airline operations, both on the ground and en-route between airports. Hence the design of an airline schedule is critical in that the desired or the ideal schedule should provide airlines with adequate "flexibility" to absorb unexpected disruptions and delays, while the schedule should also generate high "productivity" of airline assets by utilising aircraft time for revenue-making block time. Accordingly, airlines design aircraft turnaround time to absorb inbound delays due to late aircraft. The aircraft turnaround time is designed to minimise the impact of disruptions on flight departures during airline ground operations. This is a trade-off situation in which on one hand, long turnaround time reduces delays and stabilises airline operations, but on the other, long turnaround time reduces the utilisation of aircraft, because ground time could otherwise be used somewhere else in the network as revenue-making block time. Hence, there is always a desire to pursue the optimal turnaround time design for airlines.

Two models will be introduced in this section and the next. The first model is an ad hoc approach, namely the *Empirical Model* that involves the use of statistical techniques and stochastic theories to model distributions of flight delays and determine the optimal allocation of turnaround time and block time for a schedule. This approach provides a quick solution to the issue of turnaround/block time allocation by considering the uncertainties involved in real operations. The second model is an aggregate analytical model, namely the *Turnaround Time Allocation* (TTA) model, which involves modelling the stochastic distributions of flight delays and delay costs in order to explore the trade-off scenarios during airline schedule planning. This approach provides an analytical tool for exploring and evaluating scheduling policies, which is often required at the early stages of strategic schedule planning. Both models are based on stochastic and statistical theories, reflecting the stochastic nature of airline operations and the uncertainties involved in the environment of airline operations.

### *2.4.2 The Empirical Model*

This model is widely used by airlines as an ad hoc approach to model flight delays with uncertainties. The theoretical foundation of this model is based on stochastic theories, by which the actual arrival time of a flight is modelled as a stochastic variable, denoted by $t_{ij}^{A}$. The collection of previous actual arrival times of the same flight ($f_{ij}$) over a period forms a stochastic distribution, denoted by $f_i(t)$. The actual departure time of $f_{ij}$ is also a stochastic variable, denoted by $t_{ij}^{D}$ and the distribution of departure time is $g_i(t)$.

Historical data are used to plot the probability density function (PDF) of a chosen flight. According to stochastic theory, the more samples one has, the more closely the PDF will resemble the real curve, which is unknown. When the arrival time samples are plotted against the frequency of occurrence, a PDF may look like Figure 2.8. The PDF of the example Flight 902 is represented by the line with box legends. Since early arrivals (with "negative" delays) are treated as zero delays, the PDF function does not span to the negative side of the x-axis. The purpose of plotting the PDF curve is to visually study the delay pattern of this flight.

PDF curves can be converted into cumulative density functions (CDFs) as the line shown in Figure 2.8 with triangle legends. With CDF curves, we can clearly see the on-time performance (OTP) of the study flight according to past operations.

The on-time probability (zero delay, denoted by "D0") is around 40 per cent, while the 15-minute delay probability (denoted by "D15") is about 70 per cent as shown by the arrows on the figure. Similar methods can be used to construct the PDFs and CDFs when studying departure patterns of flights.

For some situations, it is a good idea to model aircraft turnaround processes aggregately. One reason is to simplify the modelling process as well as the model itself. The other reason is often due to the limited availability of operating data, or modelling "convenience" at the time of model building. In our Empirical Model, the aircraft turnaround process is modelled as a "black box" process, i.e. aggregately as a "single" process combining all activities. Hence, the relationship between the arrival time PDF of an inbound flight $f_{i-1}(t)$, turnaround operation of $f_{ij}$ and the departure time PDF of an outbound flight $g_i(t)$ can be described by Figure 2.9.

Analytically, the distribution $g_i(t)$ is a function of three variables as formulated previously in (2.1), including the actual time of arrival $t^A_{(i-1,j)}$, the actual turnaround

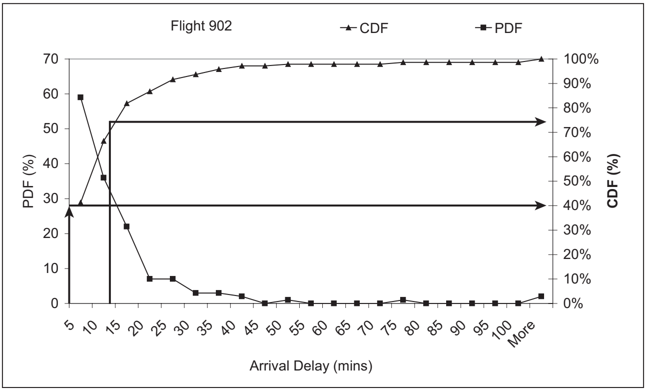

**Figure 2.8 The PDF and CDF of Flight 902**

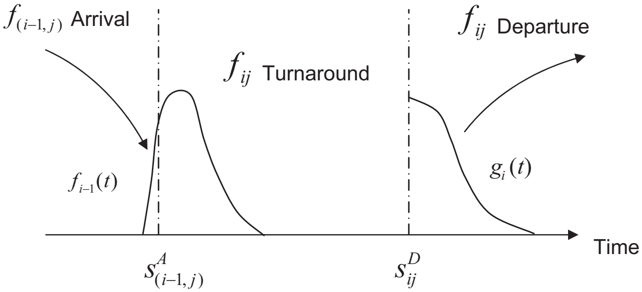

**Figure 2.9 Relationships between arrival PDF and departure PDF**

time $\hat{h}_i$, and the scheduled turnaround time $S_{ij}^{TR}$. The objective of the following model is to minimise the probability of incurring delays by adjusting the scheduled turnaround time, $S_{ij}^{TR}$. Since the actual turnaround time $\hat{h}_i$ is stochastic, the objective is to design a turnaround time that is long enough to allow $\hat{h}_i$ and meanwhile, allow some buffer to cover inbound delays and operational delays on the ground.

### *2.4.3 Model Implementation*

A simple and straightforward approach to implement the Empirical Model is to plot the CDF of the actual turnaround time ($\hat{h}_i$) from the PDF of $\hat{h}_i$, i.e. $f_i(h)$. The resulting CDF, $F_i(h)$ is illustrated in Figure 2.10. In this example, the scheduled arrival time of the inbound flight before Flight 208 is at 17:50 and the scheduled departure time at 18:20, allowing a turnaround time of 30 minutes for Flight 208. The standard turnaround time for the specific aircraft type (B737) is assumed to be 25 minutes by a low-cost carrier (hence, five minutes buffer time). The actual turnaround time CDF of Flight 208, $F_i(h)$ in Figure 2.10 shows that 50 per cent of past turnarounds took less than 30 minutes.

Airlines often have an operational target, say 80 per cent for turnaround operations, which is the on-time probability target that airlines wish to "cover" by the scheduled turnaround time. In other words, according to historical data of the study flight, there will be an 80 per cent chance that the actual turnaround time of a real operation takes less than the designed turnaround time, which is 37 minutes in this example as shown in Figure 2.10 above (the mean of the bin 35–40 mins is taken as the mid point of the chosen bin on the x-axis). Analytically, the difference between 37 and 25 minutes is the required ground buffer time, i.e. 12 minutes to achieve the 80 per cent coverage target. Accordingly, the optimal scheduled departure time for Flight 208 becomes 18:27.

The previous approach did not consider the influence of inbound delays on departure delays of Flight 208. Ideally, the average inbound delay of $f_{(i-1,j)}$ would be minimum, because most inbound delays of $f_{(i-1,j)}$ are expected to be absorbed by the scheduled block time of the inbound flight. In reality, the average inbound delay of $f_{(i-1,j)}$ is often significant, although not always large. In the above example, if the average inbound delay of $f_{(i-1,j)}$ is $\overline{d}_{(i-1,j)}^{A}$, then the CDF plotted for allocating turnaround time should be the actual departure time of $f_{ij}$, i.e. $g_i(t)$ from historical data and the CDF of $g_i(t)$, noted by $G_i(t)$ as seen in Figure 2.11. To achieve 80 per cent departure punctuality, the optimal scheduled departure time for Flight 208 in this example will be 18:37 (taking the mid point of the category bin between 18:35 and 18:40). Accordingly, the scheduled turnaround time becomes 47 minutes, which is higher than the previous result (37 minutes) that did not consider regular inbound delays.

The second approach described here is used by airlines more often than the previous one, because of the significant impact of inbound delays for most flights.

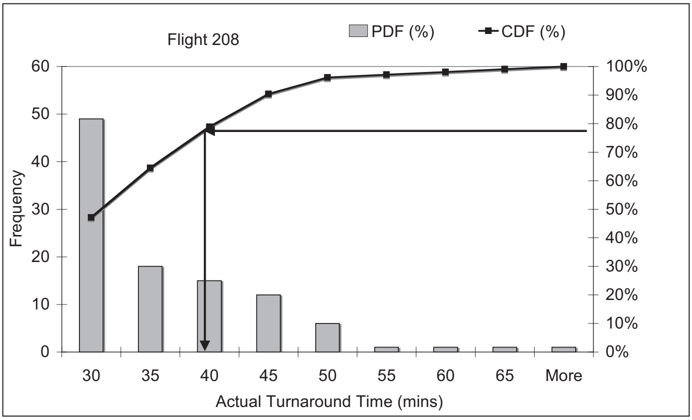

**Figure 2.10 The PDF/CDF of actual turnaround time of Flight 208 samples**

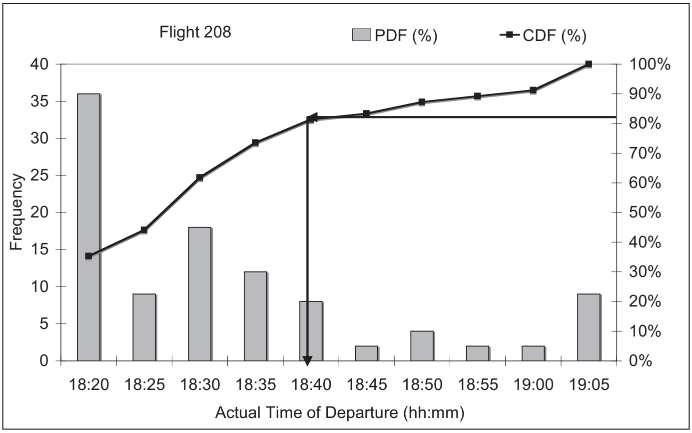

**Figure 2.11 The PDF/CDF of actual departure times of Flight 208**

It is clearly seen from this example that by considering inbound delays due to late aircraft arrival, the low-cost carrier in this example needs to schedule 47 minutes for Flight 208, in order to achieve the schedule reliability target, i.e. 80 per cent. Hence, this approach results in scheduling more time for aircraft turnarounds. One can also see that if the carrier focuses on reducing inbound delays, then the required turnaround time for this example can be reduced from 47 minutes to 37 minutes, thus leading to an improvement in aircraft utilisation and flight punctuality.

This approach is a common scheduling technique used by LCCs as well as network carriers. However, the delay propagation effect on other flights in a network is not always clear to airlines. Hence, most airline schedules do not necessarily reflect this consideration. Without this consideration in schedule planning, one can observe clear delay propagation in schedule operations, especially for LCCs and strong hubbing airlines. To counter this potential impact on schedule reliability, LCCs often deploy long buffer times in the midday as a "fire break time" in order to control delay propagation in a network. In addition, the choice of using secondary airports by LCCs also reduces the risk of incurring operational delays on the ground, because these airports are usually regional airports and have less traffic (and congestion) than major airports. In turn, this reduces the likelihood of delay propagation and its impact on airline operations.

## 2.5 The Optimal Turnaround Time – Analytical Methods

### *2.5.1 Analytical Models*

The Empirical Model introduced in Section 2.4 is often used as a quick approach to evaluate current flight delay patterns and how the planned schedule is functioning, especially on the adequacy of scheduled ground time in the schedule. The Empirical Model, however does not allow an analyst to evaluate scheduling questions such as the variation of scheduled turnaround time and the efficiency of turnaround operations at different airports. In order to evaluate the potential impact of schedule changes on flight delays and delay related costs, an analytical model, called the *Turnaround Time Allocation* (TTA) optimisation model is introduced in this section.

The objective of this model is to provide airline schedulers with an evaluation tool that can be applied at the stage of schedule planning for different scheduling considerations. This is especially valuable for considering trade-offs involved in airline schedule planning such as the use of buffer time and the efficiency of ground operations. Some simplifications and assumptions are made during the following modelling processes. Although simplification in modelling may cause gaps between the model and the real system, simplification is commonly seen in analytical approaches due to limited resources such as time and budget, and potentially numerous constraints in problem solving (Klafehn et al. 1996).

### *2.5.2 Delay Development Mechanism*

The relationship between departure delay, arrival delay of the previous flight (by the same aircraft), aircraft turnaround operation time and the scheduled turnaround time in a schedule is previously formulated by (2.1). We can see that aggregately, the departure delay of a flight is influenced by the inbound arrival delay of the aircraft as well as the actual time required to finish aircraft turnaround operations. The scheduled turnaround time is designed to control delays from both the inbound aircraft and ground operations. If the turnaround process of an aircraft is modelled as an "input-output model", then the "input" is arrival delay and the "output" would be departure delay. A critical component in an "input-output model" is the description of the mechanism by which an input is converted or transformed into an output. The transforming mechanism in modelling flight delays is the process by which inbound delay develops into outbound delay by considering the effects of the scheduled turnaround time, i.e. $S_{ij}^{TR}$, including the planned ground buffer time, ${}_{G}S_{ij}^{b}$.

The scheduled ground buffer time is designed to absorb arrival delays and unexpected delays due to ground handling disruptions. The mean turnaround time, $\bar{h}_i$ represents the standard service time for ground handling agents to complete operational procedures to turn around an aircraft for a following flight. Due to the complexity of aircraft turnaround procedures, delays to turnaround aircraft may be caused by many factors such as ground handling equipment serviceability, passenger connections, passenger delay, and aircraft arrival delay. A critical function of turnaround operations by airlines, apart from preparing aircraft for subsequent flights, is to decrease the magnitude of departure delay to the lowest possible level within the given turnaround time. Hence, the operational efficiency of ground operations is critical in controlling delay propagation in an airline network, due to flight connections by aircraft routing.

The development mechanism of departure delay is illustrated in Figure 2.12. If the arrival delay of $f_{(i-1,j)}$, noted by $d_{(i-1,j)}^{A}$ is shorter than the scheduled buffer time, ${}_{G}S_{ij}^{b}$ for the turnaround of $f_{ij}$, then the arrival delay will be partially or fully absorbed by the scheduled buffer time. The delay absorption "performance" of schedule buffer time is denoted by $m_1$, i.e. the slope of the early portion of the delay time development curve before ${}_{G}S_{ij}^{b}$ as shown in Figure 2.12. When the arrival delay is larger than the buffer time ${}_{G}S_{ij}^{b}$, the resulting departure delay of $f_{ij}$ may develop according to one of three scenarios. First, as indicated by curve $f_2$ in Figure 2.12, departure delay may develop in a linear form proportional to the amount of arrival delay, no matter how long the arrival delay is.

Second, ground handling agents may be able to maintain efficient turnaround operations under the pressure of limited turnaround time and buffer time. In such a scenario, the level of departure delay will be less than the one of inbound delay and will follow curve $f_3$. This is a desired scenario in which the planned turnaround time by airlines functions effectively as delay buffer and airlines are able to contain the scale of delay propagation in a network without tactically allocating more resources during operations.

Third, curve $f_1$ represents a typical situation in which ground operations are further disturbed by the late arrival of inbound aircraft, via late transfer of passengers, late passenger check-in, late baggage connection, or disruptions in ground handling plans. One major responsibility of airline dispatchers (or called ground controllers or ground co-ordinators) at airports is to deliver punctual departures by "operational means". Ways in which this can be done may include: skipping the loading of some cargo or goods that are not urgent (and can be deferred to a later flight), or allocating more resources to speed up aircraft turnaround. This type of "speeding up" of operations is commonly seen in the industry by both

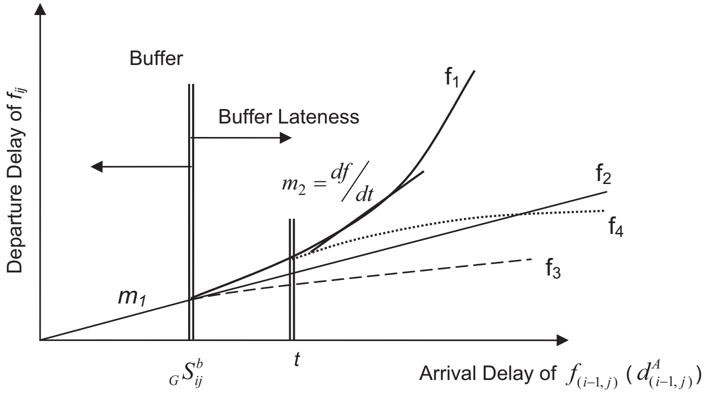

**Figure 2.12 Development of departure delay due to arrival delay of inbound aircraft**

network carriers and LCCs and is often used as a means of "fire breaking", in order to stop or significantly reduce the risk of delay propagation in an airline network.

If at time *t* (as shown in Figure 2.12), the airline dispatcher takes actions to reduce departure delay of flight $f_{ij}$, the development of departure delay following curve $f_1$ might become curve $f_4$ (illustrated by the dotted line). Accordingly, $f_{ij}$ may incur a shorter departure delay than expected in the "no-action" scenario, i.e. curve $f_1$. In addition, the reduction of the departure delay to $f_{ij}$ may reduce the risk of incurring potential knock-on delays through aircraft rotations and flight connections in a network. Nevertheless, the operating cost of $f_{ij}$ may increase in this scenario.

The curve slope (denoted by $m_2$ and shown in Figure 2.12) after the turnaround buffer time (${}_G S^b_{ij}$) is used to define the "efficiency" of ground services, i.e. the ground handling agents' capacity to respond to schedule perturbations. When the value of $m_2$ is less than or equal to one, departure delay develops at a lower rate than arrival delay such as curve $f_2$ and $f_3$. If $m_2$ is greater than one, it means that turnaround operations are further disturbed by operational disruptions or inadequacy of resources and hence, ground operations take a longer time to complete. Consequently, outbound departure flights will suffer further delays, not only due to arrival lateness but also from operational disturbance during aircraft turnaround.

The "efficiency and performance" issue of ground handling has been a critical one in airline ground operations due to the continuing pressure of cost cutting in the airline industry. To ensure the efficiency of ground operations and maintain the capacity to absorb delays during turnaround time, airlines often establish service level agreements (SLAs) with ground handling agents to achieve the goal, especially if ground handling services are outsourced to a third-party handler. SLAs outline the "benchmarks" of aircraft turnaround operations by a number of indices such as average delay time, and the occurrence of delay causes. However, most SLAs between airlines and ground handlers are commercially confidential and not available in the public domain.

### *2.5.3 Delay Development Modelling*

An analytical aircraft turnaround model is developed based on the rationale of the delay development mechanism described previously. The departure time of flight $f_{ij}$ is previously modelled by (2.1) as a function of the arrival time of previous flight, $f_{(i-1,j)}$ and the turnaround time $S_{ij}^{TR}$ of $f_{ij}$. From observations of airline operations at airports, it is seen that whenever there is little or no buffer time (i.e. ${}_{G}S_{ij}^{b}$ is small), departure delay can be modelled by *Curve A* as illustrated in Figure 2.13. When the scheduled buffer time is as long as the maximum limit, i.e. $\max({}_{G}S_{ij}^{b})$, departure delay can be modelled by *Curve C* and nearly 100 per cent arrival delays are covered.

Often, airlines are not willing to schedule excessive buffer times. However, when adequate buffer times are scheduled, any arrival delay can be absorbed by the buffer time and it is likely that there will be very little departure delay. For delays longer than the $\max({}_{G}S_{ij}^{b})$, it is assumed that delay will develop as *Curve A*. In between these two extreme cases, departure delay can be modelled by *Curve B* with a scheduled turnaround time ($S_{ij}^{TR}$) including a buffer (${}_{G}S_{ij}^{b}$). This is a one-to-one mapping function between the arrival time and departure time of two flights that are operated sequentially by the same aircraft. For any given buffer time ${}_{G}S_{ij}^{b}$, there will be a corresponding "efficiency" curve as illustrated by *Curve B* in Figure 2.13, which represents the operational efficiency of ground services under the constraint of scheduled turnaround time, $S_{ij}^{TR}$.

The "mapping function" (*Curve B*) is modelled as a piece-wise linear function in order to describe one of those potential scenarios of delay development shown previously in Figure 2.13. Other function forms besides linear functions can be adopted. Although complex function forms would allow analysts more flexibility and the capacity to address complex delay development mechanism, complex function forms may not be solvable analytically and would require advanced techniques to solve the resulting model.

The "efficiency" of delay absorption of schedule buffer time ${}_{G}S_{ij}^{b}$ is modelled by $m_1$, which is the slope of the left portion of *Curve B*. The operational efficiency of aircraft turnaround operations in dealing with delays and resource constraints is modelled by $m_2$, which is the slope of the right portion of *Curve B*. The parameter value of $m_2$ is assumed to be given from statistical analysis and is airport and handler specific, reflecting the unique operating environment of the handler and the environment in which the handler operates, i.e. the airport.

In this analytical model, it is assumed that $m_1$ is a function of schedule buffer time (${}_{G}S_{ij}^{b}$) and service efficiency of turnaround operations (denoted by $m_2$). Hence, the longer the schedule buffer time is (or the higher the operational efficiency is), the higher the efficiency of the schedule buffer time in absorbing

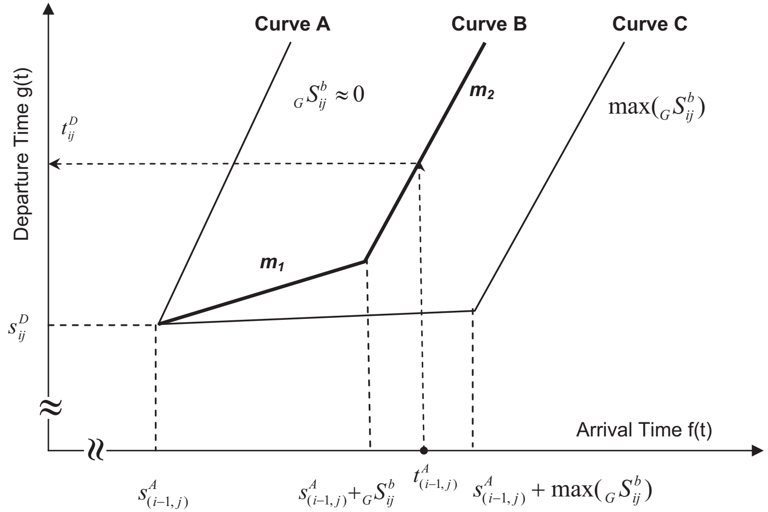

**Figure 2.13 The relationship between arrival time *f(t)*, turnaround operational efficiency ($m_2$), and departure time *g(t)***

inbound delays, represented by $m_1$. Accordingly, a longer buffer time designed for a turnaround flight corresponds to a "flatter" curve due to smaller $m_1$ value such as the one illustrated by *Curve B*. Therefore, the relationship between inbound delay absorption efficiency ($m_1$), schedule buffer time (${}_G S^b_{ij}$) and ground service efficiency ($m_2$) is modelled as a piece-wise linear function by (2.2) below, corresponding to *Curve B* illustrated in Figure 2.13.

$$m_1 = m_2 \left[ \left( \max({}_G S^b_{ij}) - {}_G S^b_{ij} \right) \Big/ \max({}_G S^b_{ij}) \right] \qquad 0 \le {}_G S^b_{ij} \le \max({}_G S^b_{ij}) \tag{2.2}$$

where ${}_G S^b_{ij}$ is the schedule buffer time designed for flight $f_{ij}$; $\max({}_G S^b_{ij})$ is the maximum buffer time that absorbs inbound delays with approximately 100 per cent probability (or the maximum limit imposed by an airline); $m_2$ is a given parameter representing the operational efficiency of aircraft turnaround of a specific ground handler at a specific airport.

With the increase of schedule buffer time from zero to the maximum value, *Curve B* changes its shape from *Curve A* and approaches *Curve C* eventually when the schedule buffer time ${}_G S^b_{ij}$ is large enough. Since $m_1$ is also a function of $m_2$, when the operational efficiency of aircraft turnaround is improved, the parameter value of $m_2$ becomes smaller. Accordingly, the corresponding $m_1$ value decreases, and this results in a flatter *Curve B*.

With a defined mapping function, as shown in Figure 2.13, the departure time ($t_{ij}^D$) of $f_{ij}$ can be formulated as a piece-wise linear function of the arrival time of $f_{(i-1,j)}$ ($t_{(i-1,j)}^A$) by (2.3 and 2.4) below, in which the operational characteristics of turnaround operations (modelled by $m_1$ and $m_2$) are described by (2.2) given above.

$$t_{ij}^D = m_1(t_{(i-1,j)}^A - S_{(i-1,j)}^A) + S_{ij}^D \qquad \text{if} \qquad S_{(i-1,j)}^A \le t_{(i-1,j)}^A \le \left(S_{(i-1,j)}^A + {}_G S_{ij}^b\right) \tag{2.3}$$

$$t_{ij}^D = m_1 * {}_G S_{ij}^b + m_2\left[t_{(i-1,j)}^A - \left(S_{(i-1,j)}^A + {}_G S_{ij}^b\right)\right] + S_{ij}^D \qquad \text{if} \qquad \left(S_{(i-1,j)}^A + {}_G S_{ij}^b\right) < t_{(i-1,j)}^A \tag{2.4}$$

where $t_{(i-1,j)}^A$ is the actual time of arrival of inbound flight $f_{(i-1,j)}$

$s_{(i-1,j)}^A$ is the scheduled time of arrival of $f_{(i-1,j)}$

$s_{ij}^D$ is the scheduled time of departure of outbound flight $f_{ij}$

${}_G S_{ij}^b$ is the scheduled buffer time for turnaround of $f_{ij}$

$t_{ij}^D$ is the actual time of departure of outbound flight $f_{ij}$

There is a one-on-one mapping between the arrival time variable ($t_{(i-1,j)}^A$) and the departure time variable ($t_{ij}^D$) because of the piece-wise linear transform function above. Since the actual arrival time is uncertain in real operations, the arrival time of $f_{(i-1,j)}$ is often modelled by a stochastic distribution, $f_{(i-1)}(t)$. Hence, the departure time distribution of $f_{ij}$, given the inbound arrival time distribution of $f_{(i-1,j)}$ by $f_{(i-1)}(t)$, is also a stochastic function, denoted by $g_i(t)$. Since the model given here by (2.3) and (2.4) is an analytical one (i.e. can be expressed by mathematical terms and operations), this model is also analytically solvable. In other words, we are able to obtain the exact function of $g_i(t)$, if we are given the function of $f_{(i-1)}(t)$ and the required parameters in (2.3) and (2.4).

### *2.5.4 Delay Cost Modelling – Passenger Delay Costs*

Flight delays incur costs to affected passengers and airlines due to the time loss for passengers and the extra resources required during schedule disruption for airlines. Delays on the tarmac incur environmental costs to society because of extra fuel burn on the tarmac. To limit the scope of this model, the costs of delays only include delay costs to passengers and delay costs to airlines due to the loss of (aircraft) time.

Passengers who suffer delays lose time as well as the potential value of the delay time. In addition to the direct value of the loss of time, delays cause disruptions to passenger itineraries, business activities, and social arrangements, so the implications of delays to passengers have a profound social, business and personal impact. This has been the argument in Europe in recent years that has led to the amendment of previous legislation to further protect air passenger rights (European Union 2005).

In a report for the Performance Review Commission of Eurocontrol in Europe, delay costs to passengers were surveyed from both public sources and airlines (Eurocontrol 2004a). According to various sources and past studies of two European carriers, passenger delay costs were modelled and adjusted in detail. A simplified approach was to use the average hourly wage rate as a proxy to the losses a passenger may incur during delays (Wu and Caves 2000). Although, the "value of time" approach could be arguable in some cases, it provides a reasonably good proxy to passenger delay cost, when there are no better alternatives or quality data for modelling.

Passenger delay cost is modelled by (2.5) below. Passenger delay cost function, $C_P(d_{ij}^D)$ is modelled as a function of departure delay time ($d_{ij}^D$) and the function form of $C_P(d_{ij}^D)$ depends on the chosen marginal delay rate, i.e. $\gamma_P^m(d_{ij}^D)$. Although the delay cost function can be in any form in a more general expression (Tosic et al. 1995), for analytical simplicity and tractability, it is assumed in the TTA model that the marginal delay cost of passengers aboard is a constant, regardless of time. It means that the rate of delay cost ($\gamma_P^m(d_{ij}^D)$) does not change as the delay increases, and hence, is a constant in (2.5). As a result, the delay cost function $C_P(d_{ij}^D)$ has a linear form after integration.

$$C_P(d_{ij}^D) = \int_{d_{ij}^D} \gamma_P^m(d_{ij}^D)d(d_{ij}^D) \tag{2.5}$$

### 2.5.5 Delay Cost Modelling – Airline Delay Costs

When delays occur, airlines also incur extra costs due to aircraft operating expenses, crew costs, and expenses at airports, e.g. extra gate occupancy time. Various factors influence the cost of delays to airlines when delay occurs. To simplify the cost model we are building, only aircraft related delay costs are considered here, i.e. the "direct and hard" costs of delays. Accordingly, aircraft delay cost is defined as: *the hourly fixed operating cost per aircraft* (Wu and Caves 2000). Readers who are interested in other cost sources and relevant information can consult the report by Eurocontrol (2004) that provides sufficient details in this regard for the delay cost of an aircraft whether on the ground or airborne.

The direct cost of delaying an aircraft on the ground is modelled by (2.6), where $\varphi_{AC}^m(d_{ij}^D)$ is the marginal delay cost function of an aircraft. As previously in (2.5), aircraft delay cost $C_{AC}(d_{ij}^D)$ is modelled as a function of departure delay time ($d_{ij}^D$). The function form of $C_{AC}(d_{ij}^D)$ depends on the given marginal delay rate of an aircraft, i.e. $\varphi^{m}_{AC}(d^{D}_{ij})$. To simplify model building, it is assumed that the marginal delay cost of an aircraft is constant regardless of time. Although it can be argued that higher delays may incur higher costs for airlines due to aircraft usage, this model assumption is reasonable and consistent with our assumption regarding aircraft delay costs given earlier.

Based on this model assumption, the aircraft delay cost function $C_{AC}(d^{D}_{ij})$ has a linear form after integrating $\varphi^{m}_{AC}(d^{D}_{ij})$ in (2.6). If it is deemed necessary in the future to consider more delay cost factors, or to use a more complex form for $\varphi^{m}_{AC}(d^{D}_{ij})$, $C_{AC}(d^{D}_{ij})$ can be modified easily according to the model requirements.

$$C_{AC}(d^{D}_{ij}) = \int\limits_{d^{D}_{ij}} \varphi^{m}_{AC}(d^{D}_{ij})d(d^{D}_{ij}) \tag{2.6}$$

*2.5.6 Delay Cost Modelling – Airline Schedule Costs*

To increase aircraft productivity, airlines tend to minimise the ground service time for turning around aircraft, so expensive aircraft time can be allocated to revenue-making block time. However, the use of the short turnaround time policy in an airline schedule is a double-edged sword. On the one hand, minimum aircraft turnaround time includes only minimum schedule buffer time which increases the risk of incurring flight delays when operational disruptions occur. Flight delays in a tightly connected airline network cause knock-on delays in a network, in which delays propagate via aircraft routing and resource connections (Wu 2005). The potential impact of knock-on delays is a multiplier effect that causes far more losses to airlines than the losses directly caused by the initial delays (Beatty 1998; Wu 2006).

On the other hand, a longer schedule buffer time included in the ground time reduces the risk of incurring flight delays, but compromises aircraft productivity and utilisation. Aircraft are expensive assets of airlines. Even for those airlines which do not financially "own" their aircraft, the leasing cost of an aircraft, e.g. B737, a popular type of aircraft for short-haul operations, was between US$100,000 and $150,000 dollars per calendar month in 2007.

There is a trade-off situation, where a shorter turnaround time (i.e. shorter ground buffer time) risks airlines having a higher probability of delayed flight departures but a high utilisation of aircraft; on the other hand, the use of a longer schedule buffer time reduces aircraft productivity, but maintains the desired operational reliability of airline schedules. Hence, the use of aircraft time as ground buffer time can be modelled as a form of "opportunity cost" in airline scheduling by $C_{AL}({}_{G}S^{b}_{ij})$ in (2.7) below, representing the cost for an airline to include schedule buffer time in aircraft turnaround operations in a flight schedule.

$$C_{AL}({}_{G}S^{b}_{ij}) = \int\limits_{S} \delta^{m}_{AL}({}_{G}S^{b}_{ij})d({}_{G}S^{b}_{ij}) \tag{2.7}$$

As seen in (2.7) above, $\delta_{AL}^{m}({}_{G}S_{ij}^{b})$ is the marginal schedule time cost function which reflects the opportunity cost of flying flight $f_{ij}$ by a specific type of aircraft. Often the larger the aircraft is, the higher the opportunity cost of aircraft time, reflecting the higher cost of owning and operating a large aircraft. It is realised from current practices in the industry that the schedule time opportunity cost increases in a non-linear fashion, increasing dramatically when the saved aircraft time is long enough for an aircraft to carry out another flight and earn additional revenues. This is often achieved in the re-assignment of aircraft routing optimisation, in which saved aircraft time of the whole fleet may change the optimal routing of aircraft, so that more flights can be accommodated in the network.

The expectation of extra revenues from conducting more flights is always the major financial incentive and driver for scheduling more flights in a network by reducing aircraft ground time, especially for LCCs. Accordingly, the marginal cost function $\delta_{AL}^{m}({}_{G}S_{ij}^{b})$ is assumed to take a linear form, meaning the marginal rate of schedule opportunity cost gets higher when schedule time usage is higher. Hence, the schedule time cost function, $C_{AL}({}_{G}S_{ij}^{b})$ in (2.7) is a function of ground buffer time ${}_{G}S_{ij}^{b}$ and takes a quadratic form after integrating the linear marginal cost function $\delta_{AL}^{m}({}_{G}S_{ij}^{b})$ in (2.7).

### *2.5.7 Turnaround Time Allocation (TTA) Model*

A cost minimisation model, called the *Turnaround Time Allocation* (TTA) model, is developed as a tool to optimise the allocation of the turnaround buffer time $({}_{G}S_{ij}^{b})$ of a single flight $(f_{ij})$ in the context of the trade-off situation that: higher turnaround buffer time reduces the associated delay cost both for passengers and the airline, but higher schedule time increases the opportunity cost of using aircraft time in other revenue-making flight operations. The objective function of the minimisation model is given by (2.8). It seeks to minimise the total cost $(C_T)$ in the model that includes the expected cost of delays $(D_C)$ and the cost of schedule time $(S_C)$. The trade-off condition is modelled by a weight factor, $\alpha$ which divides the costs and benefits between the two cost items.

$$C_T = \alpha D_C + (1-\alpha)S_C \qquad 0 \leq \alpha \leq 1 \tag{2.8}$$

The expected cost of delays, $D_C$ as modelled in (2.8) above includes passenger delay cost, $C_P(d_{ij}^{D})$ modelled by (2.5) and aircraft delay cost, $C_{AC}(d_{ij}^{D})$ modelled by (2.6). Since both passenger delay cost and aircraft delay cost are functions of departure delay time $(d_{ij}^{D})$, both functions are stochastic cost functions with the same stochastic variable $d_{ij}^{D}$, representing departure delay. To account for the stochastic feature of delay and the associated costs, the cost of delays, $D_C$ is modelled as the expected cost due to the departure delay.

The calculation of the expected cost of delay, $D_C$ is formulated by (2.9), in which $g_i'(d_{ij}^{D})$ is the stochastic distribution of departure delay, $d_{ij}^{D}$. $g_i'(d_{ij}^{D})$ is a function transformed from $g_i(t)$, which is a function of the actual departure time of $f_{ij}$, i.e. $t_{ij}^D$ as modelled below. Since $d_{ij}^D = t_{ij}^D - s_{ij}^D$ according to the definition of departure delay, the departure time PDF can be expressed by: $g_i'(d_{ij}^D) = g_i(t_{ij}^D - s_{ij}^D) = g_i(t) - s_{ij}^D$, because the scheduled time of departure, $s_{ij}^D$ is a constant. $S_C$ in (2.8) is a function of schedule buffer time, ${}_GS_{ij}^b$ and depends on the marginal schedule time cost function, $\delta_{AL}^m({}_GS_{ij}^b)$ as formulated by (2.7) earlier.

$$D_c = \int_0^{\infty} \left[C_P(d_{ij}^D) + C_{AC}(d_{ij}^D)\right] g_i'(d_{ij}^D) d(d_{ij}^D) \tag{2.9}$$

where $g_i'(d_{ij}^D) = g_i(t_{ij}^D - s_{ij}^D) = g_i(t) - s_{ij}^D$

According to earlier assumptions and formulation, the TTA model is summarised as follows by (2.10). Equation (2.10.1) represents the weight factor used to model the trade-off between expected delay costs and schedule costs. (2.10.2) describes the opportunity cost of the schedule buffer time as a function of the decision variable, namely the usage of buffer time, ${}_GS_{ij}^b$. (2.10.3) is the cost of delays including passenger delay cost as in (2.10.4) and aircraft delay cost as in (2.10.5). The departure delay PDF is converted by (2.10.6) from the departure time PDF $g_i(t)$, which is a function (piece-wise linear transform function) of the inbound arrival time $t_{(i-1,j)}^A$, and the decision variable, ${}_GS_{ij}^b$.

*Turnaround Time Allocation* (TTA) optimisation Model:

To minimise: $C_T = \alpha D_C + (1-\alpha) S_C$ (with decision variable, ${}_GS_{ij}^b$) (2.10)

Subject to the following constraints:

$$0 \le \alpha \le 1 \tag{2.10.1}$$

$$S_C = C_{AL}({}_GS_{ij}^b), \text{ where } C_{AL}({}_GS_{ij}^b) = \int_S \delta_{AL}^m({}_GS_{ij}^b) d\, {}_GS_{ij}^b \tag{2.10.2}$$

$$D_c = \int_0^{\infty} \left[C_P(d_{ij}^D) + C_{AC}(d_{ij}^D)\right] g_i'(d_{ij}^D) d(d_{ij}^D) \tag{2.10.3}$$

$$C_P(d_{ij}^D) = \int_{d_{ij}^D} \gamma_P^m(d_{ij}^D) d(d_{ij}^D) \tag{2.10.4}$$

$C_{AC}(d_{ij}^D) = \int_{d_{ij}^D} \varphi_{AC}^m(d_{ij}^D) d(d_{ij}^D)$, where $d_{ij}^D = t_{ij}^D - s_{ij}^D$, and forms the departure delay PDF, $g_i'(d_{ij}^D)$ (2.10.5)

$g_i'(d_{ij}^D) = g_i(t_{ij}^D - s_{ij}^D) = g_i(t) - s_{ij}^D$, where $g_i(t)$ is the departure time PDF with variable $t_{ij}^D$, derived from the following set of functions: (2.10.6)

$$\begin{cases} t_{ij}^D = m_1(t_{(i-1,j)}^A - S_{(i-1,j)}^A) + S_{ij}^D & \forall t_{(i-1,j)}^A, S_{(i-1,j)}^A \leq t_{(i-1,j)}^A \leq \left(S_{(i-1,j)}^A + {}_G S_{ij}^b\right) \\ t_{ij}^D = m_1 * {}_G S_{ij}^b + m_2\left[t_{(i-1,j)}^A - \left(S_{(i-1,j)}^A + {}_G S_{ij}^b\right)\right] + S_{ij}^D & \forall t_{(i-1,j)}^A, \left(S_{(i-1,j)}^A + {}_G S_{ij}^b\right) < t_{(i-1,j)}^A \end{cases}$$

where $t_{(i-1,j)}^A$ forms the arrival time PDF of inbound flight $f_{(i-1,j)}$, i.e. $f_{(i-1)}(t)$
$s_{(i-1,j)}^A$ is the scheduled time of arrival of $f_{(i-1,j)}$
$s_{ij}^D$ is the scheduled time of departure of outbound flight $f_{ij}$
${}_G S_{ij}^b$ is the decision variable (scheduled buffer time of $f_{ij}$)
$t_{ij}^D$ forms the departure time PDF of outbound flight $f_{ij}$, i.e. $g_i(t)$

The inputs required for the TTA model in (2.10) include schedule data, the operational efficiency of aircraft turnaround at the study airport (from statistics), cost parameters (including passengers, aircraft and schedule time costs), and the arrival time PDF derived from historical data. The decision variable in optimisation is the length of schedule buffer time, i.e. ${}_G S_{ij}^b$ that is required to balance the trade-off between delay costs and schedule time costs. The weight factor in optimisation, $\alpha$ can be varied to reflect the consideration of weights in strategic airline schedule planning.

## 2.6 Schedule Optimisation and Case Study

The TTA optimisation model in the last section requires a number of input parameters before being able to solve the optimisation model and obtain results. Preparing model parameters is as critical and essential as building an analytical model. Hence, the following section provides guidelines and some details regarding the preparation of model parameters, through collecting relevant data, making appropriate assumptions, to calculating model parameters as input data. Results of optimisation based on numerical analyses are given for demonstration purposes and are compared with a case study at the end of this section that uses real airline data. To explore potential trade-offs between scheduling options and the impact on flight delays and operational robustness, a number of numerical analyses are conducted, following the numerical example of optimisation given.

It should be noted that although the approaches used in this section to derive some model parameters are generic in nature and are applicable in most situations, parameter values are calculated approximately from published financial data for the purpose of model demonstration only. Hence, parameter values are derived based on the needs of this model, with some simplification involved and subject to data availability. When the TTA optimisation model is adopted to conduct empirical studies, it is highly recommended that the user should review the parameter values and make appropriate adjustments accordingly. Model parameters can also be changed to study the impact of specific parameters on model outputs, i.e. sensitivity analysis.

### *2.6.1 Model Inputs – Passenger Delay Costs*

When calculating the unit cost of delays to passengers, trip purposes and passenger characteristics are major factors that are necessary to explore. The literature on the value of time (VOT) of air passengers suggested that a passenger valued on-mode time at the wage rate for business flights and a quarter of the wage rate for leisure flights. Waiting and delay time were valued higher than on-mode time. In the report by Eurocontrol (2004), the costs of passenger delay to airlines were calculated based on two given delay cost figures provided by Austrian Airlines and an anonymous European carrier. The usage of VOT and the average hourly wage rate as a proxy to the unit passenger delay cost was discussed in the Eurocontrol report. Eventually, an (un-weighted) average of the two given cost figures from the two airlines was taken to represent the delay costs of passengers, being EUR 0.30 per passenger, per delay minute and per delay flight in Europe. A number of different projects provided different cost parameters based on different rationales and different research contexts (see Bates et al. 2001; DRI 2002; Eurocontrol Experimental Centre 2002; Institut du Transport Aérien 2000).

The differences in operating environments and the cost bases of serviced destinations in a network influence the calculation of the unit cost of passenger delay. Often the calculation of the unit cost of passenger delay itself is a challenging project, because the cost of delay involves both “hard” cost items, e.g. delay time and compensation, as well as “soft” cost items, e.g. loss of goodwill and damage of reputation. Hard cost items are easy to calculate, but soft cost items are hard to quantify. Without comprehensive studies on passenger delay cost, the most appropriate proxy to measure the cost of delay of passengers is the average hourly wage rate of passengers.

It is assumed earlier in the previous section that the marginal delay cost per passenger (denoted by $\gamma_P^m(d_{ij}^D)$) is constant, meaning the unit cost is the same for the first minute of delay and, say, the 30th minute of delay. Hence, $\gamma_P^m$ is related to the average wage rate, flight classes chosen, trip characteristics and delay time perception of passengers. A survey by the Civil Aviation Authority (CAA) in the UK showed that the average wage rate was US \$46 per hour for passengers using Heathrow Airport and US \$42 per hour for passengers using Gatwick Airport (CAA 1996). On the other hand, business passengers using London City Airport exhibited a higher average wage rate of US \$64 per working hour. The average wage rate for leisure passengers was US \$39 per hour from the same survey by CAA in 1996. Since the context of the numerical study we are to conduct later is in European aviation, for the purpose of model demonstration and simplicity, the hourly delay cost of a passenger ( $\gamma_P^m$ in (2.10.4)) is assumed to take the average wage rate of US $42 per hour for the consideration of an average passenger during waiting/delay time at an airport (Wu and Caves 2000). It will be convenient to change the cost parameter in the future, if the study target passenger is in the business class or in a low-cost cabin/flight.

### *2.6.2 Model Inputs – Aircraft Delay Costs*

Various parameter values of unit aircraft delay cost can be found in the relevant literature. Unit ground delay costs for European airlines presented in the literature were US $1330, $2007, and $3022 per hour for medium, large and heavy jets respectively (Janic 1997). The estimates of unit delay cost of an aircraft in the U.S. were US $430, $1300, and $2225 per hour with respect to small, medium and large aircraft in a study by Richetta and Odoni (1993). Although aircraft delay cost figures like these can be found easily in the literature, these parameters are often context sensitive, i.e. only valid within the context of the project and are not directly applicable to other cases without thoroughly reviewing the values. Hence, an empirical approach is needed to demonstrate how to derive an aircraft delay cost figure under the constraints of data availability and model needs faced by most practitioners in the industry.

When an aircraft is delayed at a gate either with the engines off or on, the airline not only incurs extra operating costs but also has to forego potential revenues. A comprehensive framework was given in the Eurocontrol report (2004) on the approaches to calculate aircraft delay costs and ownership costs. In many cases, the practitioners/modellers in airlines may not afford to conduct such a comprehensive project to obtain aircraft delay cost parameters, or some data required for calculation in the framework are not readily available. Accordingly, an empirical approach is introduced here to derive approximate cost parameters for both simplicity and convenience reasons.

The aircraft delay cost, denoted by $C_{AC}(d_{ij}^D)$ in (2.10.5), was previously defined as *the hourly fixed operating cost per aircraft hour*, which considered only the direct operating cost of an aircraft. Aircraft delay cost depends on aircraft types and sizes. For the purpose of demonstration, aircraft sizes are classified into three categories, namely medium, large, and heavy aircraft, as shown in Table 2.1. Aircraft operating costs of some selected airlines are calculated and listed in Table 2.2 by using published financial data from International Civil Aviation Organisation (ICAO) (ICAO 1997a; ICAO 1997b). It is noted that cost calculations in Table 2.2 were based on the average aircraft operating costs due to the unavailability of detailed cost breakdown with respect to aircraft types, fleets and sizes from published information. Practitioners and modellers in the industry usually have access to detailed cost breakdown by fleet types for their own airline. With the availability of cost breakdown details, it is highly recommended that the delay cost figure should be reviewed and calculated based on fleet types. The current empirical approach, however provides us with a proper methodology to derive an approximate value of the aircraft delay cost, when there are no better cost data available for calculation.

According to Table 2.2, aircraft operating costs were found to differ between carriers, and one of the reasons for this was due to the difference of fleet structure.

**Table 2.1 Aircraft classification**

| **Aircraft Classification**[*] | **Maximum Take-Off Weight (MTOW, lb)** | **Average Seat Capacity** |
|---|---|---|
| Medium Aircraft (narrow-body jets) | MTOW ≤ 300,000 | 150 |
| Large Aircraft (wide-body jets) | 300,000< MTOW ≤ 600,000 | 250 |
| Heavy Aircraft (jumbo jets) | 600,000< MTOW | 400 |

*Note*: [*] Classification based on Maximum Take-off Weight (MTOW) and average seat capacity.

**Table 2.2 Hourly aircraft operating costs (with engines off at gates)**

| | **British Airways (BA)** | **British Midland (BD)**[†] | **KLM (KL)** | **Lufthansa (LH)** | **American Airlines (AA)** | **United Airlines (UA)** |
|---|---|---|---|---|---|---|
| Total Operating Expenses[*] | 11,395 | 866 | 5,372 | 9,370 | 14,409 | 16,110 |
| Aircraft fuel and oil expenses[*] | (1,150) | (50) | (580) | (1,014) | (1,726) | (1,898) |
| Subtotal[+] Operating Expenses | 10,245 | 816 | 4,792 | 8,356 | 12,683 | 14,212 |
| Number of Aircraft | 260 | 33 | 115 | 280 | 656 | 593 |
| **Aircraft Operating Costs ($/hr/AC)**[*] | **4,498** | **2,822** | **4,757** | **3,407** | **2,207** | **2,736** |

*Notes*: [†] British Midland is now known as bmi and bimBaby with an IATA code of WW. BD was the old IATA code when it was still British Midland. However, BD is used through out the numerical analyses to distinguish that parameter values are based on BD's data, and not WW's operation.

[*] Units in US $ (millions).

( ) represents negative values (deduction cost items).

[+] Subtotal = (Total Operating Expenses)-(Fuel and Oil Expenses).

*Sources*: *Digest of Statistics, Financial Data Commercial Air Carriers, ICAO 1997* and *Digest of Statistics, Fleet-Personnel, ICAO 1997.*

For instance, British Airways operated 32 per cent heavy aircraft for long-haul intercontinental flights based on 1997 fleet structure (as shown in Figure 2.14) and consequently, had a high average operating cost of US $4,498. KLM operated proportionately more large jets than Lufthansa, so KLM had a higher average aircraft operating cost of US $4,757 than Lufthansa. Lufthansa had a similar aircraft fleet structure as United Airlines, but exhibited a higher operating cost of US $3,407 which was commonly seen as the cost difference between Europe and the U.S. American Airlines mainly operated large and medium aircraft and few heavy ones, so a lower operating cost of US $2,207 was reasonable. On the other hand, British Midland (which is now known as bmi/bmiBaby) used mainly narrow body jets and exhibited an hourly aircraft operating cost of US $2,822. Although cost breakdown information is commercially sensitive and often not available in the public domain, the study by Eurocontrol (2004, p. 58) provided a good guideline on the possible ranges of "aircraft block-hour direct operating costs" calculated from various industry sources.

### *2.6.3 Model Inputs – Schedule Time Costs*

Airlines tend to minimise the turnaround time of aircraft in order to produce more revenue-making flight time and increase the utilisation of assets, e.g. aircraft and terminal/ground equipment (International Air Transport Association 1997; Eilstrup 2000). This is especially true for LCCs and those carriers which use intensive shuttle services or hubbing operations (Airports Council International 2000; Gittell 1995). Accordingly, an inference based on this reasoning is that aircraft ground time can be alternatively allocated to other flights as revenue-making airborne block time provided the minimum ground time for specific types

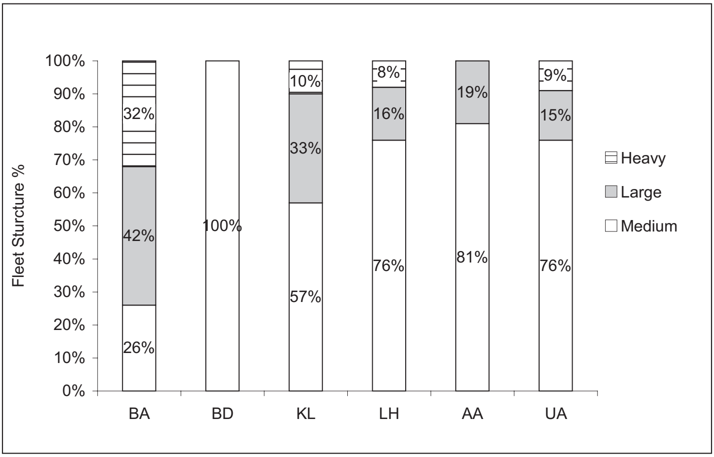

**Figure 2.14 Aircraft types and fleet structure of selected airlines**

of aircraft is met. In other words, the use of aircraft time as a buffer to control delays may improve the operational dependability of airline schedules and reduce expected departure delays, but the use of buffer time also incurs schedule time "opportunity costs". This trade-off is most obviously seen in LCCs, that reduce buffer time to the minimum allowable in order to increase aircraft utilisation and reduce schedule time costs.

To quantify the unit cost of airline schedule time (denoted by $S_C$ in (2.10.2), some assumptions are required here. It is assumed that the variation of the fixed operational costs for an airline due to the variation of total block hours is insignificant, compared with the total annual revenues. In other words, it is assumed that the change of ground time for flights on the timetable causes only changes of revenues and variable operating costs, due to changes of available aircraft block hours. Based on this reasoning, the hourly schedule time opportunity cost is defined as *the marginal hourly operating profit of an airline* and is calculated by deducting hourly variable expenses from hourly revenues as demonstrated in Table 2.3 (based on earlier ICAO financial and fleet data).

**Table 2.3 Hourly schedule time costs of selected airlines**

| | **British Airways** | **British Midland** | **KLM** | **Lufthansa** | **American Airlines** | **United Airlines** |
|---|---|---|---|---|---|---|
| **Revenues**[*] | 12,226 | 890 | 5,699 | 9,986 | 15,856 | 17,335 |
| **Variable Costs**[*]<br>Fuel and oil | (1,149) | (50) | (580) | (1,014) | (1,726) | (1,898) |
| Maintenance | (663) | (64) | (350) | (441) | (937) | (1,049) |
| Station expenses | (1,602) | (93) | (875) | (1,434) | (2,102) | (2,195) |
| Passenger service expenses | (1,637) | (139) | (535) | (1,168) | (1,775) | (1,895) |
| **Subtotal** + (Revenues-Costs) | 7,172 | 576 | 3,359 | 5,929 | 9,316 | 10,298 |
| **Flight Hours (hrs)** | 840,223 | 118,392 | 433,339 | 988,393 | 2,039,569 | 1,865,195 |
| **Schedule time costs ($/hr)** | 8,535 | 4,865 | 7,751 | 5,998 | 4,567 | 5,521 |

*Notes*: [*] Units in US $ (millions).
( ) represents negative values (deduction cost items).
[+] Subtotal = (Revenues)-(Cost Items).

*Sources*: *Digest of Statistics, Financial Data Commercial Air Carriers, ICAO 1997* and *Digest of Statistics, Fleet-Personnel, ICAO 1997.*

It is observed from Table 2.3 that U.S. airlines had a lower average schedule time cost when compared with European carriers, except for the similarity exhibited between British Midland (bmi) and some U.S. carriers. Logically, the schedule time opportunity cost of heavy jets is higher than those of large and medium jets. This is supported by evidence illustrated in Figure 2.15, in which the schedule time cost of British Airways was higher than other airlines, because British Airways operated more long-haul flights with jumbo jets (denoted by the line of "holdings of large and heavy jets" in Figure 2.15), so a higher schedule time cost. Compared with British Airways, KLM operated more medium-distance flights, but KLM exhibited a higher schedule time cost than Lufthansa and two U.S. airlines, due to the usage of larger aircraft than other carriers. Figure 2.15 also suggests that the unit cost of schedule time can be further categorised according to aircraft sizes or even the stage length of flights, if more detailed financial information is available during the modelling processes.

### *2.6.4 Model Inputs – Arrival Time Distribution*

One of the input parameters to the TTA optimisation model in (2.10) is the probability density function (PDF) for the arrival time of the inbound flight. Although it is convenient to assume that the arrival time PDF is normally distributed, there are many potential drawbacks in naively jumping to this assumption without thoroughly investigating historical flight data. Hence, some real flight data in 1999 from an anonymous European airline were collected to study potential arrival time PDFs in various conditions.

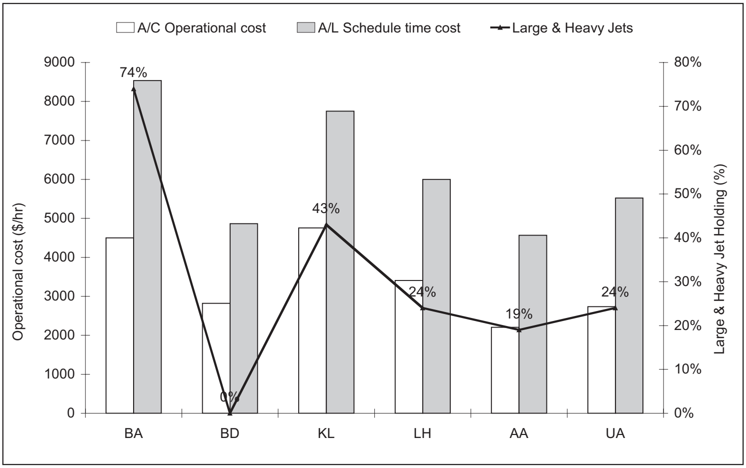

**Figure 2.15 Comparison between schedule time costs and aircraft sizes**

Various stochastic distributions were statistically tested to fit the real flight data and both *K-S test* and $\chi^2$ *goodness-of-fit test* were used to ensure the "power" of curve fitting. Fitted probability curves are shown in Figure 2.16. Three different types of arrival patterns were identified and found to be representative for three different types of operations, based on a sample size of around 90 flights for each case (operated in the same season by the same carrier). Domestic flights within the base country showed a quasi-normal arrival pattern and were fitted by Beta (18,20) function. Short-haul international flights (within EU member countries), on the other hand, exhibited a right-tailed Beta (4,14) arrival pattern. Long-haul flights (inter-continental operations) showed a Beta (2,13) arrival pattern with a long right tail.

Based on the curve fitting results, the Beta function was chosen to model the PDFs of the arrival time of inbound flights, i.e. $f_{(i-1)}(t)$ in (2.10.6), because of its analytical form and tractability in calculations. Other types of stochastic functions can be used to model arrival patterns such as the Log-Normal PDFs used in a study from fitting historical flight data of some U.S. carriers (Lan et al. 2006). The drawback of using Log-Normal functions as the model input to the TTA model is that this function is harder to deal with analytically because of a complex function form, although this function is also analytically tractable. When a complex function like Normal or Log-Normal is chosen as an input to the TTA model, one will require to conduct numerical simulations using the Monte Carlo technique, in order to evaluate the optimisation model. On the other hand, the Beta function has a simple form and can be analytically calculated in the TTA optimisation model using a spreadsheet on computers.

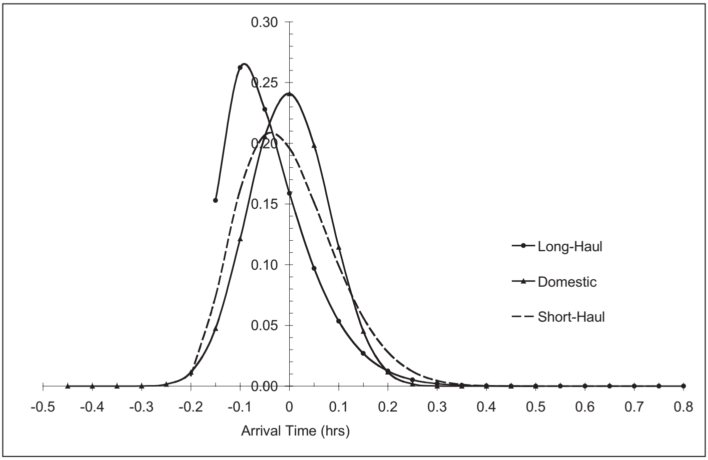

**Figure 2.16 Arrival time patterns (PDFs) fitted from real flight data**

Three types of arrival patterns, namely early arrivals, late arrivals, and normal-distributed arrivals, were employed in the following numerical analyses in this section, in order to study the influence of arrival punctuality of inbound aircraft on the departure punctuality of turnaround aircraft and the allocation of optimal schedule buffer time. For simplicity, Beta (10,3) was selected to model the late arrival pattern with the majority of flights (80 per cent) arriving within a maximum delay of twenty minutes (under a domain of 60 minutes on the x-axis) as shown in Figure 2.17. Only 20 per cent flights were punctual for the Beta (10,3) pattern. The Beta (3,10) distribution was used to model early arrival patterns, that had 90 per cent flights arriving within 14 minutes of delay and 30 per cent flights were punctual. Most arrivals modelled by Beta (3,10) had some delays, but these were relatively minor. The Beta (10,10) distribution was chosen to represent a quasi-normal arrival pattern, which had 55 per cent punctual flights with 90 per cent flights arriving within a short delay of 10 minutes.

The cumulative density functions (CDFs) of these Beta functions are illustrated in Figure 2.18. The "domain" of the chosen Beta functions is set to cover 60 minutes on the x-axis, meaning that the time range between the earliest and the latest possible arrival is 60 minutes. This is a simplification of real world cases, where an arrival delay can be as large as 120 minutes because of some very late flights. However, in analysing flight delays, it should be noted that causes of short delays are often quite different from causes of long delays (Eurocontrol 2004; Wu 2005). It is also a methodologically sound procedure to check these "sample outliers" in a statistical analysis, and for some cases, these outliers should be excluded from the main samples because of the possibility of biased results (for further suggestions on statistical analyses, readers can consult statistical texts for more information). To set the on-time arrival levels of Beta functions, we can shift the PDFs along the

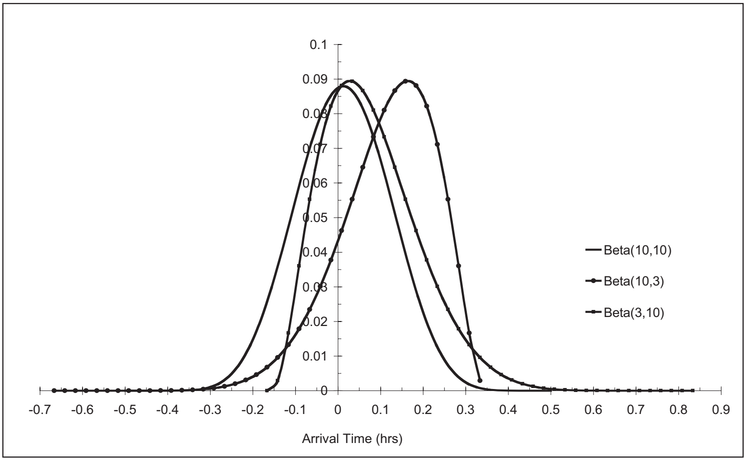

**Figure 2.17 Various Beta functions (PDFs) used in numerical analyses**

x-axis of Figure 2.17, so we are able to model arrival PDFs with various on-time performance levels and different delay patterns as demonstrated in Figure 2.18.

### *2.6.5 Optimisation Results*

The parameter values used in the TTA optimisation model are summarised in Table 2.4 based on the empirical approaches given in earlier sections. Parameter values were derived from financial data published by the International Civil Aviation Organisation (ICAO), and were intended only for case study purposes and did not reflect the views of any studied carriers hereafter. To illustrate the application of the TTA model on different types of airline operations, British Airways (BA) and British Midland (BD) (now bmi) were chosen as study airlines, representing long-haul and short-haul operation focused airlines respectively. It should be noted that parameter values given in Table 2.4 are not meant to represent the real values of specific airlines and the choice of airlines in the following study was based on data availability considerations.

The Beta (3,10) function was used to represent the arrival time PDF of inbound flights for both cases. Ground operational efficiency, i.e. the $m_2$ parameter was given the value of 2, representing a scenario in which inbound delays can cause further disruption to ground operations. The TTA optimisation model was solved on a spreadsheet and results are given in Figure 2.19 and Figure 2.20 for BA and BD cases respectively. For the case of BA, we can see in Figure 2.19 that the expected delay costs (including passenger costs and aircraft costs) decreased when the schedule buffer time was increased. The linear form comes from the assumption made earlier, i.e. a constant marginal delay time cost, so a linear delay time cost function.

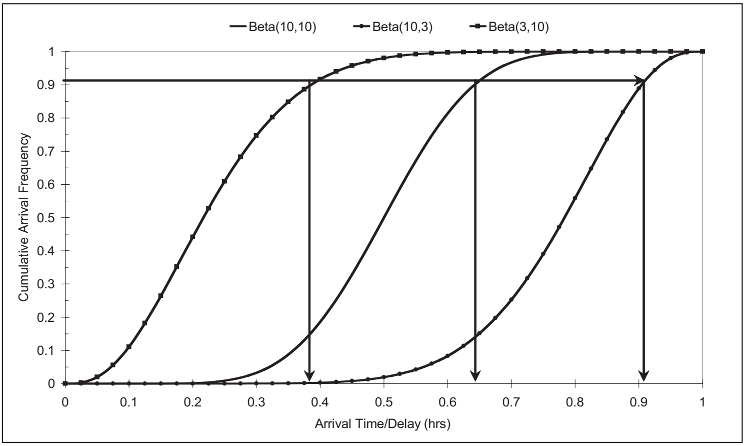

**Figure 2.18 The CDFs of chosen Beta functions**

**Table 2.4 Parameter values used in numerical analyses**

| | Aircraft Delay Cost ($/hr) $(C_{AC}(d_{ij}^{D}))$ | Passenger Delay Cost ($/hr) $(C_P(d_{ij}^{D}))$ | Airline Schedule Time Costs ($/hr) $(C_{AL}({}_G S_{ij}^{b}))$ | Ground Operation Efficiency $(m_2)$ |
|---|---|---|---|---|
| British Airways+ (BA) | 4,500 | 5,880 | 8,535 | 2 |
| British Midland* (BD) | 2,822 | 4,100 | 4,865 | 2 |

*Notes*: + Average aircraft size for BA European flights is selected to be 200 seats with an average load factor of 0.7. The average hourly wage rate of British passengers is estimated to be $42 per hour (Wu and Caves, 2000).

* Average aircraft size for BD is selected to be 150 seats with an average load factor of 0.65 (Wu and Caves, 2000).

On the other hand, the schedule time cost increased sharply as the use of buffer time increased. This was due to the assumption of a linear marginal schedule time cost in the model, so the schedule time cost followed a quadratic function as seen in Figure 2.19. Therefore, it can be observed from Figure 2.19 that the minimum of the total cost function occurred when the optimum schedule buffer time was set to be ten minutes. Hence, if the mean ground service time of a B767 was 45 minutes, then the optimal turnaround time for a B767 operation would be 55 minutes, which includes a 10-minute schedule buffer time.

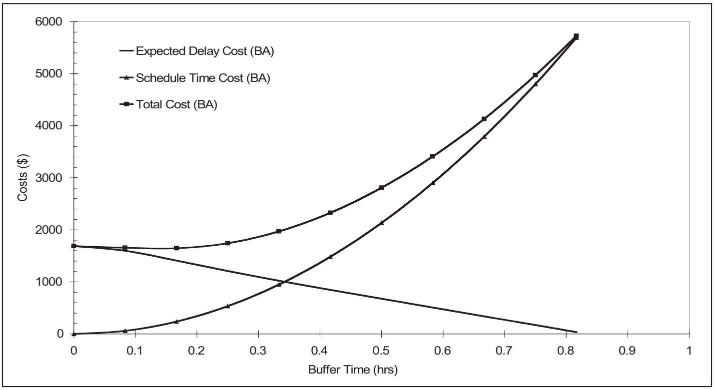

**Figure 2.19 Cost curves of Beta (3,10) arrivals for the BA example**

Compared with the BA example, cost curves in Figure 2.20 of the BD case displayed similar trends to the BA case, but the cost scale was significantly smaller. It can be seen from Figure 2.20 that the optimum schedule buffer time for this BD flight was ten minutes as well. Readers can also observe that the minimum of the total cost curve was influenced by both the "expected delay cost" and the "schedule time cost" curves. The total cost curve in Figure 2.20 was flat and concave, mainly due to the assumption of linear delay cost functions for both passengers and aircraft, compared with the quadratic schedule time cost function of airlines.

Under current model assumptions, it can be seen from Figure 2.20 that the schedule time cost increased more significantly than the improvement of expected delay cost with the use of schedule buffer time. The implication of this result validates the previous assumption that an airline is expected to save operational costs by optimising aircraft turnaround time. Also observed from Figure 2.20 is that the expected delay costs to passengers and aircraft were not as high as the cost from an airline's schedule time opportunity cost. This observation explains why airlines focus on minimising aircraft ground time and improving the utilisation of fleets, because of the high cost of aircraft schedule time.

Current results here are based on model assumptions made earlier and are only valid under those estimated parameter values. For instance, the current results were based on a "low unit delay cost" scenario, in which the passenger delay cost took a linear form. If the delay cost function assumed a quadratic form (penalising long delays) or had a higher unit delay cost parameter (higher delay compensation for passengers), then the "expected delay cost" curve would have become concave, due to higher delay costs. This case would result in a higher delay cost than schedule time cost. Accordingly, under this scenario, airlines might be more willing to increase the schedule buffer in order to minimise operating costs. More

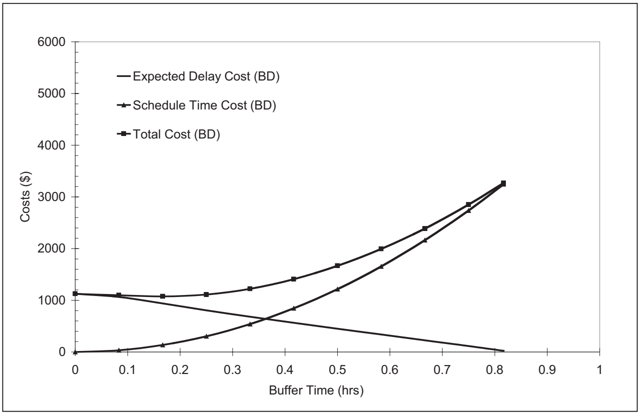

**Figure 2.20 Cost curves of Beta (3,10) arrivals for the BD example**

sensitivity analyses can be done to explore the potential influence of parameter values on optimisation results.

### *2.6.6 Case Study with Real Airline Data*

A case study is provided here to demonstrate the application of the TTA model to a real case. Flight data collected from a European airline, denoted by Airline R, were used in the case study. Flight data represented three-month operations of two typical European city-pair flights, noted by RR-X and RR-Y, with turnaround operations at the base airport of Airline R. RR-X was scheduled to arrive at 18.45 and to depart at 19.45, representing a peak-hour operation. RR-Y was scheduled to arrive at 16.30 and to leave at 17.35 hours, which was operated during off-peak periods and had a long turnaround time. B757 aircraft were used to operate these two flights in the European operation of Airline R. To model the arrival patterns, Beta functions were fitted using available flight data. Both fitted PDFs passed the *K-S Goodness of Fit Test* and the Beta (4,9) and Beta (2,5) functions were chosen to model the arrival punctuality patterns of these two study flights. The on-time performance (OTP) (zero delays, i.e. D0) was 55 per cent punctual flights for RR-X and 60 per cent for RR-Y.

The TTA model was then employed to model the use of ground buffer time of flight RR-X and to explore the potential impacts this changes may make on the operational reliability of RR-X. The CDFs of the departure punctuality of RR-X from model results were shown in Figure 2.21. Different lengths of schedule buffer times were tested in the TTA model for RR-X and this resulted in various departure CDFs, corresponding to the various buffer times adopted. It is seen from Figure 2.21 that the longer the scheduled buffer time was in the turnaround time of RR-X, the more punctual RR-X departures would be. The observed departure

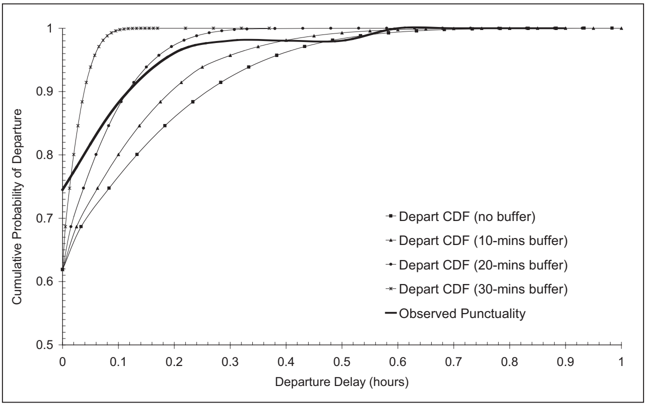

**Figure 2.21 Departure punctuality of RR-X from observations and model outputs**

CDF of RR-X was illustrated in Figure 2.21 by a thick solid line. It is seen in Figure 2.21 that the observed departure OTP of RR-X was close to the estimated departure CDF that had a schedule buffer time of 20 minutes.

The scheduled ground time of RR-X was 60 minutes and the standard turnaround time of a B757 aircraft by Airline R at the time of data collection was 40 minutes (for an European domestic operation). Consequently, the schedule buffer time was about 20 minutes, which was close to the model estimate here (also 20 minutes). However, it was also found in Figure 2.21 that the observed cumulative departure punctuality of RR-X was better with short departure delays (5 minutes) than model results and was worse than model results in some departures which had longer departure delays (more than 30 minutes). It was found from observations of the aircraft turnarounds of Airline R that long departure delays to turnaround aircraft resulted from both the long arrival delays of inbound aircraft as well as from operational delays due to disruptions to aircraft turnaround operations. As a consequence, a thicker right tail was found in the observed departure CDF of RR-X due to some extreme cases in observations that were not captured by the chosen inbound PDF, i.e. Beta functions.

To model extreme cases, one needs to adopt other types of stochastic distributions such as the Normal or Logistic distribution. However, other types of distributions may have a complex model form and this may cause some difficulties in the TTA model when trying to obtain an analytical solution. In such a case, one needs to resort to numerical methods such as statistical sampling and numerical simulation in order to obtain model solutions. The Monte Carlo method is a popular option and has been widely used in solving industrial problems (Fishman 1997).

The second case study was done by applying RR-Y's flight data to the turnaround model. The comparison between observed departure punctuality of RR-Y and estimated departure CDFs of RR-Y were shown in Figure 2.22. The observed departure CDF of RR-Y (represented by a thick sold line) developed closely to the estimated CDF that had no buffer time included. From the given flight schedule of RR-Y, it was known that the scheduled ground time of RR-Y was 65 minutes which included 25 minutes of buffer time when turning around a B757 aircraft. Model results showed that a 25-minute buffer time ought to be long enough to include 95 per cent of inbound delays to RR-Y. However, it was seen from Figure 2.22 that the turnaround punctuality of RR-Y was not commensurate with the amount of buffer time planned in RR-Y's schedule. In other words, the operational punctuality of RR-Y did not match the punctuality expected from RR-Y's schedule.

### *2.6.7 Strategies for Punctuality Management*

In trying to understand this, a hypothesis we may investigate is that schedule OTP is endogenously influenced by airline scheduling philosophy, while exogenously affected by the operating environment in which an airline operates. In other words, the hypothesis states that it is feasible for an airline to manage its schedule punctuality by adjusting its flight schedule. As demonstrated in the case studies, RR-X exhibited good turnaround punctuality with respect to its scheduled turnaround time. On the other hand, the turnaround punctuality of RR-Y matched the estimated departure CDF which included no schedule buffer time, despite having a buffer of 25 minutes embedded in the schedule.

We can see from case studies that the turnaround time of RR-Y was not long enough to absorb potential delays from inbound aircraft as well as delays from aircraft ground operations. Yet, the endogenous schedule punctuality of a turnaround aircraft can still be achieved by good management of turnaround operations such as was observed with flight RR-X (note that the inbound OTP was similar for both RR-X and RR-Y). Hence, the observed schedule punctuality of RR-X fully reflects the amount of schedule buffer time included in its schedule.

It is usually argued by airlines that flight delays are mainly caused by uncontrollable factors such as air traffic flow management, passenger boarding delays, inclement weather and so forth. However, cases like flight RR-Y are not unusual for airlines and passengers. The case study of RR-Y offers airlines some clues to the better management of schedule punctuality. Managerial strategies to improve flight punctuality are therefore, recommended to focus on two aspects: flight scheduling, and the management of operational efficiency of the aircraft ground services.

It is feasible for an airline to manage schedule punctuality by optimally adjusting flight times in a schedule. For instance, flight RR-Y did not achieve its expected OTP, even though 25 minutes of buffer time had been scheduled in its turnaround time. Airline R, therefore can improve RR-Y's departure punctuality by scheduling longer turnaround time at the airport, if a longer ground time is needed, e.g. to accommodate connecting passengers, goods or crew. In addition,

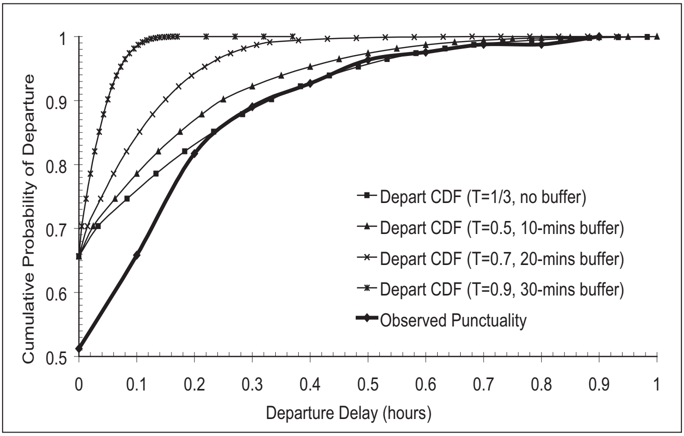

**Figure 2.22 Departure punctuality of RR-Y from observations and model outputs**

improvement of the arrival punctuality of the inbound flight to RR-Y can also help improve the departure punctuality of RR-Y, because less inbound delays often result in less ground operational disruptions and hence, potentially less departure delays for RR-Y. As a result, the departure punctuality of RR-Y can be improved by optimising flight times at the base airport of Airline R and outstations.

The management of schedule punctuality can also be achieved by improvements to the operational efficiency of aircraft turnarounds. It has been demonstrated earlier in this chapter how significantly the departure punctuality of a turnaround aircraft can be affected by the efficiency of aircraft ground services. Although short aircraft turnaround time increases the productivity of aircraft, it is also associated with a high likelihood of flight delays, affecting both airlines and passengers, because of the lack of delay absorption capacity in a tight flight schedule. On the other hand, the operation of aircraft ground services should be able to absorb some operational delays by operational means once it is realised that delays are likely to occur (Ashford et al. 1997; Braaksma and Shortreed 1971).

Most LCCs operate tight aircraft turnaround schedules at their base airports because the operational efficiency of aircraft turnarounds can be fully controlled and managed by these airlines. A longer turnaround time is often allowed at outstations, as less ground resources are available (especially at regional/secondary airports) and a longer ground time also allows some buffer against delays. Maintaining the efficiency of aircraft turnaround is believed to be the key factor for LCCs to deliver a reliable schedule of aircraft rotations (ACI 2000). However, there are still some potential risks for airlines operating tight aircraft turnaround. When schedule irregularities occur, the most effective solution to eliminate flight delays and delay propagation in an intensive aircraft rotation schedule is to cancel flights, which is often associated with high operating costs for airlines as well as inconvenience for passengers.

## 2.7 Summary

So far in this book we have treated airline ground operations at an airport as an aggregate process and based on this, we have developed a Turnaround Time Allocation (TTA) optimisation model, which allowed optimisation of the allocation of precious aircraft time in an airline schedule. An empirical model was also developed earlier that can be used by airlines to quickly adjust schedules, so to achieve the required OTP level in flight operations. Case studies and numerical analyses showed that inbound delays influenced departure delays significantly. In addition, ground operational efficiency, airline scheduling policy and the use of buffer time also influenced the operating OTP of flights. After examining two real flights, it was found that airlines could improve schedule OTP by two approaches: improving scheduling planning (optimisation) and managing the operational efficiency of airlines at airports, in particular aircraft turnaround operations.

Rather than studying airline ground operations on a “macro” level as we have in this chapter, in the coming Chapter 3 a micro perspective will be adopted to discuss the activities of airline ground operations as individual processes. Based on this view, a “micro” model will be developed. This model allows us to further explore the uncertainties involved in airline operations and how an airline may manage these uncertain factors in flight operations and scheduling, in order to achieve high operational reliability. Some widely used methodologies for modelling operational uncertainties by airlines will also be introduced in Chapter 3, including current practices on collecting delay data in the industry and some advanced models developed recently, aiming at improving our understanding of network complexity and mathematical modelling on airline operations.

## Appendix

# Notations and Symbols Introduced in Chapter 2

| | |
|---|---|
| $f_{ij}$ | flight *i* of route *j* that departs Airport A and arrives at Airport B (as in Figure 2.7) |
| $f_{(i-1,j)}$ | the flight flown before $f_{ij}$ on route *j* operated by the same aircraft |
| $s_{ij}^{A}$ | the scheduled time of arrival of $f_{ij}$ |
| $t_{ij}^{A}$ | the actual time of arrival of $f_{ij}$ |
| $s_{(i-1,j)}^{A}$ | the scheduled time of arrival of $f_{(i-1,j)}$ |
| $t_{(i-1,j)}^{A}$ | the actual time of arrival of $f_{(i-1,j)}$ |
| $s_{ij}^{D}$ | the scheduled time of departure of $f_{ij}$ |
| $t_{ij}^{D}$ | the actual time of departure of $f_{ij}$ |
| $S_{ij}^{TR}$ | the scheduled turnaround time of $f_{ij}$ at Airport A |
| $S_{ij}^{BX}$ | the scheduled block time of $f_{ij}$ |
| $d_{(i-1,j)}^{A}$ | the arrival delay of $f_{(i-1,j)}$ and $d_{(i-1,j)}^{A} = t_{(i-1,j)}^{A} - s_{(i-1,j)}^{A}$ |
| $d_{ij}^{D}$ | the departure delay of $f_{ij}$ and $d_{ij}^{D} = t_{ij}^{D} - s_{ij}^{D}$ |
| $d_{ij}^{A}$ | the arrival delay of $f_{ij}$ and $d_{ij}^{A} = t_{ij}^{A} - s_{ij}^{A}$ |
| $d_{ij}^{OP}$ | the delays due to turnaround operations of $f_{ij}$ |
| ${}_{G}S_{ij}^{b}$ | the scheduled ground buffer time of $f_{ij}$ at Airport A |
| ${}_{A}S_{ij}^{b}$ | the scheduled airborne buffer time of $f_{ij}$ en-route Airport A and B |
| $\hat{h}_{i}$ | the realised (actual) turnaround time of $f_{ij}$ |

| | |
|---|---|
| $f_i(h)$ | the stochastic distribution of $\hat{h}_i$ with mean value, $\overline{h}_i$ |
| $\hat{k}_i$ | the realised (actual) flight time of $f_{ij}$ between Airport A and B |
| $f_i(k)$ | the stochastic distribution of $\hat{k}_i$ with mean value, $\overline{k}_i$ |
| $f_i(t)$ | the stochastic distribution of the actual arrival time of $f_{ij}$, i.e. $t_{ij}^A$ |
| $g_i(t)$ | the stochastic distribution of the actual departure time of $f_{ij}$, i.e. $t_{ij}^D$ |
| $g_i'(d_{ij}^D)$ | the function of departure delay; $g_i'(d_{ij}^D) = g_i(t_{ij}^D - s_{ij}^D) = g_i(t) - s_{ij}^D$ |
| $m_1$ | the efficiency of delay absorption by the scheduled buffer time of $f_{ij}$ |
| $m_2$ | the efficiency of turnaround operations at Airport A |
| $C_P(d_{ij}^D)$ | the passenger delay cost function with a marginal delay cost function, $\gamma_P^m(d_{ij}^D)$; a function of delay time $d_{ij}^D$ |
| $C_{AC}(d_{ij}^D)$ | the aircraft delay cost function with a marginal delay cost function, $\varphi_{AC}^m(d_{ij}^D)$; a function of delay time $d_{ij}^D$ |
| $C_{AL}({}_G S_{ij}^b)$ | the opportunity cost of aircraft time with a marginal schedule time cost function, $\delta_{AL}^m({}_G S_{ij}^b)$; a function of ground schedule buffer time, ${}_G S_{ij}^b$ |
| $C_T$ | the total cost of the schedule time optimisation model, including the cost of delays, $D_C$ and the cost of schedule time, $S_C$ |
| $D_C$ | the expected cost of delays including passenger delay cost, $C_P(d_{ij}^D)$ and aircraft delay cost, $C_{AC}(d_{ij}^D)$ |
| $S_C$ | the cost of schedule time calculated by $C_{AL}({}_G S_{ij}^b)$ |
| $\alpha$ | the weight factor, representing the trade-off between delay cost and schedule time cost |

## Chapter 3

# Managing Airline Ground Operations[1]

Chapter 3 focuses on the management of airline ground operations, especially on aircraft turnaround operations and passenger flow management at airports. First, the chapter starts by discussing some issues observed in daily airline operations and the complex resource connections between flights at airports. Second, the framework and techniques widely used by airlines to collect service data of aircraft turnarounds are introduced. The use of modern technologies to assist data collection and analysis is discussed with the introduction of the ACARS system used in the industry, and the development of the ATMS framework in this book.

In Section 3.3, some analytical models widely used by airlines and ground-handling agents for dealing with task monitoring and stochastic disruption management are discussed in detail. These models include a PERT model, which is powerful in task tracking and service planning, and a Semi-Markov Chain model, to be developed in Section 3.4, which better captures the stochastic factors in aircraft ground operations. Applications of mathematical models and the ATMS framework are provided throughout this chapter to demonstrate how these tools perform in real-world environment. Finally in Section 3.5, the strategies for managing passenger flows in an airport are explored from both the airport's and the airline's perspectives. Managerial and operational implications of efficiently and effectively managing passenger flows are examined, providing insight into airport retail revenues and airline passenger management in an airport terminal environment.

### 3.1 Issues in Aircraft Turnaround Operations

Aircraft turnaround operations refer to the activities conducted to prepare an inbound aircraft at an airport for a following outbound flight that is scheduled for the same aircraft. Accordingly, the activities of aircraft turnaround operation include both the inbound and outbound exchange of passengers, crew, catering services, cargo and baggage handling. Technical activities in turning around an aircraft include fuelling, a routine engineering check and cabin cleaning. Often turnaround operations for domestic flights are different from those performed for international flights due to differences in aircraft types, on-board service requirements and security requirements. Details of aircraft turnaround activities

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[1] This chapter is partially based on the following publications: Wu and Caves (2002); (2004); and Wu (2006); (2008).

have been discussed earlier in Chapter 2. Hence, this section focuses on the discussions of some potential issues surrounding aircraft turnaround operations. Further discussions on improving the operating efficiency of aircraft ground operations will follow in the next few sections.

### *3.1.1 Limited Turnaround Time and Schedule Constraints*

Since passenger numbers and cargo/baggage loads vary from flight to flight and these numbers are only realised after the check-in is closed at the airport, the actual turnaround time of an aircraft is stochastic in nature. The *scheduled turnaround time* of an aircraft is defined as: *the time between the on-block and off-block time of the aircraft at a gate*. This scheduled turnaround time imposes constraints and operating pressure on airline ground operations, because delays to some service activities may cause delays to other services and eventually may result in departure delays. Transfer "traffic" may occur at airports during aircraft turnarounds such as transfers of flight/cabin crew, passengers and cargo/baggage between flights. The connection of airline resources (i.e. aircraft and crew), passengers and goods (i.e. baggage and cargo) can be significant for an airline that operates a hubbing network.

Under the complex resources connection mechanism among aircraft, passengers and crew, disruptions may occur to any of the processes of aircraft turnaround and may consequently cause delays to departure flights. Disruptions such as late connecting passengers, late connecting crew, missing check-in passengers, late inbound cargo/baggage or equipment breakdown are normally seen in daily airline operations. These disruptions occur randomly, although in real operations some flights may incur certain disruptions more frequently than others. The duration of the delays caused by disruptions is also stochastic. Accordingly, the impact of delays due to ground disruptions is uncertain, depending on the magnitude of disruptions and the nature of the network design. For instance, late inbound connecting passengers could be delayed by 15 minutes and cause brief delays for the outbound flight or flights in a multiple connection case. However, when connecting passengers are late by 45 minutes, this will cause significant delays to some outbound flights. The airline then needs to make a decision on whether or not to wait for the connecting passengers by holding departure flights or to leave without the connecting passengers.

While disruptions caused by air transport system capacity reduction attract much attention in the literature, mostly due to its large scale of impact (see: Arguello et al. 1998; Barnhart et al. 1998; Luo and Yu 1997; Rexing et al. 2000; Teodorovic and Stojkovic 1995; Yan and Young 1996), it is interesting to note that disruptions within this category account for roughly 40–50 per cent of total flight delays in Europe including those caused by weather (Eurocontrol 2004b; 2005). Other delay causes (the remaining 50–60 per cent) are contributed by airline operations and scheduling, in which reactionary delays may account for up to 20–30 per cent of the 50–60 per cent delay share; technical faults may account for up to 10 per cent (Eurocontrol 2004b; 2005). Delays cost money for airlines and passengers, regardless of the source of the delay. In this chapter our discussion will focus on those delay causes that airlines have better control during aircraft ground operations.

### *3.1.2 Resource Connections*

Low-cost carriers are well aware how a fast and reliable turnaround operation can improve the bottom line of an airline business and the efficiency of an airline network through high utilisation of aircraft and low exposure to unexpected delays. Since delays may occur to any of the processes in schedule execution, buffer time is usually designed in flight schedules to accommodate unexpected disruptions and any consequent delays. Buffer time may be placed in the block time of flights as well as in the ground time for aircraft turnaround operations. Since airlines have more control and flexibility over the turnaround processes on the ground, the scheduled ground time for a turnaround is seen as a tactical and effective means to stabilise aircraft routing and to prevent further knock-on delays (also known as "reactionary delays" or "delay propagation" in the industry) through the rotation lines in an airline network.

Given the resource/passenger exchange among flights, disruptions to some resources/activities may cause delay propagation in the network via aircraft rotations, unless these delays are effectively contained by tactical measures by the airline such as flight cancellations, or absorbed naturally by the designed buffer time in the schedule. Hence, we can realise the crucial role played in maintaining efficient and effective aircraft turnaround operations in daily airline operations.

## 3.2 Collecting Service Data of Aircraft Turnarounds

### *3.2.1 Delay Data Collection*

Flight data are collected by airlines in order to conduct analyses for operational improvements in the future. These data are also used to generate reports for relevant civil aviation authorities in different counties, to which airlines are required to report operational data, in particular delay statistics. Flight data are often referred to as the "OOOI data", which stands for "out of the gate, off the ground, on the ground, and into the gate". This is the standard procedure of flight operations from pushing back at the gate, taking off at the runway, landing at the runway of the destination airport and taxiing into the gate. The original purpose of this OOOI data was to trace the flight phases of an aircraft and maintain communication with an operating aircraft. In addition, the collected data may be used by some airlines for payroll purposes. A good history of flight data collection in the airline industry is available from Wikipedia (Wikipedia 2008a).

### *3.2.2 ACARS Data Recording System*

The OOOI data is often collected automatically by avionic equipment aboard an aircraft, called the Aircraft Communication Addressing and Reporting System (ACARS). ACARS together with radio or satellite networks provide airlines and air traffic control authorities with a system to trace the flight phases of an aircraft during operations. Airlines compare the OOOI data with schedules and generate flight "delay data", which provides delay statistics as well as other flight-related information, e.g. carried passengers, and any operational disruptions to flights. In some countries, airlines are required to report these statistics (except those commercial data, e.g. passenger numbers) to civil aviation authorities. For instance, the Department of Transportation (DoT) in the U.S. requires airlines to report delay data, if they are operating within the United States and territories and have at least one per cent of total domestic scheduled-service passenger revenues, as described in 14 CFR Part 234 of DoT's regulation (DoT 2005). Airlines can also report voluntarily in the current regulation in the U.S. Monthly data are collected by various U.S. government agencies, providing information including flight delays, mishandled baggage, over-sales, consumer complaints and so forth.

In Australia, a similar regulation is in place that requires airlines to report the on-time performance for each route flown, subject to reporting criteria. The OTP statistics are reported for those routes where the passenger load averages over 8,000 passengers per month and where two or more airlines operate in competition. As of February 2008, there were 48 routes that met this definition in the Australian domestic network. Airlines also report overall monthly network performance data, representing over 99 per cent of scheduled domestic flight services in Australia (BITRE 2008). Similar regulations exist in the European Union and statistics are collected by the Central Office for Delay Analysis (CODA) of Eurocontrol (see Eurocontrol's web site for more details: http://web.hq.corp.eurocontrol.int/ecoda/portal/). Flight data (OOOI data) can be collected automatically by ACARS (or similar systems) or in a manual process by airlines. In a manual system, airline ground staff, pilots and ground handling agents will each record flight data separately, and these data are then centrally collated for delay analyses and reporting purposes.

### *3.2.3 IATA Delay Coding System*

Together with the OOOI data, airlines also record causes of the delays. This information is helpful in determining the causes of delays and assists in improving airline operations and scheduling. The common framework for delay cause recording is the delay coding system developed by the International Air Transport Association (IATA) (IATA 2003). Delay causes are categorised into 12 major categories as shown in Table 3.1. There are 100 delay codes available for use, including some spare ones which can be adopted according to the individual airline's needs for data recording. Apart from the "numerical" coding system, each

**Table 3.1 IATA delay codes summary**

| Delay Codes | Delay Categories |
|---|---|
| 00–05 | Airline Internal Codes |
| 09 | Schedules<br>• Scheduled ground time less than declared minimum ground time |
| 11–18 | Passenger and Baggage<br>• from Late check-in to baggage processing delays |
| 21–29 | Cargo and Mail<br>• from documentation to late acceptance (mail only) |
| 31–39 | Aircraft Ramp Handling<br>• from aircraft documentation late to fuelling & technical issues |
| 41–48 | Technical and Aircraft Equipment<br>• from aircraft defects to scheduled cabin configuration adjustment |
| 51–57 | Damage to Aircraft & EDP/Automated Equipment Failure<br>• from damage during flight operations to late flight plans |
| 61–69 | Flight Operations and Crewing<br>• from flight plans to captain request for security check |
| 71–77 | Weather<br>• from departure station to ground handling impaired by adverse weather conditions |
| 81–89 | Airport and Government Authorities<br>• from air traffic services to ATC/ground movement control |
| 91–96 | Reactionary<br>• from load connection delay to operations control |
| 97–99 | Miscellaneous<br>• mainly industrial action with or outside own airline |

numerical delay code is associated with an alphabetical code as well. For instance, delay code 11, (late passenger check-in due to late passengers) corresponds to the alphabetical code, PD.

Based on the IATA delay-coding framework, most airlines develop their own in-house delay coding systems to satisfy the demand of data collection. This demand often stems from the pressures of performance benchmarking and efficiency improvement among various units of an airline, e.g. the flight operations unit, engineering unit, or commercial unit. Therefore, some airlines have developed complex delay coding systems such as the one used by Air New Zealand (Lee and Moore 2003). An example of an in-house delay coding system of a carrier is given in Table 3.2. This system is based on the alphabetical delay codes and codes are categorised according to the IATA framework. However, unlike the IATA system, this airline reorganises the allocation of individual codes to meet its operational and managerial demands. In Table 3.3, the ZA category represents air traffic control (ATC) related delays. Within the ZA category, most codes are "8×" IATA codes, but a “93” code (aircraft rotation due to ATC) is also included. This reorganisation is more useful and meaningful from the airline’s perspective, because it provides a better view of the true causes of delays according to key delay categories.

**Table 3.2 An in-house delay coding system of a carrier**

| Codes | Description |
|---|---|
| ZA | ATC |
| ZC | CARGO |
| ZD | SECURITY |
| ZE | ENGINEERING |
| ZF | FLIGHT CREW |
| ZJ | INFORMATION MANAGEMENT |
| ZK | CABIN CREW |
| ZM | CATERING |
| ZO | OPERATIONS |
| ZP | CUSTOMER SERVICES |
| ZR | RAMP |
| ZT | TERMINAL OPS / DISPATCH |
| ZW | WEATHER |
| ZZ | AIRPORT + AUTHORITIES |

**Table 3.3 Sub-codes under the ZA code (continuing from Table 3.2)**

| Z Code | Delay Code | Code Number | Description |
|---|---|---|---|
| ZA – ATC | AC | 81 | Awaiting revised take-off slot |
| ZA – ATC | AE | 83 | ATFM restriction at destination airport |
| ZA – ATC | AM | 89 | Departure congestion inc. ATFM restriction |
| ZA – ATC | AMO | 89 | Multiple Push-back congestion, other operations etc. |
| ZA – ATC | AMT | 89 | Tow-on problem caused by GMC/ATC |
| ZA – ATC | AT | 81 | ATFM en-route demand/capacity |
| ZA – ATC | AW | 84 | ATFM weather at destination |
| ZA – ATC | AX | 82 | ATFM staff/equipment en-route |
| ZA – ATC | RAA | 93 | “RA” caused by ATC |

### *3.2.4 Aircraft Turnaround Monitoring System (ATMS) Framework*

Punctuality data are mostly compiled from the "time stamps" acquired manually by airline staff or automatically through ACARS or similar systems. Time stamps may include the take-off time (wheel off), landing time (wheel on), arrival time (on-block at gates) and departure time (off-block at gates), i.e. the OOOI data. However, operating data of ground handling, e.g. the catering unloading start time and finish time, are hardly as well recorded by airlines for the purpose of operations research. Airlines may have some records of these time stamps, but they are often scattered among different operating units and not collated centrally for analysis purposes.

For airline operations control, the widely available ACARS time stamps are used to track the flight phases of individual aircraft in daily operations. However, the lack of time stamps during aircraft ground time makes aircraft turnaround operations a "black box", and it is hard to co-ordinate available ground resources without relying on frequent radio conversations between operations controllers, airport duty managers and ground handling staff. The lack of operating data makes it difficult to evaluate the operating performance of ground handling services and also impossible to calibrate the operational procedures of different aircraft types at different airports.

Given the crucial role played by ground operations in controlling delays in an airline network, it would be of tremendous benefit for airline operations control if live operational data were available during aircraft ground operations on a real time basis. This would allow operation controllers to take precautions regarding potential events that might later on develop into delays for a departure flight, or potentially cause serious delay propagation in the network. The potential impact of this dynamic and real-time information on airline operations control has been well-demonstrated by the work by Abdelghany et al. (2004), in which flight delays and potential breaks of resource connections are projected ahead of schedule execution on a real-time basis.

Based on the needs of collecting data during aircraft turnaround operations, a turnaround monitoring framework is developed in this section, which serves as a platform to collect operational data, benchmark turnaround efficiency and calibrate the operational procedures of different aircraft types. Secondly, a real-time monitoring system is developed based on this framework, together with a data collection tool, providing all units involved in ground operations with situational awareness and up-to-date progress of aircraft under-going turnarounds. The Aircraft Turnaround Monitoring System (ATMS) is aimed at collecting operating data on a real-time basis during aircraft turnarounds. ATMS can also be used to conduct real-time monitoring tasks by utilising collected operating data. Based on the operational needs of individual ground handling units and the functional needs of operations monitoring, the ATMS framework is developed as an open framework as shown in Figure 3.1, which allows future development of add-on modules based on the same platform and structure.

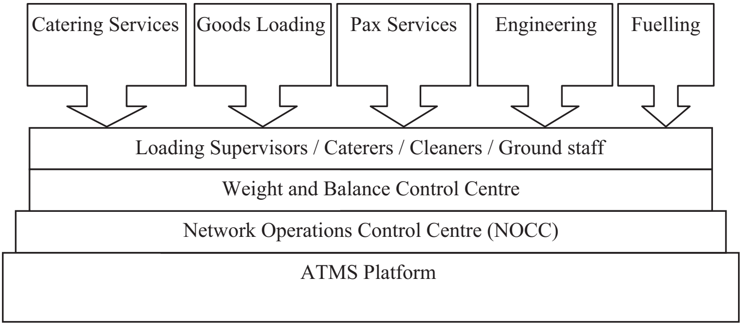

**Figure 3.1 ATMS framework**

Based on the main operational procedures of aircraft, turnaround activities are grouped into four major process flows, namely passenger, cargo, engineering check and catering in the ATMS framework. Activities within each process flow are chosen and included in the framework according to the needs of data collection and the importance of individual activities in turnaround operations. Using this framework, individual handling units only need to collect time stamps of key activities during turnarounds, so the progress of individual process flows can be easily shared between the handlers and the control centre, e.g. catering loading staff and the catering centre. Meanwhile, the collected information during turnaround operations can also be shared among different handling units, the ground operations centre at the airport and the network operation control centre at the carrier's remote headquarter. A list of key activities chosen in each process flow is given in Table 3.4. Some activities have an operational sequence to follow such as passenger, cargo and catering flows. Other activities such as refuelling and engineering checks are operated independently from other activities.

### *3.2.5 Implementation of the ATMS framework*

The ATMS framework has been implemented using mobile devices with wireless telecommunication network technology, namely GPRS (a widely used mobile phone network service, which provides internet access to mobile phone users). Given the environment in which ground handlers work on the apron and to minimise the inconvenience of entering data, Personal Digital Assistants (PDAs) were chosen as the mobile device in this implementation. Activities and flows given earlier in Table 3.4 were programmed and implemented on a Palm PDA. Collected time stamps were both stored locally on the PDA and transmitted immediately on a real-time basis through the GPRS network to a remote database server.

The data flowchart of ATMS is shown in Figure 3.2. Multiple PDAs can be used for a single aircraft turnaround operation, if the ground handling strategy belongs to the "unit strategy", meaning different units independently conduct different jobs

**Table 3.4 Activities modelled in the ATMS framework**

| Activity No. | Passenger | Cargo | Engineering | Catering |
|---|---|---|---|---|
| 1 | Position passenger steps/air bridge | Position cargo loader | Routine maintenance start | Open catering service door |
| 2 | Open passenger door | Open cargo door | Routine maintenance finish | Unload carts |
| 3 | Disembark passengers | Unload baggage | Fuelling start | Load carts |
| 4 | Onboard customs control/crewing | Unload cargo | Fuelling finish | Close door |
| 5 | Disembark crew | Load cargo | Wheel and tire check start | |
| 6 | Cabin and cockpit cleaning start | Load baggage | Wheel and tire check finish | |
| 7 | Final cleaning | Close cargo door | | |
| 8 | Board crew | Remove cargo loader | | |
| 9 | Crew check | | | |
| 10 | Board passengers | | | |
| 11 | Close passenger door | | | |
| 12 | Remove passenger steps/air bridge | | | |

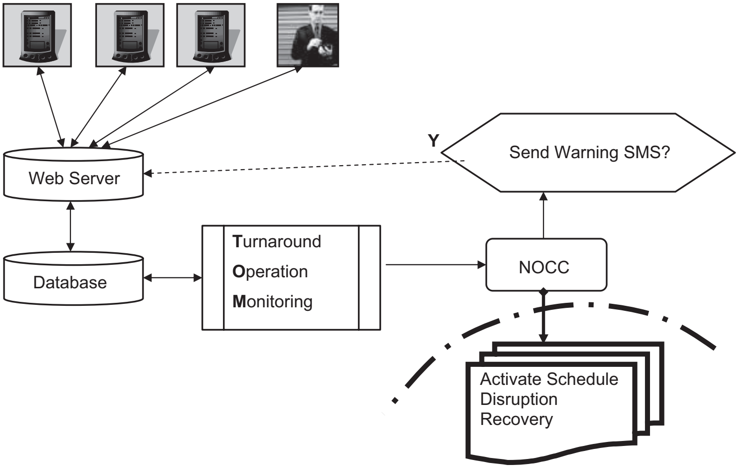

**Figure 3.2 ATMS live data flowchart**

in aircraft turnaround. If a “team strategy” is used for ground handling, then the team leader can use one PDA to control and monitor all the turnaround activities of an aircraft. An in-house real-time simulation model, namely Turnaround Operation Monitoring agent (TOM) was connected to the central database to monitor the status of multiple turnarounds at different airports (as long as there were live data input streams available), and updated in real time the estimated departure times of each monitored flight to each hand-held device on the apron.

Operation controllers at the Network Operations Control Centre (NOCC) of an airline may receive an automatic warning message from TOM, if the projected departure delay exceeds a predefined delay threshold. Operation controllers can then radio the manager of the ground handling unit to resolve the potential delay by operational means, or send text messages to the manager via PDAs and request proactive delay control actions. If the projected delay is long and cannot be resolved rapidly, the NOCC controllers have the option to activate the schedule disruption recovery protocol to deal with potential passenger itinerary disruptions, crewing disruptions and aircraft routing irregularities.

Two screen shots of the ATMS implementation on PDAs are given in Figures 3.3 and 3.4. The main menu of ATMS as shown in Figure 3.3 included six options: arrival, passenger, cargo, engineering checks, catering and departure. Arrival and departure options recorded the on/off block times of aircraft at gates, which were used as a reference to the ACARS arrival and departure time records. Activities under the “passenger” option were displayed on the PDA screen as illustrated in Figure 3.4. When an activity started/finished, the user only needed to click the activity on the screen. The current time stamp of the corresponding activity would be automatically obtained from the system time, stored and transmitted via the GPRS network to the remote database server immediately.

**Figure 3.3 The main menu of ATMS of an example flight, XY001**

[ ] Position passenger steps/
[ ] Open passenger door
[ ] Disembark passengers
[ ] Onboard customs control
[ ] Disembark crew
[ ] Cabin and cockpit
[ ] Final clean
[ ] Board crew
[ ] Crew check of a/c
[ ] Board passengers

**Figure 3.4 The input screen of the passenger processing flow of XY001**

The ATMS system was first tested in April 2005 for remote communication functions. Immediately following the test was the trial at Sydney Airport to collect ground handling data to benchmark the operational efficiency of aircraft turnaround services. The second trial took place in January 2006 at Sydney Airport to collect data to improve the aircraft turnaround procedures for the B737 family aircraft. Due to the sensitivity of some data collected during the trials, only selected results are given here to demonstrate the ATMS framework and its implementation in real airline operations.

The catering service is given here as an example because it had caused some operational problems and departure delays in recent domestic operations of the Australian carrier. Figure 3.5 shows the observed start/finish times of catering services. The reference time in the following analysis is the "actual time of departure", i.e. the un-block time at gates. Those two bars highlighted with bold lines in Figure 3.5 represent the standard start/finish time of catering services for B737, which were 38 minutes and 25 minutes before pushing back the aircraft. We can see from Figure 3.5 that many catering services started early and this was mostly due to the long scheduled turnaround time and some early arrivals.

The scheduled turnaround time for this sample group ranged from 45 minutes to 65 minutes. 32 per cent of the catering services started late and these late services also caused 43 per cent catering services to finish late. The domino effect of this delay was to delay passenger boarding start time and consequently cause departure delays to 20 per cent of the total sampled flights, i.e. 16 out of 56 flights from our sample. However, catering service was not the sole reason causing departure delays to those 16 flights during our survey. Among them, six flights were also delayed due to passengers and goods connections between flights at Sydney Airport.

The goods unloading process usually causes little trouble unless the process is delayed due to late equipment allocation or equipment breakdown. The goods loading process, however, may cause delays to turnaround operations, in particular with complex goods connections among flights. Figure 3.6 shows the observed loading start time and finish time with respect to the actual departure time of flights. It shows 22 per cent of flights had late loading starts and this was reflected by the 17 per cent late loading finishes and consequent loading delays. Early loadings that appear in Figure 3.6 were due to long turnaround times. Overall, 21 per cent of sampled departure flights were eventually delayed due to loading related reasons. Among these delayed flights, half were delayed due to load connections specifically and the rest were due to late completion of goods loading.

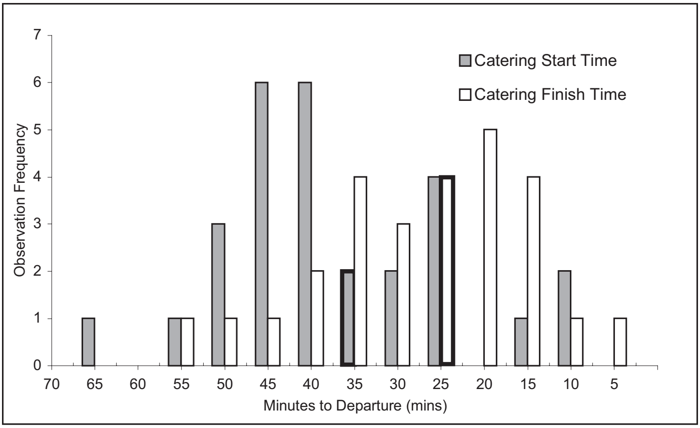

**Figure 3.5** Start and finish times of catering service

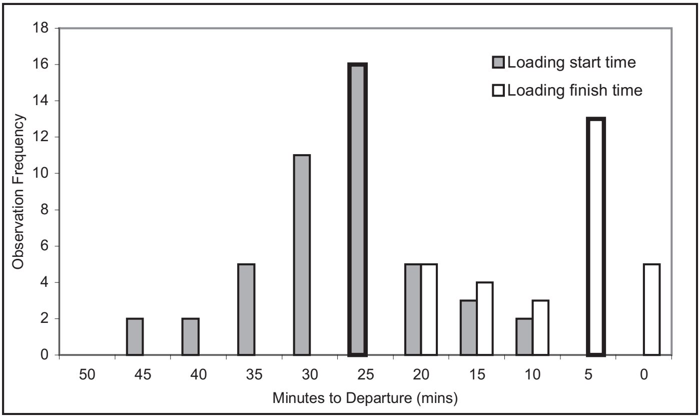

**Figure 3.6** Start and finish times of goods loading

### *3.2.6 Implications for Airline Operations*

*3.2.6.1 Operations control, delay management and ground operation efficiency* The availability of real-time turnaround operating data has significant implications for airline operations control and disruption management. The data captured by the ATMS system clearly shows the start and finish time of each turnaround activity. This real-time information improves the situational awareness of loading supervisors, airport duty managers and operations controllers. The further implication of the data availability is that operations controllers can take proactive actions to reduce departure delays and also mitigate potential delay propagation in the network.

The collected time stamps can be used to evaluate the operational efficiency of different procedures in turning around an aircraft, leading to improvements of the turnaround procedures, operational efficiency, and flight punctuality. Furthermore, the data gathered can be used as service quality indicators, which play an important role in establishing outsourcing contracts of ground handling with third party handlers. Without detailed operating data of turnaround operations, it would be hard to establish an objective service quality indicator to monitor the operational efficiency of ground handling, or the "service level" of ground handling. Lufthansa has moved towards this at its Munich and Frankfurt hub where Lufthansa does ground handling for other carriers (Mederer and Frank 2002; Schiewe 2005; Thon 2005).

*3.2.6.2 Delay-coding systems* Airlines use delay coding systems to record delay causes, so that in the future delays can be reduced by applying appropriate operational procedures. The standard IATA delay coding system consists of 100 delay codes representing different delay sources (IATA 2003). Apart from the IATA system, airlines also use in-house delay codes to encode further detail regarding the causes of delays, hoping that this information will help reduce future delays (e.g. Air New Zealand's delay coding system improvement by Lee and Moore (2003)). Given the complex involvement between the different groups involved in aircraft turnaround, a few operation co-ordinators and some radio conversations at a major airport are usually required to resolve delay code assignments for complex cases. The disadvantage of this practice, besides human resource costs, is the difficulty in determining the appropriate delay codes, which are truly "responsible" for delays. This difficulty also prohibits airlines from understanding the underlying causes of delays.

To solve this problem, some airlines use more than one delay code for flight delays. Although this seems to be a good method for tracing the causes of delays, this technique actually increases the complexity of delay code assignment and the following delay code analyses, because the delay-code trees may become too large to analyse. The developed ATMS system can significantly improve this process because operating time stamps make the delay root tracing an easy task for airlines. For instance, delays to passenger boarding finish time can be due to high passenger numbers (causing long boarding time), late start of boarding, late start/finish of cabin cleaning, late start/finish of catering service, late crewing procedures and late connecting passengers. Without clear information of individual turnaround activities, the delay code for this flight could have been assigned as "passenger boarding delay", which is in fact the consequence of delays instead of the root cause of the delays. This example demonstrates how collecting turnaround operating data can significantly improve airline operational efficiency as well as reduce delay propagation in an airline network.

*3.2.6.3 Automatic data collection systems* Although mobile computing devices can be used to collect operational data during aircraft turnaround operations based on the ATMS framework, one major drawback is that data collection still needs human interaction with mobile devices, adding extra burden to the ground handling agents, especially during peak operation hours and cold weather conditions (Thon 2005; Wu 2008). This manual data collection procedure can be semi-automated with the use of Radio Frequency Identification (RFID) tags. Until recently, RFID tags have mostly been used in the aviation industry for the tracking of baggage that has been listed on the agenda of "Simplifying the Business" by IATA (IATA 2008). Although the promotion and development of RFID use in airline and airport operations is not to replace the bar-coded boarding passes and bar-coded baggage tags in the short run, RFID has certain advantages for improving the operational efficiency of airlines and airports in areas such as the speedy processing of baggage sorting at hub airports and the high accuracy of tag reading.

Building on this RFID platform in airline operations, the data collection exercise of ATMS can be semi-automated. RFID chips can be attached to specific spots of the aircraft fuselage and RFID data readers can be mounted to ground handling equipment, together with wireless data transmission devices. For example, to collect service time stamps for cargo unloading and loading, RFID chips can be attached to a place near the cargo door, and RFID data readers can be mounted on the cargo loading trucks. When a cargo loading truck approaches the cargo door, the RFID reader automatically reads the information carried by the RFID tag near the cargo door; a time stamp of cargo unloading start time is obtained.

Often a data reader may continue reading tag information as long as a tag is within the rage of a reader. Hence, the last time stamp obtained becomes the finishing time of an activity. Based on this principle, the logging of most activities in aircraft turnaround operations can be fully automated including fuelling, baggage/cargo loading, and catering service. Some activities, however cannot be fully automated by RFID, e.g. cabin cleaning and passenger boarding. Time stamps for these services can then be manually collected on ATMS by ground staff, so this makes the data collection exercise semi-automatic.

## 3.3 Managing and Modelling Ground Service Activities

### *3.3.1 Project Evaluation and Review Technique (PERT) Model*

To manage and model airline operations, the Project Evaluation and Review Technique (PERT) model is widely used in the industry. There are two goals of using PERT in managing airline operations: first, to evaluate and improve the efficiency of airline operational procedures; second, to improve the efficiency of airline ground resources allocation, especially human resources. In the 1970s, PERT and the other competing modelling technique, Critical Path Method (CPM) started being deployed in the aviation industry. Braaksma and Shortreed (1971) used CPM to model aircraft turnaround operations and the turnaround time an aircraft took occupying a gate in an airport terminal. The established model was able to closely describe current airline operations (relative to the time the study was performed) and even to predict and evaluate future changes to aircraft turnaround procedures and activities.

A later and more recent study by Hassounah and Steuart (1993) demonstrated how a similar concept, by considering stochastic flight delays and gate schedule buffer time, could lead to the improvement of overall performance of airport gate assignment. More recently, Adeleye and Chung (2006) developed a PERT model (in a network form) and used the CPM technique to calculate aircraft turnaround time with the assistance of the simulation software, Arena. The network-form of the PERT/CPM model was also used in a study of flight delay projection by Abdelghany et al. (2004) who used the “shortest route” algorithm to calculate the most likely path by which current flight delays may cause future flight delays due to delay propagation in an airline network.

Historically, PERT and CPM were developed independently in the late 1950s, albeit with a striking similarity between the two modelling techniques (Taha 1992; Wikipedia 2008b). Today the terms PERT and CPM often refer to the same technique, that is widely used in project planning, project scheduling, project controlling and management. In the following sections, “PERT” will be used to refer to the overall scheduling and management model, while “CPM” will be specifically used when we talk about the calculation of “critical paths” in a PERT model.

PERT is a modelling methodology used to describe the execution of a project that contains a collection of activities. PERT is also used to describe the “interdependencies” between some activities within a project. The interdependent relationships between activities usually take the form of a “chronological sequence” by which an activity cannot start until a preceding activity is finished. Mathematically, a PERT model is often represented by a “network diagram” which is composed of “nodes” and “arcs”, representing individual activities of a project.

A “node” in the PERT network diagram represents an “event” which denotes a specific activity and the attributes of that activity, e.g. duration of the activity and variance of the duration. An “arc”, on the other hand represents an interdependency between two nodes, starting from a "tail" node to a "head" node and is often represented by an "arrow" in a network diagram. Readers should note that we employ the "activity on node" (AON) convention in the following model, meaning that activities are represented by nodes and arcs are used only to represent interdependencies among nodes (Wikipedia 2008b).

A network diagram, Figure 3.7 is given below, representing some key service activities of aircraft turnaround operations. The list of the nodes and their corresponding turnaround service activities is given in Table 3.5. Node 1 represents the arrival of an aircraft at a gate, i.e. the "start node" and node 4 represents the status that the aircraft is ready for departure and pushing back from the gate, i.e. the "finish node". The path (1, 2, 3, 4) represents the workflow of cargo/baggage offloading and loading. The path (1, 5, 6, 7, 8, 9, 4) models the workflow of passenger disembarkation, cabin cleaning and passenger boarding.

Path (1, 10, 4) describes aircraft refuelling and (1, 11, 4) describes the aircraft routine maintenance check during aircraft turnaround operations. Branching nodes 12 and 13 represent catering offloading and loading procedures, assuming that node 5 precedes node 12, and node 13 precedes node 8. In practice, this means that catering off-loading only starts when passenger disembarkation is completed and passenger boarding will not commence until catering loading is finished.[2] The network diagram shown above is not necessarily indicative of the standard operating procedures of a catering service. For some types of aircraft (mostly narrow-body jets), passenger disembarkation/boarding and catering processing can take place simultaneously, if there are no potential physical conflicts between two procedures.

It should be noted that the list of activities given in this example is not necessarily a complete list of all activities involved in turning around an aircraft. International operations or operations by large aircraft often involve more turnaround activities than domestic operations by smaller aircraft. In addition, low-cost carriers often offer fewer "free" services aboard, so there are also less activities required in turning around an aircraft operated by a low-cost carrier. This is why the aircraft turnaround time of low-cost operations is often shorter than that of network carriers. To simplify the given example in this section, only major activities are modelled in our example problem.

### *3.3.2 Identifying Critical Paths in a PERT Model*

One objective of applying the PERT model in project planning and management is to identify the critical path/paths of a project. A "path" in a network diagram of PERT consists of a series of activities that must be executed sequentially. An activity is said to be "critical" when the occurrence of any delays to this activity

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[2] This sequence is not always true for all types of aircraft. Depending on the location of galleys in the aircraft and the procedures of airlines, passenger handling can be conducted simultaneously with catering services, especially for short-haul low-cost operations.

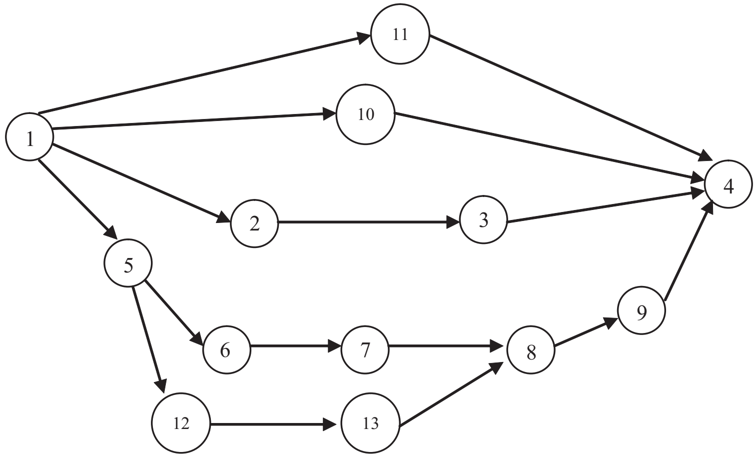

**Figure 3.7 A network representation of key aircraft turnaround activities**

**Table 3.5 List of nodes and corresponding activities in a network diagram**

| Nodes | Activities | Duration (mins) |
|---|---|---|
| 1 | Arrival at the gate (Start) | 0 |
| 2 | Cargo/baggage off-loading | 20 |
| 3 | Cargo/baggage loading | 25 |
| 4 | Ready for departure and push back (Finish) | 0 |
| 5 | Disembark passengers and crews | 10 |
| 6 | Cabin cleaning | 15 |
| 7 | ATC flow control | 3 |
| 8 | Crew and passenger boarding | 15 |
| 9 | Flight operations and crew procedures | 3 |
| 10 | Aircraft fuelling | 25 |
| 11 | Routine maintenance check | 20 |
| 12 | Catering off-loading | 10 |
| 13 | Catering loading | 10 |

results in the entire project being delayed. A path is said to be "critical" if the path consists of all critical activities in a project connecting from the start node to the finish node in the network diagram. This also means that any delay to activities on the critical path will cause delays to the entire project. Identifying the critical path has profound implications on project planning and management during operations. At planning stage, identifying the critical path can help resources allocation. During project execution, the knowledge of the critical path identifies those key activities that need the most attention and often more resources to ensure no delays occur to critical activities during actual operations.

The identification of the critical path includes two phases, namely the forward pass and the backward pass. The forward pass starts from the "start" node and is performed sequentially until the "finish" node is reached, which are node 1 and node 4 in our example. The forward pass calculates the "earliest start time" (denoted by $ES_j$) of activity *j* (at a node *j*), considering all connecting predecessor activities (denoted by *i*) and their corresponding "earliest completion time", denoted by $EC_i$. $ES_j$ can be expressed by (3.1). The $ES_j$ for the "start" node is zero and the $EC_i$ is also zero for the start node. Following the forward pass, one can calculate the $ES_j$ and $EC_i$ of all nodes in a network diagram.

$$\begin{aligned} ES_j &= \max_i \{EC_i\} \text{ where node } i \text{ precedes node } j \\ EC_j &= ES_j + D_j \end{aligned} \tag{3.1}$$

On the other hand, the backward pass starts calculating the "latest completion time" (denoted by $LC_j$) of activity *j* from the "finish" node to the "start" node. The $LC_j$ time of the "finish" node is equal to the $EC_j$ time on the longest path. The "latest start time" ($LS_j$) of activity *j* is expressed in (3.2), which is the $LC_j$ time minus activity duration, $D_j$. The $LC_i$ time of predecessor activity *i* is equal to the minimum $LS_j$ time among all successor activities *j*. $LC_i$ is expressed by (3.3). The "slack time" of an activity is the amount of time that the activity can be delayed without influencing or delaying the overall project duration. The slack time of activity *i* can be calculated by (3.4), once all other time indicators are available.

$$LS_j = LC_j - D_j \tag{3.2}$$

$$LC_i = \min_j \{LS_j\} \text{ where node } j \text{ are successors of node } i \tag{3.3}$$

$$Slack_i = LC_i - EC_i = LS_i - ES_i \tag{3.4}$$

The calculation of the earliest start time and the latest completion time provides information needed in determining whether an activity *i* is "critical" and lies on the critical path of a project. Activity *i* lies on the critical path if there is zero slack time for activity *i* and this path is the longest path in the network diagram. Readers should note that there could be more than one critical path in a complex project and the identification of critical paths is subject to the estimated activity times. In other words, when the service times of some activities are changed due to resource re-allocations or operational improvements during project execution, critical paths may change accordingly.

### *3.3.3 Managing Aircraft Turnaround Operations by PERT*

The network diagram given earlier in Figure 3.7 was used to calculate the required indicator times according to the principles detail above. Calculated indicator times are shown in the network diagram in Figure 3.8, and is listed in Table 3.6. Each node (activity) has five time attributes including $ES_i$, $EC_i$ , $LS_i$, $LC_i$, and $Slack_i$ which are organised in a designated format as shown in the legend key of Figure 3.8. We can see that the longest time required to finish the whole turnaround operation is 48 minutes. Those connected activities that had zero slack time were identified and formed a critical path, 1-5-12-13-8-9-4 (highlighted in the diagram).

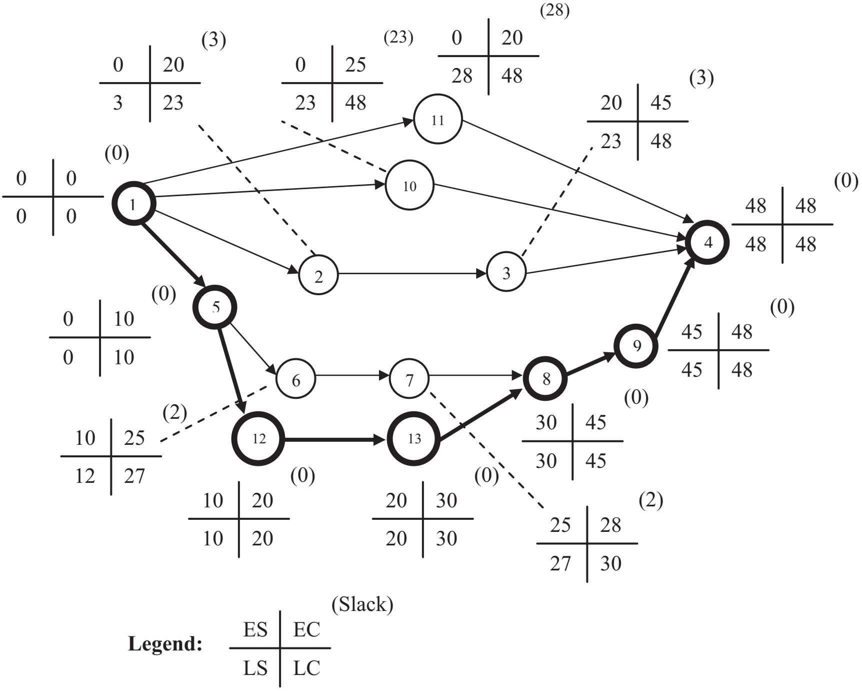

**Figure 3.8 Activity times, slack times and critical path identification**

**Table 3.6 Time calculations for the example aircraft turnaround PERT model**

| Activity (node) | Duration ($D_i$, mins) | ES (mins) | EC (mins) | LS (mins) | LC (mins) | Slack (mins) |
|---|---|---|---|---|---|---|
| 1 | 0 | 0 | 0 | 0 | 0 | **0** |
| 2 | 20 | 0 | 20 | 3 | 23 | 3 |
| 3 | 25 | 20 | 45 | 23 | 48 | 3 |
| 4 | 0 | 48 | 48 | 48 | 48 | **0** |
| 5 | 10 | 0 | 10 | 0 | 10 | **0** |
| 6 | 15 | 10 | 25 | 12 | 27 | 2 |
| 7 | 3 | 25 | 28 | 27 | 30 | 2 |
| 8 | 15 | 30 | 45 | 30 | 45 | **0** |
| 9 | 3 | 45 | 48 | 45 | 48 | **0** |
| 10 | 25 | 0 | 25 | 23 | 48 | 23 |
| 11 | 20 | 0 | 20 | 28 | 48 | 28 |
| 12 | 10 | 10 | 20 | 10 | 20 | **0** |
| 13 | 10 | 20 | 30 | 20 | 30 | **0** |

According to the calculation of slack time, one can find that the slack time for node 6 and 7 was only two minutes, meaning any delays longer than two minutes to cabin cleaning or due to air traffic flow control may potentially cause departure delays via a path other than the critical one. In addition, the slack time for cargo/baggage processing activities was only three minutes for off-loading and loading respectively. This means that the departure flight could be delayed, if delays to cargo/baggage processing exceeded the available slack time. On the other hand, there was more slack time available for aircraft refuelling (node 10) and routine maintenance checks (node 11), implying that these two services were generally not critical for the whole operation, unless excessive delays occur to these two services.

The presentation of a PERT model in the form of a network diagram is a clear way of presenting the interdependencies among various activities as well as viewing the complexity of the whole project. Often, a PERT model is given in the form of a *Gantt chart*, which is usually charted on a time scale for project management purposes. The network diagram given earlier was converted to a Gantt chart by using commercial software (OmniPlan on a Macintosh) and is illustrated in Figure 3.9. The assumed arrival time of the previous flight by the study aircraft was 8am. As one can see, the longest path (the critical path) took 48 minutes, with the aircraft being ready for pushing back at 08.48am and this path was also highlighted in the chart. On the Gantt chart, it was clear to see the

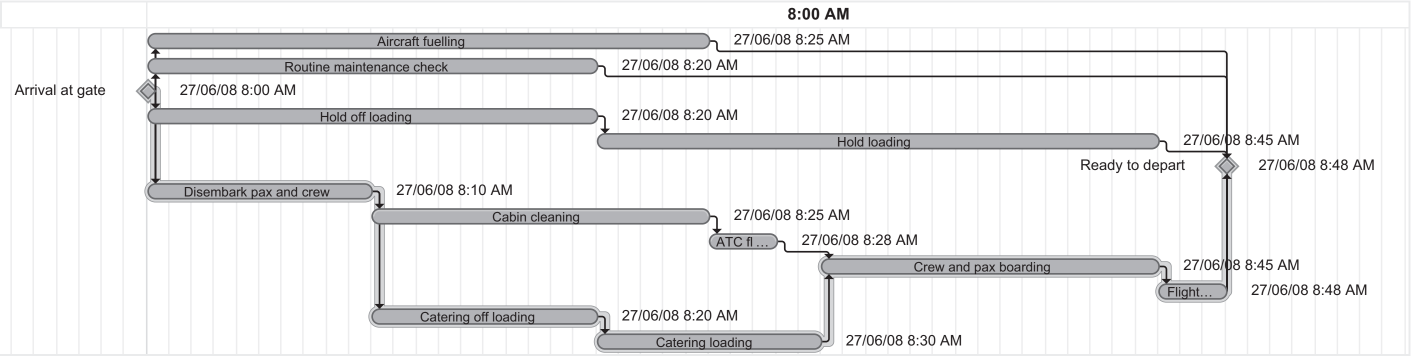

**Figure 3.9** Gantt chart expression of the example turnaround PERT model

interdependencies among activities and the duration of an activity was reflected in the length of the bar in the Gantt chart, making the chart a convenient tool for real-time management of complex operations.

This Gantt chart can be converted into a network diagram drawn with the convention of "activities on nodes" as shown in Figure 3.10. This figure was drawn according to a similar convention as earlier in Figure 3.8, but now presenting only key information on nodes including activity name, earliest start time and earliest completion time. Although this new network diagram provides similar information to Figure 3.8, the inclusion of key information on a network diagram makes project management and critical path identification easier, especially if a project involves many activities with complex resources interdependencies among activities. These network diagrams can easily be created by commercial software.

### *3.3.4 Stochastic Activity Time in PERT*

Very often in real world cases, the execution time of an activity is uncertain. Various stochastic forces may influence the execution time of an activity such as resources allocation and operational efficiency, making the completion time of a project stochastic as well. Given this modelling consideration, the uncertainties (or probability) of the service time of an activity are modelled by stochastic distributions such as the Beta distribution. To simplify time calculation in a PERT model that considers stochastic influences, the time estimate for each activity is based on three different time values:

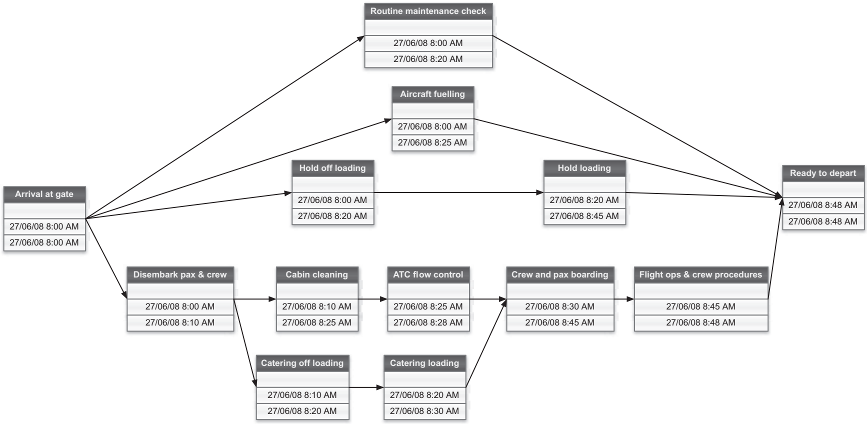

**Figure 3.10 Network diagram of the example turnaround PERT model**

$a$ : denotes the *optimistic time*, representing the time when execution goes well
$b$ : denotes the *pessimistic time*, representing the time when execution goes badly
$m$ : denotes the *most likely time*, representing the time when execution is normally conducted

Using a Beta distribution, one can model the service time distribution of an activity with the unimodal point occurring at *m* with end points at *a* and *b*. The Beta function is not the only modelling choice in PERT, but the simplicity in time calculation and satisfactory approximation of the real situation makes Beta function a good candidate distribution for PERT models. Given the time estimates for individual activities, one can derive the mean value ($\mathrm{E}[D_i]$) and variance ($\mathrm{var}(D_i)$) of an activity based on the following equations (3.5 and 3.6) (Taha 1992).

$$\mathrm{E}[D_i] = \mu_i = \frac{a+b+4m}{6} \tag{3.5}$$

$$\mathrm{var}(D_i) = \sigma^2 = \left(\frac{b-a}{6}\right)^2 \tag{3.6}$$

Given the use of stochastic distributions in PERT models, we can also estimate the probability of occurrence for each activity in the network. Let's assume that the occurrence of individual activities in a network is statistically independent, i.e. the time an activity takes is statistically *independent* from the other activities. For activity *i*, the earliest start time ($ES_i$) is the sum of a series of activities leading from the "start" node to node *i*. Since, each $ES_i$ is a random variable (with mean, $\mu_i$), according to the *Central Limit Theorem*, the sum of random variables is approximately normally distributed with the mean and variance as given in (3.7) and (3.8), in which *k* denotes the index of activities along the *longest path* leading from "start" node to node *i*. By strict mathematical modelling concepts, one needs to derive the exact distribution function of activity *i*, according to the different paths leading to a node. However, this is rather difficult, both in general and for real-world projects. Hence (3.7) and (3.8) below provide us with a reasonable estimation by applying the *Central Limit Theorem*.

$$\mu_i = \sum_k \mu_k \tag{3.7}$$

$$\sigma_i^2 = \sum_k \sigma_k^2 \tag{3.8}$$

Often it is required in project planning to calculate the probability of an activity occurring no later than a planned project milestone or deadline. For instance, we would be interested in estimating the probability that the $ES_i$ time of activity *i* occurs no later than $LC_i$, the latest completion time of the activity. According to the *Central Limit Theorem*, this probability can be calculated by (3.9), where *Z* is the standard normal distribution with mean zero and variance one, and $z_i$ is the test statistic of the milestone time. Readers who are interested in modelling details are urged to consult project management texts such as Taha (1992) and Bonini et al. (1997) for further details on PERT modelling.

$$\mathrm{P}\left[\mu_i \leq LC_i\right] = \mathrm{P}\left[\mathrm{Z} \leq \left(\frac{LC_i - \mu_i}{\sigma_i}\right)\right] = \mathrm{P}\left[Z \leq z_i\right] \tag{3.9}$$

To demonstrate how the uncertainties of activity times can be considered in a PERT model, we used the same example model from previous sections in the following demonstration. Uncertainties were considered by modelling the optimistic time, pessimistic time and the most likely time of an activity, i.e. the *a*, *b*, *m* factors in Table 3.7. The durations of activities ($D_i$) were kept the same as the previous example. According to (3.6), the variances of activities ($Var_i$) were calculated and listed in Table 3.7. These parameters were used to calculate the probability that a specific activity will occur no later than a specified milestone time according to (3.9).

**Table 3.7 Parameter calculations of stochastic service times in PERT example**

| **Activity (node)** | **Duration ($D_i$, mins)** | ***a*** | ***b*** | ***m*** | **$D_i$** | **$Var_i$** |
|---|---|---|---|---|---|---|
| 1 | 0 | 0 | 0 | 0 | 0 | 0.00 |
| 2 | 20 | 15 | 25 | 20 | 20 | 2.78 |
| 3 | 25 | 20 | 30 | 25 | 25 | 2.78 |
| 4 | 0 | 0 | 0 | 0 | 0 | 0.00 |
| 5 | 10 | 5 | 15 | 10 | 10 | 2.78 |
| 6 | 15 | 10 | 20 | 15 | 15 | 2.78 |
| 7 | 3 | 2 | 40 | 3 | 3 | 0.11 |
| 8 | 15 | 10 | 20 | 15 | 15 | 2.78 |
| 9 | 3 | 2 | 4 | 3 | 3 | 0.11 |
| 10 | 25 | 20 | 30 | 25 | 25 | 2.78 |
| 11 | 20 | 15 | 25 | 20 | 20 | 2.78 |
| 12 | 10 | 5 | 15 | 10 | 10 | 2.78 |
| 13 | 10 | 5 | 15 | 10 | 10 | 2.78 |

The corresponding probabilities of various activities in the PERT model were calculated against a milestone time, the latest completion time (*$LC_i$*). Specific activities were chosen to benchmark against other target times (shown by bold texts in Table 3.8) that had operational meanings. For instance, Activity 3 was evaluated against 48 minutes, the longest service time for the whole turnaround operation. Accordingly, the probability of Activity 3 showed that there is a 90 per cent chance that the cargo and baggage process will finish before it runs out of available slack time (3 minutes). Activities 7 and 13 were evaluated against their chosen target time, so we can see how likely it is that the start of Activity 8 will be delayed. Results showed that there is an 80 per cent chance that the cabin will be cleaned and ready for crew pre-boarding. Also catering preparation was likely to finish by the 35th minute with a 96 per cent chance. Accordingly, Activity 8 had an 82 per cent chance to finish within 48 minutes, before the cabin doors were closed and the pilots started requesting for aircraft push back. The overall processes of turning around this aircraft had only a 72 per cent chance of finishing within 50 minutes, if this was the planned aircraft turnaround time. Surely, if the planned turnaround time is increased, say to 55 minutes, then the probability of finishing turnaround operations would increase and be higher than 72 per cent.

**Table 3.8 Completion probabilities against milestone times**

| Activity | Longest Path | Mean | Variance | Milestone ($LC_i$) | $Z_i$ | Prob($Z<z_i$) |
|---|---|---|---|---|---|---|
| 2 | (1–2) | 20 | 2.78 | 23 | 1.80 | 96% |
| **3** | (1-2-3) | 45 | 5.56 | **48** | 1.27 | **90%** |
| 5 | (1-5) | 10 | 2.78 | 10 | 0.00 | 50% |
| 6 | (1-5-6) | 25 | 5.56 | 27 | 0.85 | 80% |
| **7** | (1-5-6-7) | 28 | 5.67 | **30** | 0.84 | **80%** |
| **8** | (1-5-12-13-8) | 45 | 11.11 | **48** | 0.90 | **82%** |
| 9 | (1-5-12-13-8-9) | 48 | 11.22 | 48 | 0.00 | 50% |
| 10 | (1-10) | 25 | 2.78 | 48 | 13.80 | 100% |
| 11 | (1-11) | 20 | 2.78 | 48 | 16.80 | 100% |
| 12 | (1-5-12) | 20 | 5.56 | 20 | 0.00 | 50% |
| **13** | (1-5-12-13) | 30 | 8.33 | **35** | 1.73 | **96%** |
| **4** | (1-5-12-13-8-9-4) | 48 | 11.22 | **50** | 0.60 | **72%** |

### *3.3.5 Using Gantt Charts in Managing Aircraft Turnaround Operations*

An empirical approach to managing aircraft turnaround operations in the airline industry is to apply standard operating procedures (SOPs) to turnaround operations. These SOPs are usually developed by the aircraft manufacturers and are modified by individual airlines to suit their local operational needs. SOPs are also different among different types of aircraft, depending on the aircraft engineering design and service needs. SOPs can be illustrated using Gantt charts and these charts are hence widely used in the airline industry. Gantt charts such as the one given in Figure 3.11 show a B737 turnaround SOP in Gantt chart format which is adopted by a carrier for short-haul turnaround operations.

The standard aircraft turnaround SOP benchmarks all tasks against the scheduled time of departure of a flight as shown in Figure 3.11. All tasks are required to be finished by the "latest finish times", so as to prevent resulting in knock-on delays to other tasks during aircraft turnaround or even delays to the flight departure. The interdependencies among tasks are not clearly shown on this Gantt chart, though. The principle used in the industry is that at any given time during the turnaround, all activities crossed by the time line on the chart can be operated simultaneously. For instance, at -25 minutes to departure time, a number of tasks are being executed simultaneously including: fuelling, unloading cargo/bags, catering preparation, cabin cleaning and aircraft checks.

Since activities in aircraft turnaround have certain unique characteristics such as grouped processes and sequential workflows, the prevailing strategy to conduct ground handling in the airline industry is to assign individual "workflows" to different operating units, e.g. the catering unit, baggage/cargo handling unit

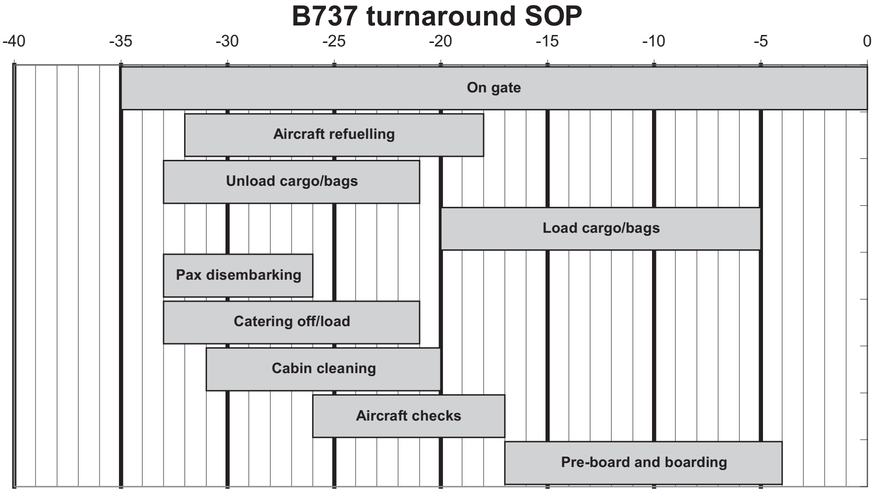

**Figure 3.11 B737 SOP for short-haul turnaround operations**

and passenger handling unit. This ground handling strategy, namely the "unit strategy", has the most benefits when the strategy is adopted by a home-base carrier or a third-party ground handling agent to handle the intensive needs of ground handling services, especially at hub airports where a significant portion of passengers are connecting passengers. However, the challenge of adopting this strategy is the need to ensure that good communication and co-ordination exists among operating units during operations.

On the other hand, some airlines, in particular low-cost carriers tend to use a "team strategy" to carry out aircraft turnaround operations. As suggested by the name, turnaround activities are conducted by a turnaround team, which is assigned to handle all turnaround activities of an aircraft (Gittel 1995; 2001). Accordingly, the handling team consists of multi-skilled staff and a team leader to ensure communication and co-ordination is well maintained during the operation. This team strategy requires a higher staffing level than the "unit strategy" and is more suitable for handling point-to-point traffic, i.e. handling basic loading and unloading duties, especially under time pressure. However, the gain from the higher operational efficiency and the capability to make up inbound delays may compensate the higher staffing cost or even the potentially higher delay costs due to delay propagation by tight aircraft rotation plans. Also, this team strategy is widely used in the car racing industry. A racing car such as a Formula One racing car would come to a pit stop during a race where a team of ground staff conducts a highly complex but well co-ordinated "turnaround operation" within a very short time, often less than ten seconds. Given the nature of highly co-ordinated turnaround tasks, it is not unusual to see errors in turning around a Formula One car in a race.

## 3.4 Managing the Stochasticity of Airline Ground Operations

### *3.4.1 Stochastic Disruptions and Modelling*

The best way to understand the stochastic characteristics of airline operations is by studying real post-operation flight data. Table 3.9 below shows the statistics summary of six flights that were operated by the same aircraft during a one-day European operation of Airline P. Sample sizes of these six flights ranged from 47 flights to 146 fights, representing the operation of a season by the carrier. Due to data confidentiality, the identification of the airline and airports cannot be revealed in the following analysis. Table 3.9 reveals that the first flight of the rotation (flight #1) tended to incur delays due to loading problems (delay code #32) as well as early morning air traffic flow management restrictions in Europe (code #81). As the aircraft executed the rotation plan, delays from earlier flights tended to accumulate along the route, and aircraft rotation (code #93) appeared to be the most likely cause of delays according to statistics. The occurrence probability of code #93 for some flights was as high as 63 per cent (e.g. flight #5), which was nearly at the end of the route. The short turnaround time (20 minutes) scheduled for this flight was also a cause of its poor on-time departure performance. Air traffic flow management (code #81) caused frequent delays to this rotation plan as seen in the statistics in Table 3.9.

The summary statistics of Airline P's operation at two different airports, Airport A and B are shown in Figure 3.12. Statistics show that the operations of Airline P at Airport A had a higher chance of incurring delays due to passenger and baggage processing, aircraft handling at ramp, technical and flight operations, while it had a lower probability of incurring delays from airport/air traffic control and reactionary delays due to aircraft rotations. From these statistics, one can see the stochastic characteristics of airline operations, which are somewhat flight dependent, operating procedures dependent, and for some cases, also airport dependent.

If we compare the statistics of Airline P with Airline Q (another European carrier) operated at the same airport (Airport B), one can see from Figure 3.13 that the occurrence frequencies of certain delays were higher for one airline than the other. Flights of Airline P had a high probability of incurring reactionary delays due to aircraft rotation and flight schedules. On the other hand, Airline Q tended to have more issues with passenger and baggage processing and other operational disruptions from ramp handling, and airport/air traffic control. This figure shows again that the causes of stochasticity in airline operations and disruptions depend not only on the airline itself, but also on the operating environment (the airport and regional air traffic management), the nature of operations (more connecting traffic or more point-to-point traffic), and schedule planning (the usage of buffer time). While some stochastic disruptions are rather unpredictable in nature, e.g. weather, a good understanding of the stochastic forces involved in airline operations and borne with the operating environment will benefit not only airline operations and control, but also schedule planning and future improvement.

**Table 3.9 Delay code frequency statistics**

| FLT | STD[†] | N | TR[*] | Delay Code A | Frq | % | Delay Code B | Frq | % | Delay Code C | Frq | % |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 530 | 143 | – | 32 | 16 | 11% | 81 | 9 | 6% | 18 | 9 | 6% |
| 2 | 745 | 144 | 30 | 93 | 20 | 14% | 81 | 17 | 12% | 12 | 8 | 6% |
| 3 | 920 | 144 | 40 | 81 | 61 | 42% | 93 | 46 | 32% | 89 | 2 | 1% |
| 4 | 1045 | 146 | 30 | 93 | 85 | 58% | 81 | 39 | 27% | 87 | 3 | 2% |
| 5 | 1305 | 146 | 20 | 93 | 92 | 63% | 81 | 26 | 18% | 32 | 9 | 6% |
| 6 | 1555 | 47 | 60 | 81 | 20 | 43% | 93 | 6 | 13% | 85 | 1 | 2% |

*Notes*: [†] Scheduled time of departure (STD) and [*] Scheduled turnaround Time (TR).

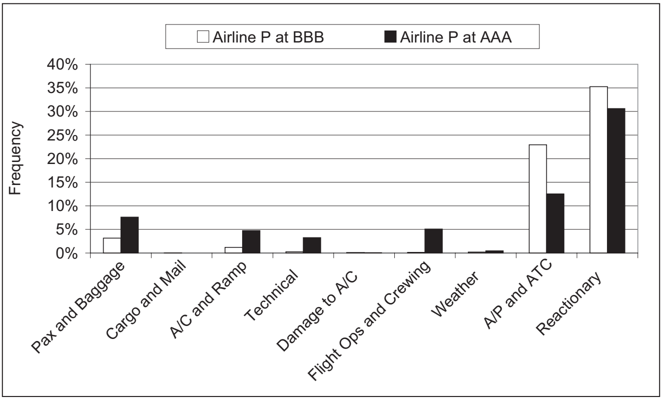

**Figure 3.12 Delay frequency of airline P operation at Airport A and B**

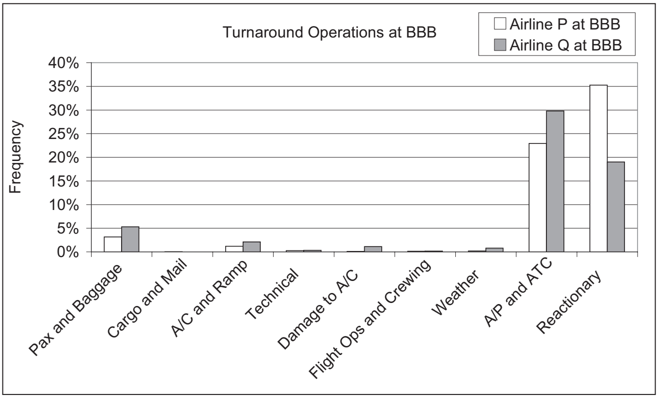

**Figure 3.13 Delay frequency of airline P and Q operation at Airport B**

The examples given previously are intra-Europe operations by two European carriers. Another example is provided here, which represents a carrier, denoted by Airline Z, that operates mostly inter-continental flights. A set of data was provided by Airline Z in 2005 which contained all flight data in the previous year, i.e. 2004. Delay causes were further grouped according to the in-house needs of Airline Z and the occurrence probability of delays due to each delay group was calculated and shown in Figure 3.14. As we can see, delays due to "reactionary" causes contributed 28 per cent to the overall operation in 2004, and there was a 10 per cent probability of incurring delays due to airport resources and airport authority issues. Passenger services caused only a 7 per cent chance of delays, while aircraft technical issues had a 6 per cent contribution to delays.

In addition, the mean delay time due to individual delay groups was calculated and noted in Figure 3.15. When the above figure was compared with Figure 3.14, a clear message was revealed. Although there was only a 6 per cent chance of incurring aircraft technical issues on the day of operation, the mean delay time of this group was as high as 132 minutes, nearly two hours. Some other frequent delay causes, e.g. reactionary and airport authority, only caused on average 73 and 18 minutes delay. In addition, delays due to airline operations (e.g. baggage and cargo processing) caused long delays, with an average of 37 minutes in 2004 operations.

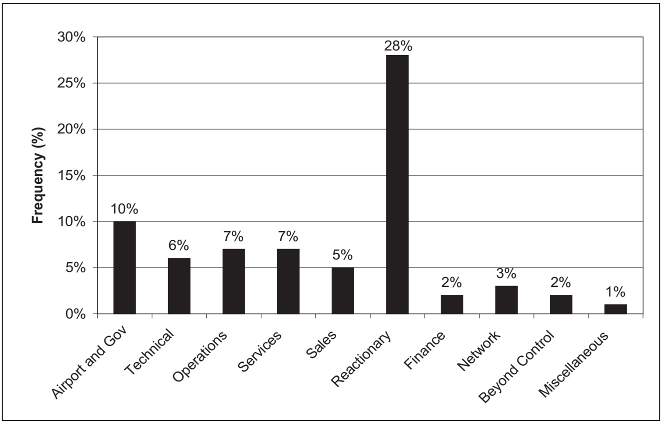

Figure 3.14 Occurrence probability of delay groups in 2004 by Airline Z

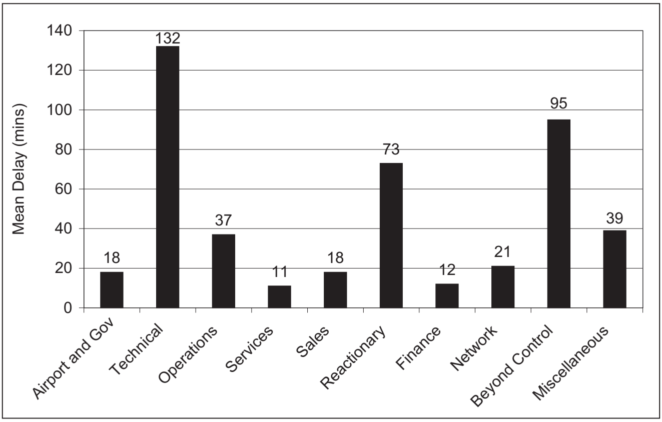

Figure 3.15 Mean delay times of delay groups of Airline Z

The lesson to learn from the example of Airline Z is that stochastic factors did significantly influence the operational robustness and schedule reliability in 2004. Technical problems, although they occurred rarely (6 per cent), caused high delays on average. This technical delay was equivalent in magnitude to the combined delays from all other airline operational causes, but the impact on the network was far greater. On the other hand, reactionary delays occurred quite often during operation in 2004 (28 per cent chance), and the average impact of reactionary delays was 73 minutes. Since most flights by Airline Z were inter-continental long-haul flights, ground operations involved more activities than domestic operations, and were subject to similar forces of reactionary delays in a network. From those examples provided in this section, one can appreciate how complex airline operations are, and the implicit connections between the forces of stochastic delays and schedule planning.

### *3.4.2 Semi-Markov Chain Model*

On a micro-level, aircraft turnaround operations are comprised of a number of sequential processes as well as individual and independent activities. Each process and activity in a turnaround operation is subject to stochastic disruptions. Given the complex inter-relationships between processes in an aircraft turnaround operation, a micro simulation model is helpful and is able to achieve the following two objectives: first, the model should be able to describe the stochastic nature of individual service processes; second, the model should be able to capture the characteristics of aircraft turnaround operations, especially the sequential operating procedures such as unloading and loading goods.

Aircraft turnaround operations are comprised of a number of parallel workflows, which are conducted simultaneously at the airport ramp to turn around an aircraft for a following flight. Major workflows include passenger disembarkation and boarding (this also involves crew cabin check and cabin cleaning), cargo and baggage unloading/loading, catering unloading/loading and other independent work such as the aircraft engineering check and fuelling. A certain order for these procedures must be followed for those activities in the same workflow and delays to an activity may delay following activities in the workflow and possibly the departure time. For instance, cabin cleaning does not start until all passengers have left the aircraft and passengers will not start boarding until cabin cleaning is finished. However, in turnaround operations by some carriers, e.g. LCCs, it is often the case that flight attendants also carry out cabin cleaning (or at least some waste collection aboard) before landing. While passengers are disembarking via the front exit of an aircraft, cleaners may enter the aircraft via the rear exit and start cleaning up the cabin without waiting for the full disembarkation of passengers.

Given the sequential nature of activities in these workflows and the stochastic disruptions within workflows, the Semi-Markov Chains are used to model these workflows. Since the operating time of activities within workflows varies according to a few factors such as labour availability and work loading, the use of

Markov Chains is selected to reflect the stochastic aspects of aircraft turnaround operations. Disrupting events in workflows, e.g. missing check-in passengers or late baggage loading, are modelled as "disrupting states" in the Markov model with proper transition probability linking to normal operations, i.e. normal "states" in the Markov Chain. Since some activities in aircraft turnaround are conducted independently and not in a sequential order, event-driven simulation techniques are combined with the Markov model. More details of the semi-Markov model and implementation in real-world cases can be found in earlier publications of the author (Wu 2006; Wu and Caves 2004; 2002). Readers who would like to gain more information about Markov Chain and its recent applications can consult econometric or statistical books, see for example: Bose (2002) and Ching (2006).

### *3.4.3 Turnaround Simulation (TS) Model*

Let $t_{ij}^{D}$ be the actual time of departure of flight *i* on route *j* (denoted by $f_{ij}$ and $\forall i \in F$ ), which forms a probability density function (PDF) of $f_{ij}$ and is denoted by $g_i(t)$ . $s_{ij}^{D}$ denotes the scheduled time of departure of $f_{ij}$, so the departure delay of $f_{ij}$ (denoted by $d_{ij}^{D}$ ) is defined by (3.10) as follows (this definition of delay is the same as the one used earlier in Chapter 2). New symbols introduced here are listed in the Appendix of this chapter.

$$d_{ij}^{D} = t_{ij}^{D} - s_{ij}^{D} \tag{3.10}$$

As formulated previously in Chapter 2, the actual time of departure of $f_{ij}$ ( $t_{ij}^{D}$ ) is a dependent variable influenced by two main factors, namely the actual time of arrival of the inbound flight $f_{(i-1,j)}$, denoted by $t_{(i-1,j)}^{A}$, and the stochastic turnaround operation time of $f_{ij}$, denoted by $\hat{h}_i$ . $\hat{h}_i$ is the (longest) time required to finish all turnaround activities, including two major turnaround processes (passenger processing and cargo/baggage processing), delays due to disruptions, and other required aircraft service activities as formulated in (3.11) below.

$$t_{ij}^{D} = t_{(i-1,j)}^{A} + \hat{h}_i = t_{(i-1,j)}^{A} + \max\left[\hat{t}_i^{cargo}, \hat{t}_i^{pax}, \hat{t}_i^{events}\right] \tag{3.11}$$

The processes for the two major workflows of the aircraft turnaround operation are modelled by two Markov Chains, namely the cargo and baggage processing flow and the passenger processing and cabin cleaning flow. Service activities in each process are modelled as major "states" in the Markov Chain model according to the purposes of service activities such as goods loading and passenger boarding. The description of states in the workflow of cargo processing is given in Table 3.10. There is a main workflow for cargo and baggage processing, namely from State 1, State 2, State 3 to State 4, representing the stages from the arrival of an inbound flight, to the departure of an outbound flight (by the same aircraft). Operational disruptions to cargo and baggage processing are represented by State 5 to State 9 as illustrated in Figure 3.16 and described earlier in Table 3.10.

Potential disruptions to cargo and baggage processing include equipment failure, lack of labour, late check-in cargo, late check-in passengers, late baggage and so forth. The directions of arrows in Figure 3.16 represent the potential Markovian transitions between states.

**Table 3.10 Cargo and baggage processing flow**

| States | State Descriptions | States | State Descriptions | IATA Delay Codes and Descriptions |
|---|---|---|---|---|
| **1** | Arrival | | | |
| **2** | Goods unloading | **5** | Cargo Processing | **22, 23, 26**<br>Late positioning and preparation |
| | | **6** | Aircraft Ramp Handling | **32, 33**<br>Lack of loading staff, cabin load<br>Lack of equipment, staff/operators |
| **3** | Goods loading | **7** | Cargo Processing | **22, 23, 26**<br>Late positioning and preparation |
| | | **8** | Aircraft Ramp Handling | **32, 33**<br>Lack of loading staff, special load<br>Lack of equipment, staff/operators |
| | | **9** | Passenger and Baggage | **11, 12, 18**<br>Late check-in, check-in congestion<br>Late baggage processing |
| **4** | Departure | | | |

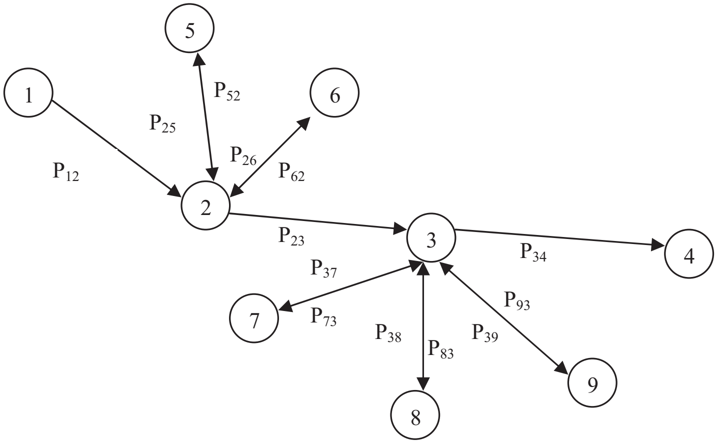

**Figure 3.16 Cargo and baggage processing flow**

$\hat{t}_i^{cargo}$ in (3.11) represents the time required to finish the cargo and baggage processing flow of flight $f_{ij}$. Activity *k* in the cargo workflow is modelled as a "Markovian state", so the cargo workflow is modelled as a Markov Chain in which each state may transit to some other states at time *t* with a state transition probability $P_{pq}$, i.e. the *stationary* probability of transition from state *p* to state *q*. This *Markovian renewal process* represents the change of states, including normal service activities and disrupting events that cause delays to turnaround operations. A total of K activities need to be carried out in this workflow and each activity *k* ($k \in$ K) has a stochastic operating time, namely the *state sojourn time*, denoted by $\hat{\phi}_{pq}^k$. The stochastic operating time of activity *k* (i.e. $\hat{\phi}_{pq}^k$) is modelled by a stochastic function, $\Phi_{pq}^k(\phi)$. The time spent in disruption "states" represents delays and these delays may or may not cause departure delay to $f_{ij}$, depending on the total time required to resolve disruptions and finish the turnaround operation. Hence, the actual time to finish cargo processing for flight $f_{ij}$ is the sum of the stochastic service times of all K activities as in (3.12), assuming delays of different states are independent and additive.

$$\hat{t}_i^{cargo} = \sum_{k=1}^{\mathrm{K}} \hat{\phi}_{pq}^k \tag{3.12}$$

Similarly, the workflow of passenger processing is modelled as a Markov Chain in which the stochastic operating time of activity $\omega$ ($\omega \in \Omega$) is $\hat{\phi}_{pq}^{\omega}$ and the transition between states follows a Markovian renewal process with stationary transition probability, $P_{pq}$. The main workflow in this process is from State_1 to State _7, representing the stages from the arrival of an inbound flight, passenger disembarkation, cabin cleaning, passenger boarding to the departure of an outbound flight, as seen in Figure 3.17.

The state of air traffic flow management (ATFM) is included as State_4, because air traffic flow restrictions are often known to airlines in advance. In this circumstance, airlines will not start boarding passengers to an outbound flight until the ATFM delay is known and the projected departure time is near. Operational disruptions to passenger and cabin cleaning process are represented by State_8 to State_13 in Figure 3.17, which include missing check-in passengers, crewing problems, and flight operation delays during the departure procedure as detailed in Table 3.11. Hence, the actual time to finish passenger processing for flight $f_{ij}$ is the sum of the stochastic service times of all $\Omega$ activities as in (3.13).

$$\hat{t}_i^{pax} = \sum_{\omega=1}^{\Omega} \hat{\phi}_{pq}^{\omega} \tag{3.13}$$

Some activities in aircraft turnaround operations are conducted independently from the two previous major workflows such as aircraft re-fueling and routine maintenance checks. These services may disrupt aircraft turnaround operations

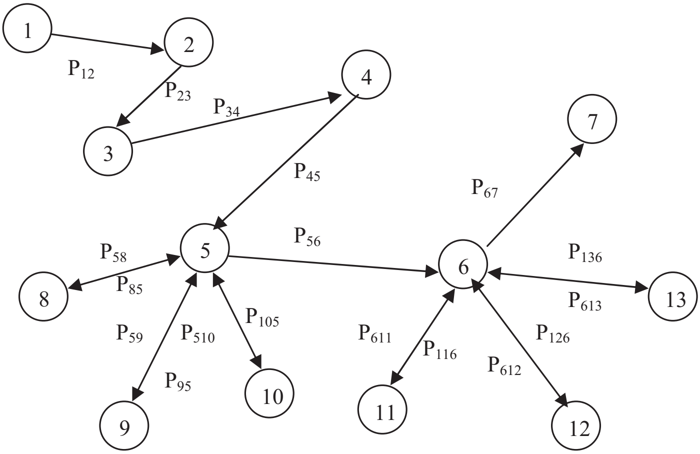

**Figure 3.17 Passenger and cabin cleaning processing flow**

**Table 3.11 Passenger/crew/cabin cleaning process flow**

| States | State Descriptions | States | State Descriptions | IATA Delay Codes and Descriptions |
|---|---|---|---|---|
| 1 | Arrival | | | |
| **2** | Disembark Passengers and Crew | | | |
| **3** | Cabin Cleaning | | | |
| **4** | ATC Flow Control | | | |
| 5 | Crew and Passenger Boarding | **8** | Crew | **63, 94, 95**<br>Late crew boarding, awaiting crew |
| | | **9** | Passengers | **11, 12, 14**<br>Late acceptance, late check-in |
| | | **10** | Missing Passengers | **15**<br>Missing check-in passengers |
| **6** | Flight Operations and Crew Procedures | **11** | Flight Operations | **61, 62**<br>Flight plan, operational requirements |
| | | **12** | Departure Process | **63, 89**<br>Airport facilities, ground movement |
| | | **13** | Weather | **71, 72**<br>Weather restriction at O/D airports, Removal of snow/ice/sand |
| **7** | Departure | | | |

when these services are delayed and the finish time of a service is later than the scheduled departure time of a flight. In addition, some disrupting events, e.g. aircraft damage during turnaround and un-scheduled aircraft change may cause delays to aircraft turnaround. Since these disrupting events and the consequent delays occur independently and unexpectedly, these events are modelled as independent stochastic events.

Four major disrupting events are modelled here, namely disruptions to refueling, engineering check delays, aircraft damage, and aircraft change delays. The occurrence probability of an event $e$ is denoted by $P^e$ and the actual delay (the elapsed time) of event $e$ is denoted by $\hat{\phi}^e$, which forms a probability density function, $\Phi^e(\phi)$. The time when an event may occur is also uncertain; some events may occur early and allow airline ground staff sufficient time to respond, while some may tend to occur at a later stage, e.g. delays due to the engineering check, and leave airlines little time to respond but delaying a flight. The time event $e$ occurs is, hence modelled as a stochastic variable $\hat{\phi}_s^e$, which forms a probability density function, $\Phi_s^e(\phi)$. Hence, the "realised time" of a disrupting event during the turnaround operation of flight $f_{ij}$ is modelled by (3.14). Together with (3.12) and (3.13) given earlier, we are able to model the actual departure time of flight $f_{ij}$ and its corresponding departure delay.

$$\hat{t}_i^{events} = \hat{\phi}_s^e + \hat{\phi}^e \tag{3.14}$$

### 3.4.4 Model Implementation – Model Parameters and Flight Data

The Turnaround Simulation (TS) model was described by the set of equations from (3.12) to (3.14). Given the complex combination of semi-Markov Chains and discrete event modelling, the Monte Carlo simulation technique was employed to implement the TS model for case studies. The Monte Carlo simulation is a technique widely used in modelling complex systems, especially those systems that are composed of stochastic sub-systems or stochastic components. A major advantage of using Monte Carlo simulation techniques is that modellers are able to change model parameters and the stochastic behaviour of system components in order to test "what-if" scenario study questions. This feature is essential when we study a complex system, as we are often interested in understanding how the system may behave under different system control strategies. Two examples include: (1) the modelling of the National Air Space (NAS) in the U.S. (NASA 2008); and (2) the MEANS model by Clarke et al. (2007) which modelled the dynamics of airline scheduling and air traffic management strategies. Readers who would like to understand more about this technique are encouraged to consult Fishman (1997) and other relevant texts.

Model parameters in the TS model were compiled from airline data, including the occurrence probabilities of disrupting events, service time of various turnaround activities, and their corresponding probability distributions. These parameters were used to simulate the major components of the TS model, including the semi-

Markov Chain and discrete event simulation. A full turnaround operation was simulated for 1,000 times in order to control simulation "noises" (Wu 2006) and meet statistical sampling requirements. Simulation results were then compared with real airline operational data in order to validate the TS model and to calibrate model parameters, following the standard simulation model building procedures (Klafehn et al. 1996).

To implement the TS model and conduct case studies, the same set of flight data from Airline R used previously in Chapter 2 was used here. Two typical European city shuttle services, denoted by flight RR-X and RR-Y were used in the following case studies. RR-X was scheduled to depart at 19.45 hours with a turnaround time of 60 minutes. Historical data of RR-X revealed that Beta (4,9) was statistically suitable for modelling the arrival distribution of inbound flights; Beta (2,5) was statistically sound for RR-Y, on the other hand. Moreover, the use of the same set of data in two different models, i.e. the TTA model in Chapter 2 and the TS model here, creates an opportunity for exploring the perspectives that different modelling methodologies may bring to the same operational problem.

Model parameters required to implement the TS model include state sojourn time functions of various states, i.e. the service time probability functions of activities and a state transition probability matrix, representing the probability of transition from one state to another. Transition probabilities between states in the workflow of cargo and baggage processing are given in Table 3.12. State sojourn time functions used in the simulation include the Normal function, Beta function and Exponential function. These parameters were generated by statistical analyses of historical flight data. Due to the lack of detailed delay codes in the data obtained from Airline R, the following parameters were generated for model demonstration purposes with the contribution of expert judgements from Airline R. More precise model parameters can be obtained by analysing historical flight data, once more detailed data are available. From Table 3.12, we can see that the probability of incurring delays due to cargo/baggage loading was 0.1 and the probability of incurring baggage loading disruption due to late check-in of bags was 0.02 for Airline R's operations.

The transition probability matrix for passenger and cabin cleaning is provided in Table 3.13. As seen, the operation of this workflow tended to incur delays and disruptions due to passengers, either because of check-in issues or because of missing checked-in passengers in terminals. The possibility of incurring delays for these reasons to the departure procedures before pushing back an aircraft was relatively low, by 0.001.

Four major disrupting events, namely fuelling delay, engineering check delay, aircraft damage on the ramp, and un-scheduled aircraft change on the day of operation were included to model the occurrence of independent disrupting events during aircraft turnaround operations. The parameters used in modelling discrete events are given below in Table 3.14. We found that delays due to fuelling and engineering check were not uncommon for this airline. The occurrence time of disruption due to fuelling was rather early (Exponential(10) distribution), while disruptions due to engineering checks tended to occur at a later stage (Exponential(30) distribution), causing a high likelihood of incurring departure delays. Although the probability of incurring disruptions due to aircraft damage and last-minute aircraft change was rather low, the potential impacts (delays) were significant, averaging around 30 to 45 minutes for aircraft damage and aircraft change respectively.

**Table 3.12 State transition probability in cargo and baggage processing**

| States | 1† | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 0.0/B | 1.0 | – | – | – | – | – | – | – |
| 2 | – | 0.0/N | 0.90 | – | 0.05 | 0.05 | – | – | – |
| 3 | – | – | 0.0/N | 0.80 | – | – | 0.1 | 0.08 | 0.02 |
| 4 | – | – | – | 1.0/B | – | – | – | – | – |
| 5 | – | 1.0 | – | – | 0.0/E | – | – | – | – |
| 6 | – | 1.0 | – | – | – | 0.0/E | – | – | – |
| 7 | – | – | 1.0 | – | – | – | 0.0/E | – | – |
| 8 | – | – | 1.0 | – | – | – | – | 0.0/E | – |
| 9 | – | – | 1.0 | – | – | – | – | – | 0.0/E |

*Note*: †State sojourn time function: B (Beta), E (Exponential), and N (Normal).

**Table 3.13 State transition probability in passenger/crew/cabin flow**

| States | 1† | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 0.0/B | 1.0 | - | - | - | - | - | - | - | - | - | - | - |
| 2 | - | 0.0/N | 1.0 | - | - | - | - | - | - | - | - | - | - |
| 3 | - | - | 0.0/N | 1.0 | - | - | - | - | - | - | - | - | - |
| 4 | - | - | - | 0.0 | 1.0 | - | - | - | - | - | - | - | - |
| 5 | - | - | - | - | 0.0/N | 0.80 | - | 0.02 | 0.10 | 0.08 | - | - | - |
| 6 | - | - | - | - | - | 0.0/N | 0.95 | - | - | - | 0.019 | 0.03 | 0.001 |
| 7 | - | - | - | - | - | - | 1.0/B | - | - | - | - | - | - |
| 8 | - | - | - | - | 1.0 | - | - | 0.0/E | - | - | - | - | - |
| 9 | - | - | - | - | 1.0 | - | - | - | 0.0/E | - | - | - | - |
| 10 | - | - | - | - | 1.0 | - | - | - | - | 0.0/E | - | - | - |
| 11 | - | - | - | - | - | 1.0 | - | - | - | - | 0.0/E | - | - |
| 12 | - | - | - | - | - | 1.0 | - | - | - | - | - | 0.0/E | - |
| 13 | - | - | - | - | - | 1.0 | - | - | - | - | - | - | 0.0/E |

*Note*: †State sojourn time function: B (Beta), E (Exponential), and N (Normal).

**Table 3.14 Disrupting events in aircraft turnaround operations**

| Event | Event Description | Occurrence Probability | Occurrence Epoch† | Event Duration |
|---|---|---|---|---|
| 1 | Fuelling Activity Delay | 0.02 | Exponential (10) | Normal (15,3) |
| 2 | Engineering Check Delay | 0.02 | Exponential (30) | Normal (20,5) |
| 3 | Aircraft Damage | 0.005 | Exponential (15) | Normal (30,5) |
| 4 | Aircraft Changes | 0.002 | Exponential (15) | Normal (45,5) |

*Note*: †The time from the start of aircraft turnaround operations.

### *3.4.5 Case Study Results*

The TS model was implemented with the previously given model parameters. The simulated departure punctuality of RR-X and RR-Y is illustrated in Figure 3.18 and is compared with the observed punctuality records. The departure punctuality of study flights was expressed as cumulative density functions (CDFs) and it is seen in Figure 3.18 that simulation results of RR-X from the TS model matched closely with the observed punctuality data. However, the simulated departure punctuality of RR-Y from the TS model did not quite match the observed departure punctuality, which showed rather poor on-time performance during the operation of RR-Y.

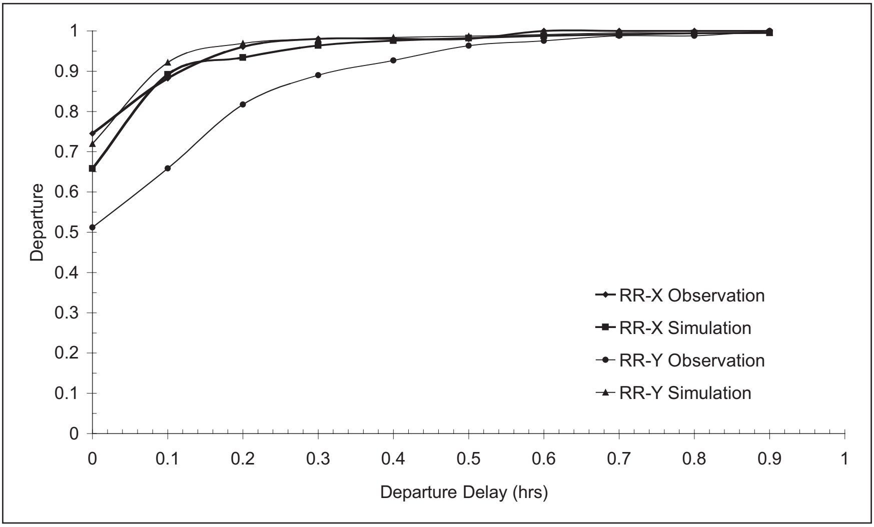

**Figure 3.18 Observed and simulated on-time performance of case study flights**

The scheduled ground time of RR-Y was 65 minutes, so some 20 minutes of schedule buffer time was included in the flight schedule (if the required standard turnaround time for a B757 European operation was 45 minutes). It was seen from the detailed simulation results given in Table 3.15 that RR-Y should be able to deliver a punctual service because of a longer ground time than RR-X. According to simulation results in Table 3.15, RR-Y's departure on-time performance should be as good as RR-X's as seen in Figure 3.18. Since the arrival punctuality of RR-Y from observations was 58 per cent, it was hence speculated that the observed poor departure punctuality of RR-Y was caused by poor operational efficiency and unexpected disruptions in the turnaround of RR-Y.

The decrease of operational efficiency of aircraft turnaround may result from labour shortage, equipment availability for ground services, and airport capacity constraints. The first two situations are more often experienced during the peak hours of airport operations, and the airport capacity constraints come from terminal capacity and runway/taxiway capacity. For instance, gate allocation for inbound aircraft can be disrupted due to the extended occupancy time of delayed flights, and runway/taxiway congestion may delay aircraft push back and taxiing. To study these potential causes of poor departure OTP of RR-Y, two scenario analyses were carried out to model RR-Y in different operational conditions. Scenario A simulated RR-Y in a condition of low aircraft turnaround efficiency. Scenario B simulated the same situation as Scenario A together with airport ground congestion for departures. An average departure push-back delay of two minutes due to airport ground congestion was included in Scenario B. Results of scenario studies are given in Table 3.15 and illustrated in Figure 3.19.

**Table 3.15 Simulation results of turnaround operations of study flights**

| | **Inbound Delay**† | **Turnaround Time*** | **Operational Delay** | **Outbound Delay** |
|---|---|---|---|---|
| RR-X | 2.3 | 51 | 2.4 | 2.6 |
| RR-Y | 2.7 | 51 | 1.9 | 2.2 |
| RR-Y in Scenario A | 2.7 | 61 | 4.2 | 4.5 |
| RR-Y in Scenario B | 2.7 | 61 | 4.2 | 6.3 |
| RR-Y in Scenario C | 2.7 | 67 | 7.1 | 7.4 |
| RR-Y in Scenario D | 2.7 | 71 | 9.6 | 9.8 |
| RR-Y in Scenario E | 2.7 | 75 | 13.1 | 13.3 |

*Notes*: †Mean time (minutes) of simulation flights and *Mean service time of simulation flights.

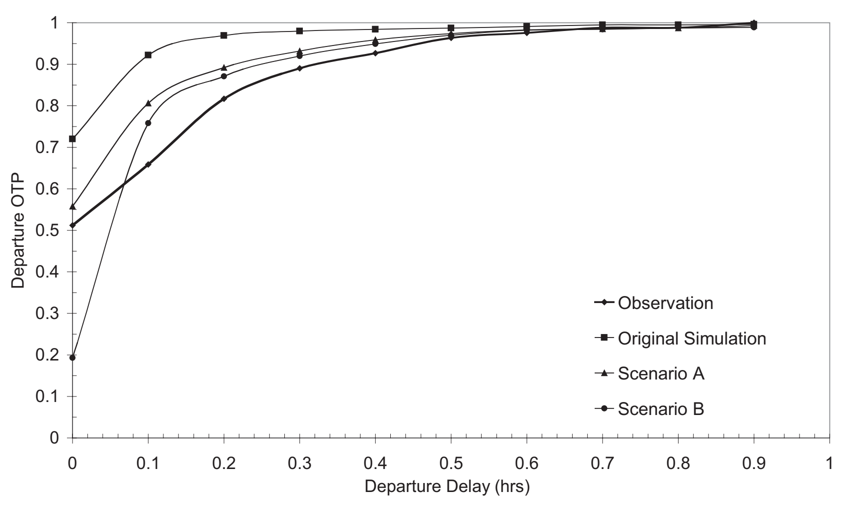

**Figure 3.19 Scenario analysis of RR-Y**

Statistics in Table 3.15 shows that the mean service time of RR-Y increased from 51 minutes in the original case to 61 minutes in Scenario A, due to the low turnaround efficiency, i.e. a longer operational time required for ground services. The mean outbound delay of RR-Y in Scenario A consequently increased to 4.5 minutes. In Scenario B, the mean service time remained 61 minutes, but the mean outbound delay increased to 6.3 minutes, because of the increase of airport congestion. When the simulated departure punctuality of RR-Y was compared with observations in Figure 3.19, it is seen that RR-Y was more likely to suffer from poor punctuality due to low turnaround efficiency. On the other hand, simulation results showed that delays from airport ground congestion only contributed a relatively small portion to departure delays in Scenario B (an extra outbound delay of 1.8 minutes on average) and did not affect the overall departure delay curve of RR-Y.

To further investigate, three more scenario studies of RR-Y in the situation of low turnaround efficiency were conducted. Scenario C modelled a turnaround operation that required 55 minutes to finish all aircraft ground services (the standard time was 45 minutes). Scenario D and E modelled the same condition but required 60 and 65 minutes of turnaround service time respectively. In other words, we are investigating the likelihood of lower ground service efficiency on the departure punctuality of RR-Y.

Simulation results from Scenario C, D and E are shown in Figure 3.20. It is seen that the observed departure punctuality of RR-Y matched closely with the departure CDF of Scenario C, which consumed 67 minutes on average to finish all turnaround services for RR-Y. Hence, it was suggested by simulation results that low turnaround efficiency of RR-Y could be the major cause of poor punctuality. Unfortunately, detailed delay codes of RR-Y were not available from the data resource to validate the speculation that low turnaround efficiency resulted in the poor departure punctuality of RR-Y. However, simulation results provided some evidence to support our hypothesis for flight RR-Y.

### *3.4.6 Implications for Airline Scheduling and Operations*

It was found from the case study of RR-X that if the efficiency of aircraft turnaround operations at an airport was assumed to be consistent, the “inherent” schedule punctuality, which reflected the turnaround efficiency and the amount of scheduled buffer time for ground operations, could be estimated before the implementation of flight schedules. For instance, RR-X was scheduled with 15-minute schedule buffer time when using a B757 aircraft, so the expected punctuality of RR-X can be approximated by the punctuality curves from simulations shown earlier in Figure 3.18. However, the observed punctuality of RR-Y showed that operational variance existed in turnaround operations and may consequently influence flight punctuality. We will come back to the topic of “inherent delays/punctuality” in Chapter 5 with a more in-depth discussion.

The major advantage of the TS model introduced in this chapter, when compared with the PERT model, is that the TS model is able to simulate the stochastic and dynamic transition behaviour between ground service activities as well as to model the occurrence of disruptions to aircraft turnaround. The occurrence probability and duration of operational disruptions can be obtained from historical flight data.

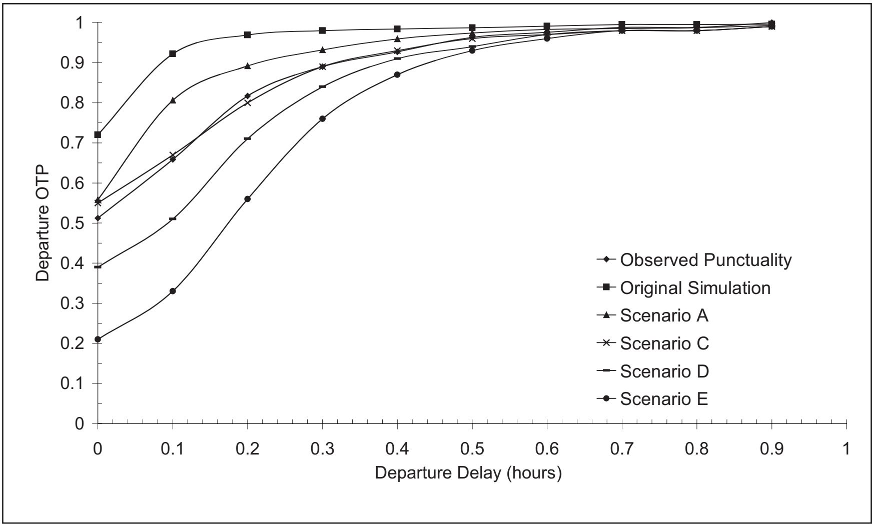

**Figure 3.20 Low turnaround efficiency scenario analysis for RR-Y**

These statistics also inform an airline of how often a specific disrupting event has occurred in the past, and when this disruption was more likely to occur. Operational improvements can be developed and implemented, targeting at improving those "weak links" in airline ground operations.

Compared with the TTA model introduced in Chapter 2, the advantage of the TS model is that it is able to simulate on a micro level the operations of individual activities and the occurrence of disruptions. Although the stochastic features of airline operations were captured in the TTA model by using stochastic flight arrival and departure functions, the TTA model was an aggregate model that had its strength in studying strategic issues such as the allocation of turnaround buffer time for different flights at different airports. In this regard, the TS model is quite suitable for conducting micro scenario analyses such as investigating the impact of improved ground service efficiency (reducing turnaround service time) or the impact of unexpected disruptions on airline operations.

For OTP benchmarking purposes, both TTA and TS models are able to provide benchmarks before schedule implementation. The concept of "inherent delays" of a flight schedule originates from the development of OTP benchmarking measures, and has important implications for airline scheduling and operational benchmarking both before and after schedule executions (Wu 2006). This concept will be further discussed in detail in Chapter 5.

## 3.5 Managing Passenger Flows at Airports

### *3.5.1 Passenger Flows – from Check-in/Transit to Boarding*

A major task of airline ground operations at an airport is to manage passengers and the resultant "flows" of passengers from check-in, immigration screening (only for international operations), security check, transit services (only for transit passengers), to boarding an aircraft at a gate. These series of operations are operated by various agencies including: airlines, immigration agencies, and security agencies, and are facilitated by an airport authority which provides the infrastructure, i.e. airport terminals and facilities. From the operational perspective of an airline, the goal of managing passenger flows at an airport is to provide quality travel services to air passengers. Airlines usually only control a few activities in passenger flow management, namely passenger check-in and passenger boarding at gates, although some airlines are more actively involved in facilitating passenger immigration and security screening, especially for premium passengers. Apart from facilitating passenger flows and providing high service quality to customers, an important operational goal for airlines is to ensure a smooth process for passengers from check-in to boarding and ensuring there are no delays to flight departures due to passenger handling at airports.

Airports play an important role in facilitating and managing passenger flows at terminals. First and foremost, an airport provides airlines with facilities (e.g.

check-in counters) and terminals that are designed for efficiently managing passenger flows. Second, an airport operator also provides (or facilitates) some relevant services such as immigration screening (for international operations) and security check for passengers. The capacity of these services and the capacity of airport terminals are critical in managing passenger movement in an airport; insufficient capacity often causes terminal congestion, passenger delays as well as a low level of service quality. From an airport operator's perspective, speedy processing of passengers from check-in to the completion of security checks also brings potential financial benefits to an airport, because passengers will have more free time to spend on "airport shopping", or at other retail businesses provided at airport terminals (Francis et al. 2003).

### *3.5.2 Passenger Arrival Patterns at Check-in Counters*

The arrival patterns of air passengers at an airport are highly related to the scheduling of flights (departure times) by airlines at a specific airport. The "access time" of an airport is largely stochastic for a passenger, considering the uncertainties involved in the travel from home to the airport by ground transport modes (Kim et al. 2004; Ndoh and Ashford 1993). Moreover, expecting a series of processes from check-in to boarding, most passengers arrive at the airport early to ensure that they can catch their flights in time. Hence, the arrival of passengers at the check-in lounge of an airport depends upon passenger expectation (and/or perception) of airport access time, time required to finish the processes before boarding, and the departure time of a scheduled flight. During peak hours, more passengers arrive than in off-peak hours, because more flights are scheduled to depart during peak hours. However, the "peak" of passenger arrivals for check-in is always earlier than the scheduled peak departure time at an airport.

The arrival pattern of passengers corresponding to a scheduled flight has been well studied by internal projects of airlines and airports for reducing check-in queues by balancing the opening of check-in counters, staffing at counters, and the expected arrival patterns of passengers (e.g. Kim et al. 2004; Park and Ahn 2003). The actual arrival pattern of passengers is often obtained by on-site observations or through passenger survey at airports. Figure 3.21 illustrates a common arrival pattern of passengers at check-in counters of an airport. This pattern resembles the one provided by Park and Ahn (2003) from a passenger survey at Seoul Gimpo International Airport in Korea. It is noted that the "shape" of the arrival pattern is not necessarily the same for all flights, because a large aircraft naturally carries more passengers than a small one. Hence, more check-in counters are needed for a flight operated by a large aircraft and counters are also opened earlier in order to accommodate the volume of check-in passengers.

Passengers start arriving at the check-in lounge about two to three hours before the scheduled departure time of a flight. Airlines use the passenger arrival pattern to allocate resources for passenger check-in, including human resources (check-in staff) and physical resources (check-in counters). At the early stage of passenger

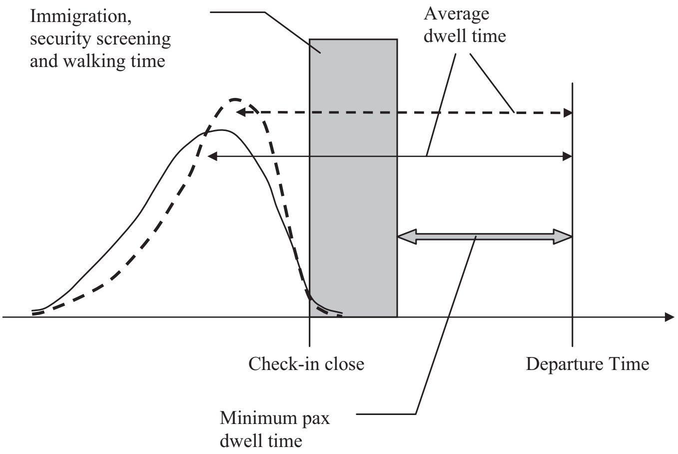

**Figure 3.21 Passenger arrival patterns and the corresponding passenger dwell time**

arrival, only limited counters and staff are needed. As the volume of passenger arrivals increases, an airline will open more counters and allocate more resources for the passenger check-in service, and through this, maintain a certain level of service quality by managing waiting time of passengers in check-in queues. Both the human resources and check-in counters cost airline money. Hence, a good prediction of passenger arrival patterns and good management of resource allocation for passenger check-in will reduce the operating costs of an airline and improve the financial bottom line as well.

While much attention has been paid to modelling and observing passenger arrival patterns, what has been overlooked in the past is that airlines' own operations may also cause changes to passenger arrival patterns at an airport. For instance, the recent advances in technology bring passengers more check-in options such as online check-in services. Air passengers can now check in up to 48 hours before the flight departure time by various means, e.g. telephone, fax or internet. To encourage passengers to check in before they arrive at airports, airlines often offer "express" check-in queues or check-in kiosks at airports for those passengers to drop off bags. These new check-in options reduce the demand for check-in counters at airports (resulting in lower operating costs for airlines) and meanwhile, provide passengers with flexibility for check-in. However, the implications of this operational advance by airlines go far beyond the issues of providing more check-in options for passengers and reducing operating costs associated with passenger check-in at airports. These airline operational improvement measures result in potential changes in the arrival patterns of passengers at an airport.

Some airlines have already observed the trend that internet checked-in passengers tend to arrive later than before. In some domestic operations, passengers can even print boarding passes (with barcodes) by checking in on the internet, then bypass the check-in lounge and go straight to security screening for departure (if they have no check-in baggage). The implication of this change is that: first, passenger "dwell time" at an airport can be significantly reduced, especially for domestic operations; second, the arrival peaks at the services following check-in, e.g. immigration and security screening, can be higher than before due to the increased concentration of passenger arrivals.

The definition of *dwell time* is: *the time between a passenger's arrival at a check-in lounge and the scheduled departure time of the flight that the passenger checks in for*. Some portions of dwell time are unavoidable and must be spent at certain processes such as check-in queues, immigration checks (for international flights), security screening, and even walking in the terminal. The remaining of the dwell time is defined as the *free dwell time* that is available for a passenger to conduct other activities such as shopping, eating, or resting in the terminal area, waiting for boarding an aircraft. It can be seen from Figure 3.21 that the later a passenger arrives, the less free dwell time a passenger will enjoy. Also, the shorter the time required to finish check-in, immigration screen, security check and walking, the longer the free dwell time available to a passenger.

In such a situation, airlines may gain in terms of operating cost reduction and better service quality to passengers due to less waiting time spent at check-in counters or even no on-site check-in at all. However, from an airport operator's perspective, the reduction of passenger dwell time at an airport and consequently the reduction of free dwell time may cause negative impacts on airport retail businesses, if the traditional wisdom and empirical observation that "the more free dwell time a passenger has, the more likely a passenger will spend" is true for most passengers (Papatheodorou and Lei 2006; Torres et al. 2005). In Addition, the shift of passenger arrival patterns at an airport may cause pressure on some services such as immigration and security check that are already under pressure due to increased security measures adopted by airports and aviation authorities worldwide after the 9/11 attack in 2001. When passengers spend more time in these time-consuming procedures at an airport, passengers will have less free dwell time and higher levels of emotional stress. This may cause a potential reduction in retail revenues for airports. This effect has also been observed by Francis et al. (2003) in a study of a secondary airport in Europe.

### *3.5.3 Passenger Behaviour at Terminals and Airport Operations*

Passenger "behaviour" at a terminal has two dimensions, namely spatial behaviour and temporal behaviour. The spatial behaviour of a passenger describes the physical relationship between the location of a passenger and the environment, i.e. airport terminals. A well designed terminal guides passengers through various "decision points", e.g. from a check-in lounge to immigration check, by using various tools including signs and the building itself by means such as a corridor linking two processes in a terminal. Passenger way-finding studies have evolved from physically quantifying way-finding (the spatial behaviour) by a number of factors, e.g. size of building and number of decision points, to involving some human elements less thought about such as the spatial behaviour of passenger in a terminal and the visibility of signs to passengers (Churchill et al. 2008). The use of a visibility index (VI), proposed originally by Braaksma and Cook (1980), was further improved to consider the weights of different visual contacts in calculating VI by Tosic and Basic (1984). Often, passengers are not aware of the full layout of terminals in an airport, except for highly experienced and frequent travellers. Hence, the spatial behaviour of a passenger in an airport is often guided or even "induced" by a simplified "corridor layout" in a terminal created by the airport operator.

The temporal dimension of passenger behaviour in an airport is more associated with the "time" a passenger may make use of during the dwell time. The previously defined dwell time and free dwell time of a passenger in an airport describes the temporal element of a passenger's movement from arriving at the check-in lounge to boarding an aircraft at the designated gate. Obviously, the temporal dimension of passenger movement is influenced by the series of processes a passenger needs to go through as well as being influenced by uncertainties involved in those processes such as service queues and delays. The temporal behaviour of passengers is of concern to an airline because flight delays may be caused by a missing checked-in passenger who is not aware of the flight departure time or even not aware of the time required to travel from his/her current location to the boarding gate.

The combined effect of the temporal and spatial behaviour of passengers in a terminal is of special interest to the airport operator. Airport revenues come from two streams, namely aeronautical revenues and non-aeronautical revenues. Aeronautical revenues of an airport mainly come from the operation of aeronautical activities, i.e. transporting passengers and freights by airlines. A major contributor to aeronautical revenues is landing fees coming from airlines. On the other hand, non-aeronautical revenues are sourced from retail sales, airport property development and commercial activities, e.g. car parks and rental car operations.

Retail businesses play a crucial role in the overall financial portfolio of an airport business. The contribution of retail revenue to an airport can range from 23 per cent (AUS$174 million) of the total revenue of Sydney Airport in 2007, 22 per cent (£241 million) of London Heathrow Airport in 2006, to 26 per cent (€301 million) of Amsterdam Airport Schiphol (BAA 2006; Schiphol Group 2007; Sydney Airport 2007). This revenue stream is crucial for improving the financial performance of an airport business. Together with separate rental revenues generated from retail spaces, the combined non-aeronautical revenue to an airport can be as high as 40 per cent of the total annual revenue. Since the sales targets of airport retailing are mostly air passengers, the combined spatial and temporal behaviour of passengers significantly influences the consumption behaviour of passengers at an airport.

In general, those factors that may influence passengers' behaviour (spatial and temporal) at an airport can be classified into two categories: exogenous and endogenous factors to the passengers. Exogenously, airline operations, airport operations and airport layout design influence passengers' behaviour. The aforementioned innovations in passenger handling technologies such as the internet check-in service, may change the arrival pattern of passengers and consequently influence the dwell time a passenger may have at the airport. Airport operations, in particular the facilitation of immigration screening and security check affect the "free" dwell time a passenger may have. Accordingly, this time constraint of a passenger's spatial behaviour may likewise constrain potential consumptions by a passenger during his/her free dwell time in a terminal, impacting the retail business of an airport. Airport layout also exogenously influences a passenger's spatial and temporal behaviour. The more time that is spent on way-finding or walking, the less free time a passenger will have to conduct other activities including shopping at an airport.

On the other hand, a passenger's spatial and temporal behaviour is profoundly influenced by his/her own socio-demographic characteristics such as income level, consumption preferences, education level and even travel purposes. Hence, how well in advance a passenger may arrive at an airport is indeed a "personal behaviour and preference" issue. These types of travel preferences of passengers have been research topics not only in aviation but also in other fields such as marketing, and transport choice studies (Hensher et al. 2005). Although exogenous factors may limit a passenger's spatial and temporal behaviour, these behaviours are also subject to the influence of the passenger's own preferences, in particular the consumption preferences in the airport terminal environment.

A study by Appold and Kasarda (2006) on the scale of U.S. airport retail activities showed that both exogenous and endogenous factors influence passengers' behaviour in an airport terminal, in particular their consumption behaviour. Some retailers tend to attract a high volume of passengers (e.g. a food store), while others have little by way of transaction volume but high unit sale values (e.g. a branded good). Clearly, the free dwell time of a passenger is an important factor (though in some cases, this factor may not be statistically significant), but more profoundly those endogenous factors, i.e. passengers' consumption preferences determine passengers' consumption behaviour in a terminal.

### *3.5.4 Managing Passenger Boarding at Gates*

Managing passenger boarding at a gate is an important operation which for many cases also lies on the "critical path" of aircraft turnaround operations, as pointed out earlier in this chapter. Since passenger boarding is one of the last activities to conduct before preparing an aircraft for departure, this activity has a high potential to cause departure delays. Within the processes from passenger check-in to passenger boarding at an airport, airlines only have control over the first and the last activity. In many delay cases due to late passenger boarding, delays occur to passengers on the path from the check-in lounge to the boarding gate, instead of boarding itself.

Delays to passenger boarding could be due to late check-in passengers, although more cases are due to missing checked-in passengers in the terminal. Although airlines often require passengers to arrive at the assigned boarding gate by a certain time prior to departure, facing a late or missing checked-in passenger is always a dilemma for an airline. Since the passenger has already checked in, it takes time to retrieve the checked luggage from the cargo hold of an aircraft. For a jumbo jet, it may take as long as 20 minutes to retrieve a bag from the loaded cargo hold, causing delays to a departure flight. Alternatively, airline ground staff will try to locate the missing passenger by searching in retail shops and via radio broadcasts in the terminal. Either of these cases have a chance of causing delays to a flight.

Apart from delays due to passengers, delays also occur with the passenger boarding process itself. As discussed earlier in Section 3.3, passenger boarding is a time-consuming process, especially for the turnaround of a large aircraft, e.g. A380 or B747. Technically, the more passengers to board an aircraft, the longer it takes to finish passenger boarding. In the industry, airlines employ different passenger boarding methods; some airlines follow the "conventional boarding method" (i.e. boarding from the back to the front rows of an aircraft), while others create more advanced but complex boarding methods in order to reduce boarding time and hopefully reduce aircraft turnaround time. A cited ground (opportunity) cost by a U.S. carrier in Nyquist and McFadden (2008) was US$30 per minute on the ground. This low unit cost can easily add up to a formidable amount for a large carrier across a network; this is why shortening aircraft turnaround time and improving aircraft utilisation is so critical for airline profitability.

The conventional passenger boarding method widely used in the industry is called *Back-to-Front Boarding*, i.e. boarding passengers from the back of a plane by a section of rows each time to the front of a plane. In this conventional boarding method, airlines often board first/business passengers and those passengers who need assistance in boarding before starting general boarding of the remaining passengers. The principle of using the Back-to-Front Boarding method is to allow passengers space once aboard in order to efficiently secure carry-on luggage as well as locate a seat. However, this boarding method is not completely efficient, as obviously when rear section passengers are boarding, the front section of the plane is not used. Hence, various computer simulation models were run in search of the "optimal" passenger boarding method in the shortest time.

In two recently published papers by Nyquist and McFadden (2008) and Steffen (2008), various boarding methods were tested via computer simulation models. Results showed that the conventional Back-to-Front method was not the optimal choice in terms of boarding time, and the *Front-to-Back* method was widely known as the worst boarding method (i.e. *the worst case*), because boarding passengers in the front section first blocks all remaining passengers to other sections of the plane. By using a more complex boarding sequence, the optimal boarding method, called the *Steffen* model, could potentially save up to 79 per cent of boarding time compared to the *worst case* (Steffen 2008). The conventional method, however, saves only 25 per cent boarding time when compared with the worst case. Since the *Steffen* model is too complex to implement and not practically feasible, a "modified optimal" boarding method based on the optimal model was tested; this modified optimal boarding model could still save up to 58 per cent of boarding time relative to the worst case.

Improvements on boarding time saving mainly come from boarding passengers in such a sequence that combines passenger boarding from the back to the front of a plane, separate odd/even row boarding, and meanwhile window-seat passengers board first, then middle-seat and aisle-seat passengers. The efficiency gain of this "modified optimal" method comes from efficient use of the whole cabin space for passenger boarding simultaneously, although some inconveniences may occur in practice, e.g. people travelling in groups will not board together under such a scheme. However, in reality, travellers are more likely to ignore such a complex boarding scheme and still board together. This scheme is similar to the current one used by Southwest Airlines in the U.S., called the *Open Seating* method. The Open Seating method assigns passengers a group number and a boarding number based on the time when a passenger checks in. When boarding starts, groups are called in a specific order and passengers in different boarding groups line up according to individual boarding numbers. Passengers have the opportunity to choose their own seats once aboard.

A slight variation of the Open Seating model and the Steffen model is the so-called *Reverse Pyramid* boarding model which was developed by the then America West Airlines (see Van den Briel et al. (2005) for more details). This scheme delicately combines the concepts of separate row boarding, back-to-front and window-middle-aisle seat boarding. The Reverse Pyramid model is illustrated in Figure 3.22. The numbers of seat blocks represent the sequence of boarding. We can see that the boarding sequence starts from the window seats of the rear section of the cabin, then proceeds to board the middle seats of the rear section and simultaneously, boards the window seats of the middle section of the cabin. The Reverse Pyramid model can save boarding time due to the reduction of potential passenger boarding conflicts between rows and between seats, as well as by using the whole cabin space for boarding simultaneously.

For some low-cost carriers who do not assign seats to passengers (i.e. free seating), the *Random Boarding* method is widely used. Passengers board a plane randomly without a pre-assigned sequence and can choose any seats aboard based on a first-come-first-serve basis. Although seemingly a "chaotic" boarding procedure without specific sequences, this boarding method outperforms the conventional Back-to-Front method with a time saving of 40 per cent according to the simulation by Steffen (2008). This is why this boarding method has been widely used by low-cost carriers due to the fast boarding time and the simplicity (also cost reduction) in implementation.

It should be noted that most simulation models on passenger boarding involve certain model assumptions and simplification including the queueing behaviour of passengers, non-group boarding, the amount of carry-on luggage and the time to store

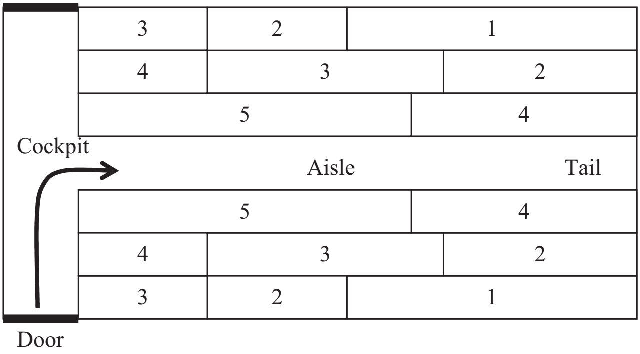

**Figure 3.22 Reverse pyramid boarding model**

carry-on luggage. These assumptions greatly reduce the complexity in modelling passenger boarding and hence, simulation results are often more optimistic than real-world operations by airlines. The random behaviour of passenger arrival at a gate also contributes to the uncertainties involved in boarding passengers. Passengers are often distracted, largely by retail shops in a terminal, from reaching the assigned arrival gate in the shortest time. While this "distraction" is essential for airport retail businesses and airport finance, it directly conflicts with passenger processing in airline operations at an airport. To resolve this conflict and improve the timeliness of passenger boarding, most airport operators have agreements in place with retailers to prevent them from selling products to a passenger whose flight departs within a certain time, e.g. in 30 minutes.

## 3.6 Summary

In Chapter 3 we have discussed some of the issues and challenges of airline ground operations at an airport including resource connections, stochastic disruptions, and the airline's own scheduling constraints. A PERT model was built to manage aircraft turnaround operations which included many activities such as passenger handling, the baggage/cargo processing, engineering checks and catering services. Real examples were given to demonstrate how the PERT model could be used in the industry to manage aircraft turnaround operations. A Semi-Markov Chain model (namely the TS model) was presented to describe, on a micro level, those activities within aircraft turnaround operations as well as to model the stochastic disruptions an airline faces in daily ground operations.

The same set of flight data used in Chapter 2 was used again here to demonstrate the differences between the macro model (TTA model in Chapter 2) and the micro model (TS model in this chapter) in modelling airline operations and the stochastic factors involved. Case study results showed the advantages of the TS model in modelling individual and stochastic activities in aircraft ground operations. Finally, Chapter 3 also discussed strategies on managing passenger flows in an airport environment from both an airport operator's and an airline's perspective. Managerial and operational implications from managing passenger flows were discussed, focusing on the implications for airport retail revenues and airline operations.

Until now we have discussed airline operations on the ground in Chapters 2 and 3. In the following Chapter 4, we will start introducing the readers to airline operations on a network scale. The "network effects" of airline operations will be further explored by considering the complexity of airline operations, airline scheduling, and the operational impacts of individual flights on an airline network. Unlike previous chapters, we will approach airline scheduling and operational issues from a "network perspective" and explain how modern airlines manage gigantic flight networks as well as millions of passengers in daily operations.

## Appendix

# Notations and Symbols Introduced in Chapter 3

| | |
|---|---|
| $ES_j$ | the earliest start time of an activity $j$ (at a node $j$) in a PERT network |
| $EC_i$ | the earliest completion time of an activity $i$ in a PERT network |
| $LC_j$ | the latest completion time of activity $j$ in a PERT network |
| $LS_j$ | the latest start time of activity $j$ in a PERT network |
| $D_j$ | the duration of activity $j$ in a PERT network |
| $F$ | the set of all flights in a schedule |
| $\hat{t}_i^{cargo}$ | the realised (actual) time to finish cargo processing of $f_{ij}$ |
| $\hat{t}_i^{pax}$ | the realised (actual) time to finish passenger processing of $f_{ij}$ |
| $\hat{t}_i^{events}$ | the realised (actual) time to a disrupting event during turnaround of $f_{ij}$ |
| K | the set of service activities of cargo and baggage workflow |
| $P_{pq}$ | the transition probability from state $p$ to state $q$ |
| $\hat{\phi}_{pq}^{k}$ | the realised (actual) time to finish a cargo activity $k$ (in state $p$) before transiting to state $q$ in the cargo workflow |
| $\Phi_{pq}^{k}(\phi)$ | the probability density function of $\hat{\phi}_{pq}^{k}$ |
| $\Omega$ | the set of service activities of passenger processing workflow |
| $\hat{\phi}_{pq}^{\omega}$ | the realised (actual) time to finish a passenger processing activity $\omega$ (in state $p$) before transiting to state $q$ in the passenger workflow |
| $\Phi_{pq}^{\omega}(\phi)$ | the probability density function of $\hat{\phi}_{pq}^{\omega}$ |

| | |
|---|---|
| $P^e$ | the probability that a disrupting event may occur |
| $\hat{\phi}^e$ | the realised (actual) delay due to event $e$ |
| $\Phi^e(\phi)$ | the probability density function of $\hat{\phi}^e$ |
| $\hat{\phi}^e_s$ | the realised (actual) time when event $e$ occurs |
| $\Phi^e_s(\phi)$ | the probability density function of $\hat{\phi}^e_s$ |