TOWARDS THE OPTIMISATION OF THE SCHEDULING OF AIRCRAFT ROTATIONS

by

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ABSTRACT

The aim of this research is to investigate the schedule punctuality and reliability issue regarding the turnaround operations of an aircraft at an airport and further to explore the influence of aircraft turnaround operations on the scheduling of aircraft rotation in a multiple airport environment. An "aircraft rotation model" is developed in this research by using a stochastic approach to consider the uncertainties in flight schedule punctuality in the air and on the ground as well as operational uncertainties in aircraft turnaround operations. The aircraft rotation model is composed of two sub-models, namely the aircraft turnaround model, which represents the operational process of a turnaround aircraft, and the enroute model, which describes the enroute flight time of an aircraft between two airports. Simulation results from the aircraft rotation model show the effectiveness of the proposed model in describing the stochastic behaviour of schedule punctuality in aircraft rotations in a multiple airport network.

Two case studies are carried out to validate the proposed aircraft rotation model. Flight data from a conventional scheduled airline and from a low-cost scheduled air carrier were collected for case studies in this research. Model results show that the proper use of schedule buffer time in aircraft rotation schedules controls the development of knock-on delays in aircraft rotations. It is found that the use of schedule buffer time should depend on the operational efficiency of aircraft ground services to a turnaround aircraft as well as depend on the arrival punctuality of inbound aircraft. When schedule reliability measures are applied to evaluate the reliability of aircraft rotation schedules in case studies, it is found that the optimised aircraft rotation schedule performs in a more stable and reliable manner than the original schedule and meanwhile minimises the system costs incurred in aircraft rotations.

Keywords: aircraft turnaround, aircraft rotation, knock-on delays, punctuality, reliability, stochastic models, Markov Chain, Monte Carlo simulations, optimisation

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by a solo marathon runner

It is a sunny bank holiday weekend in May. After dinner, I am sitting in my room to finish the last part of my thesis.

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一個孤獨的馬拉松選手

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CONFIDENTIALITY DECLARATION

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CHAPTER ONE INTRODUCTION

1.1 Research Background

Demand for air transport keeps growing while delays in the air transport system do not seem likely to subside in the future. There was 19.5%, i.e. 7.5 million, of intra-European flights delayed for more than 15 minutes in 1997 (Eurocontrol, 1998a). The Association of European Airlines (AEA) reported that 37% of intra-European flights departed late by more than 15 minutes in the first half year of 1999 (Airline Business, 1999c). Lufthansa claimed that it had paid the cost of burning 26,000 tones of fuel in airborne holding patterns in 1999 alone and United Airlines claimed that $20 million worth losses were due to insufficient air traffic services by Federal Aviation Authority in the U.S. (Flight International, 1999b). Meanwhile, Austrian Airlines estimated that delays due to air traffic control (ATC) cost it $52 million in 1999 (Airline Business, 1999a). According to Eurocontrol in Europe, more than 80% of overall delays in 1998 were caused by insufficient capacity in ATC (Airline Business, 1999b). Although the insufficiency of air transport system capacity has been blamed for the escalation of delays, it was found by AEA that airport operations and ATC accounted for 45% of departure delays while late arrivals due to aircraft rotations accounted for 40% and ground services of airlines for 15% of departure delays on the ground.

Poor schedule punctuality has cost passengers, airports and airlines a considerable amount of money. The insufficiency of infrastructure capacity, which includes airport and airspace capacity, is usually blamed for the poor schedule punctuality in air transport system when implementing flight schedules. Although airlines can do little to help the improvement of airspace congestion, it is found that airline operations at airports also contributed a significant portion of delays to the air transport system (European Civil Aviation Conference, 1996). An investigation into the punctuality issue by London Gatwick Airport revealed that airport and ATC related reasons, e.g. airport ground congestion and runway slot allocation, were responsible for 53% of total delayed flights (European Civil Aviation Conference, 1996). The other delay causes resulted from poor airline services and aircraft ground operations at airports. 61% of flights which were delayed due to airline operations in the survey resulted in more than 20 minutes delay, while only 39% of flights were delayed by more than 20 minutes due to airport and ATC reasons.

After understanding the causes of poor punctuality in the air transport system, airlines such as Lufthansa and Austrian Airlines have started task-force projects to improve schedule punctuality (Flight International, 1999b). Due to increasing delays in air transport system, Lufthansa tried to improve its schedule punctuality performance by reserving three aircraft (an Airbus A310, an A320 and a Boeing B737) at Frankfurt and Munich Airport as a back-up fleet (Flight International, 1999b). It is generally realised in the airline industry that good management of aircraft turnaround operations and aircraft rotation improves the punctuality of flight schedules and also saves airlines delay-related costs. This is especially true for low-cost airlines and intensive-hubbing airlines, when flight delays disrupt aircraft rotational schedules and increase operational costs. It is claimed by the Irish carrier, Ryanair that the way to success in the European air transport market is to work together with airports on two operational targets: increasing passenger numbers and delivering punctual turnarounds. Although hard evidence is not yet available from the industry, it is generally believed that good control of aircraft turnaround operations and proper aircraft rotation strategies maintain the competitive edge of low-cost airlines in the European aviation market (Airport Council International-Europe, 2000).

Airline operations at an airport include two major activities: airline commercial activities (passengers check in and ticketing) and aircraft turnaround operations. The *turnaround* of an aircraft at an airport stand is defined as the procedure to provide an aircraft with required services (such as catering, cabin cleaning, routine aircraft engineering check and aircraft fuelling) in order to carry out a following flight to another airport (International Air Transport Association, 1997). The turnaround operation of an aircraft can be broken down into many activities, which might be provided by more than one service provider, e.g. catering services and aircraft fuelling services as illustrated in Figure 1.1 (Ashford *et al*, 1997). One of the significant characteristics of aircraft turnaround operation is that there is more than one workflow (a sequence of aircraft service activities) taking place simultaneously during the scheduled turnaround time as illustrated in Figure 1.2. For instance, the processing of passengers begins from the disembarking of passengers and flight crews when an aircraft arrives at a gate waiting to be turned around for a following flight. Passengers for the following flight will not be boarded until aircraft cabin cleaning is finished. The aircraft will not be pushed back from a gate if any passenger is missing or if the crew's procedures with airport control tower are not finished. In addition, there are some aircraft service activities undertaken independently during the process of aircraft turnaround, e.g. aircraft fuelling and routine aircraft engineering checks. Hence, the whole process of turning around an aircraft consists of sequential activities as well as independent service activities. It is these features which make aircraft turnaround operations complicated and difficult to optimise.

A turnaround aircraft is usually scheduled to be serviced by ground handling agents at an airport during a period of time, namely the *scheduled turnaround time*. It usually consists of the *standard aircraft ground service time* and the *schedule buffer time*. The schedule buffer time in the ground time of a turnaround aircraft is designed to accommodate unexpected delays to inbound aircraft and delays to aircraft turnaround operations. The turnaround operation of an aircraft might be delayed if an inbound aircraft arrives late and consequently the departure of the turnaround aircraft might be delayed as well. Delays to departing turnaround aircraft are from delays to inbound aircraft and delays to aircraft turnaround operations. On the one hand, the inbound punctuality of a turnaround aircraft is uncertain due to uncertainties from aircraft operations in the airspace as well as aircraft operations at previously visited airport. On the other hand, since a turnaround aircraft is scheduled to be serviced by ground handling agents, delays to the start of turnaround services to an aircraft might result in a late finish of aircraft turnaround and consequently might result in disruptions to other aircraft's ground operations.

This phenomenon is especially significant for airlines operating intensive hubbing services at an airport due to relatively high passenger and baggage interchanges between aircraft.

In addition, it is realised by the airline industry that delays due to aircraft turnaround operations sometimes result from the lower ground service efficiency and poor management of aircraft turnarounds. The former is usually observed in some cases when aircraft are scheduled to be turned around in the peak hours at a busy airport. The latter occurs when check-in passengers are late for boarding an aircraft or ground services are delayed due to the shortage of equipment and staff. Since an aircraft is scheduled to rotate between airports in an operational day, any delay to a turnaround aircraft at an airport might propagate along with aircraft rotations in the network of airports and hence impair the reliability and schedule punctuality of aircraft rotation. The consequences of poor aircraft rotational quality include high delay-related operational costs and losses of passengers' good will. An estimate from Austrian Airlines revealed that only 22% of total costs of flight delays comes from direct consequences, i.e. additional airline operational costs. 24% of the total costs comes from passengers' permanent disloyalty and the more significant portion of 54% of total costs comes from the deterioration of network quality of aircraft rotation, i.e. delay escalation due to aircraft rotations (Airline Business, 1999a). Therefore, there is a need to carry out a research to investigate the characteristics of aircraft turnarounds as well as the complex relationship between aircraft turnarounds, aircraft rotations and schedule punctuality.

1.2 Research Definitions, Assumptions and Objectives

1.2.1 Definition of Terminology

The "**turnaround**" of an aircraft at an airport stand is defined in this research as the procedure to provide an aircraft with required services (such as catering, cabin cleaning and fuelling) in order to carry out a following flight to another airport. **Delays** measured in this research are based on the scheduled time of arrival (*STA*), i.e. the on-chock time, and the scheduled time of departure (*STD*), i.e. the off-chock time, of a turnaround aircraft. The duration between *STA* and *STD* is defined as the "**scheduled ground time/scheduled turnaround time**" (denoted by T_{SG} in equation (1-1)) which consists of the "**standard aircraft ground service time**" (denoted by T_G) and the "**schedule buffer time**" (denoted by T) as shown in equation (1-2). The schedule buffer time in the ground time of a turnaround aircraft is usually designed to accommodate unexpected delays to inbound aircraft and delays to aircraft turnaround operations. "**Ground services**" to an aircraft include all necessary services, e.g. cabin cleaning, engineering check, aircraft fuelling, for an aircraft to carry out a following flight (International Air Transport Association, 1997).

$$STD = STA + T_{SG} \qquad (1\text{-}1)$$

$$T_{SG} = T + T_G \qquad (1\text{-}2)$$

The "**rotation**" of an aircraft is defined in this research as the continuous visits of an aircraft to a series of airports according to a chosen flight schedule in an operational day as illustrated in Figure 1.3. The rotation of this aircraft starts at airport **J** and is turned around at airport **K** after a period of scheduled turnaround time. The complete rotation of this aircraft ends at airport **M**, in which the aircraft is held over night. Hence, the rotational schedule of an aircraft is composed of rotational legs. A "**leg**" of aircraft rotation is defined in this research to start from the on-chock time of an aircraft at the origin airport to the on-chock time of the same aircraft at the destination airport. In other words, a leg of aircraft rotation starts from the turnaround operations at the origin airport to the arrival of the aircraft at the destination airport. Hence, the scheduled time for a leg of aircraft rotation consists of two portions: the scheduled turnaround time at the origin airport and the schedule block time between two airports. If the aircraft is delayed at airport **K**, for instance, the departure delay might accumulate along the path of aircraft rotations, especially when the delay is sufficiently significant to perturb scheduled ground plans and ATC slots at following airports, i.e. airport **L**, **K** and **M**. The propagation of schedule delays along the aircraft rotational path is called the "**knock-on delay**" of aircraft rotations.

1.2.2 Definition of Research Problems and Research Assumptions

The operation of air transport system is composed of thousands of aircraft rotations in an airport network. Hence, the rotation of an aircraft is more or less influenced by the other aircraft and this is the feature which makes difficult the modelling and optimisation of aircraft rotation. There are many variables in the system of aircraft rotation which influence the operation of aircraft turnarounds and aircraft rotations. In order to simplify the research scenario, the research problem in this research is defined to investigate the turnaround and rotation problem of **a single aircraft** in a multiple airport scenario and the influence of aircraft turnaround operations on the scheduling of aircraft rotations.

The aim of this research is to model the stochastic departure punctuality of a single turnaround aircraft at an airport stand as well as to model the rotation of this aircraft in a network of airports. Hence, it is assumed in the modelling of aircraft turnaround that the turnaround operational efficiency of an aircraft is **only** related to the supply of ground services such as the availability of cargo & baggage loaders and fuelling trucks as well as airline ground operations such as passenger processing. The supply of ground services to a turnaround aircraft influences the start of a service activity and consequently influences the finish time of aircraft turnaround. The availability of ground service supplies is modelled by stochastic variables in the Markovian aircraft turnaround model to consider the stochastic occurrence feature of ground service disruptions. Although other factors might also influence the turnaround time of an airport, e.g. weather delays to turnaround operations, they are not included in the scope of this research.

The modelling of aircraft rotation includes the modelling of aircraft turnaround operations at an airport as well as the modelling of aircraft operations in the airspace between two airports. Since the modelling of the aircraft operations in the airspace is a complex issue, it is assumed in this research that the inbound delay of an aircraft when arriving at airport **K** is **only** influenced by the outbound delay at the origin airport **J** (the first leg of aircraft rotation in this case, which is illustrated in Figure 1.3), the enroute flight time in the airspace, and the arrival congestion at the destination airport **K**. These variables are modelled by stochastic variables in order to take into account the uncertainties of aircraft enroute flight time and schedule punctuality. The purpose of the proposed enroute model is to link aircraft punctuality performance between two airports. Hence, it is not necessary for this model to simulate aircraft manoeuvring performance in the airspace in a great detail.

1.2.3 Research Objectives

Based upon the above research problem definitions and research assumptions, the objective of this research, first of all, is to develop a mathematical model to describe the rotation of a single aircraft in an airport network. The proposed aircraft rotation model includes two sub-models, namely the aircraft turnaround model and the enroute model. The aircraft turnaround model is developed to model the process of aircraft turnaround at an airport by considering the stochastic characteristics of arrival punctuality of inbound aircraft as well as the uncertainties in aircraft turnaround operations. The enroute model is used to model the arrival time of an aircraft by linking the departure time at the origin airport with the enroute flight time of the aircraft between two airports.

Secondly, this research is to use the aircraft rotation model to investigate the development of knock-on delays in aircraft rotations and the influence of airline scheduling strategies of aircraft rotations on the implementation punctuality of a flight schedule. Thirdly, measures of schedule reliability are developed in this research in order to establish performance indices of aircraft rotational schedules. These schedule reliability indices are then applied in case studies to evaluate the schedule reliability of aircraft rotations under different scheduling strategies. Finally, the ultimate objective of this research is to optimise the aircraft rotational schedule by minimising system delay costs in order to improve the robustness and reliability of schedule implementation under uncertainties in the process of aircraft rotations in a network of airports, while avoiding the loss of aircraft productivity.

1.3 Research Methodology

1.3.1 Methodology to Model Aircraft Turnaround

The modelling of aircraft turnaround operation is approached in two ways, namely the aggregate approach and the dis-aggregate approach. From an aggregate point of view, the operation of aircraft turnaround can be treated as a single process which serves as the interval operation between the arrival and the departure of a turnaround aircraft. Based on this simplification, the departure time of an outbound aircraft is dependent **only** on the arrival time of the inbound aircraft and any further delays to aircraft turnaround operations. Therefore, an analytical aircraft turnaround model (AAT model) is developed in this research to model aircraft turnarounds by using an aggregate approach. The arrival time of an inbound aircraft is modelled by a stochastic distribution in the AAT model in order to consider the uncertainties in aircraft arrival punctuality. Delay due to the turnaround process is modelled by a delay function, which corresponds to the operational efficiency of aircraft turnaround and is dependent on the length of schedule buffer time in the ground time of a turnaround aircraft. Consequently, the departure time of a turnaround aircraft becomes the convolution of arrival delays of inbound aircraft and delays to aircraft turnaround operations.

On the other hand, the process of aircraft turnaround can be represented by the integration of parallel service work flows which are composed of sequential service activities from a dis-aggregate point of view. It is seen in Figure 1.2 that the process of turning around an aircraft is composed of parallel work flows and delays to one of these activities might lead to departure delays. In addition to normal turnaround activities, there might be service disruptions to these work flows, e.g. late service equipment or late boarding passengers resulting in delays to aircraft turnaround. Using a dis-aggreage approach, the Markovian aircraft turnaround model (MAT model) is developed in this research to model the operation of aircraft turnaround. The concept of Semi-Markov Chain is employed in the MAT model to simulate the transition behaviour between the operation of normal service activities and service disruptions to these activities. The departure time of a turnaround aircraft is hence dependent on the arrival time of the inbound aircraft, the operational time of individual turnaround activities as well as delays due to service disruptions to aircraft turnaround. The modelling concept is then transferred into a simulation model because it is analytically difficult to solve the aircraft turnaround problem.

Both the AAT model and the MAT model are developed to model aircraft turnarounds in this research. From a practical point of view, a suitable model to describe the aircraft turnaround problem should be able to consider the stochastic characteristics of aircraft turnaround operations. In addition, a suitable aircraft turnaround model should be applicable to given operational scenarios in order to predict the influence of scheduling changes on aircraft turnaround punctuality at an early stage of schedule planning. After considering these factors, a simulation model based on the MAT model is developed to solve the aircraft turnaround problem. The advantage of the proposed MAT simulation model is that this model is applicable to any given turnaround scenario. Secondly, the simulation model can be used to evaluate the operational efficiency of aircraft turnaround by using historical punctuality data of a turnaround aircraft. Thirdly, the simulation model contains stochastic simulation concepts and therefore, is able to simulate the uncertainties from schedule punctuality and aircraft turnaround operations. Monte Carlo simulation techniques are used in the MAT simulation model to implement stochastic simulations. Simulation programmes are coded in *Fortran 90* in a *Unix* environment on a *Sun* workstation.

1.3.2 Methodology to Model Aircraft Rotation

The aircraft rotation model (AR model) is established by the integration of the aircraft turnaround model and the aircraft enroute model to simulate the rotation of an aircraft in a multiple airport environment. The Enroute model is employed as a link between two aircraft turnaround models developed for two different airports. Based upon assumptions in this research, the Enroute model is formulated by the convolution of three stochastic variables. First of all, the departure time of an aircraft is modelled by a stochastic distribution which results from the turnaround operations of the aircraft at the origin airport. Secondly, the enroute flight time of an aircraft is represented by a stochastic variable which takes into account the uncertainties of aircraft flight time in the airspace between two airports. Thirdly, the approach delay of an aircraft in the terminal manoeuvring area (TMA) of an airport is modelled by a stochastic variable in order to consider potential aircraft arrival delays in the TMA due to spills of landing requests over the operational capacity of an airport. The Enroute model is then transferred into a simulation programme and is linked with the aircraft turnaround model to form the AR model in this research. The AR simulation programme is coded in *Fortran 90* in a *Unix* environment on a *Sun* workstation.

1.3.3 Methodology to Optimise Aircraft Rotation

Operational costs incurred by aircraft rotations include the departure delay cost to passengers and aircraft, the schedule buffer time cost to an airline and the arrival delay cost to on-board passengers and aircraft. Consequently, the AR model is optimised by re-allocating ground schedule buffer time and airborne schedule buffer time in aircraft rotation schedules in order to minimise system costs. Two optimisation methods are proposed in this research to optimise aircraft rotation schedules, namely the *Single-Leg Optimisation method* and the *Consecutive-Legs Optimisation method.* It is of interest in this research how the trade-off situation develops in a leg of aircraft rotations between the ground buffer time at the origin airport and the airborne buffer time between two airports. Hence, the Single-Leg

Optimisation method is used to optimise aircraft rotation schedules in such a condition. Also of interest is the influence of the trade-off of ground schedule buffer time at two airports on the optimisation of aircraft rotation, i.e. fixing the enroute flight time of two legs of rotation to solve the optimal ground buffer time at two airports. As a consequence, the Consecutive-Leg Optimisation method is developed to optimise aircraft rotation schedule in such a scenario. The reliability of aircraft rotation is measured by schedule reliability indices developed in this research. These reliability indices are applied to the original schedule and the optimised schedule in order to evaluate the reliability and stability of aircraft rotations as well as to evaluate the effectiveness of the optimisation of aircraft rotation.

1.4 Research Structure

1.4.1 Main Research Structure

The main research structure is illustrated in Figure 1.4. This research starts with current situation analysis of airline operations and literature review in relevant research fields. It proceeds with the definition of research problems and research assumptions. The development of the AR model starts from the development of the AAT model and the MAT model. After the comparison of modelling performance of these two models, the MAT model is chosen to integrate with the Enroute model to form the AR model in this research. A more detailed flowchart regarding the development of the methodology in this research is given in Figure 1.5. This research proceeds with the application of the AR model to two aircraft rotation studies of British Airways and EasyJet. Research conclusions and recommendations to future research are given at the end of this research.

1.4.2 Methodology Structure

The methodology structure in this research is shown in Figure 1.5. The AR model consists of the Enroute model and the Aircraft Turnaround model. After the development of the AAT model and the MAT model, the MAT model is chosen to serve as the core of the AR model to model aircraft turnaround operations for its superiority in modelling uncertainties in aircraft turnaround operations over the AAT model. The flowchart of the simulation programme used to represent the MAT model is shown in Figure 1.6. Input data required in the MAT simulation programme include airport data, historical punctuality data of an airline and aircraft ground service time history of an airline. An aircraft turnaround service time generator is built in this programme in order to generate service time of turnaround activities by featuring Monte Carlo simulation techniques.

The MAT simulation model is applied to model two major work flows in aircraft turnaround procedures, namely cargo & baggage handling and cabin cleaning & passenger processing (Braaksma and Shortreed, 1971; International Air Transport Association, 1997). For the simulation of service disruptions, four of the most frequent disrupting events in aircraft turnaround operations are chosen and simulated in this model. These events include aircraft fuelling delays, aircraft engineering delays, aircraft damage during ground operations and aircraft changes. Service disruptions are modelled as independent events in the model and thus, the occurrence of a disruption does not influence the occurrence of the others.

The structure of the Enroute model is given in Figure 1.7. Based on research assumptions made earlier, the enroute model is developed to model the arrival time of a rotational leg which is the convolution of three stochastic variables: the departure time at the origin airport, the enroute flight time in the airspace and the arrival delay in the TMA of the destination airport. An enroute flight time generator is developed to simulate the flight time of an aircraft in the airspace between two airports according to given historical flight time distributions. A TMA congestion delay generator is included in the Enroute model to simulate delays due to TMA congestion according to the landing time of an aircraft and given historical arrival delay distributions. Results of the MAT simulation programme for an airport are then integrated with aircraft turnaround simulation results at the other airports by the Enroute model to form the AR model in this research in order to model aircraft rotation in an airport network.

1.4.3 Thesis Structure

This thesis starts in the current Chapter, Introduction. A thorough review of relevant research papers in the literature regarding air traffic management is given in Chapter Two, Literature Review. Past papers regarding air traffic management are categorised and investigated on two levels, namely the system level and the airport level. The role of aircraft ground operations research is discussed in this chapter to highlight the importance of this research and its relationship with the other research topics.

The development of the aircraft turnaround model (the AAT model and the MAT model) is described in Chapter Three, Modelling of Aircraft Turnaround Operations. Detailed formulation of the AAT model is given in Chapter Three and a British Airways case study is carried out to investigate the performance of the AAT model. The MAT model is also included in Chapter Three with a thorough formulation and modelling process. The MAT model is then applied to a turnaround aircraft of British Airways. After the development of the AAT model and the MAT model, a comparison of modelling performance between the AAT model and the MAT model is given at the end of Chapter Three.

The development of the aircraft rotation model (the AR model) is given in Chapter Four, Modelling of Aircraft Rotation in a Network of Airports, which includes the application of the AR model, the optimisation of the AR model as well as the development of reliability measures of aircraft rotational schedules. Two numerical analyses are carried out to demonstrate the effectiveness of the AR model and to evaluate the feasibility of proposed schedule reliability measures.

Two case studies are implemented in this research and discussed in Chapter Five, Case Study –EasyJet and Chapter Six, Case Study –British Airways. Flight data from British Airways and EasyJet are applied to the AR model to validate the AR model as well as to evaluate the schedule punctuality of aircraft rotations for these two cases. Research conclusions are summarised in Chapter Seven, Conclusions. Further research opportunities and recommendations are given in this chapter as well.

CHAPTER TWO LITERATURE REVIEW

As air transport demand keeps growing more quickly than system capacity does, the successful management of air traffic system becomes important to the utilisation of system resources. Significant progress has been achieved by much research about air traffic system in the past two decades. The study in the field of air traffic flow management has attracted considerable attention in academia due to the increasing shortage of air traffic system capacity with respect to soaring demand for air transport. The issue of airport capacity modelling and optimisation has been studied since the 1970s. These research has contributed to the better understanding of airport capacity management as well as the higher utilisation of airport capacity.

When the demand for air traffic grows and reaches the ceiling of system capacity, the operation of a single airport starts influencing visibly and invisibly the operational efficiency of the airport network due to high correlation of air traffic operations between airports. Although the network effects of airport operations have become more significant, research which requires links between multiple operators (airport operators, airlines and airport ground handling agents) and multiple operational levels (enroute air traffic control and regional air traffic control) have not been well studied yet. Therefore, the objective of this chapter is to systematically review current research in the literature regarding the issue of air traffic management (ATM) and to highlight the importance of aircraft ground operations research in the field of air traffic management.

2.1 Literature Review Structure

The research of air traffic management is categorised into two levels in this literature review: the system level and the airport level as shown by structure charts in Figure 2.1 and Figure 2.2. The system level of air traffic management includes two main topics, namely air traffic flow management (ATFM) and airspace capacity & sectoring research. Four research areas under the topic of airspace capacity & sectoring are discussed, including airspace capacity & sectoring studies, aircraft conflict & automation studies, free flight studies and airport network flow optimisation studies.

On the airport level, research topics include airport capacity, airport facility utilisation, aircraft operations in airport terminal manoeuvring area (TMA). Research areas under the topic of airport capacity included airport capacity studies and airport capacity optimisation & artificial intelligence application. In the topic of airport facility utilisation, research areas include airport gate capacity studies and airport gate assignment problems. Three research areas are discussed under the topic of aircraft operations in TMA. They are aircraft sequencing in airport TMA, airline schedule perturbation studies and aircraft ground operations. After the thorough discussion of previous research in individual research areas, the importance of aircraft ground operations research is highlighted and potential research interests are pointed out.

Figure 2.1, Figure 2.2

This chapter starts with Section 2.1, Literature Review Structure. Research regarding the system level is discussed in Section 2.2, System Level, which includes topics about air traffic flow management and airspace capacity and sectoring research. Reviews of papers on the airport level are given in Section 2.3, Airport Level, which includes the research subjects of airport capacity, airport facility utilisation and aircraft operations in TMA. The role and importance of aircraft ground operations research is highlighted in this section as well. Concluding remarks of the literature review are given in Section 2.5, Concluding Remarks.

2.2 System Level

2.2.1 Air Traffic Flow Management (ATFM)

The flow management problem (FMP) occurs when the system capacity of the airport network decreases and results in inadequate system capacity supply and flight delays. In order to prevent airborne delays due to the shortage of airport capacity, aircraft are assigned ground holding delays at origin airports instead. The procedure of assigning ground holds to aircraft is called air traffic flow management (ATFM). A thorough investigation and definition of FMP and ATFM was given in a paper by Odoni (1987). It was concluded in the paper that FMP is a problem which has stochastic and dynamic features and therefore, strategies of air traffic flow management should be researched by means of simulation techniques.

Air traffic flow management problems were once investigated by using deterministic models at the early stage of the development of ATFM solutions (Andreatta and Romanin-Jacur, 1987; Bianco and Bielli, 1992; Richetta and Odoni, 1993; Terrab and Odoni, 1993). Later, dynamic ground holding assignments and stochastic models were proposed to solve ATFM problems (Richetta, 1995; Richetta and Odoni, 1993; Richetta and Odoni, 1994; Terrab and Odoni, 1993; Tosic and Babic, 1995; Vranas *et al*, 1994a, b). Recently, a systematic discussion of mathematical models and algorithms for air traffic flow management research has been given by Tosic *et al* (1995). A thorough investigation was made in the paper to test different model assumptions as well as the problem solving efficiency of proposed heuristics to ATFM problems. More recently still, the research focus regarding ATFM has shifted to the optimisation of air traffic flow control in a multiple airport network within a multiple time period framework (Navazio and Romanin-Jacur, 1998; Teodorovic and Babic, 1993; Vranas *et al*, 1994a, b).

The efficiency of implementing ATFM was also evaluated by using real-time dynamic simulation methods as well as aircraft trajectory analyses (Tofukuji, 1997).

These studies of the issue of FMP have identified the modelling of airport acceptance rate (AAR), i.e. the short-term airport capacity, as crucial to the success and efficiency of optimising ATFM. Due to the difficulty of predicting the AAR of an airport, AAR has been modelled by deterministic capacity profiles as well as stochastic ones in ATFM research (Andreatta and Romanin-Jacur, 1987; Richetta and Odoni, 1993; Richetta and Odoni, 1994; Richetta, 1995; Terrab and Odoni, 1993; Vranas *et al*. 1994a, b).. The purpose of ATFM is to optimally allocate inadequate system capacity to all users in order to minimise foreseen negative impacts, e.g. severe flight cancellation and flight delays. The assignment of ground holds to departing aircraft has been used as an operational strategy to minimise flight delays as well as system costs due to delays. The flow management problem is similar to a general flow problem with originating airports providing influx aircraft and destination airports receiving influx. Hence, the assignment of aircraft ground holds depends on the capacity of destination airports. It was concluded in a paper by Vranas *et al* (1994b) that "the importance of finding proper models to simulate AAR is so essential to the efficiency of air traffic flow management that it is relatively not important when correct AAR forecasts can be given, but how precisely AAR forecasts can be made in advance". Since the AAR is influenced by many factors, stochastic models were found effective in capturing the variation of airport capacity with respect to time (Peterson *et al*, 1995). However, the integration of such models into the system of ATFM is still not thoroughly investigated, though airport systems are believed to become bottlenecks to constrain the growth of air transport in the future (Flight International, 2000).

In addition to the modelling of AAR, the timing of providing reliable AAR estimates was also found by Shumsky (1998) to be important in solving the ATFM problem. The imprecision of AAR forecasts accumulates with time and causes system users excessive delay costs when airborne aircraft are required to delay landing at a congested airport. The paper by Shumsky has pointed out a way to improve the implementation of ATFM by optimising the timing of updates of AAR forecasts for future events. Unfortunately, the problem-solving efficiency of the given methodology has not yet been investigated and hence further validation of the model implementation in an airport network is needed.

A further question in the implementation of ATFM strategies is regarding the issue of user equality. The assignment of ground delay and airborne delay to an aircraft is determined by unit delay costs, expected delay probability, and flight priorities of aircraft. It was found in the literature that the First-In-First-Out (FIFO) principal remains the fairest control strategy to all airspace users but obviously not the optimal choice for solving FMP. In addition, the proper inclusion of models of aircraft enroute flight time can help improve the performance of ATFM. Since the enroute flight time of an aircraft in the airspace is influenced by many factors, the modelling of the arrival time of an aircraft at the destination airport was usually done by adopting simple assumptions, e.g. constant enroute flight time models (Janic, 1997b; Vranas et al, 1994a, b; Zenios, 1991). However, aircraft departure delay might be compensated by schedule buffer time in flight schedules or simply be caught up by pilot's "speeding up". Therefore, how to equally assign ground holding delays to balance ground and airborne delays among all users is still a future research topic (European Community, 1998a, b).

2.2.2 Airspace Capacity and Sectoring Research

While much effort has been put into the improvement of air traffic flow management, the need to increase airspace capacity receives relatively less attention in the European academia. According to delay statistics reported by Eurocontrol in Europe, 19.5% of intra-European flights in 1997 were delayed by more than 15 minutes and total delayed flights accumulated to a high of 7.5 million in the same year (Eurocontrol, 1998a). Moreover, a longer flight distance is needed for aircraft flying in the European airspace due to military restricted flight zones and ATC control hand-over among airspace sectors. Research carried out by the European Community also suggested that more research should be done regarding ATC safety, airspace capacity, and autonomous aircraft applicability studies (European Community, 1998a).

Dynamic sectoring of airspace in Europe has been under investigation by the European Community and the second phase of Air Traffic Service Route Network (ARN) has been launched in February 1999 to improve airspace capacity across Europe (European Community, 1998a; Flight International, 1999a). The modelling of the air traffic control problem has been investigated by building up an airport network model to monitor the congestion of airspace on high altitude jet routes in order to optimise flows of air traffic among airports (Zenios, 1999). Despite the complexity of the network model and traffic assignments, the paper by Zenios proposed a prototype model of air traffic control, which simulates the assignment of jet routes in a congested airspace. More recently, the development of the design and analysis model of airspace has being carried out by Eurocontrol. The programme of "European Air Traffic Control Harmonisation and Integration Programme" (EATCHIP) developed by Eurocontrol aims to model the structure of the European airspace as well as to simulate and optimise air traffic flows in the European region (Eurocontrol, 1998c). A system model named "System for Traffic Assignment and Analysis at a Macroscopic Level" (SAAM) has been successfully developed by the Airspace Modelling Service Unit of Eurocontrol to provide an integrated model and simulation system for macroscopic design, evaluation, and presentation of airspace as well as simulations of airport TMA operations.

The general objective function used in airspace network studies is the minimisation of airspace congestion costs. However, due to the dynamic and stochastic features of aircraft operations in the airspace, it is difficult to quantify delay costs of aircraft in the air. The fuel consumption problem of an aircraft on different jet routes was investigated in a paper by Janic (1994). The paper tried to optimise the enroute air traffic control problem by minimising aircraft fuel consumption. This paper provided helpful modelling fundamentals, which serve as a sound-base to approach the airspace congestion problem from an econometric point of view.

The modelling of ATC sector capacity has been approached by using mathematical models to calculate the theoretical capacity of an ATC sector (Janic and Tosic, 1991). The modelling of ATC sector capacity was also approached by using human factors, i.e. the control and conflict solving efficiency of air traffic controllers (Janic, 1997a; Ratcliffe, 1994; Tofukuji, 1993; Tofukuji, 1996). These efforts enable the realisation of the ultimate and operational capacity of an ATC sector in order to optimise the efficiency of air traffic control.

As the capacity of airspace is reaching its operational maximum under current control measures, the concept of Free Flight has emerged. The objective of developing Free Flight is to make the best use of available airspace capacity in order to optimise the efficiency of the air traffic control system. Since pilots are given more freedom to choose the optimal flight routes to fly, solving the flight conflict problem between aircraft in the Free Flight airspace becomes essential for the safety of implementing Free Flight in the future.

Stochastic theories were widely adopted to model the probability of aircraft conflicts along airways (Anderson and Lin, 1996; Geisinger, 1985; Paielli and Erzberger, 1997; Prashker *et al*, 1994; Ratcliffe, 1994; Reich, 1997; Yang and Kuchar, 1997). The conflict resolution advisory systems have been developed by avionics manufacturers to provide conflict resolution advisories to pilots according to the nature of aircraft conflicts and airway configurations. In addition, the potential aircraft conflict probability can also serve as a measure to quantify the workload of air traffic controllers as well as the risk level of aircraft collision in the air (Anderson and Lin, 1996; Geisinger, 1985; Quon and Bushell, 1994; Reich, 1997).

The automatic guidance of aircraft has been studied in a paper by Niedringhaus (1995). A model for automated integration of aircraft separation, merging, and stream management was proposed in the paper to form the foundation of the aircraft conflict resolution advisory system. An alternative approach was investigated by Ratcliffe (1995) to assess the feasibility of providing an airborne aircraft with clearance by taking into account conflict probability and resolutions. The success of the 4-dimensional guidance of aircraft in the airspace also depends on the advance of avionics technology (Benoit and Swierstra, 1990; Simpson, 1997).

The success of Free Flight relies on the conflict advisory and resolution system as well as the optimal trajectory advisory system. Currently, the "European Programme for Harmonised Air Traffic Management Research" (PHARE) by Eurocontrol has successfully demonstrated the feasibility of 4-dimensional trajectory negotiation in the future European air traffic management system (Eurocontrol, 1998b). In the U.S., Phase I of National Airspace System (NAS) lasting from 1998 to 2002 is based on the Free Flight concept as well. Hence, the successful use of advanced avionics and communication technologies might dramatically change the nature of air traffic control and management in the near future.

Potential research interests come from the integration between the use of advanced aviation technology, airspace users (pilots) and air traffic controllers. In a Free Flight environment, the capability of air traffic controllers to cope with a fast change of system capacity will be essential to the success of delivering reliable traffic control advisories. Advanced computer technology will be helpful for air traffic controllers to reduce ATC delays in peak hours and safely reduce airspace congestion in low-capacity situations (Simpson, 1997). However, the issue of human factors in ATC and the human interface with advanced control systems is still under investigation and requires more attention in the future development of modern aviation technology (Yang and Kuchar, 1997). Future research may also focus on solving congestion problems in the TMA of airports as well as airspace bottlenecks as it has been widely realised that the fluctuation of operational capacity of a major airport influences the performance of the whole airport network due to the inter-links between airports by aircraft rotations (Evans, 1997).

2.3 Airport Level

2.3.1 Airport Capacity

The improvement of airport capacity has been progressing relatively slowly due to the difficulty of expanding airports. Research about airport capacity has been focused on two subjects: the modelling of airport capacity and the optimisation & utilisation of airport capacity. The concept of airport system capacity was proposed in a paper to further define the ultimate capacity and the practical capacity of an airport (Hockaday and Kanafani, 1974). Stochastic factors of aircraft operations in the vicinity of the TMA of an airport were also investigated in the paper. A thorough discussion on airport capacity modelling was carried out in a paper by Newell (1979). Airport capacity calculation, runway configuration, aircraft mix and the aircraft queueing problem were discussed in the paper, which provided fundamental concepts for the modelling of airport capacity.

The modelling of airport capacity under constraints was presented in a paper by Fan (1992) to investigate the change of airport capacity due to marine vessel crossings near Changi Airport. The concept of airport capacity curves to model the trade-off between arrival and departure airport capacity (especially for single runway airports) was first given in a paper by Gilbo (1993; 1997). Airport capacity under constraints of arrival and departure approaching-route fixes (i.e. the mix point of arrival/departure flight routes in the TMA of an airport) was discussed in the paper by Gilbo (1997) by taking into account the interaction between runway capacity and the capacity of airway fixes in order to optimise the traffic flow through the airport system. It was found that airport capacity is mainly influenced by the layout of an airport and operational constraints.

As far as airport capacity optimisation is concerned, the aircraft sequencing technique of Maximum Position Shift (MPS) was proposed to optimise the utilisation of airport capacity by Trivizas (1994; 1998). It was also found that runway capacity models should be modified to meet modelling needs of local airports because of the effects of different operational environments (Urbatzka and Wilken, 1997). Although it is generally realised that weather changes influence airport capacity, the modelling of airport capacity hardly takes the weather factor into account due to difficulties in modelling weather uncertainties. A Markov/Semi-Markov model was proposed in a paper trying to model the influence of weather uncertainties on airport capacity (Peterson *et al*, 1995). The major contribution of the stochastic airport capacity model by Peterson *et al* was to justify the feasibility of precisely estimating airport capacity in a relatively short period of time by considering weather factors.

Due to uncertainties in the estimation of airport capacity, artificial intelligence (AI) has been employed in recent airport capacity research because of its ability to model decision-making scenarios under uncertainties. Knowledge-based system (KBS) models have been proved effective in modelling stochastic effects in airport operations (Gosling, 1987, 1990; Taylor, 1990; Wayson, 1989). Therefore, it is recommended that future work may focus on the dynamic and real-time estimation of airport capacity and its application link with ATFM system on a network scale. Papers using stochastic models and KBS models in the literature have demonstrated the effectiveness of stochastic models in providing real-time airport capacity information to airport operators. It is expected that the introduction of stochastic models and AI models in airport capacity research in the future would help utilise airport capacity as well as provide a better understanding to the modelling of airport capacity.

In addition, regarding the fluctuation of airport capacity, a question raised by Evans (1997) was how to safely reduce aircraft delays in airport TMA in an adverse weather condition. The decrease of operational capacity of a major airport does not only result in delays at that airport, but also causes ripple effects to the operation of an airport network. It was found that delays due to weather related reasons accounted for 75% of total delays at US airports in 1998 (Airline business, 1999d). The report also showed that delays due to the decrease of airport capacity at a major airport resulted in delays at the other airports in the National Air Space region in the U.S. Further delays were also found to result from the poor co-ordination between National Air Space users (i.e. airports) and the regulatory and operating body of air transport (i.e. Federal Aviation Authority in U.S.) in such a condition. Therefore, there seems a need to pay more attention to the investigation of the operational strategies of ATFM on a network scale regarding low-capacity situations at some major airports.

2.3.2 Airport Facility Utilisation

Aircraft operations at airport gates often influence the number of gates needed to meet peak hour service demand. The stochastic effects of aircraft gate occupancy time on gate requirements was studied by Steuart (1974). A scheduling strategy which took into account the stochastic effects of aircraft turnaround time was developed in the paper to minimise the requirement of gate numbers and meanwhile maintain a required level of service. The use of schedule buffer time in the ground time of aircraft turnaround was discussed in a paper to account for extra aircraft gate occupancy time due to arrival delays of turnaround aircraft (Hassounah and Steuart, 1993). Similar approaches using stochastic models have shown the effectiveness of stochastic algorithms in solving the gate number problem (Bandara and Wirasinghe, 1988; Wirasinghe and Bandara, 1990).

In addition to the gate number problem, the gate assignment problem is also an important topic in airport operations. Linear programming techniques have been widely used to solve the gate assignment problem (Hamzawi, 1986; Mangoubi and Mathaisel, 1985). More recently, efficient heuristics for solving the problem of gate re-assignment have been proposed to minimise passenger walk distance as well as to minimise the time for the task of gate re-assignment after delays in a turnaround aircraft cause serious disruptions to original gate assignments (Gu and Chung, 1999; Haghani and Chen, 1998). Due to the complexity of the gate assignment problem, the knowledge-based system (KBS) method has been applied recently to solve the airport gate assignment problem (Cheng, 1997). A knowledge-based airport gate assignment system was integrated with mathematical programming techniques to provide real-time solutions to airport operators. Earlier research work has also shown the value of AI methodologies in solving airport gate assignment problems (Gosling, 1987; 1990).

It has been realised recently by airport authorities that insufficient apron and gate capacity has started to constrain flight schedules. The better utilisation of apron facilities becomes an effective and economically efficient way to improve airport operational performance and airport capacity utilisation (Caves, 1994). Since it is generally difficult to expand airport terminals, the research focus on airport gate problems has been shifted from the optimisation of gate assignment to the utilisation of airport gates. Recent research conclusions have shown that different airline hubbing strategies and scheduling strategies result in different levels of apron facility utilisation (Caves, 1994; Gittell, 1995). The utilisation of airport facilities can be achieved by more efficient aircraft ground operations by airlines and ground handling agents. The improvement of aircraft ground operations reduces aircraft gate occupancy time and better utilises airport facilities on the one hand, and maintains good schedule punctuality on the other.

2.3.3 Aircraft Operations in Airport Terminal Manoeuvring Area (TMA)

Aircraft operations in the TMA of an airport are mainly controlled by terminal air traffic control, which consists of two control authorities: terminal radar-approach control (TRACON) and the air traffic control tower (ATCT) at an airport (Horonjeff and McKelvey, 1994). The goal of TMA air traffic control is to maintain aviation safety in the TMA of an airport and meanwhile to maximise the utilisation of airport capacity. The operation of TMA air traffic control influences the efficiency of using terminal airspace as well as airport capacity. As a consequence, the improvement of aircraft processing in airport TMA will enhance the utilisation of airport capacity as well as minimise aircraft delays due to terminal congestion.

Algorithms about the optimisation of TMA aircraft operations mainly focus on aircraft sequencing in the airport terminal area in order to minimise the time gaps between two aircraft. This problem is generally realised as the Runway Scheduling Problem (RSP). The Constrained Position Shifting (CPS) method and the Maximum Position Shift (MPS) method were developed to minimise aircraft landing delays by dynamically controlling aircraft shifts, i.e. changing the sequence of approaching aircraft in the TMA of an airport (Dear and Sherif, 1991; Venkatakrishnan *et al*, 1993). Similar approaches were also adopted in a recent paper to develop the technique of MPS featuring dynamic programming techniques to solve the runway scheduling problem (Trivizas, 1994, 1998).

The assignment of aircraft landing priority at an overloaded airport was studied in a paper by Janic (1997b). Total system delays were optimally distributed to all aircraft by assigning landing priorities to aircraft according to given criteria such as delay time and delay costs. Different aircraft sequencing strategies were discussed in the paper, and it was concluded by Janic that the principle of First Come First Serve is still the simplest and most straight forward aircraft sequencing method available, though not the optimal control strategy from the viewpoint of total system delays. Although other aircraft ranking criteria may achieve the system optimum, these aircraft shifting rules always penalise low-ranking aircraft and hence cause high delays to these aircraft. The concept of Route-Oriented Planning And Control (ROPAC) was studied in a paper by Mohleji (1996) to calculate the minimum-time path for an aircraft flying in an airport TMA. A flying time estimation model was used to maximise airport capacity by estimating the arrival time of inbound aircraft to dynamically adjust traffic flow rates to an airport. Landing aircraft were given different routes to approach the landing runway and therefore, to maximise the runway system capacity.

The utilisation of airport capacity can be optimised by applying aircraft sequencing models. However, the arrival time of an aircraft is so uncertain that terminal air traffic controllers can only react to a real-time situation, which requires quick response and decision-making skills. From the viewpoint of the system level, the optimisation of aircraft operations in TMA is only a local optimisation. What is still absent in the literature is the integration of local optimisation at airports with the ATFM system in the airport network. The concept of "Gate-to-Gate Air Traffic Management (ATM)" is therefore developed by Eurocontrol (1998). The optimisation of aircraft operations in an airport TMA is usually achieved independently from the other airports as well as from the optimisaiton of airport ground operations and airport capacity management. However, it has been observed in Europe that the effectiveness of the optimisation of airport capacity depends on the its integration with TMA operations as well as enroute ATM in the airspace. Although optimisation models have been successfully applied to improve the operational efficiency of enroute ATM, TMA operations and airport capacity management, the integration among these three sectors is still not yet established. The ultimate goal of the gate-to-gate ATM is to manage the operation of each aircraft in the air transport system from the start of aircraft ground services at the origin airport until the arrival of the aircraft at the gate of the destination airport.

2.4 Airport Ground Operations- Aircraft Turnarounds and Rotations

Ground operations at an airport include the provision of ground services to aircraft and the scheduling of ground services. Due to uncertainties from the implementation of flight schedules, scheduled ground services are sometimes perturbed. Relevant research about airport ground operations can be mainly grouped into two fields: the airline scheduling problem (ASP) and aircraft ground operations research.

The airline scheduling problem (ASP) deals with flight schedule related problems, which include flight schedule changes, aircraft and flight crew scheduling, and daily airline scheduling operations. A thorough investigation of past research about ASP was given by Etschmaier and Mathaisel (1985). The general objective of solving ASP is to utilise airline resources under constrained situations, e.g. aircraft fleet size and market demands. On the other hand, flight schedules are sometimes disturbed and are forced to change because of operational uncertainties in aircraft rotations. Then the flight operations decision problem (FODP) is encountered by airline schedulers to manage the escalation of delays in flight schedules and potential flight cancellations (Cao and Kanafani, 1997).

Dynamic programming techniques were used to solve the FODP by minimising total passenger delays, flight cancellations and airline costs (Teodorovic and Stojkovic, 1990, 1995). A decision support framework for airlines was proposed in the paper to help airlines minimise schedule perturbations on a real-time base by delaying/cancelling flights, swapping aircraft among scheduled flights or requesting the usage of backup aircraft (Jarrah and Yu, 1993). The FODP problem has been advanced in a recent paper to integrate both the flight cancellation model and the aircraft delay model into a decision support system for airlines (Cao and Kanafani, 1997). The problem of utilising airline resources at an airport was discussed in a recent paper to improve schedule punctuality after the occurrence of schedule disruptions from ground delays of ATFM in the U.S. (Luo and Yu, 1997). The research objective in Luo's paper was to deliver as many punctual flights as possible when schedule disturbance occurs.

Schedule perturbations may also happen due to inclement weather, flight delays in aircraft rotations, aircraft engineering problems and so forth. When major schedule perturbation occurs, an airline has to decide how to alleviate the consequences of schedule disturbance. Airline schedulers usually judge the consequences of schedule perturbations by experience. However, it is difficult to estimate consequences of schedule perturbations because delays at an airport might ripple into the airport network through aircraft rotations. Hence, there seems a need to develop a Schedule Disruption Management (SDM) model to manage the consequences of schedule perturbations on the network scale as well as to minimise airline operational costs due to schedule perturbations. In addition, the timing problem of re-building aircraft rotational schedules should also be considered in the SDM model to minimise the operational cost of re-constructing flight schedules. Research about the timing problem of updating airport capacity information in ATFM provides a clue to the development of its counterpart in the SDM model (Shumsky, 1998).

The gate occupancy time of an aircraft was first studied by using critical path method (CPM) at the early stage (Braaksma and Shortreed, 1971). Then, the stochastic effects of aircraft gate occupancy time on the gate number problem were discussed later in a paper by Hassounah and Steuart (1993). It was found from empirical studies in Hassounah's research that departure delays of turnaround aircraft have a significant relationship with arrivals delays of turnaround aircraft, especially when arrival delays consume available aircraft turnaround time. The departure process of an aircraft has been discussed by using stochastic models and simulation techniques to take into account the stochastic nature of aircraft ground operations (Herbert and Dietz, 1997). The problem of aircraft push-out conflicts on apron taxiways between arrival and departure aircraft was investigated by using heuristic approaches and event-driven simulation approaches to minimise departure delays (Cheng, 1998b; Teixeira, 1992). A rule-based model was then applied to simulate the gate occupancy behaviour of an aircraft including aircraft turnaround operations, simulation of aircraft arrival delays and passenger transfers between aircraft (Cheng, 1998a).

It was found from a survey by London Gatwick Airport that delays due to airline ground operations accounted for 25% of total delay causes, while delays due to ATC accounted for 30% during the survey period (European Civil Aviation Conference, 1996). In addition, airlines tend to schedule more ground time/airborne time in flight schedules due to increasing delays in the air transport system (Sunday Times, 2000). It was found that the ground operational efficiency of an airline influences the punctuality of its flight schedules and consequently the profitability of the airline (Airline Business, 1999a). The turnaround time for aircraft ground operations has been found to differ among air carriers and consequently the operational efficiency of an airline was influenced (Gittell, 1995). The optimisation of aircraft turnaround time becomes more important when it gets more difficult nowadays to maintain aircraft rotational links due to unforeseen schedule disruptions from ATC and aircraft turnaround operations (Chin, 1996; Trietsch, 1993). This is especially true for low-cost airlines which rely on the high utilisation of aircraft to increase revenue (Airport Council International, 2000). A study by Sowthwest Airlines in the U.S.A. found that with the increase of its passenger load factor in the past few years, aircraft turnaround operations become the major controllable determinant to its on-time performance and the reliability of its aircraft rotational schedules (Air Transport World, 2000). Therefore, potential research interests still remain in the field of aircraft ground operations in order to improve the operational link of aircraft turnaround at an airport as well as to maintain aircraft rotational links between airports. (Wu and Caves, 2000).

After a thorough investigation into aircraft ground operations research, it is found that there is relatively less attention paid to the issue of airport ground operations in the literature when compared with research about airport capacity and facility utilisation. It has been shown in the literature that there is a need to increase airport apron capacity and the efficiency of using large aircraft to utilise airport facilities (Caves, 1994; Chin, 1996; Uittenbogaart, 1997). Regarding the operational efficiency of airlines at apron, recent papers about the operational efficiency of aircraft on the ground have shown that ground service performance varies among carriers and influences the productivity and profitability of airlines as well (Gittell, 1995; Wu and Caves, 2000). It is realised that the improvement of ground operational efficiency and punctuality of airlines is essential to reduce operational costs especially for non-intensive hubbing airlines (Hansen and Kanafani, 1989; Nero, 1999). With the increase of operational delays in the air transport system, airlines have to design more buffer time in flight schedules in order to maintain schedule punctuality as well as aircraft rotational links (Sunday Times, 2000). However, a longer schedule time for a flight does not always guarantee the improvement of schedule punctuality and similar situations have been identified in other transport schedule studies as well (Carey, 1998). Therefore, potential research interests arise in the establishment of a reliable flight schedule which is able to utilise available resources of airlines and airports as well as to maintain the reliability of schedule implementation and aircraft rotations. Artificial intelligence (AI) and stochastic models are suitable methodologies to build a decision support system for the purpose of aircraft rotation management which includes schedule disruption management functions to cope with unexpected schedule perturbations during schedule delivery (Cao and Kanafani, 1997; Cheng, 1997, 1998a, b; Gosling, 1990; Teodorovic and Stojkovic, 1990, 1995).

2.5 Concluding Remarks

When the air transport system capacity is getting close to its ceiling, the need to successfully manage the operational efficiency of the air traffic system will become significant in the future. The development goal of the air traffic system as stated in *Air Traffic Management Strategies for 2000$^+$* by Eurocontrol is to establish a safe, reliable and environmentally sustainable gate-to-gate air transport system (Eurocontrol, 1998). The project of *National Airspace System* by Federal Aviation Authority in the U.S. also reveals the same goal for air transport system in the future (Simpson, 1997). The air transport system is composed of many portions in which the operational efficiency of individual components has been optimised but not yet been integrated with each other. In order to achieve the system optimum, the integration between sub-systems of the air traffic system is required in future work.

Demands for air transport have been rapidly growing in the 90s and it is forecast by the European Community that the volume is likely to double by 2015 in Europe alone (European Community, 1998a). While modern technologies successfully help alleviate air traffic handling pressure, more attention is needed to improve the safety of air transport, the reliability of air services, operational efficiency of airports and airlines, as well as schedule punctuality of airlines. What is needed for the air traffic system in the future would be a seamless gate-to-gate air transport service, which remains reliable under disruptions and environmentally sustainable in the future.

CHAPTER THREE MODELLING OF AIRCRAFT TURNAROUND OPERATIONS

The operation of aircraft turnaround at an airport has been modelled by two approaches, namely the Analytical Aircraft Turnaround (AAT) model which was developed from an aggregate approach and the Markovian Aircraft Turnaround (MAT) model which was from a dis-aggregate approach. Numerical analyses and computer simulations were implemented to validate proposed aircraft turnaround models by using schedule punctuality data from British Airways. A comparison between the modelling performance of the AAT model and the MAT model revealed the effectiveness of the MAT model in modelling uncertainties in aircraft turnaround operations. Therefore, the MAT model was chosen to serve as the core of the Aircraft Rotation model (AR model) developed later in the research.

Chapter Three is organised to start from Section 3.1 by discussing system costs involved in aircraft turnaround operations. The development of the AAT model is given in Section 3.2 and the application of the AAT model is described in Section 3.3. The modelling of the MAT model is given in Section 3.4 and the application of the MAT model is described in Section 3.5. A sensitivity analysis of the MAT model is carried out in Section 3.6 to investigate the sensitivity of model parameters to outputs of the MAT model. The comparison of modelling performance between the AAT model and the MAT model is given in Section 3.7 which is followed by concluding remarks of Chapter Three given in Section 3.8.

3.1 System Costs of Aircraft Delays

System costs considered in the modelling of aircraft turnaround operation include aircraft departure/arrival delay cost, passenger delay cost and schedule time opportunity cost of an airline. Due to the unavailability of detailed financial information of airlines, cost values were calculated approximately from published financial data for the purpose of the demonstration of turnaround models proposed in this research, rather than precisely reflecting cost values of any specific airline in the industry (International Civil Aviation Organisation, 1997). However, this simplification in cost calculation does not impair the potential of proposed turnaround models, as proper parameter values can be developed by potential users to implement this model, when more detailed cost information is available for analysis.

3.1.1 Unit Aircraft Delay Costs (C_{AC})

Various values of aircraft delay costs have been used in relevant literature. Unit ground delay costs for European airlines used in relevant literature were \$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 \$430, \$1300, and \$2225 per hour with respect to small, medium and large aircraft (Richetta and Odoni, 1993). Although aircraft delay cost values like these can be easily found from the literature, a further study of aircraft delay cost is provided in this research to meet analytical needs of the proposed mathematical model.

Table 3.1

When an aircraft is delayed at a gate either with engines off or on, the airline not only incurs additional operational costs but also has to forego revenue. The aircraft delay cost, denoted by C_{AC} hereafter, is defined as "the hourly fixed operating cost per aircraft", while the loss of revenue is considered later as schedule time opportunity cost, C_{AL}. Aircraft delay costs depend on aircraft types and sizes. For the purpose of this research, aircraft sizes are classified into three categories, namely medium, large, and heavy aircraft, as shown in Table 3.1.

Aircraft operating costs of major airlines are calculated and listed in Table 3.2 by using published financial data from International Civil Aviation Organisation (ICAO) (International Civil Aviation Organisation, 1997a, b). Aircraft operating costs are found to differ among air carriers, one of the reasons being the difference of the fleet structure. For instance, British Airways operates 32% of heavy aircraft for long-haul intercontinental flights (as shown in Figure 3.1) and consequently has a high average operating cost of \$4,498. KLM operates proportionately more large jets than Lufthansa, so KLM has a higher average aircraft operating cost of \$4,757. Lufthansa has a similar aircraft fleet structure to United Airlines, but exhibits a higher operating cost of \$3,407. American Airlines mainly operates large and medium aircraft and few heavy ones, so a lower operating cost of \$2,207 is reasonable. On the other hand, British Midland uses mainly narrow body jets and exhibits an hourly aircraft operating cost of \$2,822. Cost calculations in Table 3.2 are based on average aircraft operating costs due to the unavailability of detailed cost break-downs with respect to aircraft types and sizes from published information (International Civil Aviation Organisation, 1997a, b).

Table 3.2
Figure 3.1

3.1.2 Unit Passenger Delay Costs (C_P)

The unit delay cost per passenger (denoted by C_P hereafter) is related to the average wage rate, flight classes, trip characteristics and delay time perception of a passenger (CAA, 1996). A survey by the

Civil Aviation Authority (CAA) in the UK showed that the average wage rate was $46 per hour for passengers using Heathrow Airport and $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 $64 per working hour. The average wage rate for leisure passengers was $39 per hour from the same survey by British CAA in 1996.

When calculating passenger delay time costs, trip purposes and passengers' characteristics are major factors believed to explain differences between users. Literature on the value of time suggests that a passenger values on-mode time at the wage rate for business flights and a quarter of wage rate for leisure flights. Waiting and delay time is valued higher, but it is not the purpose of this paper to investigate precise cost figures of time value of passengers. Therefore, for simplicity, the hourly delay cost of a passenger is assumed as the average wage rate of $42 per hour for the consideration of a single class passenger during waiting time at an airport.

3.1.3 Unit Schedule Time Costs (C_{AL})

Airlines try to minimise the turnaround time of aircraft in order to produce more revenue-making flight time (International Air Transport Association, 1997; Eilstrup, 2000). This is especially true for low-cost airlines (Airports Council International-Europe, 2000; Gittell, 1995). Therefore, it is assumed in the quantification of the schedule time cost (denoted by C_{AL} hereafter) that scheduled ground time can be alternatively utilised as revenue-generating airborne block hours. In other words, the use of schedule buffer time for turnaround aircraft may reduce the expected departure delay, but incurs opportunity costs of schedule time.

It is assumed that the variation of fixed operational costs of an aircraft per hour due to the variation of total flight hours is insignificant when compared with the change of total annual revenues. In other words, it is assumed that the change of the scheduled ground time causes only changes of revenues and variable costs due to changes of aircraft block hours. Based on this rationale, the hourly schedule time opportunity cost is defined in this research as "the marginal hourly operating profit of an airline". It is calculated by deducting hourly variable expenses from hourly revenues as demonstrated in Table 3.3.

Table 3.3

It is observed from Table 3.3 that US airlines have lower average schedule time costs when compared with European air carriers, except for the similarity between British Midland and US carriers. Schedule time costs of heavy jets are logically higher than those of large and medium jets. This statement is supported by Figure 3.2, in which the schedule time cost of British Airways is higher than all other airlines. From Figure 3.2, it can be seen that British Airways operates more long-haul flights (observed from the line denoting holdings of large and heavy jets which corresponds to the vertical axis on the right) and consequently it has a higher schedule time cost. Compared with British Airways, KLM operates more medium-distance flights, but KLM exhibits a higher schedule time cost than Lufthansa and two US airlines. It is suggested in Figure 3.2 that schedule time costs could be categorised with respect to aircraft classes and flight range, when more detailed financial information is available. As a consequence, all these cost figures are only notional for this analysis.

Figure 3.2

3.2 Analytical Aircraft Turnaround Model (AAT model)

The "turnaround" of an aircraft is defined as the ground operational process to service an aircraft from the "on-chock" time of an aircraft at an airport gate to the "off-chock" time. From an aggregate approach, it is assumed in this model that the departure time (denoted by s) of a turnaround aircraft is influenced mainly by the arrival time of inbound aircraft (denoted by t), the turnaround service performance (denoted by m_2), and the schedule buffer time (denoted by T) included in the scheduled ground time of a turnaround aircraft. The arrival time of the inbound aircraft (t) is formulated by probability density functions (PDF), which take into account the schedule punctuality uncertainties of inbound aircraft. Delays due to occasional ground service errors and passenger lateness are not considered individually in the aircraft turnaround model but will be discussed later from a dis-aggregate point of view in this chapter. Symbols and variables used in the AAT model are summarised below.

α	weight factor, which varies between 0 and 1
C_{AC}	aircraft delay cost
C_{AL}	schedule time opportunity cost of a turnaround aircraft
$c^m_{AC}(s)$	marginal delay cost function of an aircraft
$c^m_{AL}(T-T_A)$	marginal schedule time cost function of an airline
$c^m_P(s)$	marginal delay cost function of on-board passengers
C_D	expected departure delay cost of a turnaround aircraft
C_P	passenger delay cost
C_T	total system cost
C_u	departure delay cost
$f(t)$	arrival time PDF of a turnaround aircraft
$g(s)$	departure time PDF of a turnaround aircraft
m_1	delay absorption capability of schedule buffer time
m_2	turnaround service performance

STA	scheduled time of arrival of a turnaround aircraft
STD	scheduled time of departure of a turnaround aircraft
T_{SG}	scheduled turnaround time of a turnaround aircraft
T	schedule buffer time
T_G	mean ground service time of a turnaround aircraft

3.2.1 Delay of a Turnaround Aircraft

The scheduled turnaround time (denoted by T_{SG}) of an aircraft is usually composed of two parts: the schedule buffer time, if any (denoted by T) and the mean ground service time (denoted by T_G). It can be expressed by equation (3-1). The scheduled time of departure (*STD*) of a turnaround aircraft is therefore, the time after the scheduled time of arrival (*STA*) and the scheduled turnaround time (T_{SG}). The relationship between *STA* and *STD* is represented by equation (3-2).

$$T_{SG} = T + T_G \tag{3-1}$$

$$STD = STA + T_{SG} \tag{3-2}$$

The schedule buffer time is used to absorb arrival delays and unexpected departure delays due to ground handling services, and to accommodate inevitable time gaps in flight schedules. The mean ground service time 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, aircraft ground service time may be influenced by many factors such as ground handling equipment serviceability, passenger delays, and aircraft arrival delays. Therefore, the departure punctuality of a turnaround aircraft may consequently be influenced by the reliability of ground services as well as unexpected up-stream flight delays, which might propagate along aircraft rotations.

The development mechanism of the aircraft departure delay is illustrated in Figure 3.3. If the aircraft arrival delay (t) is shorter than the schedule buffer time (T), arrival delay will be partially or fully absorbed by the schedule buffer time. The delay absorption capability of schedule buffer time is denoted by m_l, i.e. the slope of the former portion of the delay time development curve as demonstrated in Figure 3.3. When the arrival delay is longer than the buffer time (T), the corresponding departure delay may develop in three ways. First of all as indicated by curve f_2 in Figure 3.3, departure delays may develop in a linear proportion to arrival delays, no matter how long the arrival delay is. Secondly, following curve f_3, ground handling agents may be able to ensure a puncture departual and consequently departure delay does not escalate with the increase of arrival delay. Thirdly, curve f_1

represents a typical curve, when ground operation is further disturbed by late arrivals or through late transfer passengers, late passenger check-in, late baggage handling, and disruptions in ground operational plans.

Figure 3.3

The curve slope (denoted by m_2) after the turnaround buffer time (T) is defined as ground service performance, i.e. the ground handling agents' capability to respond to schedule perturbations. When the value of m_2 is less than or equal to unity, departure delays develop at a lower rate compared with arrival delays such as curve f_2 and f_3 in Figure 3.3. If m_2 is greater than one, it means that turnaround operations are disturbed by operational disorders and therefore, ground operations will need a longer time to complete. Consequently, turnaround departure aircraft suffer delays due to arrival lateness as well as turnaround operational disturbance.

One of responsibilities of airline dispatchers at airport terminals is to deliver punctual flights by operational means. If at time t (shown in Figure 3.3) the airline terminal dispatcher takes actions to reduce departure delay of a turnaround aircraft, the curve f_1 might switch to f_4. As a consequence, a shorter departure delay and the decrease of potential knock-on delays in aircraft rotations may be achieved. Nevertheless, operating costs of an airline may increase in this way (Ashford *et al*, 1997). Consequently, the departure time of a turnaround aircraft is influenced by the arrival time of inbound aircraft, the schedule buffer time, and the ground service time.

3.2.2 Modelling of Aircraft Turnarounds

The presented aircraft turnaround model in this section simulates the aggregate development of turnaround delays during aircraft ground service operations. The departure time of a turnaround aircraft is modelled by the schedule buffer time (T) and the ground service performance of ground service agents (m_i), which is illustrated in Figure 3.4. It is assumed in this model that if there is no schedule buffer time (i.e. $T=T_A$), departure delay develops as *Curve A* illustrated in Figure 3.4. If the schedule buffer time is as long as the maximum limit (T_{max}, i.e. 100% of flights arrive within the schedule buffer time), departure delay develops according to *Curve C*. In between extreme cases, ground services with a scheduled ground time (T_G) and a buffer (T) exhibit a turnaround performance curve as *Curve B*. For any given buffer time T, there will be a corresponding performance figure, which represents the ground service performance under the given schedule buffer time.

Figure 3.4

It is assumed that the value of m_i is a function of schedule buffer time (T) and ground service performance (m_2), which represents the operational efficiency of a ground handling agent in dealing with delays. Logically, a longer buffer time results in a smoother curve slope, i.e. a better arrival delay absorption ability for turnaround buffer time. Therefore, the relationship between the delay absorption capability (m_1), the schedule buffer time (T) and the ground service performance (m_2) is modelled by a piecewise linear function represented by equation (3-3) and illustrated by Figure 3.4.

$$m_1 = f(T, m_2) = \left(\frac{m_2}{T_{max} - T_A} \right) * (T_{max} - T) \qquad T_A \le T \le T_{max} \tag{3-3}$$

where T_A is the STA of a turnaround aircraft

T_{max} is the maximum buffer time to absorb 100% of inbound delays

Hence, the departure time (s) of a turnaround aircraft is formulated as a function of the arrival time of inbound aircraft (t), the schedule buffer time (T) and ground service performance (m_1 & m_2). The departure time of a turnaround aircraft (s) is represented by equation (3-4) and (3-5). Using equation (3-4) and (3-5), we are able to model departure delays of turnaround aircraft with respect to schedule buffer time (T) and ground service performance (m_2).

$$s = m_1 * (t - T_A) \qquad T_A \le t \le T \tag{3-4}$$

$$s = m_1 * (T - T_A) + m_2 * (t - T) \qquad T < t \le T_{max} \tag{3-5}$$

where $m_1 = \left(\frac{m_2}{T_{max} - T_A} \right) * (T_{max} - T) \qquad T_A \le T \le T_{max}$

3.2.3 Delay Costs

When an aircraft is delayed, both the airline and passengers suffer delay costs. The airline loses aircraft productivity due to excessive delay time and meanwhile pays more operational costs. Passengers suffer delays and lose the value of delay time. There are other costs associated with compensation and loss of goodwill of passengers, but these are not considered here. In this research, departure delay costs (C_u) include the aircraft delay cost (C_{AC}) and the passenger delay cost (C_P), which is expressed by equation (3-6), (3-7) and (3-8).

$$C_u(s) = C_{AC}(s) + C_P(s) \tag{3-6}$$

$$C_{AC}(s) = \int c_{AC}^{m}(s) ds \tag{3-7}$$

in which $c_{AC}^{m}(s)$ is the marginal delay cost function of an aircraft

$$C_P(s)=\int c_P^m(s)ds \qquad (3\text{-}8)$$

in which $c_P^m(s)$ is the marginal delay cost function of on-board passengers

$C_{AC}(s)$ is the delay cost function of an aircraft, which includes aircraft operating expenses, flight crew costs, and extra gate occupancy charges. The aircraft delay cost is formulated by a marginal delay cost function $c_{AC}^m(s)$, which can be expressed by any general form according to formulation requirements. $C_P(s)$ is the delay cost function of passengers who are on-board the delayed aircraft. The passenger delay cost is represented by a marginal delay cost function $c_P^m(s)$ in equation (3-8). Although cost functions mentioned earlier can be any form in a more general condition, it is assumed in this model that the marginal delay costs of on-board passengers and aircraft are constant, i.e. the total cost functions ($C_{AC}(s)$ & $C_P(s)$) become linear after integrating the marginal cost functions in equation (3-7) and (3-8) (Tosic *et al*, 1995).

To increase aircraft productivity, airlines try to shorten the ground service time as much as they can to keep aircraft in the air to earn revenues. However, a trade-off condition happens when a shorter schedule buffer time causes a higher probability of delayed turnaround departures, while on the other hand a longer schedule buffer time reduces the aircraft productivity. Therefore, the opportunity cost of airline schedule time is formulated by equation (3-9) to represent the cost for an airline to include schedule buffer time in aircraft turnaround schedules. As can be seen in equation (3-9), the airline schedule time cost is the integration of the marginal schedule time cost function, which is denoted by $c_{AL}^m(T-T_A)$.

$$C_{AL}(T)=\int c_{AL}^m(T-T_A)dT \qquad (3\text{-}9)$$

in which $c_{AL}^m(T-T_A)$ is the marginal schedule time cost function of an airline

The marginal schedule time cost function $c_{AL}^m(T-T_A)$ is assumed in this model to be a linear function. Hence the opportunity schedule time cost function $C_{AL}(T)$ becomes a quadratic one. It is realised from current situations in the industry that the schedule time opportunity cost gets higher when saved schedule time is long enough for an aircraft to carry out another flight and earn additional revenues. Therefore, the total schedule time cost function is formulated by a quadratic function to represent current conditions.

3.2.4 System Costs

The inbound arrival time of a turnaround aircraft (t) is modelled by stochastic PDFs to simulate uncertainties of aircraft punctuality. The turnaround operation of an aircraft is expressed by equation (3-4) and (3-5). Hence, the departure punctuality of a turnaround aircraft (denoted by $g(s)$) becomes a continuous function derived from aircraft arrival time distribution ($f(t)$), schedule buffer time (T) and ground service performance (m_2). It is expressed by equation (3-10) and illustrated by Figure 3.5.

$$g(s) = F[f(t), T, m_2] * |J_s| \quad (3\text{-}10)$$

in which $J_s = dt/ds$ ***Jacobian*** of variable transformations between s and t

Figure 3.5

Therefore, the expected departure delay cost (C_D) of a turnaround aircraft can be formulated by equation (3-11).

$$C_D = E[C_u(s)] = \int C_u(s) g(s) ds \quad (3\text{-}11)$$

In this model, the trade-off condition between the airline schedule time cost (C_{AL}) and the expected delay cost (C_D) is modelled by a weight factor α, which varies between 0 and 1 as shown in equation (3-12). Hence, the system cost (C_T) incurred in the operation of a turnaround aircraft is analytically formulated by equation (3-12). Equation (3-12) becomes equation (3-13) when C_D and C_{AL} are substituted by equation (3-11) and (3-9).

$$C_T = \alpha C_D + (1-\alpha) C_{AL} \quad (3\text{-}12)$$

$$C_T = \alpha \int_0^{s^M} C_u(s) g(s) ds + (1-\alpha) \int_o^{T^M} c_{AL}^m (T - T_A) dT \quad (3\text{-}13)$$

Therefore, the objective function of the AAT model is summarised by:

To minimise C_T:

$$C_T = \alpha C_D + (1-\alpha) C_{AL} \quad (3\text{-}14)$$

where

$$0 \le \alpha \le 1 \quad (3\text{-}15)$$

$$C_D = E[C_u(s)] = \int C_u(s) g(s) ds \quad (3\text{-}16)$$

$$C_u(s) = C_{AC}(s) + C_P(s) \quad (3\text{-}17)$$

$$C_{AL}(T) = \int c_{AL}^m (T - T_A) dT \quad (3\text{-}18)$$

$$g(s) = F[f(t), T, m_2] * |J_s| \quad (3\text{-}19)$$

$$s = m_1 * (t - T_A) \qquad T_A \le t \le T \qquad (3\text{-}20)$$

$$s = m_1 * (T - T_A) + m_2 * (t - T) \qquad T < t \le T_{max} \qquad (3\text{-}21)$$

where $m_1 = \left({m_2}/{T_{max} - T_A} \right) * (T_{max} - T) \qquad T_A \le T \le T_{max}$

3.3 Application of the Analytical Aircraft Turnaround Model

3.3.1 Numerical Analysis

With respect to the STA of an inbound aircraft, there are mainly three categories of arrival patterns, namely early arrivals, quasi-normal arrivals, and late arrivals. A graphical illustration of three aircraft arrival patterns is given in Figure 3.6. Beta functions as shown in Figure 3.6 are arbitrarily selected in this research to simulate arrival patterns of inbound aircraft ($f(t)$ in equation (3-19)) because of their analytical tractability in mathematical modelling (Ross, 1993). Due to the difficulty of analytically solving the objective function (equation (3-14)), a mathematical software **MATLAB™** was used to carry out numerical analyses.

Figure 3.6

Beta(3,10) distribution was selected to simulate an early arrival pattern having a STA of 10 minutes with respect to the arrival time domain of one hour (shown in Figure 3.6). 90% of flights arrive within 24 minutes in Beta(3,10) arrivals as shown in Figure 3.7. In other words, 90% of flights arrive within 14-minute delay time and 30% of flights arrive punctually in this case. Beta(10,10) was used to represent a quasi-normal case of arrivals with a STA of 30 minutes and 55% of punctual arrivals as shown in Figure 3.6. 90% of flights arrive within a delay of 10 minutes in Beta (10,10) case. Beta(10,3) was set to represent a late arrival pattern with a STA of 40 minutes, and has only 20% punctual flights.

Figure 3.7

Although Beta functions are analytically suitable for modelling uncertainties of schedule punctuality, it is not clear whether Beta functions are able to model the inbound arrival patterns of aircraft. As a consequence, flight punctuality data from British Airways were collected for three different routes in the summer of 1999 to validate the use of Beta functions in modelling schedule punctuality. Fitted PDFs from flight data are shown in Figure 3.8. PDFs were statistically tested by both *K-S test* and χ^2 *goodness-of-fit test* to ensure the power of curve fitting to field data. Three different types of arrival patterns represent three different routes respectively. Domestic flights show a quasi-normal distribution of Beta(18,20). Short-haul European flights on the other hand, exhibit a right-tailed arrival time distribution of Beta(4,14), which is similar to Beta(3,10) previously chosen for numerical analysis. Long-haul flights, which exhibit a Beta(2,13) arrival pattern, are more punctual than short-hauls.

Figure 3.8

The value of the unit delay cost of a passenger ($C_p(s)$ in equation (3-17)) used in numerical analyses is \$0.9/min, which is equivalent to a delay cost of \$54 per hour, per passenger (Wu and Caves, 2000). The value of the unit delay cost of an aircraft ($C_A(s)$ in equation (6)) is \$45/min for ground delays, which is equivalent to a delay cost of \$2,700 per hour, per aircraft (a B757). The opportunity cost of schedule buffer time (C_{AL}^{m} in equation (7)) is \$2.5/min, which is equivalent to \$4,500 per hour for a European short-haul route. Equal weights, i.e. $\alpha = 0.5$, on the delay cost of passengers and the airline schedule time cost are used in the following numerical analyses.

3.3.2 Schedule Control- The Use of Schedule Buffer Time

The PDF of a departing turnaround aircraft ($g(s)$ in equation (3-19)) is determined by its corresponding arrival time of inbound aircraft ($f(t)$), schedule buffer time (T) in the ground time of a turnaround aircraft, and the operational efficiency of aircraft ground services (m_2) formulated in equation (3-20) and (3-21). For instance, Beta(10,3) distribution is used to model the arrival pattern of Flight_A which has 20% on-time arrivals and 99% of flights arriving within 20-minute delay. The corresponding departure PDFs ($g(s)$) of Flight_A are shown in Figure 3.9. It is observed from Figure 1 that the more schedule buffer time is scheduled in the ground time of Flight_A, the more punctual turnaround departure flights will be. The maximum schedule buffer time (T_{max} in equation (10)) for Flight_A is twenty minutes, as it is long enough to include 99% of arrivals within buffer limits in this case.

Figure 3.9

However, it might be argued that the shape of aircraft arrival time PDFs could be centrally distributed. Hence, a further analysis was conducted to investigate the influence of shapes of quasi-normal distributions on model outputs. Three centrally distributed PDFs, Beta(3,3), Beta(5,5) and Beta(10,10) were used to test the aircraft turnaround model. The illustration of PDFs of these Beta functions is given in Figure 3.10. The STA of these cases is set at zero hour in the range between –0.5 and 0.5 hour, so the arrival punctuality in all three cases is 50%. The model outputs of three flights are shown in Figure 3.11. It is found that the shape difference of PDFs causes a change of the expected delay cost, C_D (illustrated by doted lines) and consequently a change of total system cost, C_T (illustrated by dashed lines). The schedule time cost, C_{AL} remains the same for all three cases, as these flights are operated by the same airline. Hence, the optimal schedule buffer time is found to be 15, 15 and 10 minutes for the case of Beta(3,3), Beta(5,5) and Beta(10,10) respectively when the system cost has its minimum.

Figure 3.10

Figure 3.11

It is seen in Figure 3.11 that the total system cost of the Beta(3,3) case is the highest among the three cases. The high system cost of the Beta(3,3) case is due to the high expected delay cost because of the shape of Beta(3,3) functions. It is seen in Table 3.4 that three PDFs have the same mean value of 0.5 but have different standard deviation. Beta(3,3) has the highest standard deviation which results in the "flatter" shape of Beta(3,3) as illustrated in Figure 3.10. As a result, the arrival CDFs of three cases differ from each other as shown in Figure 4. It can be seen in Figure 3.12 that it takes 0.15, 0.2 and 0.25 hours of delay for Beta(10,10), Beta(5,5) and Beta(3,3) case respectively to achieve the cumulative arrival punctuality of 90%. Hence, the expected delay cost of the Beta(3,3) case is higher than the other two cases. Therefore, it is found from previous discussion that the arrival pattern of inbound aircraft influences the optimal use of schedule buffer time through the expected delay of inbound aircraft, i.e. the arrival punctuality of inbound aircraft, instead of the shape of PDFs of inbound aircraft.

Table 3.4

Figure 3.12

3.3.3 Influence of Arrival Punctuality of Inbound Aircraft on Aircraft Turnaround Punctuality

It is realised from empirical punctuality analysis that arrival aircraft exhibit different punctuality, which might result from enroute airspace congestion and aircraft turnaround delays at outstations. It is also found from empirical analysis in relevant literature that the departure punctuality of a turnaround aircraft is related to the arrival punctuality of inbound aircraft (Hassounah and Steuart, 1993). However, the uncertainties in aircraft turnaround operation were not included in previous research. Hence, it is of interest in this research to investigate how the relationship develops between the arrival punctuality and the departure punctuality of a turnaround aircraft when considering the operational efficiency of aircraft turnarounds.

For instance, Flight_A of Airline R in Figure 3.13 exhibits an arrival pattern of Beta(10,3) with a STA time of 40 minutes within an arrival time domain of 60 minutes, i.e. 99% of flights arrive with the maximum arrival delay of 20 minutes. A similar arrival time distribution is observed from Flight_B but with a STA time of 30 minutes, i.e. worse arrival punctuality. The simulated departure PDFs of these two flights are shown in Figure 3.13. It is seen that Flight_B incurs longer departure delay than Flight_A under the same arrival pattern but different arrival punctuality of inbound aircraft. Therefore, it is found, as might be expected, that the departure punctuality of a turnaround aircraft is sensitive to the arrival punctuality of inbound aircraft.

Figure 3.13

As seen in Figure 3.13, the arrival punctuality of inbound aircraft influences the departure punctuality of a turnaround aircraft. As a consequence, different schedule buffer time should be applied to different flights in order to maintain a consistent schedule punctuality. Flight_B, in this example needs a longer buffer time than Flight_A due to the latter's better arrival punctuality. The implication of this example is that aircraft operations at outstation stops also play an important role in the improvement of schedule punctuality of turnaround aircraft at an airport as well as the schedule reliability of aircraft rotations between airports. Operational improvements are generally done at a single airport to improve the performance of schedule delivery. However, it is found in this example that improvements at a single airport do not necessarily achieve the system optimum, unless the system is optimised on a network scale.

3.3.4 Aircraft Ground Services

The scheduled ground time of an aircraft is designed to accommodate the service time of aircraft turnaround and potential delays from inbound aircraft as well as delays from aircraft turnaround operations. The arrival delay of an aircraft causes a late start of aircraft ground services and is likely to result in a late finish of aircraft turnaround. As a consequence, the scheduling of equipment and staff of ground services is influenced. The most serious influence of ground service disruption is the knock-on effect of disruptions to stand plans of the other aircraft on the ground waiting for services. When the arrival delay of a turnaround aircraft disturbs stand plans of airport gates, departure delay will probably happen and even deteriorate during turnaround operations if the operation of aircraft turnaround is not well managed. To further explain this situation, the operational efficiency of aircraft ground services is described in the AAT model by a stochastic variable, m_2 in equation (3-20) and (3-21). When the schedule perturbation is not sufficiently significant to disturb turnaround operations and the ground handling agent is able to control service time, m_2 is assigned a value which is equal to or less than unity in equation (3-20), i.e. no further delays result from turnaround disruptions in this case. Hence, a higher value of m_2 means that departure delay of a turnaround aircraft is contributed partially by the arrival delay of inbound aircraft and partially by the operational delay from aircraft turnaround.

To investigate the influence of ground service efficiency on aircraft turnaround punctuality, a numerical study was carried out by simulating a turnaround aircraft which shows Beta(10,3) arrival punctuality with a STA of zero hour within an arrival time domain between –0.5 and 0.5 and 10 minutes schedule buffer time as shown in Figure 3.14. It is seen in Figure 3.14 that if schedule disturbance from arrival delay is significant to aircraft ground services (in this case, m_2 is 2), the departure PDF of turnaround aircraft (illustrated by the dotted line in Figure 3.14) exhibits a longer right tail. On the other hand, when the better management of turnaround services can be achieved by operational means (Ashford *et al*, 1997), the departure delay of the turnaround aircraft becomes less and the right tail of the departure PDF becomes shorter (represented by the solid line in Figure 3.14). Therefore, it is found that the efficiency of aircraft turnaround operation significantly influences the departure punctuality of turnaround aircraft. Evidence from the air transport industry also revealed that low-cost airlines in Europe reduce operational costs through minimising aircraft turnaround time on the ground and maximising aircraft turnaround efficiency at hub airports to increase aircraft productivity (Airport Council Internatina-Europe, 2000).

Figure 3.14

3.3.5 Trade-offs between Aircraft Utilisation and Schedule Punctuality

The trade-off situation between schedule punctuality and aircraft utilisation is done on a regular basis by the airline industry. However, little work has been done to reveal the influence of scheduling buffer time on schedule punctuality performance and operational costs. Therefore, a weight factor α is introduced in the AAT model (equation (3-14)) to represent this trade-off situation faced by an airline. The weight factor α is set to be 0.5 to balance the trade-off condition. When a higher value of α is chosen, the emphasis is put on the cost of schedule delay, i.e. the punctuality performance. A lower value of α puts the emphasis on the utilisation of aircraft, i.e. an airline's schedule time cost. The weight factor α also reflects scheduling strategies of an airline.

For the Beta(3,10) case of British Midland (BD) and British Airways (BA), the influence of different weights on punctuality and schedule time is shown in Figure 3.15. It is observed that when α is set to emphasize the schedule punctuality performance, the required schedule buffer time becomes higher than the equal weight trade-off case with α value of 0.5. On the contrast, when more concentration is required for a shorter ground time, the α value is chosen to be lower than 0.5 and therefore, the required schedule buffer time is reduced as shown in Figure 3.15.

Figure 3.15

Three different arrival patterns are investigated to find the influence of airline scheduling strategies on the use of schedule buffer time in turnaround aircraft. Results are summarised in Figure 3.16. It can be seen from the graph that more schedule buffer time is needed for the Beta(10,3) arrival case, due to a relatively high delay costs. It is also observed in Figure 3.16 that when the scheduling emphasis is put on the overall punctuality of turnarounds, longer schedule buffer time will be needed to achieve the system optimum.

Figure 3.16

Therefore, it can be concluded that the optimal schedule time for a turnaround aircraft depends on the arrival punctuality of up-stream aircraft as well as the scheduling strategies of an airline. When the expected delay cost is relatively lower than the operational cost of an airline, the airline might choose to minimise the turnaround time to reduce operational costs and to increase fleet productivity, e.g. the Beta (10,10) and Beta (3,10) cases. However, when the schedule buffer time is available due to a low probability of having long-delayed flights, the airline could utilise the schedule buffer time to reach the system optimum without compromising punctuality performance, e.g. the Beta(10,3) case.

3.3.6 Case Studies: British Airways

Two case studies were carried out to demonstrate the effectiveness of the proposed AAT model. Flight data collected in the summer of 1999 from British Airways were used in these case studies. Flight data represent three-month operations of two typical European city-pair flights BA-X and BA-Y which were turned around at Terminal One of Heathrow Airport. BA-X was scheduled to arrive at 18.45 hours and to depart at 19.45 hours. BA-Y was scheduled to arrive at 16.30 hours and to leave at 17.35 hours. B757 aircraft was used to carry out these two flights during operations in 1999. Arrival PDFs of these two flights are statistically fitted from flight data as shown in Figure 3.17. Both PDFs passed the *K-S Goodness of Fit Test* as shown in Table 3.5 and therefore, were used to simulate arrival punctuality of these two flights. There were 55% punctual flights for BA-X and 60% for BA-Y.

Figure 3.17
Table 3.5

The aircraft turnaround model was applied to simulate the turnaround operation of BA-X as well as the departure punctuality of BA-X. The CDFs of departure punctuality of BA-X from model results are shown in Figure 3.18. Different lengths of schedule buffer time were applied in the turnaround model of BA-X and it resulted in different expected departure CDFs. It is seen from Figure 3.18 that the longer the buffer time is scheduled in the turnaround time of BA-X, the more punctual departure flights will be. The observed departure punctuality of BA-X is illustrated in Figure 3.18 by a thick solid line. It is seen in Figure 3.18 that the observed departure punctuality of BA-X is close to the estimated departure CDF having a schedule buffer time set at 0.7 hours with respect to the STA of 1/3, i.e. about 15 minutes schedule buffer time in this case.

Figure 3.18

The scheduled ground time of BA-X was 60 minutes and consequently the schedule buffer time was about 15 minutes when turning around a B757 aircraft according to the standard ground operational requirements of British Airways. Compared with model results, the observed turnaround punctuality of BA-X is found to commensureate with 15 minute buffer time. However, it is also found in Figure 3.18 that the observed cumulative departure puncutality of BA-X is relatively better within short departure delays (5 minutes) than model results and is relatively worse than model results in some departures which have longer departure delays (more than 20 minutes). It is found from observations of aircraft turnarounds by British Airways that longer delays to turnaround aircraft resulted from longer arrival delays of inbound aircraft as well as from delays due to disruptions to aircraft turnaround operations. As a consequence, a thicker right tail is found in observed departure punctuality CDF of BA-X due to some extreme cases in observations. It is also realised that the proposed aircraft turnaround model is not good at modeling extreme cases, i.e. inbound aircraft with very long arrival delays by using an aggregate model, because futher departure delays might result from stand plan disruptions.

The second case study was done by applying the turnaround model to BA-Y's flight data. The comparison between observed departure punctuality from British Airways and estimated departure CDFs of BA-Y are shown in Figure 3.19. The observed departure CDF of BA-Y (represented by a thick sold line) develops closely to the estimated CDF having a schedule buffer time set at 1/3 with respect to the STA of 1/3, i.e. no buffer time included in this case. From the given flight schedule of BA-Y, it is known that the scheduled ground time of BA-Y was 65 minutes which include 20 minute buffer time when turning around a B757 aircraft. Model results show that 20 minute buffer time ought to be long enough to include 95% of delayed arrivals. However, it is seen from Figure 3.19 that the turnaround punctuality of BA-Y was not commensurate with the amount of buffer time in BA-Y's schedule. In other words, the implemented schedule punctuality of BA-Y did not match the endogenous punctuality requirement in BA-Y's schedule.

Figure 3.19

3.3.7 Discussions: Strategies for Punctuality Managemnet

A hypothesis made earlier in this chapter is that the endogenous schedule punctuality has been set after a flight schedule is chosen by an airline. In other words, the hypothesis says that it is feasible for an airline to manage its schedule punctuality by changing its flight schedules. As demonstrated in the case studies, BA-X exhibits good turnaround punctuality with respect to its scheduled tuarnound time as shown in Figure 3.18. On the other hand, the turnaround punctuality of BA-Y (illustrated in Figure 3.19) matches the estimated departure CDF which includes no schedule buffer time, despite actually having a buffer of 20 minutes for the turnaround. It is found from case studies that the turnaround time of BA-Y was not long enough to absorb potential delays from inbound aircraft as well as delays from aircraft turnaround operations. Yet the endogenous schedule punctuality of a turnaround aircraft can be achieved by good management of turnaround operations such as flight BA-X. Hence, the schedule punctuality of BA-X is expected to be as good as it is, commensureate with 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 BA-Y are not unusual for airlines and passengers. The case study of BA-Y offers airlines some clues towards the better management of schedule punctuality. Managerial strategies to improve schedule punctuality of turnaround aircraft are therefore, recommended to focus on two aspects: airline scheduling control and the management of operational efficiency of aircraft ground services.

It is feasible for an airline to manage schedule punctuality by optimally scheduling flights. For instance, flight BA-Y did not achieve its endogenous punctuality performance, even though 20 minutes of buffer time has been scheduled in the turnaround time. British Airways, therefore can improve BA-Y's departure punctuality by scheduling longer turnaround time at the airport, if a longer ground time is needed. In addition, the improvement of the arrival punctuality of inbound aircraft of BA-Y can also help improve turnaround punctuality of BA-Y at the study airport. As a result, the departure punctuality of BA-Y can be improved by optimising scheduling control at the base airport and outstations.

The management of schedule punctuality can also be achieved by the improvement of operational efficiency of aircraft turnaround. It has been demonstrated previously in this paper how significantly the departure punctuality of a turnaround aircraft is affected by the efficiency of aircraft ground services. Although short aircraft turnaround time increases the productivity of aircraft, it also risks airlines and passengers suffering delays because of a lack of delay absorption ability in a tight turnaround schedule. On the other hand, the operation of aircraft ground services should be able to absorb operational delays to aircraft turnaround by operational means when delays are about to happen (Braaksma and Shortreed, 1971; Ashford *et al*, 1997). Most low-cost airlines in Europe operate tight aircraft turnaround schedules at their base airports because the operational efficiency of aircraft turnaround can be fully controlled and managed by these airlines. However, there is still some potential risks for airlines operating tight aircraft turnaround and rotational schedules. When schedule irregularities occur, the most likely solution to elimilate knock-on delays in intensive aircraft rotational schedules is to cancel flights.

3.4 Markovian Aircraft Turnaround Model (MAT model)

3.4.1 Model Assumptions and Definitions

The Markov process in the MAT model is assumed to be *time homogeneous* with *stationary* transient probability between states. Operational disruptions to aircraft turnaround operations are modelled by event states in this model, but some event states do not *communicate* with each other, because of the assumption of independent occurrence of disrupting activities (Ross, 1993; Taylor and Karlin, 1994). For instance, the occurrence of aircraft fuelling delay does not necessarily incur the occurrence of aircraft engineering check delay during aircraft turnaround operations. The flow of the Markov model is assumed to be *irreversible* regarding time, because aircraft turnaround procedures do not return to the starting stage (the Arrival state) but move towards an *absorbing* stage, i.e. the Departure state. Notations and definitions of symbols used in the MAT model are summarised as below.

$A_{ij}(t)$	cumulative density function (C.D.F.) of a transition from state i to state j at time t
$\alpha_{ij}(t)$	probability density function (P.D.F.) of a transition from state i to state j at time t
$B_i(t)$	survival function of state i at time t
ε_i	elapsed time of state i
ε_i^e	elapsed time of disrupting event e_i
ε_i^s	occurrence epoch of event e_i
ε_i^T	total elapsed time of event e_i
ε_k^T	total elapsed time of a Markov cycle k
p_i^e	occurrence probability of event e_i
p_{ij}	probability of a transition from state i to state j
t	departure delay time of a turnaround aircraft
T_{SG}	scheduled ground time of a turnaround aircraft
$\Phi_{ij}(t)$	probability density function (P.D.F.) of a state staying in state i until time (t-1) before transiting to state j at time t
$\Phi_i^e(t)$	sojourn time probability density function (P.D.F.) of event e_i
$\chi_i(t)$	model process in state i at time t

Ω : State space with a size of n

$$\Omega \equiv \{1,2,\ldots i \ldots n\}$$

X : State location

P : Transition probability set

$$P \equiv \begin{bmatrix} p_{11} & p_{12} & \cdots & p_{1n} \\ p_{21} & \ddots & & \vdots \\ \vdots & & \ddots & \vdots \\ p_{n1} & p_{n2} & \cdots & p_{nn} \end{bmatrix}$$

$$0 \le p_{ij} \le 1.0 \qquad \sum_{j=1}^{n} p_{ij} = 1.0$$

Φ : Sojourn time probability function

$$\Phi_{ij}(t) \equiv P[x_j(t)|x_i(t-1)]$$

A : State transient probability

$$\alpha_{ij}(t) \equiv P[x_j(t)|x_i(1), \cdots x_i(t-1)] \equiv \Phi_{ij}(t) p_{ij}$$

E : Event space with a size of m

$$E \equiv \{1, 2, \cdots e_i, \cdots m\}$$

ε : Elapsed time of a state/event

3.4.2 Transitioins between States

The transient process between state i and state j is described by a renewal process $\alpha_{ij}(t)$ with a state sojourn time function $\Phi_{ij}(t)$ and state transition probability p_{ij}. The sojourn time function $\Phi_{ij}(t)$ obeys Markovian properties, which require the sojourn time of each state to be independent and identically distributed (i.i.d.). Under the assumption of constant work labour efficiency in aircraft turnarounds, the sojourn time of a state can be expressed by an i.i.d. PDFs, which are chosen to describe the operational characteristics of an operational activity. Hence, it is possible to have more than one sojourn time distribution in a Markovian type model.

It has been proved in literature that the steady-state sojourn time of Markov Chains depends on chosen sojourn time distributions only through the mean of a sojourn time function (Ringel and Mode, 1994). Hence, the CDF of a transition from state i to state j at time t can be represented by equation (3-22).

$$A_{ij}(t) = \int_0^t \alpha_{ij}(t)dt \qquad (3\text{-}22)$$

where $\alpha_{ij}(t) = \Phi_{ij}(t) p_{ij}$

The CDF of making a transition from state i to any state at any time between 0 and t is formulated by equation (3-23).

$$\mathrm{A}_i(t) = \sum_{j=1}^{n} \mathrm{A}_{ij}(t) \qquad t \geq 0 \qquad \text{for state } i \in \Omega \ (i \neq j) \tag{3-23}$$

Hence, the survival function of state i is formulated by equation (3-24).

$$\mathrm{B}_i(t) = 1 - \mathrm{A}_i(t) \tag{3-24}$$

The expected sojourn time of state i before transiting to state j is expressed by equation (3-25). The expected sojourn time of state i regarding transitions to any state is therefore formulated by equation (3-26).

$$\varepsilon_{ij} = \mathrm{E}[t] = \int_0^\infty t\Phi_{ij}(t)dt \tag{3-25}$$

$$\varepsilon_i = \mathrm{E}[t] = \int_0^\infty t\mathrm{A}_i(t)dt \tag{3-26}$$

Therefore, the total elapsed time of a complete Markovian cycle can be expressed by equation (3-27).

$$\varepsilon_T = \sum_{i=1}^{n} \varepsilon_i \qquad \text{for state } i \in \Omega \tag{3-27}$$

3.4.3 Operataional Perturbations

Some activities in aircraft turnaround operations are not included in the model described in the previous section, because they are not normally on the critical path of aircraft turnaround operations. Disrupting events also happen occasionally during turnarounds and sometimes cause significant delays to a flight. In order to account for these operational uncertainties, independent aircraft turnaround services and operational disruptions are modelled by stochastic Monte Carlo Simulation.

The occurrence probability of event e_i is denoted by P_i^e and the sojourn time function of event e_i is denoted by $\Phi_i^e(t)$. Hence, the expected sojourn time of event e_i is expressed by equation (3-28).

$$\varepsilon_i^e = \mathrm{P}_i^e \mathrm{E}[t] = \mathrm{P}_i^e \int_0^\infty t\Phi_i^e(t)dt \tag{3-28}$$

The occurrence epoch (ε_i^s) of event e_i from the start of turnaround operations is modelled as a stochastic variable to account for the randomness of the occurrence of disrupting events. Consequently, the total elapsed time (ε_i^T) of event e_i, if occurs, can be formulated by equation (3-29).

$$\varepsilon_i^T = \varepsilon_i^s + \varepsilon_i^e \qquad (3\text{-}29)$$

Disrupting events may influence the departure punctuality of a turnaround aircraft only when the total duration of events exceeds the scheduled turnaround time (T_{SG}). Therefore, the departure delay of a turnaround aircraft comes from delays to critical work paths in turnaround operations, delays due to disrupting events, and delays to inbound aircraft. The departure delay (D_d) of a turnaround aircraft is formulated by equation (3-30).

$$D_d = D_a + Max\left[Max\left[\varepsilon_k^T\right], \varepsilon_i^T\right] - T_{SG} \qquad D_a \geq 0 \quad D_d \geq 0 \qquad (3\text{-}30)$$

3.5 Application of the Markovian Aircraft Turnaround Model

3.5.1 Simulation Scenarios

The aircraft turnaround model is applied to model two major work flows in aircraft turnaround procedures, namely cargo & baggage handling and cabin cleaning & passenger processing (Braaksma and Shortreed, 1971; International Air Transport Association, 1997). The process of cargo & baggage handling can be mainly divided into two portions, namely goods unloading and goods loading. Although these two groups of work can be sub-divided into more detailed procedures, it is not recommended at this instance to model the process on a more detailed scale for two reasons. First of all, the purpose of this model is to investigate the influence of aircraft turnaround efficiency on schedule punctuality, rather than the operational time of individual turnaround activities on a very detailed scale. In addition, the aircraft turnaround model on the current scale is sufficient for the objective of this research. Secondly, the Markov model becomes too complicated to handle, when turnaround operations are simulated on a more detailed scale.

A list of activities included in the flow of cargo & baggage handling is shown in Table 3.6. There is a major sequence of workflow (state_1, 2, 3 and 4) which starts from the arrival of an aircraft (state_1) to the departure stage (state_4, an *absorbing* state) as shown in Figure 3.20. Directions of arrows in Figure 3.20 represent the Markovian transition behaviour between states. Transition probabilities between states are given in Table 3.7. State sojourn time functions used in simulations include Normal functions, Beta functions and Exponential functions. Disrupting events in each state of the work flow of cargo & baggage handling are grouped into five categories (state_5 ~ state_9 given in Table 3.6) instead of simulating the occurrence of individual disruptions. Potential disruptions regarding cargo & baggage handling include staff and equipment unavailability, late loading, late preparation of goods and so forth.

Table 3.6

Table 3.7

Figure 3.20

The process of cabin cleaning & passenger processing is categorised into four groups of work, namely disembarking of passengers/crews, cabin cleaning, crew/passenger boarding, and flight operations & crewing as shown in Table 3.8. The state of air traffic flow management (ATFM) is included in this process because it is usually realised in advance by airline operators whether there will be ATFM on the day of operation and therefore, passenger boarding may be postponed in such a case. There is a major sequence of workflow (state_1, 2, 3, 4, 5, 6 and 7) which starts from the arrival of an aircraft (state_1) and ends in state_7 (the *absorbing* state) as shown in Figure 3.21. State transition probabilities are given in Table 3.9 together with sojourn time functions of each state. Major events are represented by state_8 ~ state_13 (as shown in Table 3.8) including missing passengers, late passenger check-in and delays from flight operations between the cockpit and the airport control tower.

Table 3.8, Table 3.9

Figure 3.21

For the simulation of operational disruptions, four of the most frequent disrupting events in aircraft turnaround operations are chosen and simulated in this paper. These events include aircraft fuelling delays, aircraft engineering delays, aircraft damage during ground operations and aircraft changes. Parameter values of these events are listed in Table 3.10. Operational disruptions are modelled as independent events in the model and thus, the occurrence of a disruption does not influence the occurrence of the others.

Table 3.10

Parameter values used in Markovian transition matrices in Table 3.7, 3.9 and 3.10 are chosen from operational experience of operations researchers in British Airways to demonstrate the modelling performance of the proposed aircraft turnaround model, due to a lack of operational data in such detail. However, the use of empirical parameter values in the model does not weaken the performance of the model, as parameter values can be substituted easily when more detailed operational data is available for analysis. Parameter values needed to implement the model can be produced from aircraft stand observation of a period of time. When monitoring information of aircraft turnaround is available, real state sojourn time functions and state transition matrices can be produced by statistical analysis.

The same flight data of two turnaround aircraft of British Airways used in Section 3.3.6 (denoted by BA-X and BA-Y) are applied to the MAT model. The simulation programme was coded in *Fortran 90* and implemented in a *Unix* environment on a *Sun* workstation. The size of simulation was 1,000 turnarounds, which were chosen to represent the operation of a short-haul intra-European route in a year. In addition, the simulation size was also significant enough to limit Monte Carlo Simulation noises. The *multiplicative congruential generator* was applied in stochastic simulations to generate pseudo-random numbers by carefully selecting *seed* numbers to ensure pseudo-random numbers not overlapping on a scale of 1,000,000 simulation runs (Fishman, G. S., 1996). Results of stochastic simulations were statistically tested to ensure the power of simulation.

3.5.2 Simulaiotn Results

The simulated turnaround punctuality of BA-X and BA-Y is illustrated in Figure 3.22 and compared with observed punctuality. The departure punctuality of study flights is expressed by cumulative density functions (CDFs) of departure flights in Figure 3.22. It is seen in Figure 3.22 that simulation results of BA-X match closely with observed punctuality performance. However, it is found that the turnaround punctuality of BA-Y from simulation does not match with observed departure punctuality, which shows rather poor departure punctuality during the operation of BA-Y in the summer of 1999.

Figure 3.22

The scheduled ground time of BA-Y was 65 minutes and therefore 20 minutes of schedule buffer time was included in flight schedules (if the required standard turnaround time for a B757 aircraft is 45 minutes). It is seen from simulation results given in Table 3.11 that BA-Y should be able to deliver a punctual service because of a longer ground time than BA-X. Secondly, since the arrival punctuality of BA-Y from observations was 58%, it is therefore speculated that the poor departure punctuality of BA-Y is contributed by poor operational efficiency in the turnaround of BA-Y, which results in longer service time than scheduled.

Table 3.11

The decrease of operational efficiency in aircraft turnaround may have resulted from the unavailability of staff or equipment in aircraft ground services. This situation is usually experienced during peak hours of airport operations and might also have resulted from operational disruptions of stand plans at an airport. In addition, the departure congestion from airport ground movements might also delay departure flights and influence departure punctuality. Therefore, two scenario analyses were carried out to model BA-Y in different operational environments. Scenario A simulates BA-Y in a condition of low aircraft turnaround efficiency. Scenario B simulates the same situation as Scenario A together with airport ground congestion for departures. An average departure delay of 2 minutes due to airport ground congestion was included in Scenario B (Feenstra, 1997). The mean turnaround time of scenario simulations is given in Table 3.11 and illustrated in Figure 3.23.

Figure 3.23

A detailed calculation in Table 3.11 shows that the mean service time of BA-Y in Scenario A increases from 51 minutes (in the original case) to 61 minutes due to low turnaround efficiency, i.e. longer operational time required for a turnaround aircraft. The mean outbound delay of BA-Y in Scenario A consequently increases to 4.5 minutes. In Scenario B, the mean service time remains 61 minutes, but the mean outbound delay increases to 6.3 minutes because of the inclusion of airport congestion. When simulated CDFs of departure punctuality of BA-Y are compared with observations in Figure 3.23, it is seen that BA-Y might be delayed due to low turnaround efficiency. On the other hand, delays from airport ground congestion only contribute a relatively small portion to departure delays in Scenario B (an extra outbound delay of 1.8 minutes on average), and results in a decrease of on-time departures only.

As a consequence, three more scenario studies of BA-Y in the condition of low turnaround efficiency were carried out in this paper. Scenario C models the turnaround operation which requires 55 minutes to finish aircraft ground services (the standard time is 45 minutes). Scenario D and E model the same condition but requiring 60 and 65 minutes of turnaround service time respectively. Simulated CDFs of departure punctuality from Scenario C, D and E are shown in Figure 3.24. It is seen that the observed departure punctuality of BA-Y matches closely with the departure CDF in Scenario C. Hence, it is concluded from simulations that low turnaround efficiency of BA-Y could be the major cause of poor punctuality and this conclusion has been validated with operations researchers at British Airways.

Figure 3.24

3.5.3 Discussions

It is found from the case study of BA-X that if the efficiency of aircraft turnaround operations at an airport is assumed to be consistent, the "endogenous schedule punctuality", which reflects the turnaround efficiency and the amount of schedule buffer time, can be estimated before the implementation of flight schedules. For instance, BA-X was scheduled with 15-minute schedule buffer time when using a B757 aircraft, so the expected punctuality of BA-X can be approximated by the punctuality curves from model simulations shown in Figure 3.22. However, the observed punctuality of BA-Y shows that operational variance still exists in aircraft turnaround and influences the schedule punctuality of turnaround aircraft.

The advantage of the aircraft turnaround model is that it enables an airline to trace the operational history of every simulation flight. Tracing turnaround procedures, airlines will be able to investigate weak links in turnaround operations, in order to manage aircraft turnaround efficiency. The turnaround operations of an example simulation flight, BA-X66, is lifted from simulation results and listed in Table 3.12. It is seen that BA-X66 is a punctual departure, even though there is an arrival delay of 6 minutes from inbound aircraft. A disturbing event, which is categorised as Type 2, the engineering check, happens in the 18^{th} minutes during the turnaround process and lasts for 25 minutes. The cargo processing is finished in the 29^{th} minute and the passenger & cabin operation is ended in the 45^{th} minutes. The total duration of the perturbation is not longer than the scheduled turnaround time of BA-X66 (60 minutes in this case) and therefore no departure delay is caused in this case.

Table 3.12

The major contribution of the proposed aircraft turnaround model, when compared with CPM models, is that the MAT model is able to simulate the stochastic and dynamic transition behaviour between ground service activities as well as to model the stochastic occurrence of disruptions to aircraft turnaround. The occurrence probability and duration of operational disruptions can be collected from historical flight data of an airline. These data can be analysed to produce the required Markovian transition matrices to implement the aircraft turnaround model.

The application of the MAT model in future research is in two directions: the simulation of aircraft turnaround operation and the optimisation of aircraft turnaround time. The simulation results of aircraft turnaround punctuality can be compared with the schedule punctuality after the implementation of a flight schedule to evaluate the operational efficiency of aircraft turnaround. On the other hand, the optimal aircraft turnaround time of a specific type of aircraft can be determined by implementing the proposed model to trade off the scheduled ground time of a turnaround aircraft and the required schedule punctuality.

3.6 Sensitivity Analysis to MAT Model

The Markovian aircraft turnaround model (the MAT model) was applied to describe the process of aircraft turnaround by using model parameters which characterise the operational performance of aircraft turnarounds. These parameters include the mean time (state sojourn time) of aircraft turnaround activities, types of sojourn time distributions as well as the occurrence of disruption events to aircraft turnarounds. Hence, a sensitivity analysis was conducted in this research to investigate the influence of these parameters on outputs of the MAT model. The earlier example flight, BA-X, is taken as a study example in the following sensitivity analyses. The scheduled ground time for BA-X's turnaround operation is 60 minutes which include 45 minutes of average turnaround service time and 15 minutes of turnaround buffer time.

3.6.1 Mean Service Time of Aircraft Turnaround

The mean service time to turn around an aircraft is determined mainly by two major work flows in aircraft turnaround operations, namely cargo & baggage processing and cabin cleaning & passenger processing. Hence, different values of mean service time in the MAT model are investigated to find the influence of the mean service time on departure punctuality of a turnaround aircraft, i.e. the mean outbound delay. The mean service time used in sensitivity analysis ranges between 35 minutes and 55 minutes. Results of simulations by using different mean ground service time are given in Table 3.13. It is found that the increase of mean service time in aircraft ground operations increases the simulated turnaround time as well as the mean outbound delay because of the decrease of turnaround buffer time. This result implies that if the mean service time of an aircraft is maintained short, it gives the airline more buffer space to absorb arrival delays to inbound aircraft and to absorb unexpected delays from operational disruptions to aircraft turnaround.

Table 3.13

3.6.2 Types of Service Time Distributions

The sojourn time function used previously in the MAT model is normal distributions. Although it has been proved in relevant literature about Markov chains that the steady-state sojourn time of Markov chains depends on chosen sojourn time distributions only through the mean of a sojourn time function (Ringel and Mode, 1994), a sensitivity analysis was carried out to test the influence of using different types of sojourn time distributions on model outputs. Beta functions and Gamma functions were used to substitute normal distributions in the MAT model. In addition, the mean value and standard deviation of Beta and Gamma functions were assigned the same value as those of Normal functions used in the MAT model in order to distinguish the difference from using different sojourn time functions.

After 1,000 runs of simulation, results in Table 3.14 show that the average ground service time in simulation cases does not change significantly when different sojourn time distributions are used in the MAT model. However, the mean outbound delay in the Beta function case is slightly higher than the others because Beta distributions tend to show thicker tails than the other two distributions. When statistics of each state in the MAT model are calculated in Table 3.15 and Table 3.16, it is found that the mean time and standard deviation of each state in two major work flows of Beta and Gamma cases are rather close to those in the Normal case. It implies that the MAT model is still applicable in a situation which service time probability functions are not known because the MAT model is influenced by state sojourn time functions only through the mean time of a sojourn time function.

Table 3.14, Table 3.15, Table 3.16

3.6.3 Occurrence of Disruptions to Aircraft Turnaround

Disruptions to aircraft turnaround are modelled by event states in two major work flows (state_5~ state_9 in cargo processing flow and state_8~ state_13 in passenger processing flow) as well as discrete event states (event_1~ event_4). The occurrence probability of disrupting events in aircraft turnaround represents the management and operational efficiency of aircraft turnaround operations. Hence, a sensitivity analysis was conducted to investigate the influence of disrupting events to aircraft turnaround operations. The occurrence probability of disruptions to turnaround services was adjusted in the MAT model to simulate a situation of low event occurrence probability (a higher turnaround efficiency case) and a situation of high event occurrence probability (a lower turnaround efficiency case). Simulation results are given in Table 3.17. It is found that when disrupting events have higher occurrence probability in aircraft turnaround process, the mean turnaround service time will increase as well as the mean outbound delay. Simulation results show that if the process of aircraft turnaround can be well managed, there will be less possibility to incur operational perturbations to aircraft turnaround and consequently an airline can maintain good punctuality performance and less likely to incur knock-on delays to aircraft rotations.

Table 3.17

The results of the sensitivity analyses showed the robustness of the MAT model in simulating aircrft turnaround operations. Two major variables, the mean service time of turnaround activities and the occurrence of service disruptions, were found significant for model outputs. This conclusion matches field observations of aircraft turnaround at an airport. On the other hand, the shape of service time PDFs was found not significant for model outputs and this conclusion is also supported by previous researches about Markov Chains (Ringel and Mode, 1994).

3.7 Comparison of Modelling Performance between AAT Model and MAT Model

When the observed departure punctuality of BA-X is compared with estimated results of the MAT model and the AAT model, it is seen from Figure 3.25 that the observed departure punctuality of BA-X is close to results from both models. Observation results show that 75% of flight BA-X departed on time and more than 95% of flights departed within 15- minute delay. It is implied in Figure 3.25 that the observed departure punctuality of BA-X commensurate with the designed schedule buffer time and actual turnaround operations of BA-X had been controlled well by the airline.

Figure 3.25

On the other hand, when the observed departure punctuality of BA-Y is compared with estimated results from the AAT model and the MAT model, it is seen from Figure 3.26 that the observed departure punctuality of BA-Y does not match the endogenous schedule punctuality of BA-Y's schedule and therefore, the turnaround performance of BA-Y is not commensurate with the designed schedule buffer time for this turnaround. It has been shown previously in Section 3.5.2 that the longer turnaround service time should be responsible for the poor departure punctuality of BA-Y. When the AAT model is applied to model turnaround irregularities, e.g. BA-Y, it is found in Figure 3.19 that the AAT model performs well in modelling the endogenous schedule punctuality of BA-Y, but is not efficient to explain turnaround irregularities. When the MAT model is applied to model BA-Y, it has been demonstrated in Figure 3.24 that the MAT model performs well both in modelling the endogenous schedule punctuality and turnaround irregularities. By carrying out scenario analyses, it is feasible to apply the MAT model to explain operational irregularities in aircraft turnarounds and hence to help an airline investigate operational difficulties in aircraft ground services.

Figure 3.26

A comparison between the AAT model and the MAT model distinguishes the performance of these two models from each other. Since the process of aircraft turnaround is modelled aggregately by the AAT model, it is not feasible for the AAT model to simulate the occurrence of operational disruptions as the MAT model does. From field observations of aircraft turnarounds, it is found that turnaround delays come mainly from longer turnaround service time and turnaround disruptions. The major contribution of the MAT model in this research when compared with CPM models and analytical models in the literature, is that the MAT model is able to simulate the stochastic and dynamic transition behaviour among ground service activities as well as to model the occurrence of service disruptions to aircraft turnarounds. The occurrence probability and duration of operational disruptions can be collected form historical flight punctuality data. These data can be analysed to produce the required Markovian transition matrices to implement the MAT model. Although the AAT model does not describe the turnaround process in a detail as the MAT does, its aggregate approach to model turnaround operations also shows promising performance as a planning and analysis tool for airlines and airport operators.

3.8 Concluding Remarks

Two models, the Analytical Aircraft Turnaround model (AAT model) and the Markovian Aircraft Turnaround model (MAT model), were developed in this chapter to model the influence of aircraft turnaround operations on schedule punctuality of turnaround aircraft. Simulation results have demonstrated the effectiveness of these two models in simulating turnaround operations of aircraft. Results from the AAT model showed that the proper use of schedule buffer time can help manage the punctuality performance of turnaround aircraft by minimising system costs. The influence of the arrival punctuality of inbound aircraft was found significant for the departure punctuality of turnaround aircraft. It was found that the arrival time distribution of a turnaround aircraft influences the optimal use of schedule buffer time. It is concluded accordingly that the scheduling of turnaround aircraft should consider the individual punctuality performance of each route and different schedule buffer time should be applied to different routes with different punctuality history. On the other hand, the schedule punctuality of a turnaround aircraft was found to be *endogenous* to reflect the turnaround efficiency as well as the amount of schedule buffer time designed for turnaround operations. Two case-study turnarounds in this chapter have demonstrated the relationship between the endogenous schedule punctuality and the observed punctuality.

The proposed Markovian Aircraft Turnaround model (MAT model) has been proved to be effective in modelling the stochastic and transitional behaviour between normal turnaround activities and service disruptions. Simulation results from case studies showed that the MAT model is able to evaluate the endogenous schedule punctuality of a turnaround aircraft as well as to analyse turnaround irregularities by considering stochastic factors involved in aircraft turnaround operations. A sensitivity analysis to the MAT model showed that the model is robust in simulating aircraft turnaround operations. The mean service time of turnaround activities and the occurrence of service disruptions to aircraft turnaround were two major factors which influence the departure punctuality of a turnaround aircraft. The shape of service time PDFs was found not significant for the MAT model outputs.

A further comparison between the AAT model and the MAT model showed that the superiority of the MAT model comes from its capability to model the stochastic characteristics of ground services and arrival punctuality of inbound aircraft. In addition, the MAT model has been successful in modelling the occurrence of operational disruptions, which have become the major source of operational uncertainties in airline operations at airports. Although the AAT model did not model the turnaround process as detail as the MAT model did, its aggregate approach to model turnaround operations also showed promising performance as a planning and analysis tool for airlines and airport operators. The feature of simulating operational disruptions makes the MAT model suitable for airlines to estimate the endogenous schedule punctuality of flight schedules by using historical operation data and then to optimise the operation of aircraft turnaround.

CHAPTER FOUR MODELLING OF AIRCRAFT ROTATION IN A NETWORK OF AIRPORTS

Delays in the air transport system seem to be inevitable, as there are many factors influencing the performance of flight schedules simultaneously. The direct consequences of delays in air transport are the loss of productivity of air carriers as well as the invisible loss of time and loyalty of passengers. The general approach to the issue of flight schedule punctuality in the past was to investigate the cumulative percentage of departure flights within a tolerance of delay, e.g. the "airline dependability statistics" defined by the Department of Transportation in the U.S. (Luo and Yu, 1997). This approach to the performance of flight schedules only measures the punctuality performance after the implementation of a flight schedule at a single airport. However, it is found that the schedule punctuality of an airline is influenced by the efficiency of aircraft turnarounds at an airport as well as the punctuality performance of inbound aircraft from out-station airports in the network of aircraft rotation (Wu and Caves, 2000).

Therefore, the objective of this chapter is to investigate the relationship between aircraft turnaround performance at an airport and schedule punctuality of aircraft rotation in a network of airports. The proposed Aircraft Rotation model (the AR model) is composed of two sub-models, namely the aircraft turnaround model and the enroute model. The MAT model proposed in Chapter 3 is employed to model the performance of aircraft turnaround at an airport. The enroute model is used to model the flight time of an aircraft between two airports by the convolution of probability density functions (PDFs) of the departure punctuality at the origin airport, the enroute flight time between two airports and the congestion in the terminal manoeuvring area of the destination airport.

This chapter begins in Section 4.1 by developing the aircraft rotation model. Applications of the aircraft rotation model are given in Section 4.2 to investigate the influence of airline scheduling strategies on the punctuality of aircraft rotation in a network of airports. System costs involved in aircraft rotations are formulated in Section 4.3. The optimisation of the use of schedule buffer time to minimise system cost is given in Section 4.4 by two approaches, namely the optimisation of a single leg and the optimisation of consecutive legs of aircraft rotations. Reliability measures of aircraft rotational schedules are developed in Section 4.5 which includes numerical analyses of two aircraft rotation examples. A sensitivity analysis is given in Section 4.6 to explain the sensitivity of the AR model optimisation to model parameters. Conclusions are drawn in Section 4.7.

4.1 Aircraft Rotation (AR) Model

4.1.1 Aircraft Rotation

A "*leg*" of aircraft rotation is defined to start from the "on-chock time" of an aircraft at the origin airport to the "on-chock time" of the same aircraft at the destination airport. The "*rotation*" of an aircraft is defined as the operational process of an aircraft assigned to fly from an origin airport to following airports until the end of the daily operation as illustrated in Figure 4.1. The rotation of this aircraft starts at airport **J** and the aircraft is turned around at airport **K** (the hub airport in this case) after a period of scheduled turnaround time. The complete rotation of this aircraft ends at airport **M**, at which the aircraft is held over night. If the aircraft is delayed at airport **K**, for instance, the departure delay might accumulate along the path of aircraft rotations, especially when the delay is sufficiently significant to perturb scheduled ground plans at following airports, i.e. airport **L**, **K** and **M**. The propagation of delays along the aircraft rotational path is called the "*Knock-on Delay*" of aircraft rotations.

Figure 4.1

4.1.2 Aircraft Rotation Model

The Aircraft Rotation model (denoted by the **AR Model** hereafter) proposed in this research, is composed of two portions: the Markovian Aircraft Turnaround Model (the **MAT Model**), which simulates uncertainties in aircraft turnaround operations on the ground and the **Enroute Model**, which models flight time uncertainties in the airspace. The development of the MAT model has been given previously in Section 3.4.

Regarding the development of the Enroute model, the inbound delay of an aircraft when arriving at airport **K** is influenced by the outbound delay at the origin airport **J** (the first leg of aircraft rotation in this case, which is illustrated in Figure 4.1), the enroute flight time in the airspace between airport **J** and **K**, and the arrival congestion at the destination airport **K**. The purpose of the proposed Enroute Model is to link aircraft punctuality performance between two airports. Hence, the inbound delay (denoted by ${}_K f_a(t)$) of an aircraft at airport **K** is modelled by the convolution of stochastic distributions, which include the departure punctuality at the origin airport **J** (denoted by ${}_J g_d(t)$), the enroute flight time between airport **J** and **K** (denoted by ${}_{JK} f^{ER}(t)$), and the arrival congestion at the destination airport **K** (denoted by ${}_K f^{TMA}(t)$). Hence, the probability density function of inbound delay of an aircraft at airport **K** is formulated by equation (4-1).

$$_{k}f_{a}(t)={}_{J}g_{d}(t)+{}_{JK}f^{ER}(t)+{}_{K}f^{TMA}(t)-T_{JK} \quad (4\text{-}1)$$

in which,

$T_{JK} = B_{JK} + \mu_{JK}^{ER}$

T_{JK} = block time of a flight between airport **J** and **K**

B_{JK} = airborne buffer time (if any)

μ_{JK}^{ER} = mean flight time of an aircraft between airport **J** and **K**

The objective of the AR model is to investigate the influence of aircraft rotational efficiency on schedule punctuality of aircraft rotations. Hence, the aircraft turnaround model simulates ***only*** uncertainties from turnaround operations of aircraft at airports and schedule punctuality, though other causes might also delay aircraft turnarounds. The enroute flight time of an aircraft is modelled aggregately by stochastic distributions to simulate uncertainties arising from air traffic control and airspace congestion instead of detailed modelling of aircraft operation in the airspace.

4.2 Schedule Punctuality of Aircraft Rotations

The simulation of aircraft rotations was implemented by computer programmes coded in *Fortran 90* and implemented on a *Sun* workstation. Numerical experiments were carried out to demonstrate the effectiveness of the AR model. The flight schedule (the original case, denoted by Case-O) used in numerical studies is shown in Table 4.1. Simulated flights start the rotation at airport **J** as shown in Figure 4.1, then go along the rotational path of airport **K**, **L**, **K** and terminate the rotation after arriving at airport **M**. The enroute flight time between two airports is simulated by *Normal* distributions with specified mean flight time and variance given in Table 4.1. The congestion at the destination airport is modelled by *Exponential* distributions with specified mean delay time. Stochastic *Monte Carlo simulation* techniques were applied in the aircraft rotation model to implement stochastic sampling from probabilistic functions. The simulation size was 1000 flights in order to limit simulation "noises" from stochastic samplings. Simulation samples from stochastic distributions are statistically tested to ensure the power of goodness of fit to original distributions.

Figure 4.1, Table 4.1

4.2.1 Propagation of Knock-On Delays

Four scenario studies were carried out to investigate the influence of turnaround performance on the development of knock-on delays in the network. Flight schedules of scenario studies are given in Table 4.1. Case-O simulates an intra-European aircraft rotational schedule of British Airways in a network consisting of four airports. Case-A models the scenario of having short turnaround time at the hub airport **K**, while Case-B models the case with long turnaround time at the hub airport. Case-C simulates the situation in which the aircraft is turned around by scheduling the same amount of turnaround time at each airport in the network. The development of knock-on delays in the study aircraft rotational network is shown in Figure 4.2 and 4.3.

Figure 4.2, Figure 4.3

It is seen in Figure 4.2 that the mean departure delay of the original schedule (Case-O) at the start of the rotation is 2.6 minutes at airport **J**. The mean departure delay propagates along the aircraft rotational path and reaches the maximum level of 5.6 minutes while departing from airport **K**. Consequently, the mean arrival punctuality, which is expressed by negative delay time in Figure 4.3, also deteriorates from –2.7 minutes of mean arrival "delay" at airport **K** to 0.6 minutes at the second visit to airport **K**.

On the other hand, it is also seen from Figure 4.2 and Figure 4.3 that when different turnaround time is scheduled at airport **K** (the hub airport in this case), the development of knock-on delays differs from the original case. It is shown in Figure 4.2 and 4.3 that when short turnaround time (Case-A) is scheduled at the hub airport, the propagation of knock-on delays becomes significant. A tight turnaround schedule at the hub airport increases the utilisation of aircraft in the network by reducing flight connection time and meanwhile reducing the connection time of transfer passengers. However, a tight turnaround schedule at the hub airport makes aircraft rotational performance too "sensitive" to control, especially when significant delays occur in the network and perturb aircraft rotations.

When compared with the scheduling policy of short turnaround time at airport **K**, it is seen in Figure 4.2 and Figure 4.3 that the long-turnaround-time policy (Case-B) "stabilises" the punctuality of aircraft rotations. When the long-turnaround-time case is compared with the original one, it is found that mean departure delays at aircraft rotational stops decrease as well as the arrival punctuality at destination airports is improved.

A case for comparison purposes, in which aircraft are turned around by scheduling the same amount of turnaround time at each rotational stop (Case-C), shows that the punctuality performance of rotations is in between the case of long turnaround time at K and the case of different turnaround time, i.e. the original case. The implication of this observation is that if the turnaround performance at each airport does not vary significantly, scheduling the same amount of turnaround buffer time at each airport stabilises the propagation of knock-on delays in the network. However, scheduling aircraft rotations in this way might reduce the utilisation of aircraft, because aircraft turnaround performance varies among airports according to a recent research by the author (Wu and Caves, 2000).

As far as the effectiveness of turnaround buffer time at the hub airport is concerned, it is found in Figure 4.2 and Figure 4.3 that the scheduling of long turnaround time at the hub airport stabilises the propagation of knock-on delays when compared with the case of scheduling short turnaround time at the hub. However, the problem encountered by airlines becomes the trade-offs between aircraft rotational performance (the propagation of knock-on delay) and aircraft utilisation (the length of turnaround time at airports).

4.2.2 Scheduling Long Buffer Time in Aircraft Rotation

It is generally realised by airlines that the stability of aircraft rotation can be controlled by placing a long period of time, which is usually called "fire-breaks", somewhere in the aircraft rotational path. Hence, three scenario studies were carried out to investigate the performance of placing fire-breaks in the network. Flight schedules of Case-D, E and F are given in Table 4.1. The fire-break is scheduled at the hub airport **K** in Case-D by placing 35 minutes of turnaround buffer time. The fire-break is placed at the spoke airport **L** in Case-E. A comparison case, Case-F, shows the same flight schedule as the original Case-O without any turnaround buffer time at airports. Simulation results are illustrated in Figure 4.4 and Figure 4.5.

Figure 4.4, Figure 4.5

It is observed in Figure 4.4 and 4.5 that the development of knock-on delay in the network becomes significant when there is no turnaround buffer time scheduled in aircraft rotation (shown by the "No Buffer" case, Case-F). By the end of the rotational schedule of the study aircraft, the average inbound delay at airport **M** increases to the level of 15.3 minutes. The propagation of knock-on delays in Case-F is still slightly absorbed by the airborne buffer time (10-minute airborne buffer time in the study network) in block hours between airports. Otherwise, the development of knock-on delays in Case-F would be more significant than the current result.

When the long buffer time (35 minutes) is scheduled at airport **K** (Case-D), it is seen in Figure 4.4 and 4.5 that the overall punctuality performance of aircraft rotation is better controlled than in the original schedule (Case-O). In addition, the average outbound delay time at each rotational stop is maintained within the level of 4 minutes in this case. So is the inbound punctuality improved in this scenario. When the long buffer time (35 minutes) is scheduled at airport **L**, which is a spoke airport in the network, it is found from Figure 4.4 and 4.5 that the rotational punctuality at airports on the rotational path after airport **L** is improved. In other words, the scheduling of the long break time in aircraft rotational schedules stabilises the punctuality performance of aircraft rotation at those airports which are scheduled to be visited after the "fire-break" stop in the network.

4.2.3 Scheduling Strategies of Hubbing Aircraft

A comparison between the case of scheduling long turnaround time (65 minutes in Case-B) at airport **K** and the case of scheduling long schedule buffer time (35 minutes buffer, i.e. 80 minutes turnaround time in Case-D) at airport **K** is shown in Figure 4.6 and Figure 4.7. It is found that the longer the scheduled turnaround time is, the better the knock-on delay is controlled at each stop in the network.

Figure 4.6, Figure 4.7

For airlines tending to use intensive hubbing schedules, it is found in this case study that a short turnaround time at the hub airport (Case-A) causes a higher risk of having knock-on delays during an operational day. On the other hand, if the policy of adopting long turnaround time at the hub airport is used (Case-B), it is found to be effective in stabilising the propagation of knock-on delays in the network. This demonstrates that the aircraft rotation model can be applied to simulate different scheduling strategies of aircraft rotation in a hubbing network.

The flight schedule of Case-G (given in Table 4.1) allows short turnaround time at spoke airports, i.e. airport **J**, **L** and **M**, while Case-I schedules short turnaround time at spoke airports as well as long turnaround time at the hub airport **K**. The simulation results of these two cases are compared with the one from the original schedule (Case-O) as illustrated in Figure 4.8. It is seen in Figure 4.8 that scheduling short turnaround time (55 minutes, in Case-G) at spoke airports in a network increases both departure and arrival delays in aircraft rotations, due to knock-on delay effects. However, it is found that when a long turnaround time (65 minutes, in Case-I) is scheduled at the hub airport, the development of knock-on delays in Case-I is controlled much better than Case-G. As a consequence, if the scheduling policy of an airline is to schedule short turnaround time at spoke airports, a long turnaround time at the hub airport will be needed to absorb operational uncertainties from aircraft rotations in a network.

Figure 4.8

However, an airline might want to maintain the minimum level of aircraft turnaround time at its hub airport, in contrast to previous cases. Hence, Case-H is set to simulate the aircraft rotational schedule with long turnaround time at spoke airports, while Case-J includes long turnaround time at spoke airports and short turnaround time at the hub airport (as shown in Table 4.1). It is found from simulation results in Figure 4.9 that the policy of scheduling long turnaround time at spoke airports

(Case-H) maintains better punctuality performance than the original schedule. When compared with Case-H, simulation results of Case-J show that the inclusion of short turnaround time at the hub airport increases the risk of having higher knock-on delays in aircraft rotation, though a portion of delays is still absorbed by long buffer time at spoke airports.

Figure 4.9

Case-I and Case-J are compared to reveal more about the influence of scheduling strategies of hubbing aircraft on aircraft rotational performance. It is found in Figure 4.10 that the long turnaround time at spoke airports in Case-J reduces the generation of departure delays into the rotation system, though most of the delays are contributed by the hub airport due to a short-turnaround-time policy. On the other hand, it is seen in Figure 4.10 that although short turnaround time at spoke airports causes a higher level of departure delay, the long turnaround time scheduled at the hub airport absorbs most punctuality uncertainties from spoke airports. Regarding the arrival punctuality in both cases, it is observed clearly the inter-link between the departure punctuality at up-stream airports and the arrival punctuality at following airports as shown in Figure 4.11.

Figure 4.10, Figure 4.11

4.2.4 Discussions

Although the knock-on delay accumulated in aircraft rotation may be absorbed naturally when the rotation of the aircraft comes to an end at the last rotational stop, the influence of scheduling turnaround buffer time on the punctuality of aircraft rotation is found to be significant from simulation results in previous sections. Therefore, it is concluded that the proper scheduling of turnaround buffer time in aircraft rotation helps control the development of knock-on delays in the network.

As far as the scheduling of hubbing aircraft is concerned, it is found that scheduling sufficient buffer time in aircraft rotational schedules stabilises the punctuality performance of aircraft rotations. The inclusion of buffer time, either at spoke airports or at the hub airport, reduces the risk of having severe knock-on delays, when compared with the case without proper inclusion of buffer time in aircraft rotation. However, two questions remain. One is, where is the optimum location to schedule long turnaround time or a long "fire-break" time in a network? The other is, the achievement of aircraft rotational punctuality at the expense of too great a loss in aircraft utilisation due to the use of excessive flight time for buffering.

Hence, the AR model will be optimised in following sections in Chapter 4 to investigate the significance of the optimisation of aircraft rotational schedules on minimising operational costs due to delays. Costs due to delays of aircraft rotation are modelled mathematically. The AR model, then is optimised to minimise system costs by scheduling optimal buffer time in aircraft rotational schedules.

4.3 Formulation of System Costs in Aircraft Rotation

Symbols and notations used in the formulation of system costs are summarised as below. In order to simplify the formulation of system costs in aircraft rotation, two legs (Flight *i* and Flight *j*) of aircraft rotations are considered from a network of airports as shown in Figure 4.12.

Figure 4.12

B_A	scheduled buffer time of Flight *i* at airport **A**
B_B	scheduled buffer time of Flight *i* at airport **B**
B_{AB}	scheduled buffer time of Flight *i* enroute airport **A** and **B**
${}_G C_A$	unit ground delay cost of an aircraft
${}_A C_A$	unit airborne delay cost of an aircraft
${}_A C_T^i$	total operational costs of Flight *i* departing from airport **A** to airport **B**
C_{AL}^A	opportunity cost of ground schedule buffer time at airport **A**
${}_d C_D^A$	expected departure delay costs of a turnaround aircraft at airport **A**
C_{AL}^{AB}	opportunity cost of airborne schedule buffer time between airport **A** and **B**
${}_a C_D^B$	expected arrival delay costs of Flight *i* when arriving at airport **B**
${}_d C_{DP}^A$	expected departure delay costs of passengers on-board Flight *i*
${}_d C_{DA}^A$	expected departure delay costs of Flight *i*
${}_B f_a^i(t)$	arrival probability density function (PDF) of Flight *i* arriving airport **B**
${}_A g_d^i(t)$	departure probability density function (PDF) of Flight *i* departing airport **A**
$h(t)$	time value of an air passenger as a function of delay time
$k(t)$	schedule time opportunity cost of an airline as a function of schedule buffer time

Operational costs (${}_A C_T^i$) incurred by Flight *i* (shown in Figure 4.13) include the ground schedule buffer time opportunity cost at airport **A** (C_{AL}^A), the expected departure delay cost of passengers and aircraft at airport **A** (${}_d C_D^A$), the airborne schedule buffer time opportunity cost in the block time between airport **A** and **B** (C_{AL}^{AB}), and the expected arrival delay cost of passengers and aircraft at airport **B** (${}_{a}C_{D}^{B}$). Hence, the total operational cost of Flight i can be formulated by equation (4-2).

Figure 4.13

$$ {}_{A}C_{T}^{i} = ({}_{d}C_{D}^{A} + C_{AL}^{A}) + ({}_{a}C_{D}^{B} + C_{AL}^{AB}) \tag{4-2}$$

Aircraft departure delays at the origin airport incur delay costs to air passengers and airlines. The departure delay cost of a delayed aircraft (${}_{d}C_{D}^{A}$) is therefore, composed of the delay cost of on-board passengers (${}_{d}C_{DP}^{A}$) and the delay cost of the aircraft (${}_{d}C_{DA}^{A}$). The departure delay cost is modelled by equation (4-3).

$$ {}_{d}C_{D}^{A} = {}_{d}C_{DP}^{A} + {}_{d}C_{DA}^{A} \tag{4-3}$$

It is generally realised that there would be a higher risk for passengers to miss connection flights at the destination airport when the delay time of an aircraft is getting longer. Hence, it is assumed in this model that the time value of a passenger can be formulated by a *quadratic* function ($h(t)$) to simulate the reception of delays of passengers as well as the loss of time value of passengers. Hence, the expected delay cost of on-board passengers (${}_{d}C_{DP}^{A}$) can be formulated by equation (4-4).

$$ {}_{d}C_{DP}^{A} = \mathrm{E}[h(t)] = \int_{0}^{\infty} h(t)\, {}_{A}g_{d}^{i}(t)dt = \int_{0}^{\infty} (C_{P}^{u}t + C_{P}^{m}\frac{t^{2}}{2})\, {}_{A}g_{d}^{i}(t)dt \tag{4-4}$$

in which, $h(t) = C_{P}^{u}t + C_{P}^{m}\dfrac{t^{2}}{2}$

Equation (4-4) can be rewritten as equation (4-5) by substituting $h(t)$ into equation (4-4).

$$ {}_{d}C_{DP}^{A} = \mathrm{E}[h(t)] = \int_{0}^{\infty} (C_{P}^{u}t + C_{P}^{m}\frac{t^{2}}{2})\, {}_{A}g_{d}^{i}(t)dt = C_{P}^{u}\mu_{g} + \frac{C_{P}^{m}}{2}(\mu_{g}^{2} + \sigma_{g}^{2}) \tag{4-5}$$

in which $\mu_{g} = \mathrm{E}[t] = \int_{0}^{\infty} t\, {}_{A}g_{d}^{i}(t)dt$

$$\sigma_{g}^{2} = \mathrm{E}[(t-\mu_{g})^{2}] = \int_{0}^{\infty} (t-\mu_{g})^{2}\, {}_{A}g_{d}^{i}(t)dt$$

The expected delay cost of an aircraft (${}_{d}C_{DA}^{A}$) is formulated by a linear cost function as shown in equation (4-6).

$$_{d}C_{DA}^{A} = \mathrm{E}[C_{A}t] = _{G}C_{A}\mu_{g} \tag{4-6}$$

Hence, the total expected departure delay cost of Flight i at airport **A** can be re-written by equation (4-7).

$$_{d}C_{D}^{A} = _{d}C_{DP}^{A} + _{d}C_{DA}^{A} = C_{P}^{u}\mu_{g} + \frac{C_{P}^{m}}{2}(\mu_{g}^{2} + \sigma_{g}^{2}) + _{G}C_{A}\mu_{g} \tag{4-7}$$

Similarly, the expected arrival delay cost of Flight i at airport **B** is expressed by equation (4-8).

$$_{a}C_{D}^{B} = _{a}C_{DP}^{B} + _{a}C_{DA}^{B} = C_{P}^{u}\mu_{f} + \frac{C_{P}^{m}}{2}(\mu_{f}^{2} + \sigma_{f}^{2}) + _{A}C_{A}\mu_{f} \tag{4-8}$$

in which $\mu_{f} = \mathrm{E}[t] = \int_{0}^{\infty} t\, _{B}f_{a}^{i}(t)dt$

$$\sigma_{f}^{2} = \mathrm{E}[(t-\mu_{f})^{2}] = \int_{0}^{\infty}(t-\mu_{f})^{2}\, _{B}f_{a}^{i}(t)dt$$

The scheduling of buffer time in aircraft rotational schedules (if any) maintains schedule punctuality, though it reduces the utilisation of aircraft. Hence, the opportunity cost of scheduling buffer time (B_{A}) in the turnaround time of Flight i at airport **A** is formulated by a quadratic function ($k(t)$) to account for the increasing value of the schedule time opportunity cost. The cost of scheduling buffer time in the turnaround time at airport **A** is formulated by equation (4-9). The cost of scheduling airborne buffer time (B_{AB}) in the block time of Flight i between airport **A** and **B** is modelled by equation (4-10).

$$C_{AL}^{A} = k(B_{A}) = _{A}C_{AL}^{u}B_{A} + \frac{_{A}C_{AL}^{m}}{2}B_{A}^{2} \tag{4-9}$$

in which, $k(t) = _{A}C_{AL}^{u}t + \frac{_{A}C_{AL}^{m}}{2}t^{2}$

$$C_{AL}^{AB} = k(B_{AB}) = _{AB}C_{AL}^{u}B_{AB} + \frac{_{AB}C_{AL}^{m}}{2}B_{AB}^{2} \tag{4-10}$$

Similarly, the operational costs incurred by Flight j ($_{B}C_{T}^{j}$) is formulated by the sum of the ground schedule buffer time opportunity cost at airport **B** (C_{AL}^{B}), the expected departure delay cost of passengers and aircraft at airport **B** ($_{d}C_{D}^{B}$), the airborne schedule buffer time opportunity cost between airport **A** and **B** (C_{AL}^{AB}), and the arrival delay cost of passengers and aircraft at airport **A** ($_{a}C_{D}^{A}$), as shown by equation (4-11).

$${}_{B}C_{T}^{j} = ({}_{d}C_{D}^{B} + C_{AL}^{B}) + ({}_{a}C_{D}^{A} + C_{AL}^{AB}) \tag{4-11}$$

Therefore, the system cost of all flights between airport **A** and **B** can be expressed by equation (4-12). Weight factors in equation (4-12), α^{A} and β^{A}, are used to simulate the trade-off situation between the use of schedule buffer time for departure punctuality and delay costs due to flight delays. It is realised that the inclusion of schedule buffer time in aircraft rotational schedules can improve the departure and arrival punctuality at the origin airport as well as at the destination airport. However, the inclusion of schedule buffer time in flight schedules reduces the utilisation of aircraft and meanwhile, causes the increase of airline operational costs, i.e. the invisible opportunity cost of schedule buffer time. Therefore, weight factors are employed to model the trade-off situation between schedule punctuality and operational costs in this model.

The objective of this model is to minimise total system costs (C_T) by optimising aircraft rotational schedules, i.e. the use of schedule buffer time at airport **A** (B_A), at airport **B** (B_B), and in the block time between airports (B_{AB}).

$$C_T = \Pi_{AB} = \sum_{i,j} ({}_{A}C_{T}^{i} + {}_{B}C_{T}^{j}) \qquad \forall i, j \in \Pi_{AB} \tag{4-12}$$

in which,

$${}_{A}C_{T}^{i} = (\alpha^{A}\,{}_{d}C_{D}^{A} + \beta^{A}C_{AL}^{A}) + (\alpha^{AB}\,{}_{a}C_{D}^{B} + \beta^{AB}C_{AL}^{AB})$$

$${}_{B}C_{T}^{j} = (\alpha^{B}\,{}_{d}C_{D}^{B} + \beta^{B}C_{AL}^{B}) + (\alpha^{AB}\,{}_{a}C_{D}^{A} + \beta^{AB}C_{AL}^{AB})$$

$$\alpha^{A} + \beta^{A} = 1$$

$$\alpha^{B} + \beta^{B} = 1$$

$$\alpha^{AB} + \beta^{AB} = 1$$

$${}_{d}C_{D}^{A} = {}_{d}C_{DP}^{A} + {}_{d}C_{DA}^{A} = C_{P}^{u}\mu_{g} + \frac{C_{P}^{m}}{2}(\mu_{g}^{2} + \sigma_{g}^{2}) + {}_{G}C_{A}\mu_{g}$$

in which $\quad \mu_{g} = \mathrm{E}[t] = \int_{0}^{\infty} t\,{}_{A}g_{d}^{i}(t)dt$

$$\sigma_{g}^{2} = \mathrm{E}[(t-\mu_{g})^{2}] = \int_{0}^{\infty} (t-\mu_{g})^{2}\,{}_{A}g_{d}^{i}(t)dt$$

$${}_{a}C_{D}^{B} = {}_{a}C_{DP}^{B} + {}_{a}C_{DA}^{B} = C_{P}^{u}\mu_{f} + \frac{C_{P}^{m}}{2}(\mu_{f}^{2} + \sigma_{f}^{2}) + {}_{A}C_{A}\mu_{f}$$

in which $\quad \mu_{f} = \mathrm{E}[t] = \int_{0}^{\infty} t\,{}_{B}f_{a}^{i}(t)dt$

$$\sigma_f^2 = E[(t-\mu_f)^2] = \int_0^{\infty} (t-\mu_f)^2 \, {}_B f_a^i(t)dt$$

$$C_{AL}^{AB} = k(B_{AB}) = {}_{AB}C_{AL}^u B_{AB} + \frac{{}_{AB}C_{AL}^m}{2} B_{AB}^2$$

$$C_{AL}^A = k(B_A) = {}_A C_{AL}^u B_A + \frac{{}_A C_{AL}^m}{2} B_A^2$$

$$C_{AL}^B = k(B_B) = {}_B C_{AL}^u B_B + \frac{{}_B C_{AL}^m}{2} B_B^2$$

4.4 Optimisaiton of Aircraft Rotation Model

The optimal schedule buffer time B_A^*, B_B^*, and B_{AB}^*, which is scheduled in the turnaround time at airport **A**, airport **B** and enroute airport **A** and **B** respectively, can be solved by setting partial derivatives of the objective function (equation (4-12)) as zero against three decision variables as shown by equation (4-13).

$$\frac{\partial C_T}{\partial B_A} = 0 \qquad \text{to get } B_A^* \qquad (4\text{-}13)$$

$$\frac{\partial C_T}{\partial B_B} = 0 \qquad \text{to get } B_B^*$$

$$\frac{\partial C_T}{\partial B_{AB}} = 0 \qquad \text{to get } B_{AB}^*$$

The expected departure delay cost (${}_d C_D^A$) of Flight i at airport **A** in equation (4-7) is a function of the mean and variance of the PDF of departure delay (${}_A g_d^i(t)$). The departure delay PDF (${}_A g_d^i(t)$) is influenced by the inbound punctuality of Flight j (${}_A f_a(t)$), the turnaround performance at airport **A** (${}_A f_{TR}^i(t)$) and the amount of scheduled turnaround time (T_{SG}) at airport **A**, which includes the mean turnaround service time (T_G) and the ground buffer time (B_A). Hence, the expected departure delay cost (${}_d C_D^A$) is a function of schedule buffer time (B_A). So is the schedule time cost (C_{AL}^A) a function of schedule buffer time (B_A). Then, equation (4-13) can be rewritten as equation (4-14).

$$\frac{\partial C_T}{\partial B_A} = \partial\left(\sum_i \alpha^A {}_d C_D^A + \beta^A C_{AL}^A\right) / \partial B_A = 0 \qquad \text{to get } B_A^* \qquad (4\text{-}14)$$

$$\frac{\partial C_T}{\partial \mathrm{B}_B} = \partial(\sum_j \alpha^B{}_d C_D^B + \beta^B C_{AL}^B)/\partial \mathrm{B}_B = 0 \qquad \text{to get } \mathrm{B}_B^*$$

$$\frac{\partial C_T}{\partial \mathrm{B}_{AB}} = \partial[\sum_{i,j} (\alpha^A{}_a C_D^B + \beta^A C_{AL}^{AB}) + (\alpha^B{}_a C_D^A + \beta^B C_{AL}^{AB})]/\partial \mathrm{B}_{AB} = 0 \qquad \text{to get } \mathrm{B}_{AB}^*$$

Since it is mathematically difficult to get a closed form solution to equation (4-14), the minimisation problem formulated by equation (4-12) was solved by numerical analyses. Stochastic simulation techniques were employed to simulate the turnaround time of an aircraft by sampling from chosen PDFs (Wu and Caves, 2000). Monte Carlo simulation techniques were used in programming numerical analyses to carry out the task of stochastic sampling from PDFs. Simulation programmes were coded in *Fortran 90* and implemented on a *Sun* workstation in a *Unix* environment. The size of simulation was 1,000 rotations of an aircraft in a network of four airports as shown in Figure 4.1. The original aircraft rotational schedule is given in Table 4.2. The operation of the study rotation starts at airport **J** and ends at airport **M** by the end of an operational day. The rotation schedule was obtained from British Airways to model a typical aircraft rotational path of a European short-haul flight. The base airport of the study network in this case is airport **K** which represents London Heathrow Airport.

Table 4.2

Decision variables in the objective function (equation (4-12)) are the amount of schedule buffer time scheduled in the aircraft rotation schedule, i.e. B_A, B_B, and B_{AB}. It is of interest in this research how the trade-off situation develops in a leg of aircraft rotations between the ground buffer time at an airport, e.g. B_A, and the airborne buffer time between two airports, e.g. B_{AB}. Also of interest is the influence of the trade-off of schedule buffer time between two airports, e.g. B_A and B_B, on the optimisation of aircraft rotation. Therefore, the numerical analyses were carried out from two aspects. One is to optimise the scheduling of a single leg. The other is to optimise two consecutive legs of aircraft rotation, i.e. fixing the enroute flight time of two legs of rotation to solve the optimal buffer time at two subject airports, e.g. fixing B_{AB} to solve B_A^* at airport **A** and B_B^* at airport **B**.

The value of the unit delay cost of a passenger (C_P^m in equation (4-12)) used in numerical analyses is \$0.03/min^2, which is equivalent to a delay cost of \$54 per hour, per passenger (Wu and Caves, 2000). The value of the unit delay cost of an aircraft (${}_G C_A$ in equation (4-12)) is \$45/min for ground delays, which is equivalent to a delay cost of \$2,700 per hour, per aircraft (a B757). The delay cost of an aircraft in the air is \$65 per minute. The opportunity cost of schedule buffer time (${}_A C_{AL}^m$ in equation (4-12)) is \$2.5/min^2, which is equivalent to \$4,500 per hour for a European short-haul route. Equal weights in the objective function (equation (4-12)), i.e. $\alpha^A = \beta^A = 0.5$, on the delay cost of passengers and the airline schedule time cost are used in the following numerical analyses.

4.4.1 Optimisation of a Single Leg

The optimisation of Leg_JK (from airport **J** to **K**) is shown in Figure 4.14. The minimum system cost occurs when the scheduled turnaround time at airport **J** is 57 minutes (12 minutes of buffer) and the scheduled airborne time between airport J and **K** is 60 minutes (10 minutes of buffer). It is found in Figure 4.14 that the increase of ground time at airport **J** trades off the increase of airborne time between two airports and therefore, there exists the system minimum. In order to show the trade-off situation in detail, the cross section of the system cost surface in Figure 4.14 is shown in Figure 4.15 by cutting the cost surface at 60-minute airborne time. The trade-off situation between the increase of scheduled ground time and the change of system costs is clearly observed by the cross-section profile in Figure 4.15. The optimisation of aircraft rotational schedules of Leg_KL, Leg_LK and Leg_KM is shown in Figure 4.16, 4.17 and 4.18 respectively. Trade-off situations are observed in these cases as well.

Figure 4.14, Figure 4.15, Figure 4.16, Figure 4.17, Figure 4.18

When the punctuality of the optimal schedule is compared with the original schedule, it is observed from Figure 4.19 that both the arrival and departure punctuality performance of the schedule after single-leg optimisation are improved. The improvement in schedule punctuality also results in the decrease of total system costs from $2,246,994 in the original schedule to $2,071,912 in the "single-leg optimisation" case as shown in Table 4.3. It is found from Figure 4.19 that the original schedule is close to the optimal case, according to results of simulations shown in Table 4.3.

Figure 4.19, Table 4.3

4.4.2 Optimisation of Consecutive Legs (Optimisation of Trade-offs at Two Airports)

The optimisation of a single rotational leg has been demonstrated in the previous section. However, the optimisation might be required when an airline faces the trade-off of turnaround time between two airports. There might be different marketing considerations at these airports for an airline, or simply the airline operates a hubbing schedule and adopts a short-connection-time policy at its base airport. Hence, the trade-off situation becomes trading off the turnaround buffer time at two airports, i.e. the optimisation of two legs of aircraft rotations. The optimisation of trade-offs of aircraft turnaround time at two airports was carried out by fixing the block time between two airports. Ten minutes of airborne buffer time were included in the block time of the studied rotation, in order to simulate the delay absorption effects of airborne buffer time. The studied rotation network was segmented into two portions. Leg_JKL was chosen to trade off aircraft turnaround time between airport **J** and **K**. Leg_LKM was chosen to trade off aircraft turnaround time between airport **L** and **K**. The same parameters as those in the previous section were used in the optimisation of Leg_JKL and Leg_LKM. Simulation results of Leg_JKL and Leg_LKM are shown in Figure 4.20 and Figure 4.21.

Figure 4.20, Figure 4.21

The optimisation of Leg_JKL suggests that the optimal aircraft turnaround time at airport **J** is 60 minutes and the optimal time at airport **K** is 60 minutes as well. It is seen from Figure 4.20 that when the turnaround time at airport J is short, the total delay cost of Leg_JKL increases significantly because the up-stream delay at airport **J** escalates along the rotational path into airport **K** and **L**. Hence, the system cost surface has its minimum when the turnaround time at airport **J** is higher. This observation supports the argument set previously in this chapter that the optimisation of aircraft rotational schedules would be able to minimise system costs. A similar observation is also found in the optimisation of Leg_LKM (shown in Figure 4.21), which results in 64-minute optimal aircraft turnaround time at airport **L** and 62 minutes at airport **K**.

When the optimisation results of consecutive legs are compared with the original schedule (shown in Table 4.3), it is found that the optimisation of trade-offs of turnaround time at two airports causes the increase of turnaround time at spoke airports (in this case, it means airport **J**, **L** and **M**). Meanwhile, the total system cost in this case is found to be higher than the one of the optimal schedule because the airborne block time in the current optimisation case is fixed and not optimised in this case. When the schedule punctuality of the current case is compared with the one of the original schedule and the optimal schedule, it is observed from Figure 4.19 that the aircraft rotation punctuality performance after consecutive-leg optimisation is in between the punctuality performance of the original schedule and the optimum schedule.

4.4.3 Discussions

The trade-off situation between the punctuality of aircraft rotation and the inclusion of schedule buffer time in aircraft rotational schedule has been demonstrated in this section. It is found that when schedule buffer time is optimally designed in aircraft rotational schedules, the system can achieve the optimum by minimising system costs. It is also found that each leg in an aircraft rotational network should be optimised individually to achieve the system optimum by considering the stochastic punctuality of inbound aircraft as well as the turnaround efficiency at each airport.

When the system cost is minimised, it is found in Figure 4.19 that the departure and arrival punctuality varies among airports. The departure punctuality at the study airports varies between 65% and 80% in the optimal schedule after single leg optimisation, and the arrival punctuality varies between 65% and 75%. The current simulation of aircraft rotational punctuality is the result of placing equal emphasis on delay costs and airline schedule time cost in the objective function (equation (4-12)). If the emphasis in the objective function is put on delay costs, we shall be expecting better punctuality in aircraft rotations, since more schedule buffer time will be needed to minimise system costs.

4.5 Feasibility and Reliability of Aircraft Rotation Schedules

4.5.1 Reliability Measures of Aircraft Rotational Schedules

The reliability of a schedule is usually used to represent the adherence to a planned schedule, i.e. a schedule with pre-planned timetables. The issue of schedule reliability has been widely discussed in the literature of manufacturing and transport studies (Adamski and Turnau, 1998; Leon *et al*, 1994). The robustness of scheduling job shops in a manufacturing factory was studied by Leon *et al* (1994). The objective of the research was to investigate the performance of a planned job shop schedule in the presence of disruptions. The measures of schedule reliability considered in Leon's work included the weighted measure of mean service time and mean delay time, the expected delay of a schedule, the operational efficiency of manufacturers as well as the average slack time (buffer time) in a planned schedule. It was concluded that the expected delay is superior to the other as a measure for indicating reliability, though it usually takes time to calculate the measure through model simulations. Without time-consuming schedule simulations, the average slack time of a schedule was found to be a good surrogate to schedule robustness (Leon *et al*, 1994).

The reliability of train schedules has been widely investigated in the literature because of the significance of knock-on delays in train schedules. The risk of train delay for arrival/departure was proposed as a surrogate to measure the reliability of train schedules (Carey, 1994; 1998; 1999; Ferreira and Higgins, 1996; Higgins *et al*, 1995). The expected delay of a train was also used to measure the schedule adherence in the literature because the measure accounts for both the delay time and the probability of delay (Carey, 1994; 1998; 1999; Carey and Kwiecinski, 1995; Ferreira and Higgins, 1996; Hallowell and Harker, 1998; Higgins *et al*, 1995). Descriptive statistics of a train schedule, e.g. the standard deviation (SD) and the variance (VAR) of schedule delay, were also proposed in the literature as alternative measures to schedule reliability because these statistics account for the variability in the implementation of a planned timetable (Carey, 1994; Hallowell and Harker, 1996). The concept of the aggregate schedule reliability was developed by Carey (1999) who tried to model the reliability of a train trip as a whole instead of modelling the schedule reliability of a train at a station. The aggregate reliability measure was modelled by calculating the mean probability that a train does not suffer knock-on delays.

It is found in the literature that the reliability measures of a planned timetable include the probability of delays, the expected delay of a schedule as well as descriptive statistics of the on-time performance of a timetable, e.g. SD and VAR. Although *ex ante* heuristic measures of schedule reliability have been discussed in the literature, the premises to calculate these reliability measures include the choice of suitable simulation models and plenty of historical schedule performance data recorded by the operator of the schedule (Carey, 1999). The usefulness of the schedule reliability measures is not only to provide schedule operators with estimated schedule performance figures before the implementation of a schedule but more importantly to help design reliable and robust schedules at the early planning stage. Therefore, it is of interest in this research to develop reliability measures of aircraft rotational schedules in order to achieve two goals. One is to find the optimum schedule in which "exogenous disruptions" cause the least knock-on delays. The other is to develop suitable schedule reliability surrogates to aircraft rotations with respect to the characteristics of aircraft rotations. Following the practice found in the literature, four reliability surrogates to aircraft rotations are proposed in this research including the mean delay of aircraft rotations, the standard deviation of aircraft arrival/departure time, the expected delay of aircraft rotations, and the regularity of aircraft rotation schedules.

4.5.1.1 Mean delay of aircraft rotations

The mean delay time (denoted by μ^D) of a schedule is the most commonly used measure of the reliability of a timetable because the measure is easy to understand and easy to produce from recorded punctuality data. The mean delay of a schedule can be calculated by statistic methods after the implementation of a schedule according to managerial requirements. There are two measures of mean delay to aircraft rotations, namely the mean arrival delay (denoted by μ_a^D) and the mean departure delay (denoted by μ_d^D). However, the mean delay of a leg of aircraft rotation (denoted by μ_{LEG}^D and shown in equation (4-15)) is proposed as the reliability measure of aircraft rotations for two reasons. First of all, the mean delay of a leg is easy to calculate and use from schedule punctuality data. Secondly, in some cases, the departure delay of an aircraft could be absorbed and the aircraft still arrives punctually or within minor arrival delay at the destination airport, if ample airborne time is designed in the schedule. Hence, the measure of mean delay of a leg is used to reflect the departure punctuality, the delay absorption effects of airborne time and the arrival punctuality of an aircraft.

$$\mu_{LEG}^D = \mu_a^D + \mu_d^D \qquad (4\text{-}15)$$

4.5.1.2 Standard deviation of aircraft arrival/departure time

The standard deviation of aircraft arrival/departure time (denoted by SD_a for arrival time and SD_d for departure time in this research) is defined as the deviation of an observation from its mean, i.e. the mean delay of all observations (Walpole and Myers, 1990). Although the mean delay of a schedule has been used as a surrogate to measure the reliability of a flight schedule, the scattering of actual arrival/departure time to the planned timetable is not sufficiently reflected solely by the surrogate of the mean delay. Hence, the standard deviation of aircraft arrival/departure time is proposed to be a supportive surrogate to the reliability measure of mean delay.

4.5.1.3 Expected delay of aircraft rotations

The expected arrival delay of an aircraft (denoted by $E[D]_a$) is defined as the mathematical expectation of delay of an aircraft and can be expressed by equation (4-16) (Walpole and Myers, 1990). The expected departure delay of an aircraft (denoted by $E[D]_d$) is formulated by equation (4-17).

$$\mathrm{E}[D]_a = \int t f_a(t)dt \tag{4-16}$$

where $f_a(t)$ is the probability density function (PDF) of inbound aircraft

$$\mathrm{E}[D]_d = \int t f_d(t)dt \tag{4-17}$$

where $f_d(t)$ is the probability density function (PDF) of outbound aircraft

The accumulated expected delay of a leg is therefore, defined as the accumulation of expected departure delay and arrival delay (denoted by $E[D]_{LEG}$) of a leg, as shown in equation (4-18). The advantage of this reliability measure, when compared with the measure of mean delay, is the inclusion of event occurrence probability in the calculation of the expected delay. Hence, the expected delay of an aircraft represents the effects of both the delay duration as well as the occurrence probability of the delay.

$$\mathrm{E}[D]_{LEG} = \mathrm{E}[D]_a + \mathrm{E}[D]_d \tag{4-18}$$

4.5.1.4 Regularity of aircraft rotation schedules

The *regularity* of a flight schedule (denoted by R_{REG}) is defined in this research as the percentage (likelihood) of the successful implementation of a pre-planned flight schedule, e.g. the rotational schedule of an aircraft. Hence, the regularity of a schedule also indicates the operational feasibility of the schedule (Chinn, 1996; Leon *et al*, 1994). When disruptions happen to the rotation of an aircraft and are likely to result in serious delays, the airline has to make decisions on two questions: is the disruption going to influence the rest of the rotation? and is it necessary to cancel flights to stop the escalation of knock-on delays? If the link between legs of aircraft rotation is broken, it brings the irregularity to the flight schedule. The implication of the schedule irregularity is that the schedule needs to be changed due to high possibility of severe knock-on effects in the schedule and the knock-on effects can not be absorbed by operational means in aircraft turnarounds. Hence, the *regularity* of a schedule also reflects how robust the schedule is planned to be against unforeseen disruptions as well as the operational capability of the airline to manage aircraft rotations. The calculation of schedule regularity in this research is based on the given *delay time threshold* which is seen as the minimum tolerable delay at a rotational stop to cause significant knock-on effects in following aircraft rotations, if the link of aircraft rotation is not broken.

4.5.2 Simulation and Optimisation of Aircraft Rotation- Numerical Analysis

Two aircraft rotations, one of a major schedule airline (denoted by Airline R) and one of a low-cost airline (denoted by Airline P) were studied in this research. The aircraft rotation of Airline R (represented by Aircraft_A) represents the rotation of an aircraft between five airports as illustrated in Figure 4.22. The aircraft rotation of Airline P (represented by Aircraft_B) represents the rotation of an aircraft between two European cities as shown in Figure 4.23. The rotational schedule of Aircraft_A is given in Table 4.4 including scheduled ground time, scheduled airborne time and mean turnaround service time of each leg in the rotation. Rotational schedule of Aircraft_B is given in Table 4.5. It is seen from Aircraft_A's rotation schedule that the scheduled turnaround time at the hub airport of Airline R (Airport K in this case) is shorter than those at spoke airports (Airports J, L, M and N in this case). A long schedule break time for the rotation of Aircraft_A is designed in the ground time of Leg_4 which is scheduled 90 minutes at Airport K. On the other hand, it is seen from Aircraft_B's rotation schedule that short aircraft turnaround time is scheduled at the hub airport of Airline_P, i.e. Airport X and long turnaround time is designed in the ground time of Leg_5. It is also found that ample airborne time is designed in the rotation of Aircraft_B.

Figure 4.22, Figure 4.23, Table 4.4, Table 4.5

The AR model was applied to simulate the rotation of Aircraft_A and Aircraft_B. The simulation size for each aircraft was 1,000 simulation runs of aircraft rotations. The original rotation schedules of these two cases were both optimised to minimise the system costs involved in aircraft rotations. Simulation results of the rotation of Aircraft_A are shown in Figure 4.24 and Figure 4.25. It is seen in Figure 4.24 that the outbound punctuality of the original schedule of Aircraft_A deteriorates along the rotation, though the outbound punctuality of Leg_4 is well controlled due to a long schedule break time at airport K. The development of knock-on delay of Aircraft_A is clearly seen in Figure 4.24. It is also observed in Figure 4.24 that the inbound punctuality of Aircraft_A decreases and results in an average arrival delay of 10 minutes by the end of the rotation at airport N. When the rotational schedule of Aircraft_A is optimised, it is found in Figure 4.24 that the outbound punctuality of each rotational leg is improved and controlled within 6 minutes. Hence, the inbound punctuality of the rotation is significantly improved as shown in Figure 4.25.

Figure 4.24, Figure 4.25

The optimised rotation schedule of Aircraft_A is given in Table 4.4 for comparison purposes and illustrated in Figure 4.26 and Figure 4.27 including the comparison with the original rotation schedule. It is seen from Figure 4.26 that the optimisation of Aircraft_A's rotation tends to schedule more ground time than the original schedule does. On the other hand, optimisation results in Figure 4.27 suggest that the optimal schedule airborne time for the rotation of Aircraft_A is close to the original schedule. It is observed both in Figure 4.26 and Figure 4.27 that the optimised ground time and airborne time of Aircraft_A increases gradually along aircraft rotation in order to control the development of knock-on delays in aircraft rotations. The comparison of system costs between the original schedule and the optimal schedule is shown in Figure 4.28. It is found that the design of the long "fire-break" time in the original schedule causes the increase of system costs. It is also seen in Figure 4.28 that the optimisation of the rotation of Aircraft_A reduces the system costs and meanwhile improves the punctuality of aircraft rotation.

Figure 4.26, Figure 4.27, Figure 4.28

Simulation results of the original schedule of Aircraft_B are shown in Figure 4.29 and Figure 4.30. It is clearly seen that knock-on delays accumulate along the path of the rotation in the original schedule. The outbound delay of Aircraft_B gradually increases and by the end of the rotation, the outbound delay of Leg_10 is about 15 minutes. On the other hand, it is found in Figure 4.30 that the inbound punctuality of Aircraft_B is good due to long scheduled airborne time in each rotation leg. However, the inbound punctuality is slowly consumed by the deterioration of outbound punctuality in each leg of the rotation. When the simulation results of the optimal schedule are compared with the results from the original schedule in Figure 4.29 and Figure 4.30, it is found that the outbound delay of the rotation is improved under this circumstance as well as the inbound punctuality being well controlled.

Figure 4.29, Figure 4.30

The result of schedule optimisation of Aircraft_B is given in Table 4.5 and illustrated in Figure 4.31 and Figure 4.32. The schedule optimisation allocates more scheduled ground time for Aircraft_B in order to minimise the delay cost to air passengers and the aircraft. The optimised ground time of the rotation of Aircraft_B gradually increases from 35 minutes in Leg_1 to 45 minutes in Leg_10 due to the need to control delay accumulation in aircraft rotation. On the other hand, it is seen in Figure 4.32 that the optimised schedule allocates less airborne time in each leg of the rotation than the original schedule does. It is realised from the original schedule of Aircraft_B that there is ample airborne time scheduled for the rotation of Aircraft_B, so the inbound punctuality of the rotation is good. The decrease of airborne schedule time in the optimised schedule reduces system costs and meanwhile maintains schedule punctuality and stability.

Figure 4.31, Figure 4.32

It is speculated that the ample airborne time scheduled for the rotation of Aircraft_B is aimed to ensure the punctuality of arrivals. The short turnaround time for Aircraft_B at Airport **X** carries the risk for Airline P of the potential development of knock-on delays if one of the rotational legs is seriously delayed due to unforeseen causes. It is found that the total duration of a rotation leg of Aircraft_B in the original schedule is close to the one of the optimised schedule as shown in Table 4.5. Hence, a scenario study is conducted to optimise the allocation of schedule time of Aircraft_B by fixing the departure time slot and the arrival time slot of each rotation leg, i.e. fixing the total duration of each leg of the rotation. Simulation results of the scenario study (denoted by the "fixed-slot" schedule hereafter) are given in Figure 4.31 and Figure 4.32. It is found that the allocation of schedule time in the fixed-slot case is close to the results of the optimal schedule. When system costs of three schedules are compared in Figure 4.33, it is seen that system costs of the optimal schedule and the fixed-slot schedule are both lower than the one of the original schedule. The reduction of system costs in the optimal schedule comes mainly from the significant reduction of outbound delays in the rotation of Aircraft_B.

Figure 4.33

4.5.3 Reliability of Aircraft Rotational Schedules

The reliability/robustness of an aircraft rotational schedule is measured by the mean delay of a leg, the standard deviation of aircraft departure time, the expected delay of a leg and the schedule regularity. These reliability measures are used to calculate the reliability of the original schedule and the optimised schedule of Aircraft_A. The mean delay of Aircraft_A's rotation is shown in Figure 4.34. It is found that the mean delay of Aircraft_A is improved after the aircraft rotational schedule is optimised. The mean delay of Leg_6 of the rotation is reduced from 25 minutes in the original schedule to 5 minutes in the optimal schedule. It is found that the optimal schedule is believed to be more stable and reliable in terms of the control of mean delay of aircraft rotation. When the reliability of aircraft rotation is measured by the standard deviation of aircraft punctuality, it is found in Figure 4.35 that the SD_d of the departure time in the original schedule increases significantly, though the SD_d of the optimal schedule also increases gradually. The increase of SD_d in aircraft rotation results from the development of knock-on delays in some rotations. The higher the SD_d value of a schedule is, the less reliable the schedule is. The significant increase of SD_d in the original schedule shows that aircraft rotations tend to suffer knock-delays once significant disruption occurs to the operation of Aircraft_A.

Figure 4.34, Figure 4.35

The expected delay of the rotation of Aircraft_A is calculated from simulation results and shown in

Figure 4.36. It is clearly seen that the expected delay ($E[D]_{LEG}$) of the original schedule increases significantly, though it decreases in Leg_4 due to a long scheduled turnaround time. The increase of the expected delay in the original schedule shows that there is higher probability for Aircraft_A to suffer knock-on delays in the rotation. The expected delay of the optimal schedule is controlled within the range between 0 and 5. Hence, the optimal schedule of Aircraft_A is more reliable and stable in terms of the expected delay.

Figure 4.36

The schedule regularity of aircraft rotation is measured according to different delay time thresholds. Delay thresholds used in numerical analyses are 30, 45 and 60 minutes at each airport in the rotation of Aircraft_A. Regularity measures are denoted by the threshold of schedule modification, e.g. R_{REG_30}, R_{REG_45} and R_{REG_60}. Regularity measures of the original schedule are compared with the regularity measures of the optimal schedule in Figure 4.37. It is seen that schedule regularity decreases as the rotation of Aircraft_A proceeds. The R_{REG_60} of the optimal schedule is improved from 93% in Leg_10 of the original schedule to 97% in the optimised schedule. If the threshold of schedule modification is set lower, e.g. 30 and 45 minutes, the decrease of schedule regularity is clearly seen in Figure 4.37. It is found that the regularity R_{REG_30} of Aircraft_A is significantly improved from 87% in the original schedule to 96% in the optimal schedule. Therefore, it is concluded that the optimisation of the rotational schedule improves the schedule reliability and stability.

Figure 4.37

These reliability measures were also applied to the rotation of Aircraft_B to measure the reliability of Aircraft_B's schedule and the performance of schedule optimisation. In terms of mean leg delay of Aircraft_B, it is seen in Figure 4.38 that the mean delay is improved in the optimal schedule of Aircraft_B. The mean delay of Aircraft_B's rotation in the optimised schedule is controlled within the range between –1 and 7 minutes, while the mean delay in the original schedule deteriorates from –4 minutes to 15 minutes by the end of the rotation. The departure SD_d value of the optimal schedule is also found in Figure 4.39 to be improved when compared with the SD_d of the original schedule. However, the SD_d value after schedule optimisation is still high and increases gradually along the rotation of Aircraft_B. This phenomenon is due to the intensive rotation of Aircraft_B in an operational day as well as short scheduled ground time for turnarounds. The high SD_d value of Aircraft_B's schedule reveals the high risk of Airline P on suffering from significant knock-on effects to the rotation of Aircraft_B if disruptions occur.

Figure 4.38, Figure 4.39

When the expected delay in the original schedule of Aircraft_B is compared with the one in the optimised schedule, it is found in Figure 4.40 that the expected delay in the original schedule fluctuates due to long ground time in Leg_5. It is realised that the low expected delay in the original schedule results from long airborne time in Aircraft_B as shown in Figure 4.40. As a consequence, a part of the expected departure delay is absorbed by ample airborne buffer time. However, the reliability of the optimal schedule still outperforms the original one as the expected delay in the optimal schedule is more stable and is well controlled within a low delay range (as shown in Figure 4.40).

Figure 4.40

Regularity measures, i.e. R_{REG_30}, R_{REG_45} and R_{REG_60} of the rotation of Aircraft_B were computed and shown in Figure 4.41. It is found that under the threshold of 60 minutes, the regularity of Aircraft_B's original schedule deteriorates from nearly 100% at the start of the rotation to 96% by the end of the rotation. If the threshold is set at 45 and 30 minutes, the regularity of the original schedule becomes 95% and 92% respectively by the end of the rotation. When compared with the original schedule, it is found in Figure 20 that R_{REG_30}, R_{REG_45} and R_{REG_60} of the optimal schedule are stabilised within the interval between 99% and 97% by the end of the rotation. The high regularity figures in the optimised schedule represent the schedule reliability as well as the practical feasibiltiy of Aircraft_B's rotation.

Figure 4.41

4.5.4 Aggregate Schedule Reliability Measures

The reliability measures proposed earlier represent the schedule reliability of aircraft rotation with respect to the implementation performance of individual legs as well as the general view of schedule reliability. In order to reveal the aggregate reliability of a schedule, two aggregate reliability measures are proposed in this research, namely the aggregate mean delay and the aggregate expected delay. The aggregate mean delay (denoted by μ_{AGG}^{D}) of a schedule is defined as the accumulation of mean delay of all legs in the aircraft rotation schedule as shown in equation (4-19). The aggregate expected delay of a schedule (denoted by $E[D]_{AGG}$) is expressed as the accumulation of expected delays of all legs in the rotation as shown in equation (4-20).

$$\mu_{AGG}^{D} = \sum_{i=1}^{n} \mu_{LEG-i}^{D} \qquad (4\text{-}19)$$

$$\mathrm{E}[D]_{AGG} = \sum_{i=1}^{n} \mathrm{E}[D]_{LEG-i} \qquad (4\text{-}20)$$

Results of schedule reliability in terms of aggregate measures are given in Table 4.6. It is seen that the aggregate mean delay of Aircraft_A is improved from 66 minutes in the original schedule to 10 minutes in the optimised schedule. The aggregate expected delay of Aircraft_A is also improved from 69 minutes in the original schedule to 25 minutes in the optimised schedule. Regarding the aggregate reliability of Aircraft_B's rotation, it is seen in Table 4.6 that the aggregate mean delay is improved from 26 minutes in the original schedule to 24 minutes in the optimised schedule. However, the aggregate expected delay increases from 17 minutes in the original schedule to 29 minutes in the optimised schedule.

Table 4.6

The increase of the aggregate expected delay of Aircraft_B in the optimal schedule is due to the reduction of airborne time in aircraft rotation which compromises the inbound punctuality of Aircraft_B in order to achieve the system optimum. It is seen in Figure 4.38 and Figure 4.40 that delays in aircraft rotation escalate and result in the unstability of the schedule. The optimised schedule, on the other hand, shows relatively stable performance in terms of all reliability indicators. Hence, it is concluded that the effectiveness of aggregate reliability measures depends on the design of a schedule, i.e. the use of schedule buffer time.

4.5.5 Discussions

Although the development of knock-on delays in a pre-planned schedule has been widely realised in the transport industry, this research is the first known attempt to model aircraft rotations and to give evidence of knock-on effects in aircraft rotational schedules. The development of knock-on delays is found to result from unforeseen operational disruptions to aircraft turnaround at airports, the congestion in the airspace and the scheduling strategy of aircraft rotations. Two numerical analyses in this research have shown the influence of scheduling strategies on the control of knock-on delays. It is found that the scheduling of long break-time in aircraft rotation can control the development of knock-on delays, though the cost of scheduling long break-time is high. In addition, evidence from numerical studies showed that aircraft rotation schedules should be optimised, in order to improve the reliability and feasibility of the schedule. After schedule optimisation, it is seen that aircraft rotations have become more reliable in terms of the mean delay time, the variability of aircraft arrival/departure time, the expected delay and the schedule regularity.

The reliability of aircraft rotational schedule is measured by four reliability surrogates in this research. It is found that the schedule reliability can be easily measured by the mean delay and the standard deviation of aircraft rotations. However, it is not easy to realise the whole picture of the stability of aircraft rotations from both measures as they only reflect partial characteristics of the rotation. On the other hand, the reliability measure of the expected delay shows the advantage of considering effects from both delay time and the probability of occurrence, though it needs sophisticated statistics skills to produce the reliability measure. From the managerial point of view of an airline, the regularity of a schedule reflects how well the schedule is designed to resist schedule disruptions as well as how well the daily turnaround of aircraft is operated.

Therefore, it is recommended that reliability measures of the mean delay and the standard deviation are suitable for preliminary investigation to a flight schedule because it is easy to calculate these measures and they also reveal some significant information regarding schedule reliability. The expected delay, on the other hand, should be the major reliability surrogate of a flight schedule as the measure considers two important stochastic factors in schedule punctuality, namely the occurrence probability of delays and the length of delays. The schedule regularity measure is recommended to serve as the indicator of the operational feasibility of a flight schedule because the measure reflects the robustness of the schedule design and the operational feasibility of the schedule. On the other hand, since the aggregate schedule reliability indicators measure the accumulation of mean delay and expected delay of a rotational schedule, the indication of these aggregate surrogates does not reveal the absolute reliability of a schedule. Therefore, supportive information of schedules is needed when trying to explain the implication of these aggregate reliability measures.

4.6 Sensitivity Analysis to the Optimisation of the AR Model

The use of parameter values in the modelling of system cost depends on the operational characteristics of an airline and also affects the system optimisation results. Hence, it is of interest in this research to investigate the influence of cost parameters on the optimisation of aircraft rotational schedules and the sensitivity of the AR model to the changes of cost parameters. Four parameters were studied in this sensitivity analysis including the unit cost of delay time of a passenger, the unit cost of delay time of an aircraft, the unit cost of schedule buffer time and the weight factors in the objective function (equation (4-12)). The rotation of Aircraft_B was taken as an example in sensitivity analysis.

4.6.1 Unit Cost of Passenger Delay

Optimised ground time and airborne time of Aircraft_B's rotation is shown in Figure 4.42 and Figure 4.43. The unit delay cost of a passenger studied in this analysis ranges from $30 per hour to $80 per hour. It is seen in Figure 4.42 that the change of unit passenger delay cost does not significantly affect the allocation of ground time in the optimised schedule, though the increase of passenger delay cost does cause the slight increase of ground time. Regarding the airborne time in the optimised schedule, the increase of passenger delay cost also causes minor changes to the optimisation results. Therefore, it is found in this study that the use of passenger delay unit cost does not significantly influence the optimisation of aircraft rotational schedules.

Figure 4.42, Figure 4.43

4.6.2 Unit Cost of Aircraft Delay

The unit delay cost of an aircraft reflects the operational cost of the aircraft as well as the cost of the consequences of aircraft delay. Values of unit delay cost of an aircraft used in the literature range from $430 per hour for a small aircraft operated by U.S. carriers to $6,000 per hour claimed by Scandinavian Airlines System (SAS) (Eilstrup, 2000; Richetta and Odoni, 1993). Hence, a sensitivity analysis was done to investigate the influence of the choice of aircraft delay cost on the optimisation of aircraft rotational schedules. It is seen in Figure 4.44 that the change of unit aircraft delay cost causes a slight difference in the allocation of ground time in the optimal schedule. A higher value of aircraft delay cost causes the increase of ground time in order to minimise total system costs. On the other hand, it is found in Figure 4.45 that more airborne time in aircraft rotation is scheduled when higher cost values are used in the optimisation model. However, the change to the system optimum due to the different uses of aircraft delay cost is not significant according to analysis results given in Figure 4.44 and Figure 4.45.

Figure 4.44, Figure 4.45

4.6.3 Unit Cost of Schedule Time

The value of schedule time in an aircraft rotation schedule represents the profitability of the route and the productivity of the aircraft in use. It has been found that the opportunity cost of schedule time varies from $4,500 per hour to $8,500 per hour for different airlines (Wu and Caves, 2000). Hence, a sensitivity analysis was carried out to study the model sensitivity to the use of schedule buffer time under different levels of schedule time costs. It is found in Figure 4.46 that the high schedule time opportunity cost hinders the use of long scheduled ground time and airborne time for Aircraft_B's rotation. It is found in Figure 4.47 that the increase of unit schedule time cost significantly decreases the schedule airborne time in the optimal schedule. These findings support the observation in the airline industry that low-cost airlines tend to schedule less turnaround time in aircraft rotations due to high schedule time opportunity cost in order to increase aircraft utilisation.

Figure 4.46, Figure 4.47

4.6.4 Trade-offs in Aircraft Rotation

The trade-off situation between the cost of passengers/aircraft delay and the cost of schedule buffer time is modelled in equation (4-12) by two weight factors: α and β. When the weight is put on α, more schedule time will be required to optimise the system in order to control the increase of delay costs. While the weight is on β, less schedule time will be scheduled in the system because of the increasing cost to the use of schedule time. The influence of the trade-off situation on the scheduling of aircraft rotation is shown in Figure 4.48 and Figure 4.49. It is seen in Figure 4.48 that when the emphasis of the system optimisation is on passenger/aircraft delay costs, more ground time is designed in aircraft rotation in order to reduce delay costs, e.g. the case denoted by "Alfa=0.8" in Figure 4.48. The emphasis on passenger/aircraft delay costs is also reflected on increasing airborne time (shown in Figure 4.49) when α is set higher than the equal-weight case (in which α is set at 0.5).

Figure 4.48, Figure 4.49

Therefore, the sensitivity analysis has shown that the optimal schedule of aircraft rotation is significantly influenced by the schedule time cost of an airline as well as the scheduling strategies of an airline when facing the trade-off between aircraft productivity and schedule punctuality. The influence on the optimal schedule due to different uses of unit passenger delay cost and unit aircraft delay cost is found not significant to the model. In addition, it is worth pointing out that different parameter values used in the model generate different results of schedule optimisation which only corresponds to the optimisation premises set by an airline.

4.7 Concluding Remarks

A mathematical model was proposed to simulate the rotation of aircraft in a network of airports. The effectiveness of the AR model has been demonstrated in this chapter and the development of knock-on delay in aircraft rotation has been observed from simulation results of the AR model. It was found that turnaround buffer time in aircraft rotational schedules helps maintain the control of knock-on delay in aircraft rotation. When aircraft are scheduled to hub at the base airport of an airline, results from simulations showed that scheduling a long turnaround time at the hub improves the punctuality of aircraft rotation. Although a short connection time at the hub airport increases the utilisation of aircraft, simulation results revealed the potential risk of the short-turnaround-time policy to worsen aircraft rotational punctuality.

The optimisation of aircraft rotational schedules was implemented for two cases, i.e. single leg optimisation and consecutive leg optimisation. Trade-offs between ground schedule time and airborne schedule time were clearly observed in the optimisation of a single leg of rotations. Trade-offs between ground time at two airports were also found significant in the optimisation of consecutive legs of rotations. It was found from numerical analyses that the schedule punctuality performance at an airport influences the punctuality performance at following rotational stops, because legs of aircraft rotations interact with each other. Hence, according to simulation results, the optimisation of aircraft rotational schedules showed an improvement in reducing system costs. It was also found that the schedule punctuality at each airport in the rotational schedule varies as a result of schedule optimisation and different scheduling considerations at airports.

The AR model was also applied to two numerical study examples in this chapter. Results of numerical analyses showed that the development of knock-on delays results from unforeseen operational disruptions to aircraft turnaround at airports, the congestion in the airspace as well as the scheduling strategy of aircraft rotations. The schedule of aircraft rotation was then optimised by balancing the allocation of schedule buffer time in the ground time and in the airborne time of an aircraft in order to minimise system costs. Simulation results showed that the optimised aircraft rotational schedule is more reliable and stable than the original schedule in terms of the mean delay, system costs, the expected delay and schedule regularity.

The reliability of a schedule was measured by four reliability surrogates, namely the mean delay, the standard deviation of aircraft arrival/departure time, the expected delay and the schedule regularity. After the evaluation of the effectiveness of schedule reliability measures through numerical analyses, it is recommended that the mean delay and the standard deviation are suitable reliability measures for preliminary investigation to a flight schedule. The expected delay, on the other hand, is suggested to be the major reliability surrogate to a flight schedule. The schedule regularity is recommended to serve as the indicator of the operational feasibility of a flight schedule for the managerial purposes of an airline. Aggregate measures of schedule reliability proposed in this research showed that caution is needed to interpret the implication of the aggregate reliability of a schedule, because aggregate reliability measures are influenced by the scheduling strategies of an airline, especially the use of schedule buffer time. Therefore, supportive information of schedules is needed when trying to explain the implication of these aggregate reliability measures.

Operational uncertainties in air transport system are inevitable. However, the optimisation of aircraft rotational schedule would be able to minimise system costs, then stabilise the rotational performance of aircraft. Regarding the management of aircraft rotation, the proposed AR model has shown its applicability in the management of aircraft rotation as well as being a suitable tool for planning and simulations of aircraft rotation schedules. The AR model can be applied to optimise aircraft rotations under different scheduling strategies and different performance parameters in the model.

CHAPTER FIVE CASE STUDY – EASYJET

Punctuality data from EasyJet was collected to carry out a case study in order to validate the proposed aircraft rotation model (the **AR** model in Chapter Four). Schedule punctuality data from September 1999 to August 2000 for all routes was provided by EasyJet. The route between London Luton Airport (represented by **LTN** hereafter) and Amsterdam Schiphol Airport (represented by **AMS** hereafter) was chosen for this case study. The aircraft rotational schedule (the winter schedule in 1999-2000 term) on the LTN-AMS route is given in Table 5.1. There were eight segments in one-day aircraft rotation between LTN and AMS. The rotation started at 05:40 hours departing from LTN and finished at 19:30 hours arriving at LTN. The scheduled turnaround time (TSG) at AMS varies from 30 minutes to 45 minutes and the scheduled turnaround time at LTN varies from 30 minutes to 55 minutes. There was a long turnaround time for flight EZY207 which also served as a mid-day "fire-break time" in the daily rotational schedule in order to control the punctuality of aircraft rotation on the LTN-AMS route.

Table 5.1

The structure of case study is illustrated by Figure 5.1. This case study starts from Section 5.1, Current Situation Analysis, which contains analyses of turnaround disruption history and turnaround efficiency at both LTN and AMS airports. Model parameters required to run the AR model are calculated after detailed data analyses in this section. The calibration of the MAT model is described in Section 5.2, MAT Model Calibration. Model parameters for the MAT model are calculated and analysed in this section by applying the MAT model to LTN and AMS airports. The calibration of the Enroute model is given in Section 5.3, Enroute Model Calibration, in order to model the enroute flight time of an aircraft between LTN and AMS. The simulation of aircraft rotations on the LTN-AMS route is presented in Section 5.4, AR Model Application. Results from simulation are discussed and compared with observation results from EasyJet. The aircraft rotational schedule on the LTN-AMS route is then optimised and results are given in Section 5.5, AR Model Optimisation. Results from schedule optimisation are compared with both observation and simulation results in this section. Four schedule reliability surrogates are applied in this case study to quantify the reliability of aircraft rotations on the LTN-AMS route. Measurements of schedule reliability and stability are discussed in Section 5.6, Reliability of Aircraft Rotations on LTN-AMS Route. Concluding remarks are given in the last section, Section 5.7.

Figure 5.1

5.1 Current Situation Analysis

5.1.1 Turnaround Disruption History Analysis (Luton Airport)

The turnaround process of an aircraft is modelled in the MAT model by Semi-Markov chains which use two sets of model parameters to describe the turnaround process: transition probability between states (p_{ij}) and state sojourn time function ($\Phi_{ij}(t)$) (please refer to Chapter Three for details). Hence historical data about aircraft turnaround operations is statistically analysed to explore required model parameters to run the MAT model. Historical data of 16,106 aircraft turned around at LTN Airport during the period from September 1999 to August 2000 is analysed to characterise the operational performance of ground services at LTN Airport. Standard IATA delay codes are employed by EasyJet to record delay causes and delay duration. The turnaround process of an aircraft is modelled in the MAT model by two workflows, namely cargo & baggage handling and cabin cleaning & passenger processing. These two workflows are modelled by states which represent normal turnaround activities and other states which represent operational disruptions to aircraft turnarounds. Detailed categorisation of delay codes for these two workflows is given previously in Table 3.6 and Table 3.8 in Chapter Three.

The analysis result of the cargo & baggage processing flow is given in Table 5.2. It is found from statistical results that there is 0.06 probability to have passenger & baggage handling problems and 0.09 probability to have aircraft ramp handling problems. These operational disruptions cause mean delay to aircraft turnaround varying from 10 minutes to 15 minutes. On the other hand, the statistical analysis result of the cabin cleaning & passenger processing is shown in Table 5.3. It is found that there is a high probability of 0.11 to encounter crewing problems for turnaround aircraft. It is also found that there is a probability of 0.1 to have missing check-in passengers at airport gates. Statistical results show that delays due to cabin cleaning & passenger processing vary from 11 minutes to as long as 88 minutes, the latter being due to weather causes.

Table 5.2, Table 5.3

Individual disrupting events are categorised into four events which are listed previously in Table 3.10. Statistical analysis results of the occurrence probability and the duration of these events are given in Table 5.4. It is found from Table 5.4 that the occurrence probability of disrupting events is around 0.02. Regarding the duration of disrupting events, the change of aircraft causes a long delay of 58 minutes and the damage of aircraft causes 28 minutes delay time due to extra engineering checks required in this circumstance. On the other hand, aircraft fuelling delay and aircraft engineering check delay cause about 20 minutes delay at LTN Airport.

Table 5.4

5.1.2 Turnaround Efficiency Analysis (Luton Airport)

Punctuality data of two turnaround flights at LTN, EZY207 and EZY209, are analysed in this section to explore the operational efficiency of ground services by EasyJet at LTN Airport. Regression analysis is carried out to investigate the turnaround efficiency of EasyJet, i.e. the relationship between arrival delay of inbound aircraft and departure delay of outbound aircraft. Results of regression analyses of EZY207 and EZY209 are given in Figure 5.2 and Figure 5.3 respectively and regression equations are listed in Table 5.5.

Figure 5.2, Figure 5.3, Table 5.5

It is found from Figure 5.2 that departure delays of turnaround aircraft are well controlled by EasyJet's ground services as the slope of the regression equation is 0.66 which is less than 1.0. However, it is found that the y-axis interception of the regression equation in Figure 5.2 is 14.2. It implies that there is a probability that inbound aircraft with minor arrival delays might suffer departure delays according to historical punctuality information. For EZY209's case, it is found in Figure 5.3 that the slope of regression equation is 0.50 which is less than EZY207's. In other words, it is found from regression results of EZY209 that the turnaround efficiency of EZY209 is better than EZY207's, though the y-axis interception of EZY209's regression equation is still as high as 13.4.

5.1.3 Turnaround Disruption History Analysis (Amsterdam Schiphol Airport)

The analysis result of the cargo & baggage processing flow of ground services at AMS is given in Table 5.6. It is found from statistical results that there is 0.01 probability to have aircraft ramp handling problems which cause average delay of 17 minutes to turnaround services and a high probability of 0.1 to encounter passenger & baggage problems which incur 15 minutes delay to turnaround aircraft. There is a relatively low probability of 0.001 to encounter cargo & mail processing disruptions at AMS Airport. On the other hand, the statistical analysis result of the cabin cleaning & passenger processing is shown in Table 5.7. It is found that there is a low probability of 0.004 to encounter crewing problems for turnaround aircraft at AMS as well as a low probability of 0.04 to have missing check-in passengers at airport gates. However statistical results show that there is a high probability of 0.1 for turnaround aircraft at AMS to encounter delays due to "departure processes", i.e. delays due to airport facilities and airport ground movements. The mean departure delay in this category (State_12) is 13 minutes at Amsterdam Schiphol Airport. When statistical results of turnaround disruption history from AMS are compared with the ones from LTN, it is found that there is a higher probability to encounter aircraft crewing problems and passenger check-in & boarding problems at LTN than at AMS. In addition, turnaround aircraft are apt to have departure delays at AMS which is mainly due to airport congestion. Overall, delays to cargo processing and passenger processing at AMS are longer than the ones at LTN.

Table 5.6, Table 5.7

Statistical analysis results of the occurrence probability and the duration of individual turnaround disruptions at AMS are given in Table 5.8. It is found that the occurrence probability of fueling delay is the highest, 0.02 at Schiphol Airport. On the other hand, there is a relatively low probability to encounter other disrupting events such as engineering check delays, aircraft damage and aircraft changes for turnaround aircraft. However, when compared with results from LTN, it is found that the average delay time due to these disrupting events is longer for turnaround aircraft at AMS which range from 15 minutes to 210 minutes.

Table 5.8

5.1.4 Turnaround Efficiency Analysis (Amsterdam Schiphol Airport)

Punctuality data of four turnaround flight, EZY202, EZY204, EZY206 and EZY208, are analysed in this section to explore the operational efficiency of ground services at AMS Airport. Results of regression analyses are given in Figure 5.4, Figure 5.5, Figure 5.6 and Figure 5.7 and regression equations are listed in Table 5.9.

Figure 5.4, Figure 5.5, Figure 5.6, Figure 5.7
Table 5.9

It is found that the slopes of regression lines in four cases are close to 1.0 which means that the departure delay of a turnaround aircraft is nearly completely explained by the arrival delay of inbound aircraft at AMS. The values of $\mathbf{R}^2$ from regression analyses also show an acceptable goodness-of-fit of observation data to regression lines. On the other hand, the y-axis interception of regression lines increases as the day proceeds from EZY202 to EZY208. It implies that it tends to result in longer departure delays to turnaround aircraft at AMS if the aircraft is scheduled to be serviced at AMS after mid-day, i.e. in the later portion of aircraft rotations.

When the turnaround efficiency at AMS is compared with the one at LTN, it is found that the service efficiency at LTN is better. It is also found from the rotational schedule of the LTN-AMS route that the scheduled turnaround time at LTN is 30 minutes which is shorter than the one at AMS (an average of 40 minutes). Although the scheduled turnaround time at LTN is low, it is realised after this current situation analysis that the turnaround efficiency at LTN is less stable than its counterpart at AMS especially for long-delay flights. This conclusion is also validated by OR analysts at EasyJet and this is also the reason why EasyJet tends to schedule a long turnaround buffer time for the mid-day turnaround aircraft at LTN (EZY 207 in this case) in order to stabilise the punctuality of aircraft rotations.

5.2 MAT Model Calibration

The MAT model proposed in Chapter Three is to model the departure punctuality of turnaround aircraft at an airport by simulating the arrival punctuality of inbound aircraft as well as the turnaround efficiency of ground services. In addition, the MAT model can also be employed to calibrate the turnaround efficiency of ground service providers by using observed punctuality data of inbound aircraft and outbound aircraft. Hence, the MAT model is employed in this section to calibrate the turnaround efficiency of ground handling agents at both LTN and AMS by using observed punctuality data from EasyJet. The results of punctuality analysis of observation data are given in Table 5.10. It is seen that the mean departure delay (μ_d) on the LTN-AMS route is within the range between 8 minutes and 12 minutes. The mean arrival delay (μ_a) varies from -2.8 minutes to 3 minutes. The calculation of the mean arrival delay in Table 5.10 includes early arrival samples which generate "negative arrival delays." Hence the mean arrival delay shows negative values. The expected departure delay ($E[D]_d$) varies from 9.5 minutes to 13 minutes and the expected arrival delay ($E[D]_a$) from -5.9 to 1.5 minutes.

Table 5.10

5.2.1 MAT Model Application to Luton Airport

5.2.1.1 Current situation analysis (Luton)

There are three flights, EZY203, EZY207 and EZY209, which are turned around at LTN in the daily rotational schedule on the LTN-AMS route. Punctuality data of these flights are statistically analysed and analysis results are given in Table 5.11. Inbound delays from observation of three flights vary between 3 and 5 minutes and outbound delays between 8 and 12 minutes. The calculated inbound delay in Table 5.11 includes only "positive delays", i.e. to exclude early arrivals, so values of calculated inbound delay are different from those given in Table 5.10. The scheduled turnaround time (*TSG*) for these flights varies from 30 to 55 minutes.

Table 5.11

5.2.1.2 MAT model calibration (Luton)

The arrival PDF of inbound aircraft to EZY203 at LTN is simulated by Beta(2,5) which has mean arrival delay of 4.5 minutes (as shown in Table 5.11). When the departure punctuality of EZY203 from observation is compared with simulation results from the MAT model, it is found in Figure 5.8 that the simulation results from the case, which the mean turnaround time (*TG*) is 25 minutes, are close to the observed departure punctuality. The simulated CDF in Figure 5.8 also passed the *Kolmogrov-Smirnov Two-Sample Test* which ensures the *goodness-of-fit* of the simulation result to the observation result (Conover, 1980; Heave and Worthington, 1988). The *K-S test* value of EZY203 is 0.12 which is lower than the critical value, 0.2072, and hence the null hypothesis (H_o: Fitting is good) is not rejected in this instance. The mean departure delay from simulation results of EZY203 is 13.2 minutes which is close to the observed average departure delay, 12.4 minutes. Hence the calibrated mean turnaround time for EZY203 at LTN is 25 minutes (as given in Table 5.11).

Figure 5.8

When the MAT model is employed to calibrate the turnaround efficiency of EZY207 and EZY209, it is found in Figure 5.9 and Figure 5.10 that the mean turnaround service time is 40 and 20 minutes for EZY207 and EZY209 respectively. The power of goodness-of-fit of two cases is validated by *K-S Two-Sample Tests* given in Table 5.11. Punctuality results of these two flights from the simulation model are also found close to observed punctuality as given in Table 5.11. It is seen from above analyses that when the longer scheduled turnaround time is allowed for turnaround operations, it usually takes a longer time for the same activities to be finished such as EZY207. This phenomenon is called "behavioural response" by Carey (1998) and is also observed in other transport modes which operate scheduled timetables. Although the change of aircraft crews usually takes place during the long turnaround time of the mid-day flight at LTN and in some cases it causes turnaround delays, the above phenomenon still exists in most turnaround operations according to the observation of OR analysts at EasyJet.

Figure 5.9, Figure 5.10

5.2.2 MAT Model Application to Schiphol Airport

5.2.2.1 Current situation analysis (Schiphol)

There are four flights, EZY202, EZY204, EZY206 and EZY208, to be turned around at AMS in the daily aircraft rotational schedule on the LTN-AMS route. Punctuality data of these flights are statistically analysed and punctuality results are given in Table 5.12. Observed average inbound delays of these flights vary between 4 and 6 minutes and outbound delays between 8 and 12 minutes. The scheduled turnaround time (TSG) for these flights varies from 30 minutes to 45minutes.

Table 5.12

5.2.2.2 MAT model calibration (Schiphol)

The turnaround operation of EZY202 at AMS is simulated by featuring Beta(2,5) inbound PDF which generates 5.4 minutes arrival delay. When the simulated departure CDF of EZY202 is compared with the observed departure CDF, it is found in Figure 5.11 that the mean turnaround service time (*TG*) for EZY202 is 35 minutes. The mean departure delay from simulation results is 7 minutes for EZY202 which is slightly lower than observed mean departure delay, 9.5 minutes (as shown in Table 5.12). The simulated CDF also passed the *K-S Two-Sample Test* as shown in Table 5.12.

Figure 5.11

When the MAT model is used to calibrate the turnaround efficiency of EZY204, EZY206 and EZY208, it is found in Figure 5.12, Figure 5.13 and Figure 5.14 that the mean turnaround service time is 30, 35 and 25 minutes for EZY204, EZY206 and EZY208 respectively. Punctuality results of these flights from simulation are also found close to the observed punctuality as shown in Table 5.12. It is seen from the above analyses that the behavioural response in aircraft turnaround operations also exists in the turnaround operations at AMS. In other words, when the scheduled turnaround time is longer, the mean service time also gets longer as shown in Table 5.12. The K-S test result given in Table 5.12 also shows that the performance of MAT model calibration for EZY204, EZY206 and EZY208 is acceptable.

Figure 5.12, Figure 5.13, Figure 5.14

5.3 Enroute Model Calibration

The Enroute model proposed in Chapter Four is to model the enroute flight time of an aircraft between two airports in order to serve as a link between two aircraft turnaround models at two airports. The enroute flight time between two airports is modelled by a Normal distribution as described by equation (4-1) and the congestion in the TMA of the destination airport is modelled by an Exponential function. The arrival time of an aircraft is therefore modelled by the convolution of departure delay at the origin airport, the enroute flight time and the TMA delay time at the destination airport. Hence, the Enroute model is used in this section to calibrate the enroute flight time between LTN and AMS in order to investigate the relationship between the real flight time and the scheduled block time.

5.3.1 Enroute Model Calibration: from Luton to Schiphol

The enroute flight time from LTN to AMS is calibrated by using the departure CDF at the origin airport (LTN in this case) and the arrival CDF at the destination airport (AMS in this case). Calibration results of four flights, EZY201, EZY203, EZY207, and EZY209, are given in Table 5.13. The scheduled block time between LTN and AMS for these flights is 70 minutes. The simulated enroute flight time of EZY201 is 55 minutes with a TMA congestion time of 5 minutes. Hence, the mean block time becomes 60 minutes for EZY201 which is quite close to the average block time of 59 minutes provided by EasyJet. The simulated arrival delay of EZY201 at AMS is 4.8 minutes which is close to the observed arrival delay of 5.5 minutes. The comparison of simulated CDF of EZY201 and the observed CDF of EZY201 is illustrated in Figure 5.15. It is clearly seen in Figure 5.15 that the simulated arrival CDF is close to the observed CDF of EZY201 in this instance. Simulation results of EZY203, EZY207 and EZY209 are shown in Figure 5.16, Figure 5.17 and Figure 5.18. The simulated arrival delays of these flights are also close to the observation results as given in Table 5.13. When the *K-S Two-Sample Test* is applied to these cases, the test result (given in Table 5.13) shows that tested *K-S values* are lower than the critical values and hence, simulation results show the power of goodness-of-fit to observation data.

Figure 5.15, Figure 5.16, Figure 5.17, Figure 5.18, Table 5.13

5.3.2 Enroute Model Calibration: from Schiphol to Luton

The results of the enroute flight time calibration from AMS to LTN are given in Table 5.14. Four flights, EZY202, EZY204, EZY206 and EZY208, are investigated in this section. It is found, as shown in Table 5.14, that the average flight time from AMS to LTN is about 55 minutes and the average TMA delay varies from 3 minutes to 5 minutes. When the simulated arrival CDF of EZY202 is compared with the observed arrival CDF in Figure 5.19, it is seen that the simulation result is close to the observation result. When simulation results of other flights are compared with observations in Figure 5.20, Figure 5.21 and Figure 5.22, it is found that the Enroute model is good at modelling the enroute flight time between two airports. In addition, the average block time between AMS and LTN according to statistical analysis of EasyJet is about 59 minutes (in the year of 1999-2000) which is close to the simulation results from the Enroute model in this research as well.

Figure 5.19, Figure 5.20, Figure 5.21, Figure 5.22, Table 5.14

5.4 AR Model Application

5.4.1 Model Parameters

The AR model proposed in Chapter Four is applied in this section to model aircraft rotations on the LTN-AMS route. Model parameters required in the AR model include parameters for the MAT model, parameters for the Enroute model and parameters for the system cost calculation. Different sets of parameters are applied for different flights which are turned around at different airports at different times of the day. For instance, flight EZY203 departs from LTN at 09.15 hours **GMT** in the morning after a scheduled turnaround time of 30 minutes at LTN. Hence, the occurrence probability of turnaround disruptions at LTN is applied to EZY203 and the turnaround efficiency of EasyJet at LTN is applied to model the turnaround operation of EZY203. Then, EZY203 arrives at AMS at 10.25 hours GMT after 70 minutes of scheduled block time. Hence, the model parameters for EZY203 are applied to the Enroute model in order to simulate the enroute flight time between LTN and AMS.

The value of the unit delay cost of a passenger ($C_P(s)$ in equation (4-12)) used in the AR model is \$0.03/min^2, which is equivalent to a delay cost of \$54 per hour, per passenger (Wu and Caves, 2000). Since detailed information for delay cost calculation is highly confidential and not available from EasyJet, nominal values from the previous analysis and rough cost figures from EasyJet are used in the following cost calculations in the AR model. The value of the unit delay cost of an aircraft ($C_A(s)$ in equation (4-12)) is \$45/min for ground delays, which is equivalent to a delay cost of \$2,700 per hour, per aircraft (a B737). The opportunity cost of schedule buffer time (C_{AL}^{m} in equation (4-12)) is \$2.5/min^2, which is equivalent to \$4,500 per hour for a European short-haul route. Equal weights, i.e. $\alpha = 0.5$, on the delay cost of passengers and the airline schedule time cost are used in the simulation of aircraft rotations.

5.4.2 Simulation Results

Simulation results from the AR model are given in Table 5.15. It is seen that the mean departure delay in aircraft rotation varies from 7 minutes to 14 minutes at the end of the rotation. The mean arrival delay is within the range between -4 and 3 minutes. The standard deviation of departure/arrival delay increases gradually from 14 to 28. In other words, the development of knock-on delays is significant in simulation cases. The expected departure delay, on the other hand, varies from 10 to 14, while the expected arrival delay is from -4 to 0.8.

Table 5.15

Simulation results of the AR model are compared with observations in order to validate the simulation performance of the AR model. Comparisons between simulation and observation results are made according to four indices: the departure/arrival punctuality, the mean departure/arrival delay time, the expected arrival/departure delay time and the standard deviation of departure/arrival delay.

5.4.2.1 Punctuality

The comparison of departure punctuality between simulation and observation results is given in Figure 5.23. It is found that the simulated departure punctuality from the AR model is somewhat better than observations, the difference between simulated punctuality and observed punctuality varying from 2% to 15% in this case. The departure punctuality of EZY207 is supposed to be as good as simulation results because of a long turnaround time (55 minutes) scheduled for this aircraft to be turned around at LTN. However, the observation result in Figure 5.23 shows that the observed departure punctuality of EZY207 is not as good as simulated. The departure punctuality of the LTN-AMS route varies in a daily operation between 20% and 50%. The scheduled long turnaround time for EZY207 in the mid day does not effectively stabilise the departure punctuality afterwards. On the other hand, the comparison of arrival punctuality between simulation and observation results in Figure 5.24 shows that the simulation results are close to observations which range between 60% and 80%.

Figure 5.23, Figure 5.24

5.4.2.2 Mean delay time

When the mean departure delay from simulation is compared with observation in Figure 5.25, it is found that the simulation result is fairly close to observations. It is seen in Figure 5.25 that the mean departure delay decreases from EZY203 to EZY207 due to the long turnaround time for EZY207 at LTN in the mid day. It is also found that the mean departure delay increases gradually after EZY207 due to knock-on effects in aircraft rotation. Differences between observation and simulation results are seen in Figure 5.25 such as flight EZY209. After a detailed investigation into simulation data, it is found that the difference comes from extreme simulation cases (5% over 60 minutes delay) due to knock-on delays in aircraft rotation. However, in the real-world operation by EasyJet, the potential development of knock-on delay is controlled by flight cancellation or aircraft swap. Regarding the mean arrival delay, it is seen in Figure 5.26 that the mean arrival delay also increases along aircraft rotation.

Figure 5.25, Figure 5.26

5.4.2.3 Expected delay time

The expected departure delay from the AR model is compared with the observed expected delay in Figure 5.27. It is seen that the simulation result is close to the observation result, though there is still a minor difference between them (two minutes maximum). Both simulation and observation results suggest that the expected departure delay increases along aircraft rotations. On the other hand, the expected arrival delay from the AR model is compared with the observed expected delay in Figure 5.28. The difference of expected arrival delay between simulation and observation results is controlled within two units in this instance.

Figure 5.27, Figure 5.28

5.4.2.4 Standard Deviation

The standard deviation of departure delay represents the degree of data scattering. Hence, it is used in this research as a surrogate to measure the reliability of a schedule. The standard deviation of departure delay from the AR model is compared with the standard deviation from observation in Figure 5.29. It is seen that the standard deviation of observation remains around 15, while the standard deviation from simulation results increases gradually from 13 to 25 by the end of aircraft rotations. The discrepancy between these two sets of data comes from the increase of delays due to knock-on effects in the simulation of aircraft rotation in the AR model. In the real-world operation, EasyJet cancels flights or swaps aircraft if any up-stream aircraft suffers long delays which are not likely to be controlled by operational means, i.e. ground operations. However, the proposed AR model does not feature the "flight cancellation" function and consequently the AR model generates more "extreme cases" than real-world operations and results in higher deviation in simulations. The similar phenomenon is seen in Figure 5.30 when the standard deviation of arrival delay from the AR model is compared with its counterpart from observation data.

Figure 5.29, Figure 5.30

5.4.3 Discussions

From the results of simulation, it is found that the performance of the AR model in modelling aircraft rotations is acceptable, though differences between simulation and observation results still exist. The difference mainly comes from two aspects. First of all, uncertainties occurred in the real-world operation of aircraft rotation are not fully included and modelled in the AR model due to some model assumptions and simplifications in the modelling process. Hence, simulation results can only be as close as possible to observation data. Secondly, the proposed AR model does not include the feature of "flight cancellation" when an aircraft suffers long delays. In the real-world operations, an airline will try to control the propagation of knock-on delays in aircraft rotations by all operational means and consequently delays of extreme cases are controlled within a tolerable range (usually two to three hours). This is also the reason why the standard deviation of departure/arrival delay from the simulation model is higher than its counterpart from observation data.

5.5 AR Model Optimisation

The aircraft rotational schedule of the LTN-AMS route is optimised in this section by using the "Single-Leg Optimisation" method proposed in Section 4.4. The objective of schedule optimisation is to minimise total system costs (C_T) which include passenger delay costs (C_{DP}), aircraft delay costs (C_{DA}) and schedule time opportunity costs (C_{AL}). Model parameters used in the schedule optimisation are the same as those in the application of the AR model in Section 5.4. Results of schedule optimisation are given in Table 5.16. It is seen that the mean departure delay in aircraft rotation is controlled between 5 and 8 minutes and the mean arrival delay is below -2 minutes. The expected departure delay is controlled within 8 and 10 minutes and the expected arrival delay within -3 and -4 minutes, i.e. more early arrivals than observation data. However, the standard deviation of departure/arrival delay time still increases gradually along aircraft rotations from 13 to 25.

Table 5.16

5.5.1 Optimisation Results

The aircraft rotational schedule of the LTN-AMS route is optimised by reallocating schedule buffer time in aircraft rotations in order to minimise system costs. The optimised schedule time of the LTN-AMS route is given in Table 5.17, which includes the original schedule for comparison purposes. It is seen in Table 5.17 that the optimised schedule designs more buffer time in the scheduled turnaround time on the ground and meanwhile reduces the use of airborne buffer time in the enroute block time. When the total schedule time of a leg in the optimisation case is compared with the one in the original case, it is found in Figure 5.31 that the total leg time after schedule optimisation is slightly higher than the original schedule leg time. An increase of 7% schedule time, or 59 minutes of schedule time in total, is required in the optimised aircraft rotation schedule due to the increasing use of buffer time in flight schedules.

Figure 5.31, Table 5.17

The system costs of each leg on the LTN-AMS route are listed in Table 5.18. When the total system costs in the optimisation schedule are compared with the one in the original schedule in Figure 5.32, it is seen that the system cost of the original schedule increase significantly along aircraft rotations. The system cost of the optimised schedule also grows gradually, but a significant reduction of system costs, **27%** reduction or **$4,221,185** saving of system costs **per 1,000 rotations**, after schedule optimisation is clearly observed in Figure 5.32. In order to investigate the composition of system costs, the break-downs of the system costs in both the original and the optimised schedule are listed in Table 5.18 and compared in Figure 5.33. It is found that the share of passenger delay cost decreases from 64% in the original schedule to 57% in the optimised case. The share of aircraft delay cost also decreases from 26% to 21%. The share of schedule time cost increases from 10% to 22% due to the increasing use of schedule buffer time in the optimised schedule.

Figure 5.32, Figure 5.33, Table 5.18

Results of schedule optimisation are compared with both observation data and simulation results from the AR model in terms of four indices: the departure/arrival punctuality, the mean departure/arrival delay, the expected departure/arrival delay and the standard deviation of departure/arrival delay.

5.5.1.1 Punctuality

The departure punctuality of the optimised schedule is compared in Figure 5.34 with observation data and simulation results. It is seen that the departure punctuality of each segment on the LTN-AMS route is improved significantly after schedule optimisation. The improvement of departure punctuality in these segments of aircraft rotation varies from 20% to 30%. The optimised schedule generates better departure punctuality for all segments ranging between 60% and 70%. The improvement of the departure punctuality in the optimised schedule is due to the increase of scheduled turnaround time for each leg in the schedule. On the other hand, the arrival punctuality of the optimised schedule, compared with the observation data and the simulation results in Figure 5.35, is slightly improved by only 5% to 10% in the optimisation case. Although the scheduled block time in the optimised schedule is slightly less than the original schedule (as shown in Table 5.17), the arrival punctuality of each segment is improved after schedule optimisation due to the improvement of departure punctuality for each leg in aircraft rotations.

Figure 5.34, Figure 5.35

5.5.1.2 Mean delay time

The mean departure delay of the optimised schedule is compared with the one of the observation data and simulation results in Figure 5.36. It is seen that the mean departure delay of the optimised schedule is controlled within the range between 4 minutes and 8 minutes. When compared with the other two cases, it is found that the mean departure delay in the optimised schedule is significantly less. The mean arrival delay of the optimised schedule is also less than the other two cases as shown in Figure 5.37. Overall, the optimisation of aircraft rotational schedule stabilises the development of knock-on delays in aircraft rotations by optimally allocating schedule buffer time to minimise system costs. It is seen in Figure 5.36 and Figure 5.37 that both departure and arrival delay in aircraft rotations are well controlled under this circumstance.

Figure 5.36, Figure 5.37

5.5.1.3 Expected delay time

The expected departure delay of the optimised aircraft rotation is compared with the one of the observation data and the simulation results in Figure 5.38. It is seen that the expected departure delay of segments in the rotation between LTN and AMS is maintained between 8 and 10, while the results from the observation and simulation vary from 10 to 14. In contrast, the expected arrival delay of the optimised schedule is shown in Figure 5.39 to be substantially improved when compared with observation data and simulation results.

Figure 5.38, Figure 5.39

5.5.1.4 Standard Deviation

The comparison of the standard deviation of departure delay of the optimised case is made in Figure 5.40 with observation data and simulation results. It is found that the scattering of departure delay is slightly improved after schedule optimisation. However, the standard deviation of departure delay of the optimised schedule still grows increasingly due to extreme cases in the simulation and optimisation of aircraft rotations. The same results are observed in Figure 5.41 which presents the comparison of the standard deviation of arrival delay of the optimised schedule with both observation data and simulation results.

Figure 5.40, Figure 5.41

5.5.2 Discussions

From previous discussions, it is found that the optimisation of aircraft rotations effectively improves the reliability and stability of aircraft rotations. When the results of the optimisation are compared with observation data from EasyJet and simulation results from the AR model, it is seen that the performance of aircraft rotation is improved in terms of schedule punctuality, mean delay time and expected delay. Although the total schedule time of the rotation between LTN and AMS after optimisation is 59 minutes more than the original schedule, the stability of the aircraft rotational schedule is maintained as well as the total system cost being reduced by 27% or $4,221,185 per thousand aircraft rotations after schedule optimisation.

EasyJet is also working pragmatically on the issue of improving the reliability of aircraft rotations. EasyJet uses intensive aircraft rotations between airports and tends to minimise the turnaround time of aircraft on the ground. The risk of operating such a flight schedule is the significant development of knock-on delays in aircraft rotations which is usually accompanied with a high likelihood of flight cancellation in order to control the quality of aircraft rotation. According to internal reports from EasyJet, the schedule regularity of EasyJet might be as low as 65% for specific routes. As a consequence, EasyJet is also trying to design more buffer time in its schedule by considering the stochastic nature of aircraft rotations. Although the amount of schedule buffer time to be "squeezed" into EasyJet's schedule is limited, it is generally believed that the aircraft rotation schedule would be better stabilised by designing more buffer time in aircraft rotations.

5.6 Reliability of Aircraft Rotations on LTN-AMS Route

Four schedule reliability surrogates are used in this section to measure the reliability of aircraft rotations on the LTN-AMS route. These reliability measures include the mean delay time of a segment of aircraft rotations, the expected delay time of a segment, the standard deviation of departure delay of a segment and the regularity of aircraft rotational schedules (detailed definition of reliability indices is given in Chapter Four).

5.6.1 Mean Delay Time

The mean delay time of each leg in the aircraft rotation on the LTN-AMS route after optimisation is compared with observation results in Figure 5.42. It is clearly seen that the aircraft rotation after optimisation is more reliable than the original schedule because the mean delay time of each rotational segment in the optimised schedule is controlled under 4 minutes. The mean delay time in the original schedule varies from 5 minutes to as high as 16 minutes by the end of the rotation. Therefore, it is found that the optimised aircraft rotational schedule is more reliable and stable in terms of the level of mean delay time of aircraft rotations.

Figure 5.42

5.6.2 Expected Delay Time

The expected delay time of each segment of the original schedule is illustrated in Figure 5.43 and compared with the expected delay time of the optimised schedule. It is seen in Figure 5.43 that the expected delay of the optimised schedule is less than the one of the original schedule and is controlled within 6 minutes. In comparison, the expected delay from the original schedule fluctuates between 4 minutes and 15 minutes. Hence, in terms of the expected delay time of aircraft rotations, the schedule optimisation improves the reliability and stability of aircraft rotations.

Figure 5.43

5.6.3 Standard Deviation of Departure Delay

When the standard deviation of departure delay time of each leg from the optimised schedule is compared with the one from the original schedule, it is seen in Figure 5.44 that the standard deviation of the optimised schedule increases gradually along aircraft rotations. However, it is seen in Figure 5.44 that the standard deviation of the original schedule does not increase with aircraft rotations. The discrepancy in this comparison comes from the assumptions made in the AR model in this research. It has been discussed previously in Section 5.4.2.2 and Section 5.5.1.4 that the development of knock-on delays in the AR model generates more extreme cases (flights with long delays) which are more likely to be cancelled by an airline in the real-world operation. However, the "flight cancellation module" is not featured in the present AR model in the research. Hence, the standard deviation of simulation data has a higher value than the observation results from EasyJet. Hence, it is suggested to include the "flight cancellation module" in future research in order to improve the performance of the proposed AR model in simulating aircraft rotations.

Figure 5.44

5.6.4 Schedule Regularity

The schedule regularity of aircraft rotation is measured according to four delay time thresholds: 30, 45, 60 and 90 minutes at each airport in the rotation. Regularity measures are denoted by the threshold of schedule modification, e.g. R_{REG_30}, R_{REG_45}, R_{REG_60} and R_{REG_90}. Regularity measures of the original schedule are compared with the regularity measures of the optimal schedule in Figure 5.45 and Figure 5.46. It is seen that schedule regularity decreases as the rotation proceeds. The R_{REG_90} of the original schedule is improved from 96% for EZY208 to 99% in the optimised schedule. The R_{REG_60} is improved from 93% for EZY208 in the original schedule to 98% in the optimised schedule. When the chosen delay time thresholds are lower, it is seen in Figure 5.46 that R_{REG_45} and R_{REG_30} decrease significantly along the rotation of aircraft. After the optimisation of the schedule, R_{REG_30} is improved from 86% in the original schedule to 95% as shown and R_{REG_45} is improved from 91% in the original schedule to 97%. Therefore, it is concluded that the optimisation of aircraft rotation schedule stabilises the schedule regularity.

Figure 5.45, Figure 5.46

5.6.5 Discussions

Analysis results in this section suggest that the reliability of aircraft rotation on the LTN-AMS route is improved after schedule optimisation. The schedule reliability in terms of the mean delay time and the expected delay time shows that the schedule stability of the optimised schedule is improved and better controlled than the original schedule. Although the reliability index of the standard deviation of delay time did not reflect the benefit of schedule optimisation at this instance, the index of schedule regularity strongly suggests that the aircraft rotation is more stable and reliable after schedule optimisation. Therefore, it is concluded that the aircraft rotation on the LTN-AMS route could be stabilised by the optimisation methodology proposed in this research in order to reduce system costs and meanwhile improve the reliability of schedule implementation.

5.7 Concluding Remarks

Punctuality data from EasyJet was used in this case study to carry out the simulation and optimisation of the LTN-AMS route. Observation data was used to calibrate the simulation of the AR model in order to produce sound simulations of aircraft rotations. The performance of the optimised schedule is compared with simulation results and observation data in terms of four indices: the departure/arrival punctuality, the mean departure/arrival delay time, the expected departure/arrival delay time and the standard deviation of departure/arrival delay time. As far as schedule reliability is concerned, the reliability of the optimised schedule is evaluated by four reliability surrogates, namely the mean delay time, the expected delay time, the standard deviation of departure delay and the schedule regularity. Findings in this case study are summarised below.

First of all, the current situation analysis to the turnaround disruption history and turnaround efficiency at LTN and AMS suggests that different ground service providers show different operational efficiency. It is found from the results of turnaround efficiency analysis that the service efficiency at LTN is better than at AMS. It is also found from the rotational schedule of the LTN-AMS route that the scheduled turnaround time at LTN is 30 minutes which is shorter than the one at AMS (an average of 40 minutes). However, the turnaround operation at LTN is less stable than its counterpart at AMS especially for long-delayed flights. This conclusion is also validated by OR analysts at EasyJet and this is also the reason why EasyJet tends to schedule a long turnaround buffer time for mid-day turnaround aircraft at LTN (EZY 207 in this case) in order to stabilise the regularity and punctuality of aircraft rotations.

Secondly, the calibration of the MAT model in Section 5.2 shows that the MAT model is good at simulating the operations of aircraft turnaround. It is found that the mean service time to turn around an aircraft is shorter at LTN than at AMS. It is also found that the mean service time varies according to the length of the scheduled turnaround time. As a consequence, it is seen from analysis results that when the longer time is available for turning around an aircraft, the departure punctuality of the flight is not necessarily improved such as EZY207. The calibration of the Enroute model shows that the mean enroute flight time between LTN and AMS is about 60 minutes which includes 3 to 5 minutes of arrival delays in the TMA of the destination airport. This calibration result suggests that the performance of the Enroute model is good and the calibrated enroute block time (60 minutes) is close to the average block time given by EasyJet (59 minutes).

Thirdly, the performance of the AR model in simulating aircraft rotations is good according to comparisons between the results of simulation and observation data. However, differences between the simulation results and the observation data still exist. The discrepancy mainly comes from two aspects. First of all, uncertainties occurred in the real-world operations of aircraft turnaround and aircraft rotations are not perfectly modelled in the AR model due to some model assumptions and simplifications in the modelling process. Hence, minor discrepancy between observation data and simulation results is possible. Secondly, the proposed AR model does not include the feature of "flight cancellation" to deal with those aircraft suffering long delays in the rotation. In the real-world operations, an airline will try to control the propagation of knock-on delays in aircraft rotations by all operational means and consequently delays of extreme cases are controlled within a tolerable range (usually two to three hours). This is also the reason why the standard deviation of departure/arrival delay from the simulation model is higher than its counterpart from observation data.

Fourthly, the optimisation of aircraft rotation effectively improves the reliability and stability of aircraft rotations. When the results of the optimisation are compared with observation data from EasyJet and simulation results from the AR model, it is seen that the performance of aircraft rotation is improved in terms of schedule punctuality, mean delay time and expected delay time. Although the total schedule time of the daily rotation between LTN and AMS after optimisation is 59 minutes longer than the original schedule, the stability of the aircraft rotational schedule is maintained as well as the total system cost is reduced by 27% or $4,221,185 per thousand rotations after schedule optimisation

Finally, analysis results of schedule reliability suggest that the reliability of aircraft rotation on the LTN-AMS route is improved after schedule optimisation. The schedule reliability in terms of the mean delay time and the expected delay time shows that the schedule stability of the optimised schedule is improved and better controlled than the original schedule. Although the reliability index of standard deviation of delay time did not reflect the benefit of schedule optimisation at this instance, the index of schedule regularity strongly suggests that the aircraft rotation is more stable and reliable after schedule optimisation. Therefore, it is concluded after this case study that the aircraft rotation on the LTN-AMS route could be stabilised by the optimisation methodology proposed in this research in order to reduce system costs and meanwhile improve the reliability of schedule implementation.

CHAPTER SIX CASE STUDY - BRITISH AIRWAYS

Punctuality data from British Airways was collected to carry out the second case study in order to further validate the proposed AR model and to compare the scheduling difference between a schedule airline (British Airways) and a low-cost airline (EasyJet). Punctuality data from December 1999 to May 2000 for all European short-haul routes was provided by British Airways. A typical aircraft rotation route for a B757 (aircraft registration number: GBMRH) of British Airways was chosen for this study. The aircraft rotational schedule (the winter schedule in 1999-2000) is given in Table 6.1. The study rotation started from London Heathrow Airport (**LHR** hereafter) in the morning. The aircraft flew to Amsterdam Schiphol Airport (**AMS** hereafter) and returned to LHR. Then this aircraft proceeded five segments of shuttle services between LHR and Paris Charles de Gaulles Airport (**CDG** hereafter). There were seven segments in one-day aircraft rotation for this aircraft. The rotation started at 07:00 hours (times are based on GMT hereafter) departing from LHR and finished at 22:00 hours arriving at CDG. The scheduled turnaround time (*TSG*) at AMS was 60 minutes. The scheduled turnaround time at LHR varied from 75 minutes to 80 minutes and the schedule turnaround time at CDG was 55 minutes. The standard ground service time for a B757 of British Airways is 55 minutes at any airport.

Table 6.1

The structure of this case study is the same as the one illustrated by Figure 5.1. This case study starts from Section 6.1, Current Situation Analysis, which contains analyses of turnaround disruption history and turnaround efficiency at LHR, AMS and CDG airports. Model parameters required to run the AR model are calculated after detailed data analyses in this section. The calibration of the MAT model is described in Section 6.2, MAT Model Calibration. Model parameters for the MAT model are calculated and analysed in this section by applying the MAT model to LHR, AMS and CDG airports. The calibration of the Enroute model is given in Section 6.3, Enroute Model Calibration, in order to model the enroute flight time of an aircraft between LHR and AMS and between LHR and CDG. The simulation of aircraft rotation is presented in Section 6.4, AR Model Application. Results from simulation are discussed and compared with observation results from British Airways. The aircraft rotation schedule is then optimised and results are given in Section 6.5, AR Model Optimisation. Results from schedule optimisation are compared with both observation and simulation results in this section. Four schedule reliability surrogates are applied to this case study to evaluate the reliability of aircraft rotation on the study route. Measurements of schedule reliability are discussed in Section 6.6, Reliability of Aircraft Rotations. Concluding remarks are given in the last section, Section 6.7.

6.1 Current Situation Analysis

6.1.1 Turnaround Disruption History Analysis (LHR)

The result of the cargo & baggage processing flow analysis is given in Table 6.2. It is found that there is a probability of 0.003 of encountering cargo processing problems for turnaround aircraft at LHR. There is a relatively higher probability of 0.02 for aircraft ramp handling problems to occur. Although more detailed delay codes were not recorded by ground crews of British Airways, it is speculated that aircraft ramp handling problems are due to busy ground operations at London Heathrow Airport. Delays due to cargo and baggage processing problems vary from 11 minutes to 25 minutes. According to statistical analysis of passenger processing at LHR, it is found in Table 6.3 that there is a high probability of 0.16 of encountering delays due to departure flight operations which result from departure slot allocation and ground congestion at LHR. Delays occurred in the processing of passengers and cabin cleaning vary between 12 minutes and 45 minutes, the latter being due to weather causes.

Table 6.2, Table 6.3, Table 6.4

The analysis of disrupting events at LHR in Table 6.4 shows that there is a high probability, 0.02, for aircraft damage (including aircraft damage during flight operations & ground operations and aircraft defects coded as **TD** by the **IATA** delay code system) to occur during ground operations by British Airways at LHR and the resulted departure delay for a turnaround aircraft is about 23 minutes. There is a relatively low probability to have aircraft engineering delay events and aircraft change delay events, but they result in long departure delays (43 and 69 minutes respectively) to turnaround aircraft as shown in Table 6.4.

6.1.2 Turnaround Efficiency Analysis (LHR)

Punctuality data of three turnaround flights at LHR, BA308, BA318 and BA326, are used to evaluate the turnaround efficiency of ground operations by British Airways at LHR. Regression results of punctuality data are given in Table 6.5 and illustrated in Figure 6.1, Figure 6.2 and Figure 6.3. It is seen from linear regression results in Table 6.5 that the slope of regression equations is less than 1. In other words, the arrival delay is usually absorbed by aircraft turnaround buffer time at LHR, though the value of R^2 of linear regression equations is not high (0.6 maximum). The standard ground service time for a B757 by British Airways at LHR is 55 minutes. The scheduled turnaround time for these flights are around 80 minutes. Hence, there are 25 minutes of schedule buffer time for aircraft turnaround operations at LHR. When quadratic functions are employed in regression analysis, it is found that quadratic functions fit observation data better for the case of BA308 as shown in Figure 6.1. It implies that the departure delay of turnaround aircraft might increase more sharply when the arrival delay of inbound aircraft exceeds 60 minutes.

Table 6.5
Figure 6.1, Figure 6.2, Figure 6.3

6.1.3 Turnaround Disruption History Analysis (AMS)

The disruption history of turnaround aircraft at AMS is given in Table 6.6. It is seen that the occurrence probability of cargo processing disruption and passenger & baggage processing problem is relatively low when compared with aircraft ramp handling disruption. This result is similar to that of LHR, but delays to turnaround operations at AMS are shorter. Delays due to cargo & baggage process at AMS are between 5 minutes and 14 minutes. The occurrence probability of the passenger processing flow is given in Table 6.7. It is found that departure delays to turnaround operations at AMS are lower when compared with LHR. However, it is seen that there is a high probability of 0.11 to encounter departure delay due to departure procedures at AMS. This is mainly due to airport ground congestion at AMS. There is 0.003 probability to encounter the event of aircraft damage which includes aircraft damage during flight operations & ground operations and aircraft defects. The consequent delay due to aircraft damage is as high as 142 minutes because AMS is not the base airport of British Airways so it takes a longer time to solve such a disruption.

Table 6.6, Table 6.7, Table 6.8

6.1.4 Turnaround Efficiency Analysis (AMS)

Regression analysis was applied to the punctuality data of a turnaround flight, BA427, at AMS. Regression results are illustrated in Figure 6.4 and given in Table 6.9. The scheduled turnaround time was 60 minutes for a B757 to turn around at AMS, so the buffer time for BA427 is limited. Analysis results in Figure 6.4 show that the slope of the regression line is 0.9 which is close to 1.0 and the value of R^2 of the regression line is 0.75. Hence, it is concluded that the turnaround efficiency of BA427 at AMS is well controlled.

Table 6.9
Figure 6.4

6.1.5 Turnaround Disruption History Analysis (CDG)

The disruption history analysis of the cargo & baggage processing of aircraft turnaround at CDG is given in Table 6.10. It is seen that the occurrence probability of aircraft ramp handling is 0.03 and the resulting delay to aircraft turnaround operation averages 12 minutes. Regarding the disruption probability and duration in the passenger processing flow, analysis results in Table 6.11 show that there is a higher probability of 0.06 to encounter delays due to aircraft departure process at CDG. The consequent delay due to this disruption averaged 29 minutes. The analysis result of disrupting events at CDG is shown in Table 6.12. It is seen that the occurrence probability of disrupting events at CDG is lower than its counterparts at LHR and AMS. There is a higher probability of aircraft damage and aircraft fuelling delays at CDG than the other two events.

Table 6.10, Table 6.11, Table 6.12

6.1.6 Turnaround Efficiency Analysis (CDG)

The scheduled turnaround time at CDG was 55 minutes which is equivalent to the standard turnaround service time of a B757 of British Airways. Regression results of two turnaround flights, BA309 and BA319, are given in Table 6.13 and illustrated in Figure 6.5 and Figure 6.6. It is seen from regression analysis results that the departure delay of a turnaround aircraft at CDG is highly correlated to the arrival delay of its inbound flight. It implies, first of all, that the turnaround efficiency of BA309 and BA319 at CDG is well managed. Secondly, the scheduled turnaround time for these two flights is just enough for a B757 to be serviced. Hence, the arrival delay due to late inbound aircraft is not likely to be absorbed by ground operations at CDG and it is more likely that the arrival delay might influence turnaround operations and result in equivalent or higher departure delay to turnaround aircraft.

Table 6.13
Figure 6.5, Figure 6.6

6.2 MAT Model Calibration

In addition to regression analysis in the previous section, the MAT model was also employed to calibrate the turnaround efficiency of British Airways at LHR, AMS and CDG by using historical punctuality data of inbound aircraft as well as departure punctuality records of outbound aircraft. Results of punctuality analysis of the study aircraft rotation are given in Table 6.14. It is seen that the mean departure delay on the study route is between 6 and 15 minutes with the standard deviation varying between 16 and 24. The mean arrival delay is between 4 and 13 minutes, while the standard deviation varying between 19 and 28. The expected departure delay of observation varies from 6 to 15 minutes. It is found from the aircraft turnaround schedule and punctuality analysis results that delays incurred to earlier flights in a rotation schedule might be absorbed by ample turnaround time scheduled at LHR as well as by scheduled airborne block time. Hence, it is seen that the mean departure delay decreases to 6 minutes by the end of the rotation.

Table 6.14

6.2.1 MAT Model Application to LHR

6.2.1.1 Current situation analysis (LHR)

Three turnaround flights at LHR, BA308, BA318 and BA326, were studied to calibrate the turnaround efficiency of British Airways at LHR. Punctuality analysis results of these flights are given in Table 6.15. The scheduled turnaround time for these flights varies from 75 minutes to 80 minutes, while the standard ground service time for a B757 by British Airways being 55 minutes at LHR. It is seen in Table 6.15 that the mean arrival delay is about 15 minutes and the departure delay varies from 6 to 12 minutes.

Table 6.15

6.2.1.2 MAT model calibration (LHR)

When the arrival punctuality of BA308 was applied to the MAT model to calibrate the turnaround efficiency of British Airways at LHR, it is seen in Figure 6.7 that the simulated departure CDF of BA308 shows a similar shape as observation data. After the *K-S test*, it is found that the tested K-S value of simulation CDF of BA308 is 0.06 which is lower than the critical *K-S test* value, 0.21, for this case. Hence, the hypothesis that the simulated CDF fits observation data is not rejected. The mean turnaround time after the MAT model calibration is 60 minutes. In the comparison of observation data and simulation results of BA308 from the MAT model, it is seen in Table 6.15 that the simulation result of the MAT model is close to observation data. When the punctuality data of BA318 and BA326 was applied to the MAT model, it is seen in Figure 6.8 and Figure 6.9 that the simulation CDF is close to the observation CDF. Both simulation results of BA318 and BA326 passed the *K-S goodness-of-fit test* as shown in Table 6.15. It is also found that simulation results are close to observation data for these two cases. The calibrated turnaround time for these two flights is about 55 minutes.

Figure 6.7, Figure 6.8, Figure 6.9

6.2.2 MAT Model Application to AMS

6.2.2.1 Current situation analysis (AMS)

There is one flight, BA427, turned around at AMS on the study route. The punctuality analysis of BA427 is given in Table 6.16. The scheduled turnaround time for BA427 at AMS was 60 minutes which is just 5 minutes more than the standard turnaround time of a B757 according to British Airways operational standards. The mean departure delay of BA427 is 14 minutes with the mean inbound delay of 13 minutes.

Table 6.16

6.2.2.2 MAT model calibration (AMS)

The result of the MAT model calibration for BA427 is illustrated by Figure 6.10 and shown in Table 6.16. It is seen in Figure 6.10 that there are more flights in observation which were delayed more than 60 minutes than simulation results. The calibration results in Table 6.16 show that the mean turnaround time of BA427 is 45 minutes which is shorter than the standard turnaround time of a B757 aircraft (55 minutes). It implies that the turnaround efficiency at AMS is better than the standard turnaround efficiency defined by British Airways. However, observation results also suggest that there is a higher probability for BA427 to suffer long delay. The result of K-S test in Table 6.16 suggests that the goodness-of-fit of BA427 simulation is acceptable and the mean delay values from simulation are close to observation in this case.

Figure 6.10

6.2.3 MAT Model Application to CDG

6.2.3.1 Current situation analysis (CDG)

Two flights, BA309 and BA319, are turned around at CDG on the study aircraft rotation route. The scheduled turnaround time for these two flights at CDG was 55 minutes. It implies that if the operational efficiency of ground service providers is normal, i.e. 55 minutes for a B757, the arrival delay from inbound aircraft might not be absorbed by turnaround operations at CDG. It is seen from punctuality analysis results given in Table 6.17 that the inbound delay of these flights is about 15 minutes and the outbound delay is about 15 minutes as well.

Table 6.17

6.2.3.2 MAT model calibration (CDG)

The MAT model calibration for BA309 in Figure 6.11 suggests that observation data has more long-delayed flights than simulation results, though the K-S test value for this case (0.08) is still under the critical rejection value of statistical hypothesis testing. The K-S test value for the MAT model calibration of BA319 is 0.07 as illustrated in Figure 6.12. The punctuality analysis from simulation results when compared with observation in Table 6.17 shows that the simulation result is statistically acceptable. The calibrated turnaround time at CDG is 40 minutes for BA309 and 45 minutes for BA319. However, the limited ground time scheduled at CDG makes it difficult to absorb inbound delays for these two flights.

Figure 6.11, Figure 6.12

6.3 Enroute Model Calibration

6.3.1 Enroute Model Calibration: between LHR and AMS

The enroute flight time between LHR and AMS was calibrated by using the departure CDF at the origin airport and the arrival CDF at the destination airport. There are two flights, BA426 and BA427, between LHR and AMS in the study rotation. Calibration results are given in Table 6.18 and illustrated in Figure 6.13 and Figure 6.14. The scheduled block time for these two flights was 75 minutes. According to the scheduling policy of British Airways, the inbound delay (including ground taxi time) at AMS is 6 minutes and 7 minutes at LHR. When the result of Enroute model calibration is compared with observation, it is found in Table 6.18 that the simulation result of the Enroute model is good and the calibration results of both flights passed the *K-S goodness-of-fit test*. The calibrated mean flight time between LHR and AMS is 65 minutes or 72 minutes including arrival delays in the TMA of the destination airport.

Table 6.18

Figure 6.13, Figure 6.14

6.3.2 Enroute Model Calibration: from LHR to CDG

There are three flights, BA308, BA318 and BA326, flying from LHR to CDG in the study aircraft rotation. The results of the enroute flight time calibration from LHR to CDG are shown in Table 6.19. The scheduled block time was 65 minutes for BA308 and BA318 and 60 minutes for BA326. The calibrated enroute flight time is 57 minutes for BA308 and BA318 and 50 minutes for BA326. When the simulation CDF of inbound aircraft is compared with the observed arrival CDF of BA308, it is seen in Figure 6.15 that the simulation CDF is close to the observation curve. After the K-S test, it is found that the K-S test value for BA308 case is 0.06 which is lower than the critical value for this case. Hence, the calibration result of BA308 is statistically acceptable. In addition, the mean departure and arrival delay from simulation results is found close to observation results in Table 6.19. The enroute flight times of BA308 and BA318 are higher than BA326. This might be due to the congestion of airspace for the former two flights because of their scheduled flight time (12.55 arrival for BA308 and 17.20 arrival for BA318).

Table 6.19

Figure 6.15, Figure 6.16, Figure 6.17

6.3.3 Enroute Model Calibration: from CDG to LHR

There are two flights, BA309 and BA319, flying from CDG to LHR on the study route. The Enrotue model calibration result is presented in Table 6.20 and illustrated in Figure 6.18 and Figure 6.19. The mean departure and arrival delay from simulation is found close to observation results in Table 6.20. It is also found that the calibrated enroute flight time of BA319 is longer than BA309. This situation is reflected by the scheduling of these two flights. There was a longer scheduled block time, 85 minutes, for BA319 and 70 minutes for BA309. Both calibrated CDFs of arrival aircraft passed the K-S test as shown in Table 6.20.

Table 6.20

Figure 6.18, Figure 6.19

6.4 AR Model Application

6.4.1 Model Parameters

The value of the unit delay cost of a passenger ($C_p(s)$ in equation (4-12)) used in the AR model is \$0.03/min^2, which is equivalent to a delay cost of \$54 per hour, per passenger (Wu and Caves, 2000). The value of the unit delay cost of an aircraft ($C_A(s)$ in equation (4-12)) is estimated by British Airways to be \$120 per minute for ground delays, which is equivalent to a delay cost of \$7,200 per hour, per aircraft (a B757). The opportunity cost of schedule buffer time (C_{AL}^{m} in equation (4-12)) is estimated by British Airways to be \$5.5/min^2, which is equivalent to \$9,900 per hour for LHR-CDG route. Equal weights, i.e. $\alpha = 0.5$, on the delay cost of passengers and the airline schedule time cost are used in the simulation of aircraft rotation.

6.4.2 Simulation Results

Simulation results of the AR model are presented in Table 6.21. The mean departure delay on the study route varies from 8 minutes to 15 minutes with standard deviation varying from 13 to 26. The mean arrival delay is between 5 minutes and 14 minutes with standard deviation valued being between 16 and 27. The development of knock-on delay in aircraft rotation is not significant for this case because there is ample turnaround time scheduled at LHR for aircraft turnaround operations. However there are some potential weak links in the rotation schedule such as BA426-BA427, BA308-BA309 and BA318-BA319 due to short turnaround time on the ground. The performance of the AR model is evaluated in the following sections by four factors: the departure/arrival punctuality, the mean departure/arrival delay, the expected departure/arrival delay and the standard deviation of departure/arrival delay.

Table 6.21

6.4.2.1 Punctuality

The simulated departure punctuality of all segments in the study rotation is compared with the observed departure punctuality in Figure 6.20. It is seen that the departure punctuality from simulation is close to the one from observation except flight BA426. The difference between the departure punctuality from simulation and the one from observation varies from 0% to 10%. The arrival punctuality from simulation results is shown in Figure 6.21. It is seen that the observed arrival punctuality is somewhat lower than the arrival punctuality from simulation except BA426. It is seen in Figure 6.20 that the observed departure punctuality of segments in the study rotation varies between 30% and 40% and the arrival punctuality being between 30% and 50%.

Figure 6.20, Figure 6.21

6.4.2.2 Mean delay time

When the mean departure delay from simulation is compared with observation data in Figure 6.22, it is seen that the simulation result is close to observations. The maximum difference between the observed mean departure delay and the simulated departure delay is 2 minutes. The mean arrival delay from simulation is compared with the mean arrival delay from observations in Figure 6.23. It is found that the maximum difference between the arrival delay from simulation and observation is 2 minutes. Overall, the AR model has simulated the fluctuation of delays in the study aircraft rotation.

Figure 6.22, Figure 6.23

6.4.2.3 Expected delay time

The expected departure delay from the AR model is compared with the observed expected delay in Figure 6.24. It is seen that the difference between the model output and the observation result is 3 minutes maximum for the last segment, BA326. Simulation performance is relatively good for the other segments in the rotation according to Figure 6.24. The comparison of the expected arrival delay is shown in Figure 6.25. It is seen that the expected arrival delay from simulation is close to the one from observation. The maximum difference between these two cases is 2 minutes.

Figure 6.24, Figure 6.25

6.4.2.4 standard deviation

The standard deviation of departure delay from the AR model is compared with the standard deviation from observation in Figure 6.26. It is seen that the standard deviation from observation varies between 15 and 24 but the standard deviation of departure delay from simulation increases gradually from 14 to

20 by the end of the rotation. The similar phenomenon is seen in Figure 6.27 when the standard deviation of arrival delay from the AR model is compared with its counterpart from observation data.

Figure 6.26, Figure 6.27

6.4.3 Discussions

The performance of the AR model is presented in the previous sections and compared with observation results. It is seen that the AR model successfully simulates the rotation of the LHR-AMS-CDG route. However minor discrepancy between the model output and the observation data still exists due to model assumptions and simplifications in the modelling process as well as operational uncertainties in the real-world situation. As far as the effectiveness of the AR model is concerned, the performance of the present model is acceptable to serve as a schedule analysis and planning tool for an airline. A flight cancellation module could be included in future research in order to improve the modelling of the management of schedule implementation of an airline, e.g. flight cancellation and aircraft swap between routes.

6.5 AR Model Optimisation

The result of schedule optimisation is given in Table 6.22. It is seen that the mean departure and arrival delay both decrease. The mean departure delay is controlled within 7 minutes with a standard deviation under 19. The mean arrival delay is controlled under 1 minute, though the standard deviation is still high. The expected departure delay after optimisation is maintained under 9 minutes. It implies that the departure punctuality of aircraft rotation after schedule optimisation is improved.

Table 6.22

6.5.1 Optimisation Results

The optimisation of aircraft rotation schedule is done by re-allocating schedule buffer time in aircraft rotation in order to minimise system costs. The optimised schedule time of segments in the study rotation is given in Table 6.23 and illustrated in Figure 6.28. It is seen that the optimised schedule time of most segments in the rotation is higher than the original schedule except the last segment, BA326. The total rotation time after optimisation is 1,005 minutes which is 45 minutes more or 5% more than the original schedule.

Table 6.23

Figure 6.28

When the system cost of the original schedule is compared with that after schedule optimisation in Figure 6.29, it is seen that the system cost of the original schedule increases significantly along aircraft rotation. Although the system cost of the optimised schedule also grows gradually along aircraft rotation, a significant reduction of system cost is seen in the optimisation case in Figure 6.29. A total saving of $9,305,127 (43%) per thousand aircraft rotation (which is equivalent to one and a half-year operation of the study aircraft) is gained after schedule optimisation. In order to investigate the change of system costs before and after schedule optimisation, the break-down of system cost for the original schedule and the optimised schedule is listed in Table 6.24. It is seen in Figure 6.30 that the passenger delay cost decreases 8% and the aircraft delay cost decreases 11%. Since the use of schedule time is increased after schedule optimisation, the share of schedule time cost increases by 19%.

Table 6.24

Figure 6.29, Figure 6.30

The effectiveness of schedule optimisation is evaluated by comparing observation data, simulation results and optimisation results in following sections. The comparison is made by four factors: the departure/arrival punctuality, the mean departure/arrival delay, the expected departure/arrival delay and the standard deviation of departure/arrival delay.

6.5.1.1 Punctuality

The departure punctuality of the optimised schedule is compared in Figure 6.31 with observation data and simulation results. It is seen that the departure punctuality of each segment in the rotation is significantly improved after schedule optimisation. The improvement of departure punctuality in the rotation varies between 10% and 50%. The departure punctuality after schedule optimisation is maintained above 75% as shown in Figure 6.31. Regarding the comparison of the arrival punctuality between three cases, it is seen in Figure 6.32 that the arrival punctuality is also significantly improved after schedule optimisation. The arrival punctuality after schedule optimisation is maintained about 70% which is 10% to 30% higher than the other two cases.

Figure 6.31, Figure 6.32

6.5.1.2 Mean delay time

The mean departure delay of the optimised schedule is shown in Figure 6.33 and compared with the departure delay from the observation data and the simulation result. It is seen that the mean departure delay after schedule optimisation is controlled under 6 minutes. Regarding the mean arrival delay, it is found in Figure 6.34 that the mean arrival delay is significantly improved after schedule optimisation when compared with simulation and observation results. A maximum improvement of 14 minutes to mean arrival delay is found from the optimisation case. Hence, the optimisation of aircraft rotation schedule is found effective in terms of the control of departure/arrival delay.

Figure 6.33, Figure 6.34

6.5.1.3 Expected delay time

The expected departure delay of the optimised schedule is compared with the expected departure delay of the observation data and the simulation result in Figure 6.35. It is seen that the expected departure delay is less for the optimisation case. The expected departure delay after optimisation is maintained under 9 minutes. Regarding the expected arrival delay after schedule optimisation, it is seen in Figure 6.36 that the expected arrival delay is controlled under zero. It is found that the expected arrival delay after schedule optimisation is significantly improved.

Figure 6.35, Figure 6.36

6.5.1.4 Standard deviation

The comparison of the standard deviation of departure delay after schedule optimisation is made in Figure 6.37 with observation and simulation results. It is seen that the standard deviation of the optimisation case is less than the other two cases, though it still increases gradually from 10 to 19. The similar result is seen in the comparison of standard deviation of arrival delay of the optimisation case with the observation and simulation case in Figure 6.38. Overall, the deviation of departure/arrival delay in the optimisation case is improved when compared with the other two cases.

Figure 6.37, Figure 6.38

6.5.2 Discussions

The effectiveness of the AR model optimisation is presented in previous sections. It is seen that the optimisation of aircraft rotation improves the reliability of the schedule in terms of flight punctuality, mean delay time and expected delay. Although the total schedule time of the study rotation increases by 45 minutes (5%) after optimisation, a system cost saving of $9,305,127 (43%) per thousand aircraft rotation (which is equivalent to one and a half-year operation of the study aircraft, GBMRH) is gained after schedule optimisation.

It is found in the result of schedule optimisation in Table 6.23 that the leg-time of early rotation legs, i.e. BA426, BA427 and BA308, is higher than the original schedule and the optimised leg-time decreases for later rotation legs. The optimisation tends to allocate more buffer time for early legs in a rotation in order to reduce delays from early segments of the rotation. The ample buffer time in early legs of the rotation also reduces the development of knock-on delays in the early rotation and hence reduces the use of schedule buffer time in later rotational legs. This is called the influence of "morning readiness" on the reliability of aircraft rotation.

When the British Airways's case is compared with EasyJet's case, it is found that there are two major differences between these two case studies. First of all, EasyJet uses intensive aircraft rotation schedules on the study route so the development of knock-on delay is more significant (as shown in Figure 5.36) than the case of British Airways. The schedule optimisation improves more significantly the reliability of EasyJet's schedule than British Airways's case in terms of the control of knock-on delays in aircraft rotation. Secondly, it is seen in the rotation schedule of the British Airways's case that there is ample turnaround time (80 minutes) scheduled at LHR. Hence the development of knock-on delay in British Airways's case is somewhat controlled by this scheduling policy. This scheduling policy of British Airways has been discussed previously in Chapter Four and compared with other scheduling policies including EasyJet's case, i.e. intensive rotation schedules. The disadvantage of British Airways's scheduling policy is that the mean departure delay at outstations is usually higher than the one at the base airport (as shown in Table 6.21) and consequently the arrival delay at the base airport is also higher than at outstations. Although the scheduled turnaround time at LHR is high (80minutes in this case), it is usually consumed by arrival delays to inbound aircraft so the effectiveness of the control of knock-on delays by long scheduled turnaround time at LHR is also limited.

6.6 Reliability of Aircraft Rotation

The reliability of aircraft rotation in British Airways's case was investigated by applying four schedule reliability indices, namely the mean delay time of a segment in the rotation, the expected delay time of a segment, the standard deviation of departure delay of a segment and the regularity of aircraft rotation schedules, to the optimised schedule and the original schedule.

6.6.1 Mean Delay Time

The mean delay time of each leg in the study rotation after optimisation is compared with observation (original) results in Figure 6.39. It is seen that the aircraft rotation after schedule optimisation is more reliable than the original one because the mean delay of each leg in the optimisation case is maintained under 5 minutes. The mean leg delay time in the original schedule varies from 6 minutes to 29 minutes. Hence, it is found that the schedule reliability is significantly improved after optimisation in terms of the level of mean leg delay time in aircraft rotations.

Figure 6.39

6.6.2 Expected Delay Time

The expected delay time of each segment of the original schedule is compared in Figure 6.40 with the expected leg delay time after schedule optimisation. It is seen that the expected leg delay in the original schedule increases from 15 minutes at the start of the rotation and to as high as 25 minutes in the mid day and decreases to 6 minutes by the end of the rotation. The expected delay after schedule optimisation is maintained between 5 and 7 minutes in this instance. Hence, it is found that the schedule optimisation improves the reliability and stability of aircraft rotations in terms of the expected leg delay time in the rotation schedule.

Figure 6.40

6.6.3 Standard Deviation of Departure Delay

When the standard deviation of the departure delay time in the optimisation case is compared with the one of the original case in Figure 6.41, it is seen that the standard deviation of the optimised schedule increases gradually from 10 to 19 at the end of the rotation. According to observation results in Figure 6.41, it is found that the standard deviation in the original schedule varies between 16 and 23. This discrepancy like the one found in EasyJet's case study comes from the operational control of airlines to knock-on delays in aircraft rotation. Hence, it is recommended that airline adjustments in the management of aircraft rotation, e.g. aircraft changes and flight cancellation, should be included in future research in order to improve the AR model.

Figure 6.41

6.6.4 Schedule Regularity

The schedule regularity of the original schedule is compared with the one of the optimised schedule in Figure 6.42 and Figure 6.43 by four thresholds of schedule modification: 30, 45, 60 and 90 minutes (denoted by R_{REG_30}, R_{REG_45}, R_{REG_60} and R_{REG_90} respectively). It is seen in Figure 6.42 that the schedule regularity (R_{REG_60} and R_{REG_90}) for the first few legs is lower in the original schedule and it increases gradually as the rotation proceeds in a day. Regarding the schedule regularity for lower thresholds, i.e. R_{REG_30} and R_{REG_45}, it is observed in Figure 6.43 that the schedule regularity varies between 80% and 90% for most of legs in the rotation. When the schedule regularity of the optimisation case is compared with observation results, it is found that the improvement of schedule regularity ranges between 1% to 7% in terms of R_{REG_90} and 5% to 14% in terms of R_{REG_60}. The improvement of schedule regularity is between 2% and 12% in terms of R_{REG_45} as shown in Figure 6.43 and 2% to 15% in terms of R_{REG_30}. Therefore, it is seen from above analysis that the schedule regularity of aircraft rotation is higher after schedule optimisation.

Figure 6.42, Figure 6.43

6.6.5 Discussions

Results presented in this section suggest that the reliability of aircraft rotation on the study route is improved after schedule optimisation. The schedule reliability in terms of the mean delay time and the expected delay time shows that the reliability of the optimised schedule is higher and better-controlled than the original one. In addition, the regularity analysis of the optimised schedule strongly suggests that the robustness and reliability of schedule implementation is improved after optimisation. Therefore, it is concluded that the optimisation of the LHR-AMS-CDG route by British Airways improves the punctuality as well as the reliability of aircraft rotation.

6.7 Concluding Remarks

Punctuality data from British Airways was used in this case study to validate the AR model in this research. Observation data was used to calibrate the MAT model and the Enroute model in order to evaluate the operational efficiency of turnaround operations by British Airways and the airspace congestion between LHR, AMS and CDG airports. Simulation results from the AR model were compared with observation data in order to evaluate the modelling performance of the AR model. The study rotation was then optimised by minimising system costs. The effectiveness of the schedule optimisation was evaluated by comparing optimisation results with simulation and observation data through four reference factors: the departure/arrival punctuality, the mean departure/arrival delay, the expected departure/arrival delay and the standard deviation of departure/arrival delay. In addition, the implementation reliability of the optimised schedule was evaluated by four schedule reliability indices, namely the mean delay time, the expected delay time, the standard deviation of departure delay and the schedule regularity. Findings in this case study are given as follows.

First of all, the aircraft rotation schedule of the LHR-AMS-CDG route by British Airways shows that there is less turnaround time scheduled at outstations (60 minutes for B757 turnaround at AMS and 55 minutes at CDG) and longer turnaround time allowed for aircraft turnaround at LHR (75 to 80 minutes). Hence, the development of knock-on delays in the rotation could be controlled by ground operations at the base airport of British Airways, i.e. LHR. Observation results of the study rotation given in Table 6.14 also shows that the departure delay at outstations is higher when compared with the one at LHR. The study of turnaround disruption history at LHR shows that there is a high probability (0.16) to have departure delays due to departure flight operation procedures, e.g. airport tower control and airport ground congestion delay. The turnaround efficiency analysis of British Airways at LHR suggests that the departure delay of a turnaround aircraft might escalate significantly when the arrival delay exceeds 60 minutes. The turnaround history analysis at CDG also shows that there is a high probability (0.11) to have departure delays due to flight operation procedures. Although the scheduled turnaround time at outstations for the study route is less than at LHR, regression analysis results at CDG and AMS show that the turnaround efficiency at outstations is relatively good when compared with LHR.

Secondly, the results of the calibration of the MAT model shows that the modelling performance of the MAT model is good as shown in Table 6.15, Table 6.16 and Table 6.17. It is found that the average turnaround time for a B757 at different airports is not constant. It is found that the average turnaround time of a B757 at AMS and CDG is about 45 minutes while the same aircraft's turn time is 50 to 60 minutes at LHR. This might be due to the worse aircraft turnaround efficiency by British Airways at LHR or more operational procedures being required by British Airways for aircraft turnaround operations at its base airport. The calibration result of the Enroute model shows that the average flight time between airports varies according to the time of flight as well as the congestion of the destination airport TMA.

Thirdly, the modelling performance of the AR model was evaluated by comparing simulation results with observation data on the study rotation. It is found that the modelling performance of the AR model is good in terms of the departure/arrival punctuality, the mean departure/arrival time and the expected departure/arrival time. Although minor discrepancy between simulation and observation results still exits when the modelling performance was evaluated by the standard deviation of departure/arrival delay time, the performance of the AR model in simulating aircraft rotations is still statistically approved.

Fourthly, the aircraft rotation schedule was optimised by minimising system costs. It is found that the optimisation of aircraft rotation improves the reliability of the schedule in terms of flight punctuality, mean delay time and expected delay. Although the total schedule time of the study rotation increases by 45 minutes (5%), a system cost saving of $9,305,127 (43%) per thousand aircraft rotation (which is equivalent to one and a half-year operation of the study aircraft, GBMRH) is gained after schedule optimisation. It is found in Table 6.23 that the leg-time of early rotation legs, i.e. BA426, BA427 and BA308, is higher than the original schedule and the optimised leg-time decreases for later rotation legs. The optimisation tends to allocate more buffer time for early legs in this case in order to reduce delays from early segments in the rotation. The ample buffer time in early legs of the rotation also reduces the development of knock-on delay and hence reduces the use of schedule buffer time in later rotational legs. This is the influence of lack of "morning readiness" on the reliability of aircraft rotation.

Fifthly, when the British Airways's case is compared with EasyJet's case, it is found that there are two major differences between these two case studies. First of all, EasyJet uses intensive aircraft rotation schedules on the study route so the development of knock-on delay is more significant (as shown in Figure 5.36) than the case of British Airways. The schedule optimisation improves more significantly the reliability of EasyJet's schedule than British Airways's case in term of the control of knock-on delay in aircraft rotation. Secondly, it is seen in the rotation schedule of the British Airways's case that there is ample turnaround time (80 minutes) scheduled at LHR. Hence the development of knock-on delay in British Airways's case is somewhat controlled by this scheduling policy. This scheduling policy of British Airways has been discussed previously in Chapter Four and compared with other scheduling policies including EasyJet's case, i.e. intensive rotation schedules. The disadvantage of the scheduling policy in the study rotation is that the mean departure delay at outstations is usually higher than the one at the base airport (as shown in Table 6.21) and consequently the arrival delay at the base airport is also higher than at outstations. Although the scheduled turnaround time at LHR is high (80 minutes in this case), it is usually consumed by arrival delays to inbound aircraft so the effectiveness of the control of knock-on delays by long scheduled turnaround time at LHR is also limited.

Finally, schedule reliability analysis suggests that the reliability of aircraft rotation on the study route is improved after schedule optimisation. The schedule reliability in terms of the mean delay time and the expected delay time shows that the reliability of the optimised schedule is higher and better-controlled than the original one. In addition, the regularity analysis of the optimised schedule strongly suggests that the robustness and reliability of schedule implementation is improved after optimisation. Therefore, it is concluded that the optimisation of the LHR-AMS-CDG route by British Airways improves the punctuality as well as the reliability of aircraft rotation.

CHAPTER SEVEN CONCLUSIONS AND RECOMMENDATIONS

7.1 Research Conclusions

The Aircraft Rotation model (AR model) was developed in this research to simulate the turnaround operations of an aircraft on the ground as well as the rotation of the aircraft between airports. Two sub-models were included in the AR model, namely the Aircraft Turnaround model which was developed to model aircraft turnaround operations and the Enroute model which was employed to integrate aircraft turnaround models at different airports to simulate aircraft rotations. The Aircraft Turnaround model was developed by two approaches, namely the aggregate approach (the AAT model) and the dis-aggregate approach (the MAT model). The comparison of the modelling performance between these two approaches was made in this research and the MAT model was chosen to serve as the core module in the AR model. The AR model was used to simulate the rotation of an aircraft in a multiple airport environment.

The AR model was applied in two case studies (British Airways and EasyJet) to optimise aircraft rotation schedule by minimising system costs through the re-allocation of schedule time in an aircraft rotation schedule. The effectiveness of the AR model optimisation was evaluated by four factors (the departure/arrival punctuality, the mean departure/arrival delay, the expected departure/arrival delay and the standard deviation of departure/arrival delay) and was validated by comparisons with observation and simulation results from case studies. The reliability of the implementation of a flight schedule was evaluated by four reliability surrogates, namely the mean segment delay time in the rotation, the expected segment delay time, the standard deviation of departure delay and the regularity of schedule implementation. The schedule reliability of the aircraft rotation in case studies was investigated by these indices to ensure the effectiveness of schedule optimisation in aircraft rotation.

Research conclusions found in the model development are summarised in Section 7.1.1, Conclusions from Model Development. Research findings obtained in the implementation of case studies are given in Section 7.1.2, Conclusions from Case Studies. Recommendations for future research are presented in two sub-sections of Section 7.2, Recommendations for Future Research. Section 7.2.1, Improvement and Application of the AR model, summarises potential improvements and future applications of the AR model. Recommendations for future research directions in the field of air traffic management (ATM) are given in Section 7.2.2, Recommendations for Future Research in ATM.

7.1.1 Conclusions from Model Development

Numerical study using the Analytical Aircraft Turnaround model (the AAT model) showed that the proper use of schedule buffer time can help manage the punctuality of turnaround aircraft by minimising system costs. The influence of the arrival punctuality of inbound aircraft was found significant for the departure punctuality of turnaround aircraft. It was found that the arrival time distribution of a turnaround aircraft influences the optimal of schedule buffer time. It is concluded accordingly that the scheduling of turnaround aircraft should consider the individual punctuality history of each route and different schedule buffer time should be applied to different routes with different punctuality histories. On the other hand, the departure punctuality of a turnaround aircraft was found to be *endogenous* for the flight schedule to reflect the turnaround efficiency of ground operations at an airport as well as the amount of scheduled turnaround time designed for turnaround operations. In other words, the proposed aircraft turnaround model could be used as a simulation tool for an airline to estimate schedule punctuality before the implementation of a new schedule by using proper model parameters such as turnaround efficiency of ground operations and flight schedules.

The proposed Markovian Aircraft Turnaround model (the MAT model) has been proved to be effective in modelling the stochastic and transitional behaviour between normal turnaround activities and service disruptions. Simulation results from numerical studies showed that the MAT model is able to evaluate the *endogenous schedule punctuality* of a turnaround aircraft as well as to analyse turnaround irregularities by considering stochastic factors involved in aircraft turnaround operations. A sensitivity analysis to the MAT model showed that the model is robust in simulating aircraft turnaround operations. The mean service time of turnaround activities and the occurrence of service disruptions to aircraft turnaround are two major factors which influence the departure punctuality of a turnaround aircraft. The shape of service time probability density functions (PDFs) was found not significant for the MAT model outputs.

A further comparison between the AAT model and the MAT model showed that the superiority of the MAT model comes from its capability to model the stochastic characteristics of ground services and arrival punctuality of inbound aircraft. In addition, the MAT model has been successful in modelling the occurrence of operational disruptions, which have become the major source of operational uncertainties in airline operations at airports. Although the AAT model did not model the turnaround process as much detail as the MAT model did, its aggregate approach to model turnaround operations also showed promising performance as a planning and analysis tool for airlines and airport operators. The feature of simulating operational disruptions makes the MAT model suitable for airlines to estimate the endogenous schedule punctuality of flight schedules by using historical operation data.

The effectiveness of the AR model was demonstrated in Chapter Four and the development of *knock-on delay* in aircraft rotation was observed in numerical studies of the AR model. It was found that the turnaround buffer time in aircraft rotation schedules helps maintain the control of knock-on delay in aircraft rotation. When aircraft are scheduled to hub at the base airport of an airline, results from simulations showed that scheduling a long turnaround time at the hub improves the punctuality of aircraft rotation. Although a short connection time at the hub airport increases the utilisation of aircraft, simulation results revealed the potential risk of the short-turnaround-time policy to worsen aircraft rotational punctuality.

The optimisation of aircraft rotation schedules was implemented by two methods, i.e. single leg optimisation and consecutive leg optimisation. Trade-offs between ground schedule time and airborne schedule time were clearly observed in the optimisation of a single leg of rotations. Trade-offs between ground time at two airports were also found significant in the optimisation of consecutive legs in aircraft rotation. It was found from numerical analyses that the schedule punctuality at an airport influences the punctuality at following rotational legs, because legs of aircraft rotations interact with each other. The schedule of aircraft rotation was then optimised by the re-allocation of schedule time in aircraft rotation in order to minimise system costs. The optimisation of aircraft rotation schedules showed a significant reduction in system costs. It was found that the schedule punctuality at each airport in the study rotation varies as a result of schedule optimisation and different scheduling considerations of airlines.

The implementation reliability of a schedule was measured by four reliability surrogates, namely the mean delay, the standard deviation of aircraft arrival/departure time, the expected delay and the schedule regularity. After the evaluation of the effectiveness of schedule reliability measures, it was recommended that the indices of mean delay and standard deviation are suitable for preliminary investigation to a flight schedule. The expected delay, on the other hand, was suggested to be the major reliability surrogate to a flight schedule. The schedule regularity was recommended to serve as the indicator of the operational reliability of a flight schedule for the managerial and planning purposes of an airline. Aggregate measures of schedule reliability proposed in this research showed that caution is needed to interpret the implication of the aggregate reliability of a schedule, because aggregate reliability measures are influenced by the scheduling strategies of an airline, especially the use of schedule buffer time.

7.1.2 Conclusions from Case Studies

In considering the EasyJet case, first of all, the current situation analysis of the turnaround disruption history and turnaround efficiency at LTN and AMS suggested that different ground service providers show different operational efficiency. It was found from the results of turnaround efficiency analysis that the service efficiency at LTN is better than the one at AMS. It was also found from the rotation schedule of the LTN-AMS route that the scheduled turnaround time at LTN was 30 minutes which is shorter than the one at AMS which averaged 40 minutes. However, the turnaround operation at LTN was less stable than its counterpart at AMS especially for long-delayed flights. The calibration of the MAT model showed that the mean service time to turn around an aircraft is shorter at LTN than at AMS. It was also found that the operational aircraft turnaround time varies according to the length of the scheduled turnaround time. When more time was allowed for aircraft turnaround, it tended to take longer time to finish the same activity. This phenomenon has been identified as the *behavioural response* in relevant literature and is also observed in other transport modes with pre-planned schedules. The calibration of the Enroute model showed that the mean enroute flight time between LTN and AMS is about 60 minutes which includes 3 to 5 minutes of arrival delays in the TMA of the destination airport.

Secondly, the performance of the AR model in simulating aircraft rotation was statistically acceptable according to comparisons between the results of simulation and observation. However, differences between the simulation results and the observation data still exist. The discrepancy mainly came from two aspects. First of all, uncertainties occurred in the real-world operations of aircraft rotation that were not fully modelled in the AR model due to model assumptions and simplifications in the modelling process. Hence, simulation results can only be as close as possible to observation data. Secondly, the proposed AR model did not include the management feature of flight cancellation or aircraft swap to deal with long-delayed aircraft in the rotation. This was also the reason why the standard deviation of departure/arrival delay from the simulation model was higher than its counterpart from observation.

Thirdly, when the results of the optimisation were compared with actual data from EasyJet and simulation results from the AR model, it was seen that the performance of aircraft rotation is improved in terms of schedule punctuality, mean delay time and expected delay time. Although the total schedule time of the rotation on the LTN-AMS route after optimisation was 59 minutes longer than the original schedule, the total system cost was reduced by 27% or $4,221,185 per thousand rotations after schedule optimisation, using nominal parameters for EasyJet's case study. The schedule reliability in terms of the mean delay time and the expected delay time showed that the schedule stability of the optimised schedule was improved and better controlled than the original one. Although the reliability index of standard deviation of delay time did not reflect the benefit of schedule optimisation in this instance, the index of schedule regularity strongly suggested that the aircraft rotation is more stable and reliable after schedule optimisation.

In considering the British Airways case, first of all, the aircraft rotation schedule of the LHR-AMS-CDG route by British Airways showed that there was less turnaround time scheduled at outstations (60 minutes for B757 turnaround at AMS and 55 minutes at CDG) and longer turnaround time allowed for aircraft turnaround at LHR (75 to 80 minutes). Hence, the development of knock-on delay in the rotation might be controlled by ground operations at LHR. Analysis of the flight data also showed that the departure delay at outstations was higher when compared with the one at LHR. The study of turnaround disruption history at LHR showed that there was a high probability (0.16) to have departure delays due to departure flight operation procedures, e.g. airport tower control and airport ground congestion delay, at LHR. The turnaround efficiency analysis of British Airways at LHR suggested that the departure delay of a turnaround aircraft might escalate significantly when the arrival delay of the inbound aircraft exceeds 60 minutes. Although the scheduled turnaround time at outstations for the study route was less than its counterpart at LHR, regression analysis for CDG and AMS showed that the turnaround efficiency at outstations was relatively good when compared with LHR. The result of the MAT model calibration showed that the average turnaround time of a B757 at AMS and CDG was about 45 minutes while the same aircraft's turn time was 50 to 60 minutes at LHR. This might be due to worse aircraft turnaround efficiency by British Airways at LHR or more operational procedures being required by British Airways for aircraft turnaround operations at its base airport. The calibration result of the Enroute model showed that the average flight time between airports varied according to the time of flight as well as the congestion of the destination airport terminal maneuvour area (TMA).

Secondly, the comparison between simulation results of the AR model with the observation data suggested that the modelling performance of the AR model was statistically good in terms of the departure/arrival punctuality, the mean departure/arrival time and the expected departure/arrival time. Although minor discrepancy between simulation and observation still exits when the modelling performance was evaluated by the standard deviation of departure/arrival delay time, the performance of the AR model in simulating aircraft rotations was still statistically approved. After schedule optimisation, it was found that the reliability of aircraft rotation was improved in terms of flight punctuality, mean delay time and expected delay. Although the total schedule time of the study rotation is increased by 45 minutes (5%), a system cost saving of $9,305,127 (43%) per thousand aircraft rotation (which is equivalent to one and a half-year operation of the study aircraft, GBMRH) was gained after schedule optimisation. It was found (in Table 6.23) that the leg-time of early rotation legs (BA426, BA427 and BA308) was higher than the original schedule and the optimised leg-time decreases for later rotation legs. The optimisation tends to allocate more buffer time for early legs in this case in order to reduce delays from early segments in the rotation. The ample buffer time in early legs of the rotation also reduced the development of knock-on delay and hence reduced the use of schedule buffer time in later rotational legs. This is called the influence of "morning readiness" on the reliability of aircraft rotation.

When British Airways's case was compared with EasyJet's case, it was found that there were two major differences between these two case studies. First of all, EasyJet used intensive aircraft rotation schedules on the study route so the development of knock-on delay was more significant (as shown in Figure 5.36) than the case of British Airways. The schedule optimisation improved more significantly the reliability of EasyJet's schedule than British Airways's case in terms of the control of knock-on delay in aircraft rotation. Secondly, it was seen in the rotation schedule of the British Airways's case that there was ample turnaround time (80 minutes) scheduled at LHR. Hence the development of knock-on delay in British Airways's case was somewhat controlled by this scheduling policy. The disadvantage of the scheduling policy in the study rotation is that the mean departure delay at outstations is usually higher than the one at the base airport (as shown in Table 6.21) and consequently the arrival delay at the base airport is also higher than at outstations. Although the scheduled turnaround time at LHR was high (80 minutes in this case), it was usually consumed by arrival delays to inbound aircraft so the effectiveness of the control of knock-on delay by long scheduled turnaround time at LHR was also limited.

Finally, analysis of schedule reliability suggested that the reliability of aircraft rotation on the study route operated by British Airways was improved after schedule optimisation. The schedule reliability in terms of the mean delay time and the expected delay time showed that the reliability of the optimised schedule was higher and better-controlled than the original one. In addition, the regularity analysis of the optimised schedule strongly suggested that the robustness and reliability of schedule implementation was improved after optimisation. Therefore, it is concluded that the optimisation of the LHR-AMS-CDG route by British Airways improves the punctuality as well as the reliability of aircraft rotation. The same applies to the EasyJet case.

Overall, the major contribution of this research comes from the modelling of aircraft rotation in a multiple airport environment as well as the modelling of aircraft turnaround operations at airports. This is the first known attempt, according to the author's knowledge, in the literature to try to model aircraft rotation from a stochastic point of view. The aircraft rotation model proposed in this research successfully simulates operational uncertainties in aircraft ground operations and uncertainties from schedule implementation. Although, the function of airline schedule operations needs to be improved in future application by including flight cancellations and aircraft swaps between routes, the AR model has been proved to be a good simulation and analysis tool for airlines. The AR model could be used to optimise aircraft rotation schedules as well as to evaluate the endogenous punctuality and the reliability of aircraft rotations before the implementation of a new schedule. In addition, the AR model can also be employed to investigate the influence of different scheduling strategies on aircraft rotational punctuality and reliability. From a practical point of view, it is seen from two case studies done for British Airways and EasyJet that the AR model has shown its feasibility to be applied by the industry as a planning and simulation tool.

7.2 Recommendations for Future Research

7.2.1 Improvement and Application of the Aircraft Rotation Model

After the application of the AR model to two case studies, it was found that further improvement is needed to polish the AR model in simulation and optimisation of aircraft rotations. First of all, a part of the cost parameters applied in the AR model are commercially confidential information for airlines and it is very unlikely that academic research can acquire detailed information about operational costs and revenue of an airline such as EasyJet. Hence, the representativeness of the model output can be challenged. However, this problem does not impair the applicability of the AR model because the model parameters can be easily modified when proper cost parameters are available for use.

Secondly, it was found in case studies that the AR model does not include some features of airline schedule operations, i.e. flight cancellations and aircraft swap between routes, and results in the higher level of data deviation than real-world operations as seen in EasyJet's case. Hence, it is recommended that these aspects be included in future application of the AR model in order to simulate the real-time management of aircraft rotations in the real world.

It is generally realised by the airline industry that the rotation reliability of an aircraft is influenced by the other aircraft through ground operations at airports as well as airborne operations in the airspace. Therefore, the AR model could be extended in the future to model the interaction between aircraft rotations in a multiple airport environment. In addition, the optimisation methodology employed in the AR model could be used by an airline to optimise its flight schedule as well as to optimise the assignment of aircraft fleet in its network. The objective of this optimisation is to minimise system costs and meanwhile to maximise the reliability and robustness of schedule implementation.

7.2.2 Recommendations for Future Research in Air Traffic Management

Previous research in the literature has shown that the air traffic system has the characteristics of high complexity of operation and manipulation with the involvement of multiple users as well as inherent stochastic effects on system performance. Potentially productive research topics in the field of air traffic management are therefore summarised after the literature review in this research.

First of all, a link for system-wide integration is needed between broad-network air traffic flow management and local traffic control in the airport TMA. Recent research has already revealed the benefit of optimising operational efficiency of air traffic flow management (ATFM) in a network of airports (Navazio and Romanin-Jacur, 1998; Vranas, 1994a, b). The utilisation of airport system capacity, i.e. enroute airspace capacity and airport runway capacity, influences the performance of ATFM. Relevant ATFM studies have shown the importance of airport capacity control to the success of ATFM (Peterson *et al*, 1995; Shumsky, 1998; Vranas, 1994a, b). On the other hand, techniques to increase enroute airspace capacity, e.g. Reduced Vertical Separation Minima (RVSM) by Eurocontrol in Europe, also help improve the efficiency of utilising scarce airspace capacity (Eurocontrol, 1998c). However, these three major portions of air transport research, i.e. ATFM, airport TMA operations and enroute airspace operations, have not yet been well integrated to achieve the maximum of system performance (Airline Business, 1999d). It is predicted by Eurocontrol that all enroute delays in Europe could be eliminated by 2006-8 when capacity-enhancing measures start functioning (Flight International, 2000). By then, the capacity bottleneck in the air traffic system will be airports if demands for air transport keep growing as predicted. Hence, it is suggested that future research regarding ATFM should focus on the system integration of enroute ATFM with local air traffic operations at airports in order to achieve the goal of "Gate-to-Gate Air Traffic Management" (Eurocontrol, 1998). Advanced methodologies for the modelling of air traffic flow distributions in an airport network are needed to improve the reliability of system capacity allocation. In addition, the integration between airspace capacity and airport capacity is needed to achieve the higher utilisation of system capacity and meanwhile minimise system costs due to capacity shortage.

Secondly, the optimisation of air traffic operations in the airport TMA is found to influence the operational performance of an airport as well as the schedule delivery performance of airlines. Optimising airport runway capacity by using aircraft sequencing techniques and advanced navigation technology is able to improve the utilisation of constrained runway capacity at an airport (Eurocontrol, 1998b; Mohleji, 1996; Trivizas, 1994, 1998). In addition, the optimisation of airport capacity will not succeed without a comprehensive and precise airport capacity information system (Simpson, 1997). Relevant literature has demonstrated the feasibility and capability of modelling airport capacity by stochastic models and artificial intelligence techniques (Gosling, 1987, 1990; Peterson *et al*, 1995; Richetta, 1995; Taylor, 1990; Wayson, 1989). Recent studies also showed the feasibility of integrating knowledge-based systems with stochastic simulation models to dynamically update airport operational information to maximise airport performance (Cheng, 1998a, b). Hence, it is recommended that future work focuses on the establishment of airport information system which includes functions for aircraft processing in the TMA (metering, spacing and sequencing aircraft) as well as a reliable airport capacity allocation and prediction mechanism.

Thirdly, there is relatively less attention paid to the issue of airport ground operations research in the literature. It has been shown in the literature that there is a need to increase airport apron capacity and to encourage the use of large aircraft to utilise airport facilities (Caves, 1994; Chin, 1996; Uittenbogaart, 1997). Regarding the operational efficiency of airlines on the apron, recent papers about the operational efficiency of aircraft on the ground have shown that ground service performance varies among carriers and influences the productivity and profitability of airlines as well (Gittell, 1995; Wu and Caves, 2000). It is realised that the improvement of ground operational efficiency and punctuality of airlines is essential to reduce operational costs especially for non-intensive hubbing airlines (Hansen and Kanafani, 1989; Nero, 1999). With the increase of operational delays in the air transport system, airlines have to design more buffer time in flight schedules in order to maintain schedule punctuality as well as aircraft rotational links (Sunday Times, 2000). However, a longer schedule time for a flight does not always guarantee the improvement of schedule punctuality and similar situations have been identified in other transport schedule studies (Carey, 1998). Therefore, potential research interests arise in the establishment of a reliable flight schedule which is able to utilise available resources of airlines and airports as well as to maintain the reliability of schedule implementation and aircraft rotations.

Artificial intelligence (AI) and stochastic models are suitable methodologies to build a decision support system for the purpose of aircraft rotation management which includes schedule disruption management functions to cope with unexpected schedule perturbations during schedule delivery (Cao and Kanafani, 1997; Cheng, 1997, 1998a, b; Gosling, 1990; Teodorovic and Stojkovic, 1990, 1995).

Although operational uncertainties in the air transport system are inevitable, the ultimate goal of this research is not trying to eliminate potential uncertainties in the system but to develop a methodology which helps an airline utilise available resources to minimise system costs and meanwhile maximise the reliability and robustness of schedule implementation in the presence of operational uncertainties in air transport system.

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GLOSSARY

(1) **Turnaround**: The "turnaround" of an aircraft at an airport gate is defined in this research as the procedure to provide an aircraft with required services (such as catering, cabin cleaning and fuelling) in order to carry out a following flight to another airport.

(2) **Delays**: Delays measured in this research are based on the scheduled time of arrival (*STA*), i.e. the on-chock time of an aircraft at the airport gate, and the scheduled time of departure (*STD*), i.e. the off-chock time. Delay codes used in this research are based on standard IATA delay codes (International Air Transport Association, 1997).

(3) **Scheduled Turnaround/Ground Time**: The duration between *STA* and *STD* is defined as the "scheduled ground time/scheduled turnaround time" (denoted by T_{SG} in equation (1)) which consists of two portions: the "standard aircraft ground service time" (denoted by T_G) and the "schedule buffer time" (denoted by T) as shown in equation (2). The schedule buffer time (if any) in the ground time of a turnaround aircraft is usually designed to accommodate unexpected delays to inbound aircraft and delays to aircraft turnaround operations.

$$STD = STA + T_{SG} \tag{1}$$

$$T_{SG} = T + T_G \tag{2}$$

(4) **Ground Services**: "Ground services" to a turnaround aircraft at an airport gate include all necessary service activities, e.g. cabin cleaning, engineering check, aircraft fuelling, for an aircraft to carry out a following flight (International Air Transport Association, 1997).

(5) **Rotation**: The "rotation" of an aircraft is defined in this research as the continuous visits of an aircraft to a series of airports according to a chosen flight schedule in an operational day as illustrated by Figure 1.3. The rotation of this aircraft starts at airport **J** and is turned around at airport **K** after a period of scheduled turnaround time. The complete rotation of this aircraft ends at airport **M**, in which the aircraft is held over night.

(6) **Legs/Segments**: A "leg/segment" of aircraft rotation is defined in this research to start from the "on-chock time" of an aircraft at the origin airport to the "on-chock time" of the same aircraft at the destination airport. In other words, a leg of aircraft rotation starts from the turnaround operations at the origin airport to the arrival of the aircraft at the destination airport. Hence, the scheduled time for a leg of aircraft rotation consists of two portions: the scheduled turnaround time at the origin airport and the schedule block time between two airports.

(7) **Knock-On Delay**: If an aircraft is delayed at an airport, the departure delay might accumulate along the path of aircraft rotations especially when delays are sufficiently significant to perturb scheduled ground plans at an airport and ATC slots at following airports. The propagation of delays along with aircraft rotations is called the "knock-on delay" of aircraft rotations.

Chapter 3 Tables

TABLE 3.1 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

*Classification with respect to MTOW (Maximum Take-off Weight) and seat capacity

TABLE 3.2 Hourly Aircraft Operating Costs With Engines off At Gates

	British Airways (BA)	British Midland (BD)	KLM	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: * Units in US $ (millions)
( ) Values of cost items
+ Subtotal = (Total Operating Expenses)-(Fuel and Oil Expenses)

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

TABLE 3.3 Hourly Schedule Time Costs of Major 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* 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)
( ) Values of cost items
+ Subtotal = (Revenues)-(Costs)

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

TABLE 3.4 Descriptive statistics of chosen Beta functions

	Mean[a]	Median	Standard Deviation
Beta(10,10)	0.5	0.5	0.14
Beta(5,5)	0.5	0.5	0.18
Beta(3,3)	0.5	0.5	0.21

[a]The range of the independent variable in this case is between 0 and 1.

TABLE 3.5 K-S test of simulated arrival pdfs of BA-X and BA-Y

	PDF	**K-S test value**	**Sample Size**	**Significant K-S value**	**Goodness of Fit**
BA-X	Beta(4,9)	0.0528	51	0.1679	Yes
BA-Y	Beta(2,5)	0.1042	82	0.1331	Yes

TABLE 3.6 Cargo & Baggage Processing

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

TABLE 3.7 State Transition Probability in Cargo & Baggage Processing

States	*1*[a]	*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

[a]State sojourn time function: B (Beta), E (Exponential), and N (Normal)

TABLE 3.8 Passenger/Crew/Cabin Cleaning Process

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

TABLE 3.9 State Transition Probability in Passenger/Crew/Cabin Processing

States	*1*[a]	*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

[a]State sojourn time function: B (Beta), E (Exponential), and N (Normal)

TABLE 3.10 Disrupting Events in Aircraft Turnaround Operations

Event	Event Description	Occurrence Probability	Occurrence Epoch[a]	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)

[a]The time from the start of aircraft turnaround operations

TABLE 3.11 Simulation Results of Turnaround Operations of Study Flights

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

[a]Mean time (minutes) of simulation flights
[b]Mean service time of simulation flights

TABLE 3.12 Turnaround Performance of BA-X66

Operation Results*	Inbound Delay	Operational Time	Operational Delay	ATC Flow Control	Outbound Delay
(minutes)	6	39	0	0	0

CARGO	**States**	State Time	**PASSENGER**	**States**	State Time
	1	6		*1*	6
	2	9		*2*	11
	3	14		*3*	10
	4	0		*4*	0
	Total Flow Time	***29***		*5*	16
				6	2
				7	0
				Total Flow Time	***45***

EVENTS	Disruptions	When	Duration	Total Duration
	2	18	25	*43*

TABLE 3.13 Sensitivity analysis to the mean service time of aircraft turnaround operations

Mean Service Time	Simulated Service Time	Mean Outbound Delay
35	44	1.8
40	49	2.6
45 (Original Case)	54	3.8
50	59	5.6
55	64	8.4

TABLE 3.14 Sensitivity analysis to the types of service time distributions

	Beta PDFs	Normal PDFs	Gamma PDFs
Mean Turnaround Time	45	45	45
Simulated Turnaround time	54.9	54.4	54.2
Mean Outbound Delay	4.3	3.7	3.8

TABLE 3.15 Cabin cleaning & passenger processing simulations by using different state sojourn time PDFs

	Beta PDFs		*Normal PDFs*		Gamma PDFs	
States	mean	Std. Deviation	*mean*	*Std. Deviation*	mean	Std. Deviation
1	2.3	4.1	*2.3*	*4.1*	2.3	4.1
2	9.9	3.1	*10.1*	*2.9*	9.9	2.9
3	14.9	2.9	*14.9*	*2.9*	15	2.9
4	0	0	*0*	*0*	0	0
5	14.8	4.9	*15.1*	*5.1*	15.2	4.9
6	5	1.9	*5.1*	*2*	4.8	1.9
7	0.2	0.5	*0.2*	*0.5*	0.2	0.5

TABLE 3.16 Cargo & baggage processing simulations by using different state sojourn time PDFs

	Beta PDFs		*Normal PDFs*		Gamma PDFs	
States	mean	Std. Deviation	*mean*	*Std. Deviation*	mean	Std. Deviation
1	2.3	4.1	*2.3*	*4.1*	2.3	4.1
2	20.1	4.8	*19.8*	*4.9*	19.9	5
3	24.8	4.9	*24.9*	*5*	24.9	4.9
4	0.2	0.5	*0.2*	*0.5*	0.2	0.5

TABLE 3.17 Sensitivity analysis to state transition probability in the MAT model

	Lower Probability	Original	Higher Probability
Mean Turnaround Time	45	45	45
Simulated Turnaround time	52.2	54.4	56.4
Mean Outbound Delay	2.4	3.7	4.9

Chapter 4 Tables

TABLE 4.1 Flight Schedules in Case Studies

	Flight Legs (From/To)	Aircraft Rotation Schedule (service time/ TR time)[a]	(turnaround buffer time)[b]	Enroute Model (mean flight time/block time)[c]	(simulation PDFs)[d]	
Case-O	1 (J-K)	45/55	10	50/60	N(50,5)	E(5)
(Original Schedule)	2 (K-L)	45/60	15	60/70	N(60,5)	E(3)
	3 (L-K)	45/55	10	70/80	N(70,5)	E(5)
	4 (K-M)	45/60	15	55/65	N(55,5)	E(3)
Case-A	1 (J-K)	45/55	10	50/60	N(50,5)	E(5)
(Short TR at K)	2 (**K**-L)	45/50	**5**	60/70	N(60,5)	E(3)
	3 (L-K)	45/55	10	70/80	N(70,5)	E(5)
	4 (**K**-M)	45/50	**5**	55/65	N(55,5)	E(3)
Case-B	1 (J-K)	45/55	10	50/60	N(50,5)	E(5)
(Long TR at K)	2 (**K**-L)	45/65	**20**	60/70	N(60,5)	E(3)
	3 (L-K)	45/55	10	70/80	N(70,5)	E(5)
	4 (**K**-M)	45/65	**20**	55/65	N(55,5)	E(3)
Case-C	1 (J-K)	45/60	**15**	50/60	N(50,5)	E(5)
(Even TR time)	2 (K-L)	45/60	**15**	60/70	N(60,5)	E(3)
	3 (L-K)	45/60	**15**	70/80	N(70,5)	E(5)
	4 (K-M)	45/60	**15**	55/65	N(55,5)	E(3)
Case-D	1 (J-K)	45/55	10	50/60	N(50,5)	E(5)
(Long Buffer at K)	2 (**K**-L)	45/80	**35**	60/70	N(60,5)	E(3)
	3 (L-K)	45/55	10	70/80	N(70,5)	E(5)
	4 (**K**-M)	45/80	**35**	55/65	N(55,5)	E(3)
Case-E	1 (J-K)	45/55	10	50/60	N(50,5)	E(5)
(Long Buffer at L)	2 (K-L)	45/60	15	60/70	N(60,5)	E(3)
	3 (**L**-K)	45/80	**35**	70/80	N(70,5)	E(5)
	4 (K-M)	45/60	15	55/65	N(55,5)	E(3)
Case-F	1 (J-K)	45/45	**0**	50/60	N(50,5)	E(5)
(No Buffer)	2 (K-L)	45/45	**0**	60/70	N(60,5)	E(3)
	3 (L-K)	45/45	**0**	70/80	N(70,5)	E(5)
	4 (K-M)	45/45	**0**	55/65	N(55,5)	E(3)
Case-G	1 (**J**-K)	45/50	**5**	50/60	N(50,5)	E(5)
(Short TR at JLM)	2 (K-L)	45/60	15	60/70	N(60,5)	E(3)
	3 (**L**-K)	45/50	**5**	70/80	N(70,5)	E(5)
	4 (K-**M**)	45/60	15	55/65	N(55,5)	E(3)
Case-H	1 (**J**-K)	45/65	**20**	50/60	N(50,5)	E(5)
(Long TR at JLM)	2 (K-L)	45/60	15	60/70	N(60,5)	E(3)
	3 (**L**-K)	45/65	**20**	70/80	N(70,5)	E(5)
	4 (K-**M**)	45/60	15	55/65	N(55,5)	E(3)
Case-I	1 (**J**- K)	45/50	**5**	50/60	N(50,5)	E(5)
(Short TR at JLM	2 (**K-L**)	45/65	**20**	60/70	N(60,5)	E(3)
& Long TR at K)	3 (**L**-K)	45/50	**5**	70/80	N(70,5)	E(5)
	4 (**K-M**)	45/65	**20**	55/65	N(55,5)	E(3)
Case-J	1 (**J**- K)	45/65	**20**	50/60	N(50,5)	E(5)
(Long TR at JLM	2 (**K-L**)	45/50	**5**	60/70	N(60,5)	E(3)
& Short TR at K)	3 (**L**-K)	45/65	**20**	70/80	N(70,5)	E(5)
	4 (**K-M**)	45/50	**5**	55/65	N(55,5)	E(3)

a "Service time" is the mean turnaround service time for an aircraft (B767 in this case); "TR time" stands for turnaround time

b "Turnaround buffer time" is the time difference between TR time and Service Time

c "Mean flight time" is the mean flight time between two airports; "Block time" is the scheduled airborne time for a flight

d Normal distributions are denoted by $N(\mu,\sigma)$; Exponential distributions by $E(\mu)$

TABLE 4.2 Aircraft Rotational Schedules Used in Numerical Analyses

Flight Legs (From/To)	Aircraft Rotation Schedule (service time/ TR time)[a]	(turnaround buffer time)[b]	Enroute Model (mean flight time/block time)	(simulation PDFs)	
1 (J-K)	45/55	10	50/60	N(50,5)[c]	E(5)[d]
2 (K-L)	45/60	15	60/70	N(60,5)	E(3)
3 (L-K)	45/55	10	70/80	N(70,5)	E(5)
4 (K-M)	45/60	15	55/65	N(55,5)	E(3)

Notes: a "service time" means the mean time of turnaround services for a B767
"TR time" means the scheduled turnaround time of an aircraft at an airport
b Turnaround buffer time is the time difference between TR time and service time
c Normal (N(μ,σ)) distributions are used to simulate the enroute flight time of an aircraft
d Exponential (E(β)) distributions are used to simulate delays due to airport congestion

TABLE 4.3 Optimisation result of the original aircraft rotation schedule

	Leg_JK (Airport **J**)		Leg_KL (Airport **K**)		Leg_LK (Airport **L**)		Leg_KM (Airport **K**)		**System Cost**
Original Schedule	55/45[a]	60/50[b]	60/45	70/60	55/45	80/70	60/45	65/55	
Delay Costs		365,209		514,708		645,949		721,127	**2,246,994**
Single Leg Optimisation	**57**/45	**60**/50	**60**/45	**70**/60	**61**/45	**81**/70	**62**/45	**65**/55	
Delay Costs		360,388		500,677		588,074		622,773	**2,071,912**
Consecutive Leg Optimisation	**60**/45	60/50	**60**/45	70/60	**64**/45	80/70	**62**/45	65/55	
Delay Costs		395,171		523,334		625,703		729,117	**2,273,154**

Notes: a (scheduled turnaround time/mean turnaround time)
b (scheduled block time/mean flight time)

TABLE 4.4 Rotational schedule of Aircraft_A

	Scheduled Ground Time	Average Ground Service Time	Turnaround Buffer Time	Scheduled Airborne Time	Average Flight Time	Airborne Buffer Time
Leg_1	60 (62)[a]	50	10 (12)	60 (61)	50	10 (11)
Leg_2	45 (51)	40	5 (11)	75 (75)	65	10 (10)
Leg_3	60 (63)	50	10 (13)	80 (84)	70	10 (14)
Leg_4	**90 (55)**	**40**	**50 (15)**	**85 (85)**	**75**	**10 (10)**
Leg_5	60 (66)	50	10 (16)	85 (90)	75	10 (15)
Leg_6	45 (58)	40	5 (18)	75 (77)	65	10 (12)

[a] The optimised schedule time is given in parentheses in this table for comparison purposes

TABLE 4.5 Rotational schedule of Aircraft_B

	Scheduled Ground Time	Average Ground Service Time	Turnaround Buffer Time	Scheduled Airborne Time	Average Flight Time	Airborne Buffer Time
Leg_1	25 (35)	20	5 (15)	65 (55)	45	20 (10)
Leg_2	30 (41)	25	5 (16)	65 (56)	45	20 (11)
Leg_3	25 (37)	20	5 (17)	65 (56)	45	20 (11)
Leg_4	30 (43)	25	5 (18)	65 (56)	45	20 (11)
Leg_5	**50 (39)**	**20**	**30 (19)**	**65 (56)**	**45**	**20 (11)**
Leg_6	30 (45)	25	5 (20)	65 (57)	45	20 (12)
Leg_7	25 (40)	20	5 (20)	65 (57)	45	20 (12)
Leg_8	30 (45)	25	5 (20)	65 (58)	45	20 (13)
Leg_9	25 (44)	20	5 (24)	65 (58)	45	20 (13)
Leg_10	30 (45)	25	5 (20)	65 (59)	45	20 (14)

[a] The optimised schedule time is given in parentheses in this table for comparison purposes

TABLE 4.6 Aggregate reliability measures to Aircraft_A and Aircraft_B

	Original Schedule of Aircraft_A	Optimal Schedule of Aircraft_A	Original Schedule of Aircraft_B	Optimal Schedule of Aircraft_B
Aggregate Mean Delay (μ_{AGG}^{D})	66	**10**	26	**24**
Aggregate Expected Delay ($\mathrm{E}[D]_{AGG}$)	69	**25**	17	**29**

Chapter 5 Tables

TABLE 5.1 Aircraft rotation schedule on the LTN-AMS route

	from LTN	to AMS	turnaround at AMS		from AMS	to LTN	turnaround at LTN
Flight Number	**STD**[a]	**STA**	**TSG**	**Flight Number**	**STD**[b]	**STA**[c]	**TSG**[d]
EZY201	05:40	06:50	45	EZY202	07:35	08:45	30
EZY203	09:15	10:25	40	EZY204	11:05	12:15	55
EZY207	13:10	14:20	40	EZY206	15:00	16:10	30
EZY209	16:40	17:50	30	EZY208	18:20	19:30	-

[a] all time shown in the table is based on GMT.
[b] STD stands for "scheduled time of departure"
[c] STA stands for "scheduled time of arrival"
[d] TSG stands for "scheduled turnaround time"

TABLE 5.2 Disruption probability and duration in the Cargo & Baggage process **(LTN)**

States	State Description	States	State Description	Occurrence Probability (p_{ij})	State Sojourn Time ($\Phi_{ij}(t)$)	
1	*Arrival*				μ	σ
2	*Goods unloading*	*5*	Cargo Processing	0.001[a]	15[b]	10
		6	Aircraft Ramp Handling	0.09	10	8
3	*Goods loading*	*7*	Cargo Processing	0.001	15	10
		8	Aircraft Ramp Handling	0.09	10	8
		9	Passenger & Baggage	0.06	12	9
4	*Departure*					

[a] the occurrence probability of each disruption state
[b] the mean delay time and standard deviation of each disruption state

TABLE 5.3 Disruption probability and duration in the Passenger/Crew/Cabin Cleaning process (**LTN**)

States	State Description	States	State Description	Occurrence Probability (p_{ij})	State Sojourn Time ($\Phi_{ij}(t)$)	
					μ	σ
1	*Arrival*					
2	*Disembark Passengers & Crew*					
3	*Cabin Cleaning*					
4	*ATC Flow Control*					
5	*Crew & Passenger Boarding*	*8*	Crew	0.11[a]	18[b]	19
		9	Passengers	0.09	12	9
		10	Missing Passengers	0.1	11	8
6	*Flight Operations & Crew Procedures*	*11*	Flight Operations	0.006	16	16
		12	Departure Process	0.09	11	8
		13	Weather	0.006	88	103
7	*Departure*					

[a] the occurrence probability of each disruption state
[b] the mean delay time and standard deviation of each disruption state

TABLE 5.4 Occurrence probability of disrupting events in aircraft turnaround operations (**LTN**)

Event	Event Description	Occurrence Probability (p_{ij})	Occurrence Epoch[a]	Event Duration ($\Phi_{ij}(t)$)
1	Fuelling Activity Delay	0.02	Exponential (15)	Normal (17,16)
2	Engineering Check Delay	0.01	Exponential (20)	Normal (19,21)
3	Aircraft Damage	0.02	Exponential (20)	Normal (28,19)
4	Aircraft Changes	0.02	Exponential (20)	Normal (58,48)

[a] the time from the start of aircraft turnaround operations

TABLE 5.5 Regression results of turnaround efficiency of EZY207 & EZY209 at LTN Airport

Flight Number	Regression Equations[a]	R^2
EZY207	$y = 0.6633x + 14.22$	0.68
EZY209	$y = 0.4967x + 13.36$	0.57

[a] variable "x" stands for "arrival delays of inbound aircraft"; "y" for "departure delays"

TABLE 5.6 Disruption probability and duration in the Cargo & Baggage process (**AMS**)

States	State Description	States	State Description	Occurrence Probability (p_{ij})	State Sojourn Time ($\Phi_{ij}(t)$)	
1	*Arrival*				μ	σ
2	*Goods unloading*	*5*	Cargo Processing	0.001[a]	20[b]	15
		6	Aircraft Ramp Handling	0.01	17	6
3	*Goods loading*	*7*	Cargo Processing	0.001	20	15
		8	Aircraft Ramp Handling	0.01	17	6
		9	Passenger & Baggage	0.1	15	9
4	*Departure*					

[a] the occurrence probability of each disruption state

[b] the mean delay time and standard deviation of each disruption state

TABLE 5.7 Disruption probability and duration in the Passenger/Crew/Cabin Cleaning process (AMS)

States	State Description	States	State Description	Occurrence Probability (p_{ij})	State Sojourn Time ($\Phi_{ij}(t)$)	
1	*Arrival*					
2	*Disembark Passengers & Crew*					
3	*Cabin Cleaning*					
4	*ATC Flow Control*				μ	σ
5	*Crew & Passenger Boarding*	*8*	Crew	0.004	9[b]	5
		9	Passengers	0.01	18	11
		10	Missing Passengers	0.04	11	7
6	*Flight Operations & Crew Procedures*	*11*	Flight Operations	0.001	18	3
		12	Departure Process	0.1	13	10
		13	Weather	0.003	23	10
7	*Departure*					

[a] the occurrence probability of each disruption state
[b] the mean delay time and standard deviation of each disruption state

TABLE 5.8 Occurrence probability of disrupting events in aircraft turnaround operations (AMS)

Event	Event Description	Occurrence Probability (p_{ij})	Occurrence Epoch[a]	Event Duration ($\Phi_{ij}(t)$)
1	Fuelling Activity Delay	0.02	Exponential (15)	Normal (16,6)
2	Engineering Check Delay	0.0006	Exponential (20)	Normal (15,2)
3	Aircraft Damage	0.003	Exponential (20)	Normal (52,43)
4	Aircraft Changes	0.001	Exponential (20)	Normal (210,237)

[a] the time from the start of aircraft turnaround operations

TABLE 5.9 Regression results of turnaround efficiency at AMS Airport

Flight Number	Regression Equations[a]	R^2
EZY202	$y = 0.9132x + 10.295$	0.85
EZY204	$y = 1.0394x + 9.1906$	0.95
EZY206	$y = 1.0261x + 13.409$	0.90
EZY208	$y = 0.8513x + 13.947$	0.76

[a] variable "x" stands for "arrival delays of inbound aircraft"; "y" for "departure delays"

TABLE 5.10 Punctuality analysis of aircraft rotation on the LTN-AMS route **(observation)**

from	to	Flight Number	Mean **Dept** Delay[a]		Mean **Arr** Delay[b]		Expected Dept Delay (**E[D]**$_d$)	Expected Arr Delay (**E[D]**$_a$)
			μ_d	σ_d	μ_a	σa		
LTN	AMS	**EZY201**	8.9	12	0.4	15	10.7	-2.8
AMS	LTN	**EZY202**	9.5	12	-1.6	15	10.1	-3.5
LTN	AMS	**EZY203**	12.4	15	-0.4	16	13.8	-2.5
AMS	LTN	**EZY204**	11.9	14	0.8	15	9.7	-1.0
LTN	AMS	**EZY207**	8.0	12	-2.8	16	9.5	-5.9
AMS	LTN	**EZY206**	10.4	12	0.6	11	9.5	0.2
LTN	AMS	**EZY209**	9.8	15	0.03	16	11	-2.7
AMS	LTN	**EZY208**	12.4	15	3.2	17	13	1.5

[a] μ_d stands for the mean departure delays of all samples;σ stands for the standard deviation

[b] the calculation of the mean arrival delay (μ_a) includes all simulation samples, i.e. to include "negative delays" of early arrivals.

TABLE 5.11 Results of MAT model calibration **(turnarounds at LTN)**

Flight Number	Inbound A/C Arrival PDF	Observation[a] μ_{in}[b]	Observation[a] μ_{out}	**Simulation** μ_{in}[b]	**Simulation** μ_{out}	Mean T/R Time (TG)	Scheduled TR (TSG)	Goodness-of-Fit Test Value
EZY203	Beta(2,5)	5.1	12.4	4.5	13.2	25	30	0.12[c]
EZY207	Beta(2,6)	5	8	5.2	7.3	40	55	0.16[d]
EZY209	Beta(2,5)	3.2	9.8	3.5	9.4	20	30	0.07[e]

[a] μ_{in} stands for the mean inbound delay; μ_{out} stands for the mean outbound delay

[b] the calculation of μ_{in} includes only "positive delays", i.e. to exclude early arrivals.

[c] the critical *K-S test* value is 0.2072 for EZY203 case

[d] the critical *K-S test* value is 0.1628 for EZY207 case

[e] the critical *K-S test* value is 0.1628 for EZY209 case

TABLE 5.12 Results of MAT model calibration **(turnarounds at AMS)**

Flight Number	Inbound A/C Arrival PDF	Observation[a] μ_{in}[b]	Observation[a] μ_{out}	**Simulation** μ_{in}[b]	**Simulation** μ_{out}	Mean T/R Time (TG)	Scheduled TR (TSG)	Goodness-of-Fit Test Value
EZY202	Beta(2,5)	5.5	9.5	5.4	7.0	35	45	0.12[c]
EZY204	Beta(2,5)	6.2	9.4	6.5	7.8	30	40	0.08[d]
EZY206	Beta(3,9)	4.1	8.4	3.7	8.4	35	40	0.08[e]
EZY208	Beta(2,5)	5.9	12.4	5.4	10.2	25	30	0.08[f]

[a] μ_{in} stands for the mean inbound delay; μ_{out} stands for the mean outbound delay

[b] the calculation of μ_{in} includes only "positive delays", i.e. to exclude early arrivals.

[c] the critical *K-S test* value is 0.1628 for EZY202 case

[d] the critical *K-S test* value is 0.2072 for EZY204 case

[e] the critical *K-S test* value is 0.1628 for EZY206 case

[f] the critical *K-S test* value is 0.1628 for EZY208 case

TABLE 5.13 Results of Enroute model calibration **(from LTN to AMS)**

Flight Number	Observation[a] μ_d	Observation[a] μ_a	**Simulation** μ_d	**Simulation** μ_a	Enroute Flight Time[b]	TMA Delay[c]	Scheduled Block Time	Goodness-of-Fit Test
EZY201	8.9	5.5	8.4	4.8	N(55,5)	E(5)	70	0.11[d]
EZY203	12.4	6.2	12.4	5.8	N(55,5)	E(1)	70	0.14[e]
EZY207	8.0	4.1	8.0	3.5	N(55,5)	E(3)	70	0.13[f]
EZY209	9.8	5.9	9.8	4.9	N(55,5)	E(3)	70	0.08[g]

[a] μ_d stands for the mean departure delay; μ_a stands for the mean arrival delay
[b] the enroute flight time of an aircraft is modelled by Normal functions (denoted by $N(\mu, \sigma)$)
[c] the TMA delay to an inbound aircraft is modelled by Exponential functions (denoted by $E(\mu)$)
[d] the critical K-S test value is 0.1628 for EZY201 case
[e] the critical K-S test value is 0.2072 for EZY203 case
[f] the critical K-S test value is 0.1628 for EZY207 case
[g] the critical K-S test value is 0.1628 for EZY209 case

TABLE 5.14 Results of Enroute model calibration **(from AMS to LTN)**

Flight Number	Observation[a] μ_d	Observation[a] μ_a	**Simulation** μ_d	**Simulation** μ_a	Enroute Flight Time	TMA Delay	Scheduled Block Time	Goodness-of-Fit Test
EZY202	9.5	5.0	9.5	4.7	N(55,5)	E(3)	70	0.11[d]
EZY204	11.9	5.0	11.9	5.4	N(55,5)	E(3)	70	0.14[e]
EZY206	10.4	3.2	10.4	5.4	N(55,5)	E(5)	70	0.13[f]
EZY208	12.4	7.9	12.4	7.8	N(55,5)	E(5)	70	0.08[g]

[a] μ_d stands for the mean departure delay; μ_a stands for the mean arrival delay
[b] the enroute flight time of an aircraft is modelled by Normal functions (denoted by $N(\mu, \sigma)$)
[c] the TMA delay to an inbound aircraft is modelled by Exponential functions (denoted by $E(\mu)$)
[d] the critical K-S test value is 0.1628 for EZY202 case
[e] the critical K-S test value is 0.2072 for EZY204 case
[f] the critical K-S test value is 0.1628 for EZY206 case
[g] the critical K-S test value is 0.1628 for EZY208 case

TABLE 5.15 Punctuality analysis of aircraft rotation on the LTN-AMS route **(simulation)**

from	to	Flight Number	Mean **Dept** Delay[a] μ_d	σ_d	Mean **Arr** Delay[b] μ_a	σ_a	Expected Dept Delay ($\mathbf{E[D]}_d$)	Expected Arr Delay ($\mathbf{E[D]}_a$)
LTN	AMS	**EZY201**	8.8	14	-1.5	17	11.1	-1.3
AMS	LTN	**EZY202**	7.4	15	-4.3	17	10.2	-4.3
LTN	AMS	**EZY203**	12.0	19	-2.0	20	13.4	-2.2
AMS	LTN	**EZY204**	10.9	20	-1.6	21	12.3	-2.3
LTN	AMS	**EZY207**	8.9	20	-3.2	21	11.2	-3.6
AMS	LTN	**EZY206**	10.6	22	0.4	23	12.1	-0.8
LTN	AMS	**EZY209**	13.4	26	1.2	27	14.1	-0.6
AMS	LTN	**EZY208**	13.6	27	3.4	28	13.7	0.8

[a] μ_d stands for the mean departure delays of all samples;σ stands for the standard deviation
[b] the calculation of the mean arrival delay (μ_a) includes all simulation samples, i.e. to include "negative delays" of early arrivals.

TABLE 5.16 Punctuality analysis of aircraft rotation on the LTN-AMS route **(optimisation)**

from	to	Flight Number	Mean **Dept** Delay[a] μ_d	σ_d	Mean **Arr** Delay[b] μ_a	σ_a	Expected Dept Delay ($\mathbf{E[D]}_d$)	Expected Arr Delay ($\mathbf{E[D]}_a$)
LTN	AMS	**EZY201**	5.0	13	-2.3	16	8.2	-2.7
AMS	LTN	**EZY202**	4.3	14	-2.4	16	7.9	-2.9
LTN	AMS	**EZY203**	5.8	19	-3.2	20	8.6	-4.2
AMS	LTN	**EZY204**	5.1	20	-2.3	21	8.1	-3.6
LTN	AMS	**EZY207**	6.1	22	-2.9	23	8.6	-4.3
AMS	LTN	**EZY206**	5.1	21	-2.0	22	7.9	-3.4
LTN	AMS	**EZY209**	7.6	25	-2.6	26	9.8	-4.0
AMS	LTN	**EZY208**	5.6	22	-2.5	24	8.5	-3.8

[a] μ_d stands for the mean departure delays of all samples;σ stands for the standard deviation
[b] the calculation of the mean arrival delay (μ_a) includes all simulation samples, i.e. to include "negative delays" of early arrivals.

TABLE 5.17 Optimisation results of aircraft rotational schedule on LTN-AMS route

from	to	Flight Number	Scheduled Turnaround Time (TSG)		Scheduled Block Time (T_B)		Total Leg-Time	
			original	**optimised**	**original**	**optimised**	**original**	**optimised**
LTN	AMS	**EZY201**	40	50	70	67	110	117
AMS	LTN	**EZY202**	45	52	70	65	115	117
LTN	AMS	**EZY203**	30	45	70	65	100	110
AMS	LTN	**EZY204**	40	52	70	65	110	117
LTN	AMS	**EZY207**	55	60	70	67	125	127
AMS	LTN	**EZY206**	40	53	70	67	110	120
LTN	AMS	**EZY209**	30	40	70	68	100	108
AMS	LTN	**EZY208**	30	45	70	68	100	113
						Total Time	**870**	**929**

TABLE 5.18 System costs comparison between the optimised schedule and the original schedule

Flight Number	Total Cost (C_T)		Passenger Delay Cost (C_{DP})		Aircraft Delay Cost (C_{DA})		Schedule Time Cost (C_{AL})	
	original	**optimised**	**original**	**optimised**	**original**	**optimised**	**original**	**optimised**
EZY201	1,019,916	866,298	425,911	278,058	390,881	248,241	203,125	340,000
EZY202	956,490	764,041	436,384	308,020	316,980	212,896	203,125	243,125
EZY203	1,535,960	1,138,232	874,155	562,255	505,556	263,479	156,250	312,500
EZY204	1,630,075	1,084,672	986,221	586,898	487,604	254,649	156,250	243,125
EZY207	2,055,124	1,621,174	1,313,831	973,703	460,047	307,472	281,250	340,000
EZY206	2,252,272	1,627,309	1,548,547	1,034,923	547,478	299,886	156,250	292,500
EZY209	3,063,964	2,213,436	1,174,868	1,450,080	685,970	407,732	203,125	355,625
EZY208	2,951,300	1,928,754	2,102,428	1,232,349	692,625	340,780	156,250	355,625
Total	**15,465,101**	**11,243,916**	**9,862,345**	**6,426,286**	**4,087,141**	**2,335,135**	**1,515,625**	**2,482,500**
shares (%)	100%	100%	64%	57%	26%	21%	10%	22%
changes %		**-27%**		**-7%**		**-5%**		**+12%**

Chapter 6 Tables

TABLE 6.1 Aircraft rotation schedule of Aircraft GBMRH

Flight Number	STD[b]	STA[c]	TSG[d]	Flight Number	STD	STA	TSG
BA426	07:00[a] **LHR**	08:15 **AMS**	60 **at AMS**	BA427	09:15 **AMS**	10:30 **LHR**	80 **at LHR**
BA308	11:50 **LHR**	12:55 **CDG**	55 **at CDG**	BA309	13:50 **CDG**	15:00 **LHR**	75 **at LHR**
BA318	16:15 **LHR**	17:20 **CDG**	55 **at CDG**	BA319	18:15 **CDG**	19:40 **LHR**	80 **at LHR**
BA326	21:00 **LHR**	22:00 **CDG**					

[a] all time shown in the table is based on **GMT**.
[b] STD stands for "scheduled time of departure"
[c] STA stands for "scheduled time of arrival"
[d] TSG stands for "scheduled turnaround time"

TABLE 6.2 Disruption probability and duration in the Cargo & Baggage process (**LHR**)

States	State Description	States	State Description	Occurrence Probability (p_{ij})	State Sojourn Time ($\Phi_{ij}(t)$) μ	σ
1	*Arrival*				μ	σ
2	*Goods unloading*	*5*	Cargo Processing	0.003[a]	11[b]	9
		6	Aircraft Ramp Handling	0.02	25	24
3	*Goods loading*	*7*	Cargo Processing	0.003	11	9
		8	Aircraft Ramp Handling	0.02	25	24
		9	Passenger & Baggage	0.02	15	14
4	*Departure*					

[a] the occurrence probability of each disruption state
[b] the mean delay time and standard deviation of each disruption state

TABLE 6.3 Disruption probability and duration in the Passenger/Crew/Cabin Cleaning process **(LHR)**

States	State Description	States	State Description	Occurrence Probability (p_{ij})	State Sojourn Time ($\Phi_{ij}(t)$)	
					μ	σ
1	*Arrival*					
2	*Disembark Passengers & Crew*					
3	*Cabin Cleaning*					
4	*ATC Flow Control*					
5	*Crew & Passenger Boarding*	*8*	Crew	0.04[a]	23[b]	19
		9	Passengers	0.02	15	14
		10	Missing Passengers	0.02	12	12
6	*Flight Operations & Crew Procedures*	*11*	Flight Operations	0.0004	17	10
		12	Departure Process	0.16	14	16
		13	Weather	0.004	45	40
7	*Departure*					

[a] the occurrence probability of each disruption state

[b] the mean delay time and standard deviation of each disruption state

TABLE 6.4 Occurrence probability of disrupting events in aircraft turnaround operations **(LHR)**

Event	Event Description	Occurrence Probability (p_{ij})	Occurrence Epoch[a]	Event Duration ($\Phi_{ij}(t)$)
1	Fuelling Activity Delay	0.003	Exponential (15)	Normal (15,15)
2	Engineering Check Delay	0.002	Exponential (20)	Normal (43,37)
3	Aircraft Damage	0.02	Exponential (20)	Normal (23,39)
4	Aircraft Changes	0.006	Exponential (30)	Normal (69,47)

[a] the time from the start of aircraft turnaround operations

TABLE 6.5 Regression results of turnaround efficiency at LHR

Flight Number	Regression Equations[a]	R^2
BA308	$y = 0.57x + 3.22$	0.60
	$y = 0.0075x^2 - 0.0424x + 3.4941$	0.76
BA318	$y = 0.60x + 6.35$	0.47
	$y = 0.0045x^2 + 0.2831x + 6.8174$	0.49
BA326	$y = 0.29x + 3.68$	0.20
	$y = 0.0042x^2 + 0.0485x + 3.0914$	0.29

[a] variable "x" stands for "arrival delays of inbound aircraft"; "y" for "departure delays"

TABLE 6.6 Disruption probability and duration in the Cargo & Baggage process (AMS)

States	State Description	States	State Description	Occurrence Probability (p_{ij})	State Sojourn Time ($\Phi_{ij}(t)$) μ	σ
1	*Arrival*					
2	*Goods unloading*	*5*	Cargo Processing	0.001[a]	5[b]	1
		6	Aircraft Ramp Handling	0.02	14	6
3	*Goods loading*	*7*	Cargo Processing	0.001	5	1
		8	Aircraft Ramp Handling	0.02	14	6
		9	Passenger & Baggage	0.003	5	1
4	*Departure*					

[a] the occurrence probability of each disruption state

[b] the mean delay time and standard deviation of each disruption state

TABLE 6.7 Disruption probability and duration in the Passenger/Crew/Cabin Cleaning process (AMS)

States	State Description	States	State Description	Occurrence Probability (p_{ij})	State Sojourn Time ($\Phi_{ij}(t)$)	
1	*Arrival*					
2	*Disembark Passengers & Crew*					
3	*Cabin Cleaning*					
4	*ATC Flow Control*				μ	σ
5	*Crew & Passenger Boarding*	*8*	Crew	0.002	6[b]	4
		9	Passengers	0.02	8	3
		10	Missing Passengers	0.03	9	6
6	*Flight Operations & Crew Procedures*	*11*	Flight Operations	0.001	5	1
		12	Departure Process	0.11	19	8
		13	Weather	0.008	19	18
7	*Departure*					

[a] the occurrence probability of each disruption state
[b] the mean delay time and standard deviation of each disruption state

TABLE 6.8 Occurrence probability of disrupting events in aircraft turnaround operations (AMS)

Event	Event Description	Occurrence Probability (p_{ij})	Occurrence Epoch[a]	Event Duration ($\Phi_{ij}(t)$)
1	Fuelling Activity Delay	0.001	Exponential (15)	Normal (20,10)
2	Engineering Check Delay	0.0001	Exponential (20)	Normal (20,10)
3	Aircraft Damage	0.003	Exponential (20)	Normal (142,161)
4	Aircraft Changes	0.002	Exponential (30)	Normal (10,15)

[a] the time from the start of aircraft turnaround operations

TABLE 6.9 Regression results of turnaround efficiency at AMS

Flight Number	Regression Equations[a]	R^2
BA427	$y = 0.90x + 10.81$	0.75

[a] variable "x" stands for "arrival delays of inbound aircraft"; "y" for "departure delays"

TABLE 6.10 Disruption probability and duration in the Cargo & Baggage process (**CDG**)

States	State Description	States	State Description	Occurrence Probability (p_{ij})	State Sojourn Time ($\Phi_{ij}(t)$)	
1	*Arrival*				μ	σ
2	*Goods unloading*	***5***	Cargo Processing	0.001[a]	5[b]	1
		6	Aircraft Ramp Handling	0.03	12	8
3	*Goods loading*	***7***	Cargo Processing	0.001	5	1
		8	Aircraft Ramp Handling	0.03	12	8
		9	Passenger & Baggage	0.02	9	10
4	*Departure*					

[a] the occurrence probability of each disruption state

[b] the mean delay time and standard deviation of each disruption state

TABLE 6.11 Disruption probability and duration in the Passenger/Crew/Cabin Cleaning process **(CDG)**

States	State Description	States	State Description	Occurrence Probability (p_{ij})	State Sojourn Time ($\Phi_{ij}(t)$)	
1	*Arrival*					
2	*Disembark Passengers & Crew*					
3	*Cabin Cleaning*					
4	*ATC Flow Control*				μ	σ
5	*Crew & Passenger Boarding*	*8*	Crew	0.001	5[b]	1
		9	Passengers	0.02	10	7
		10	Missing Passengers	0.03	17	15
6	*Flight Operations & Crew Procedures*	*11*	Flight Operations	0.001	5	1
		12	Departure Process	0.06	29	26
		13	Weather	0.001	5	1
7	*Departure*					

[a] the occurrence probability of each disruption state
[b] the mean delay time and standard deviation of each disruption state

TABLE 6.12 Occurrence probability of disrupting events in aircraft turnaround operations **(CDG)**

Event	Event Description	Occurrence Probability (p_{ij})	Occurrence Epoch[a]	Event Duration ($\Phi_{ij}(t)$)
1	Fuelling Activity Delay	0.003	Exponential (15)	Normal (12,9)
2	Engineering Check Delay	0.001	Exponential (20)	Normal (20,10)
3	Aircraft Damage	0.009	Exponential (20)	Normal (49,48)
4	Aircraft Changes	0.001	Exponential (30)	Normal (20,10)

[a] the time from the start of aircraft turnaround operations

TABLE 6.13 Regression results of turnaround efficiency at CDG

Flight Number	Regression Equations[a]	R^2
BA309	$y = 0.86x + 3.04$	0.89
BA319	$y = 0.89x + 4.36$	0.78

[a] variable "x" stands for "arrival delays of inbound aircraft"; "y" for "departure delays"

TABLE 6.14 Punctuality analysis of aircraft rotation on the LHR-AMS-CDG route **(observation)**

from	to	Flight Number	Mean **Dept** Delay[a]		Mean **Arr** Delay[b]		Expected Dept Delay **($E[D]_d$)**	Expected Arr Delay **($E[D]_a$)**
			μ_d	σ_d	μ_a	σ_a		
LHR	AMS	**BA426**	10	22	8	28	9	6
AMS	LHR	**BA427**	14	24	12	27	13	9
LHR	CDG	**BA308**	12	23	13	26	12	10
CDG	LHR	**BA309**	15	23	14	25	14	11
LHR	CDG	**BA318**	12	20	12	21	13	10
CDG	LHR	**BA319**	15	21	10	21	15	8
LHR	CDG	**BA326**	6	16	4	19	6	3

[a] μ_d stands for the mean value departure delays of all samples; σ stands for the standard deviation

[b] the calculation of the mean arrival delay (μ_a) includes all simulation samples, i.e. to include "negative delays" of early arrivals.

TABLE 6.15 Results of MAT model calibration **(turnarounds at LHR)**

Flight Number	Inbound A/C Arrival PDF	Observation[a] μ_{in}[b]	μ_{out}	**Simulation** μ_{in}[b]	μ_{out}	Mean T/R Time (**TG**)	Scheduled TR (**TSG**)	Goodness-of-Fit Test Value
BA308	Beta(2,5)	15	12	15	10	60	80	0.06[c]
BA318	Beta(2,4)	16	12	17	11	55	75	0.07[d]
BA326	Beta(2,3)	15	6	14	5	50	80	0.05[e]

[a] μ_{in} stands for the mean inbound delay; μ_{out} stands for the mean outbound delay
[b] the calculation of μ_{in} includes only "positive delays", i.e. to exclude early arrivals.
[c] the critical *K-S test* value is 0.21 for BA308 case
[d] the critical *K-S test* value is 0.23 for BA318 case
[e] the critical *K-S test* value is 0.23 for BA326 case

TABLE 6.16 Results of MAT model calibration **(turnarounds at AMS)**

Flight Number	Inbound A/C Arrival PDF	Observation[a] μ_{in}[b]	μ_{out}	**Simulation** μ_{in}[b]	μ_{out}	Mean T/R Time (**TG**)	Scheduled TR (**TSG**)	Goodness-of-Fit Test Value
BA427	Beta(2,7)	13	14	13	11	45	60	0.08[c]

[a] μ_{in} stands for the mean inbound delay; μ_{out} stands for the mean outbound delay
[b] the calculation of μ_{in} includes only "positive delays", i.e. to exclude early arrivals.
[c] the critical *K-S test* value is 0.21 for BA427 case

TABLE 6.17 Results of MAT model calibration **(turnarounds at CDG)**

Flight Number	Inbound A/C Arrival PDF	Observation[a] μ_{in}[b]	μ_{out}	**Simulation** μ_{in}[b]	μ_{out}	Mean T/R Time (**TG**)	Scheduled TR (**TSG**)	Goodness-of-Fit Test Value
BA309	Beta(3,7)	15	15	14	11	40	55	0.08[c]
BA319	Beta(2,4)	14	15	14	14	45	55	0.07[d]

[a] μ_{in} stands for the mean inbound delay; μ_{out} stands for the mean outbound delay
[b] the calculation of μ_{in} includes only "positive delays", i.e. to exclude early arrivals.
[c] the critical *K-S test* value is 0.21 for BA309 case
[d] the critical *K-S test* value is 0.23 for BA319 case

TABLE 6.18 Results of Enroute model calibration **(between LHR and AMS)**

Flight Number	Observation[a] μ_d	μ_a	**Simulation** μ_d	μ_a	Enroute Flight Time[b]	TMA Delay[c]	Scheduled Block Time	Goodness-of-Fit Test
BA426 **LHR AMS**	10	8	10	8	N(65,5)	E(6)	75	0.11[d]
BA427 **AMS LHR**	14	12	14	13	N(65,5)	E(7)	75	0.09[e]

[a] μ_d stands for the mean departure delay; μ_a stands for the mean arrival delay
[b] the enroute flight time of an aircraft is modelled by Normal functions (denoted by $N(\mu, \sigma)$)
[c] the TMA delay to an inbound aircraft is modelled by Exponential functions (denoted by $E(\mu)$)
[d] the critical K-S test value is 0.23 for BA426 case
[e] the critical K-S test value is 0.21 for BA427 case

TABLE 6.19 Results of Enroute model calibration **(from LHR to CDG)**

Flight Number	Observation[a] μ_d	Observation[a] μ_a	**Simulation** μ_d	**Simulation** μ_a	Enroute Flight Time	TMA Delay	Scheduled Block Time	Goodness-of-Fit Test
BA308	12	13	12	12	N(57,5)	E(7)	65	0.06[d]
BA318	12	12	12	12	N(57,5)	E(7)	65	0.08[e]
BA326	6	4	6	4	N(50,5)	E(7)	60	0.03[f]

[a] μ_d stands for the mean departure delay; μ_a stands for the mean arrival delay

[b] the enroute flight time of an aircraft is modelled by Normal functions (denoted by N(μ , σ))

[c] the TMA delay to an inbound aircraft is modelled by Exponential functions (denoted by E(μ))

[d] the critical K-S test value is 0.21 for BA308 case

[e] the critical K-S test value is 0.23 for BA318 case

[f] the critical K-S test value is 0.23 for BA326 case

TABLE 6.20 Results of Enroute model calibration **(from CDG to LHR)**

Flight Number	Observation[a] μ_d	Observation[a] μ_a	**Simulation** μ_d	**Simulation** μ_a	Enroute Flight Time	TMA Delay	Scheduled Block Time	Goodness-of-Fit Test
BA309	15	14	15	12	N(60,5)	E(7)	70	0.05[d]
BA319	15	10	15	10	N(73,5)	E(7)	85	0.08[e]

[a] μ_d stands for the mean departure delay; μ_a stands for the mean arrival delay

[b] the enroute flight time of an aircraft is modelled by Normal functions (denoted by N(μ , σ))

[c] the TMA delay to an inbound aircraft is modelled by Exponential functions (denoted by E(μ))

[d] the critical K-S test value is 0.21 for BA309 case

[e] the critical K-S test value is 0.23 for BA319 case

TABLE 6.21 Punctuality analysis of aircraft rotation from simulation results

from	to	Flight Number	Mean **Dept** Delay[a]		Mean **Arr** Delay[b]		Expected Dept Delay ($E[D]_d$)	Expected Arr Delay ($E[D]_a$)
			μ_d	σ_d	μ_a	σ_a		
LHR	AMS	**BA426**	10	13	8	16	11	8
AMS	LHR	**BA427**	12	18	11	20	13	10
LHR	CDG	**BA308**	12	21	11	23	13	10
CDG	LHR	**BA309**	15	23	14	25	15	12
LHR	CDG	**BA318**	13	24	11	26	14	9
CDG	LHR	**BA319**	14	26	9	27	15	6
LHR	CDG	**BA326**	8	22	5	23	10	3

[a] μ_d stands for the mean departure delays of all samples;σ stands for the standard deviation
[b] the calculation of the mean arrival delay (μ_a) includes all simulation samples, i.e. to include "negative delays" of early arrivals.

TABLE 6.22 Punctuality analysis of aircraft rotation from optimisation results

from	to	Flight Number	Mean **Dept** Delay[a]		Mean **Arr** Delay[b]		Expected Dept Delay ($E[D]_d$)	Expected Arr Delay ($E[D]_a$)
			μ_d	σ_d	μ_a	σ_a		
LHR	AMS	**BA426**	4	10	-2	13	8	-2
AMS	LHR	**BA427**	4	12	-1	15	8	-1
LHR	CDG	**BA308**	6	15	0	17	9	-1
CDG	LHR	**BA309**	5	16	1	18	8	0
LHR	CDG	**BA318**	6	18	0	21	9	-1
CDG	LHR	**BA319**	6	18	1	20	9	0
LHR	CDG	**BA326**	7	19	0	21	9	-1

[a] μ_d stands for the mean departure delays of all samples;σ stands for the standard deviation
[b] the calculation of the mean arrival delay (μ_a) includes all simulation samples, i.e. to include "negative delays" of early arrivals.

TABLE 6.23 Optimisation results of aircraft rotational schedule

from	to	Flight Number	Scheduled Turnaround Time (TSG)		Scheduled Block Time (T_B)		Total Leg-Time	
			original	**optimised**	**original**	**optimised**	**original**	**optimised**
LHR	AMS	**BA426**	62	72	75	80	135	152
AMS	LHR	**BA427**	60	66	75	80	135	146
LHR	CDG	**BA308**	80	81	65	70	145	151
CDG	LHR	**BA309**	55	64	70	74	125	138
LHR	CDG	**BA318**	75	72	65	70	140	142
CDG	LHR	**BA319**	55	61	85	85	140	146
LHR	CDG	**BA326**	80	67	60	63	140	130
						Total ime	**960**	**1,005**

TABLE 6.24 System costs comparison between the optimised schedule and the original schedule

Flight Number	Total Cost (C_T)		Passenger Delay Cost (C_{DP})		Aircraft Delay Cost (C_{DA})		Schedule Time Cost (C_{AL})	
	original	**optimised**	**original**	**optimised**	**original**	**optimised**	**original**	**optimised**
BA426	1,933,086	1,322,578	447,929	168,197	1,383,407	559,006	101,750	595,375
BA427	2,573,361	1,355,300	728,378	230,178	1,668,981	623,246	176,000	501,875
BA308	2,971,651	1,688,374	888,710	364,891	1,685,565	739,108	397,375	584,375
BA309	3,512,138	1,788,373	1,209,213	420,586	2,098,048	746,286	204,875	621,500
BA318	3,623,368	2,015,136	1,183,539	547,303	1,801,831	838,084	638,000	629,750
BA319	3,396,821	1,881,607	1,262,130	539,283	1,799,194	792,323	335,500	550,000
BA326	3,401,986	2,055,916	830,729	562,428	1,196,259	863,740	1,375,000	629,750
Total ($)	**21,412,411**	**12,107,284**	**6,550,628**	**2,832,866**	**11,633,285**	**5,161,793**	**3,228,500**	**4,112,625**
shares (%)	100%	100%	31%	23%	54%	43%	15%	34%
changes %		**-43%**		**-8%**		**-11%**		**+19%**

Chapter 1 Figures

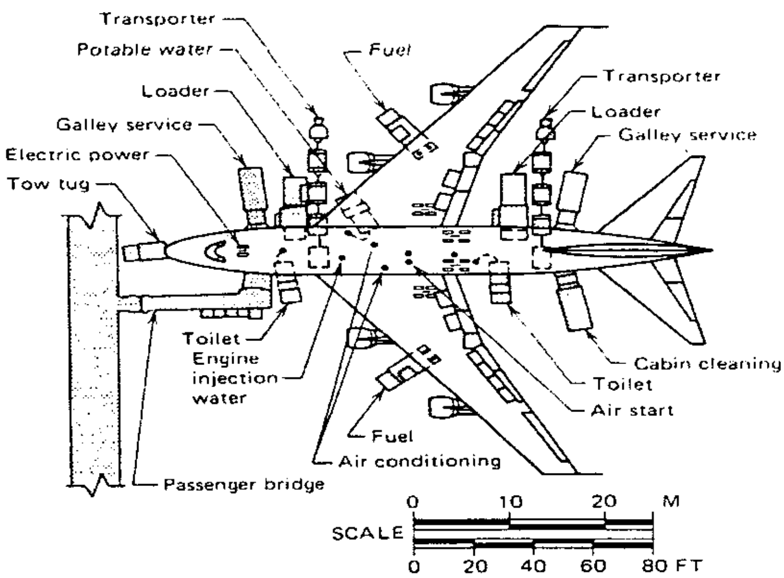

FIGURE 1.1 The position of aircraft ground service equipment at an aircraft stand (Sources: Ashford *et al*, 1997)

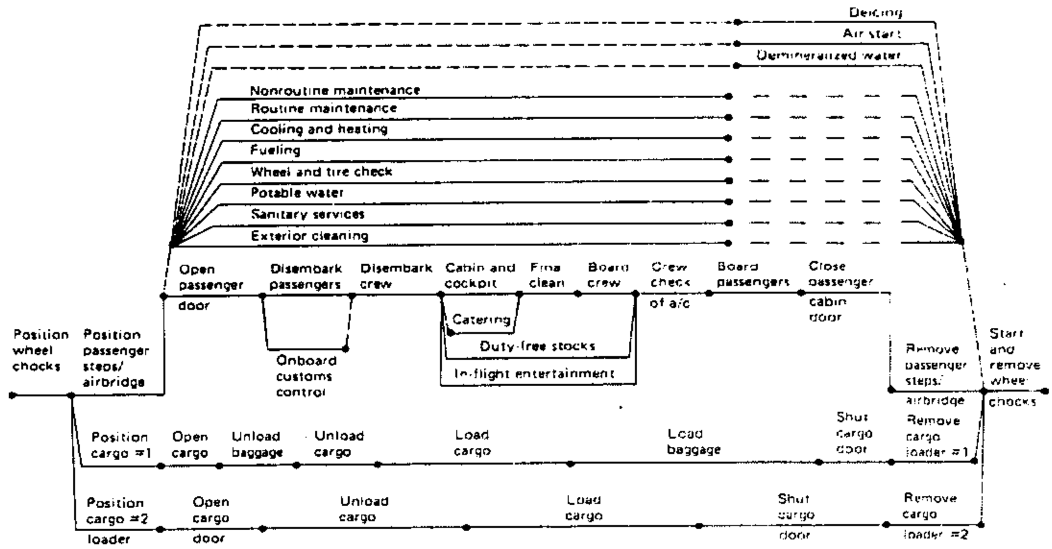

Figure 6.18. Critical path of turnaround ground handling for a passenger transport aircraft taking cargo.

FIGURE 1.2 Operational flows of aircraft turnaround

(Sources: Ashford *et al*, 1997)

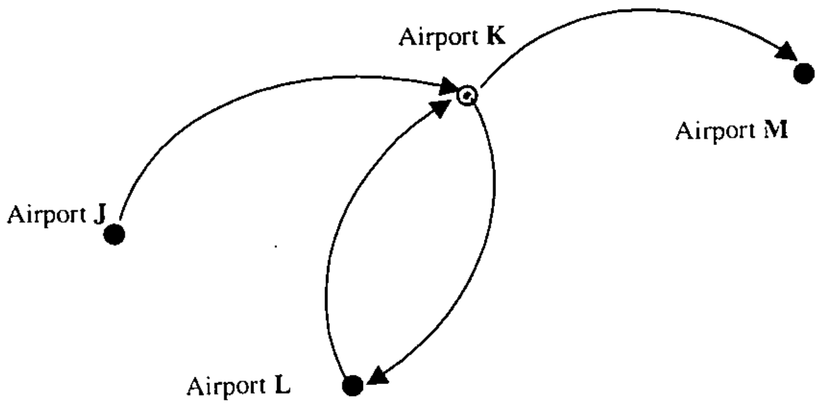

FIGURE 1.3 Aircraft rotation in a network of airports

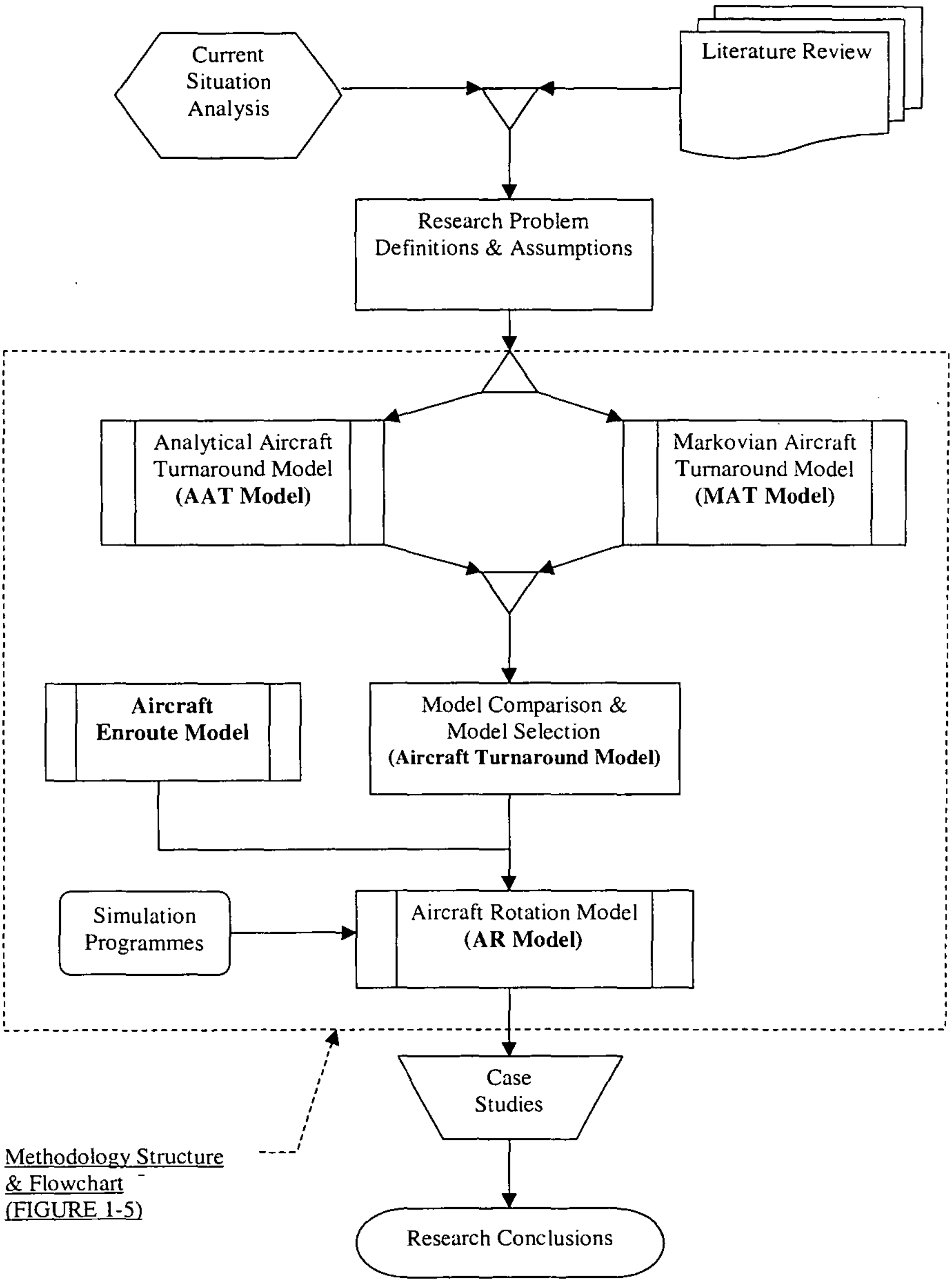

FIGURE 1.4 Main research structure and flowchart

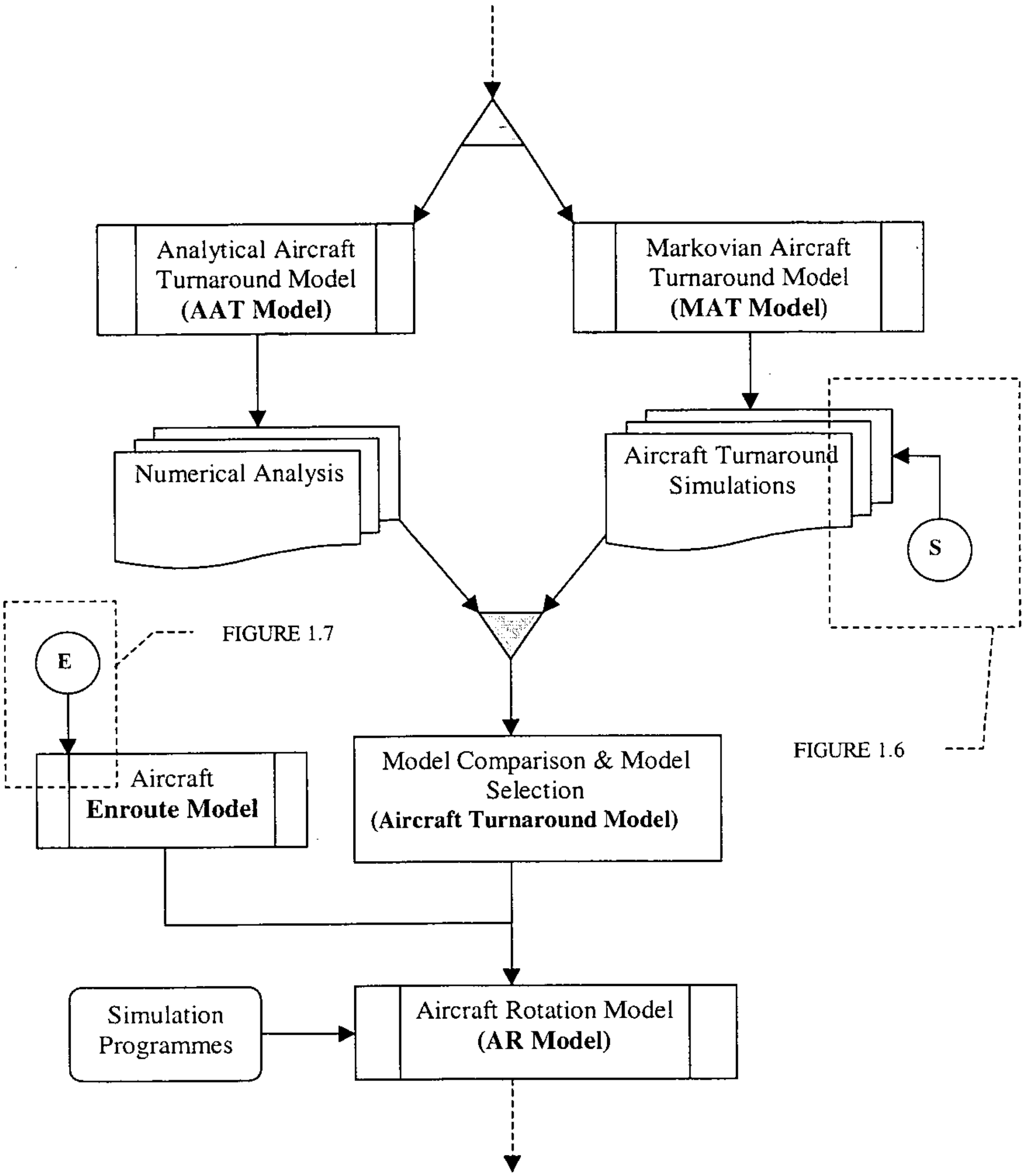

FIGURE 1.5 Methodology structure and flowchart

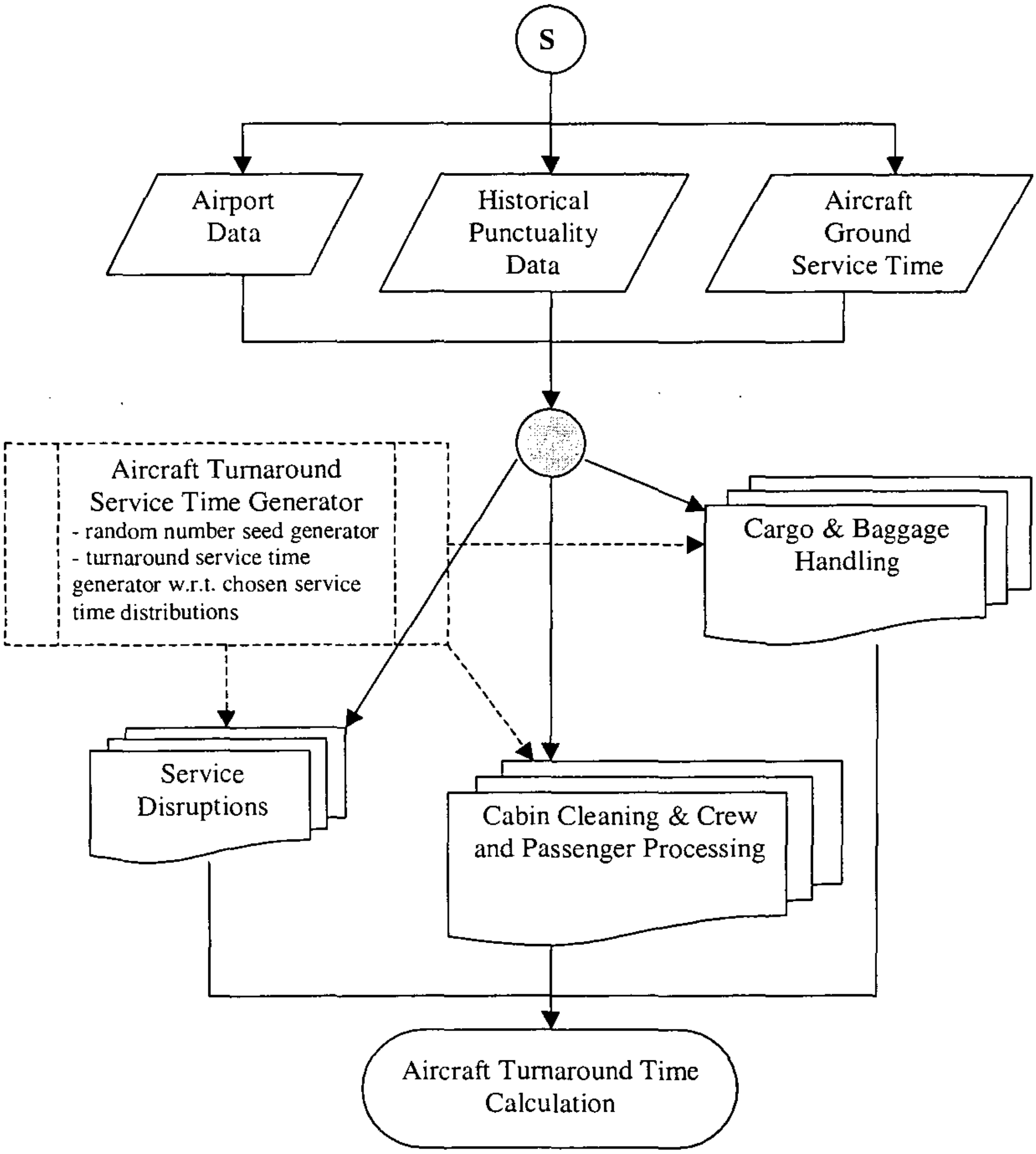

FIGURE 1.6 Methodology structure and flowchart of the MAT simulation model

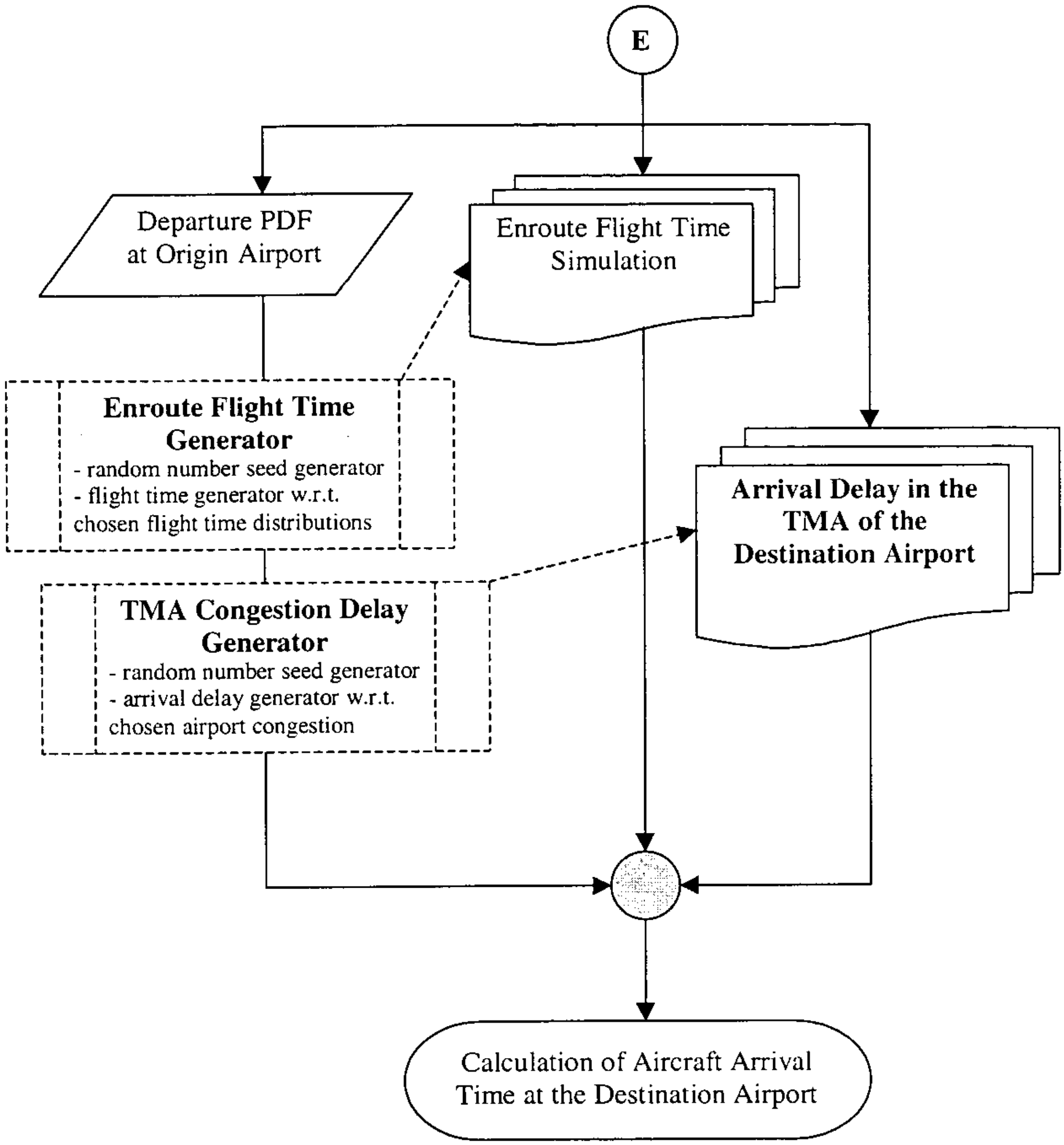

FIGURE 1.7 Methodology structure and flowchart of the Enroute simulation model

Chapter 2 Figures

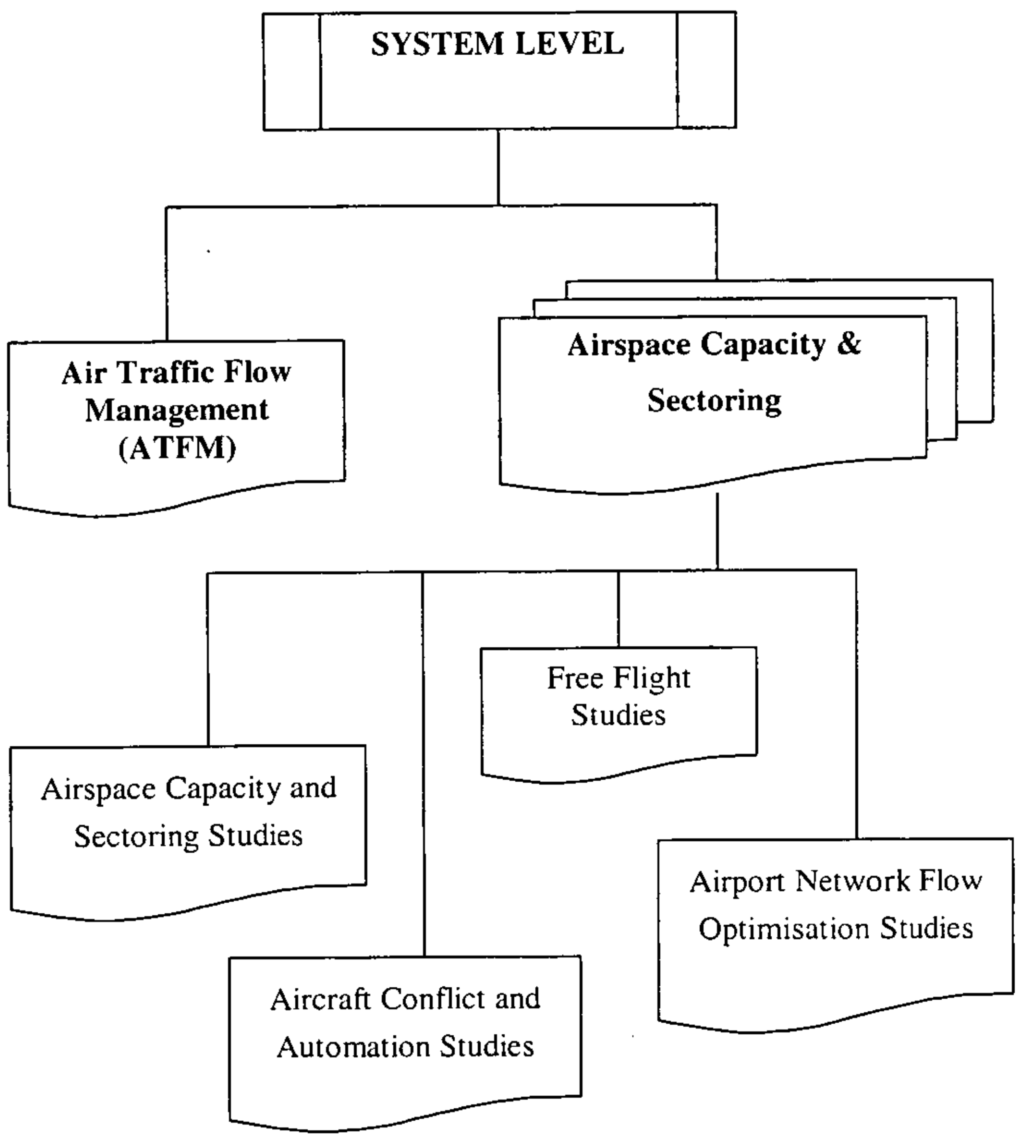

FIGURE 2.1 Literature review structure on the system level

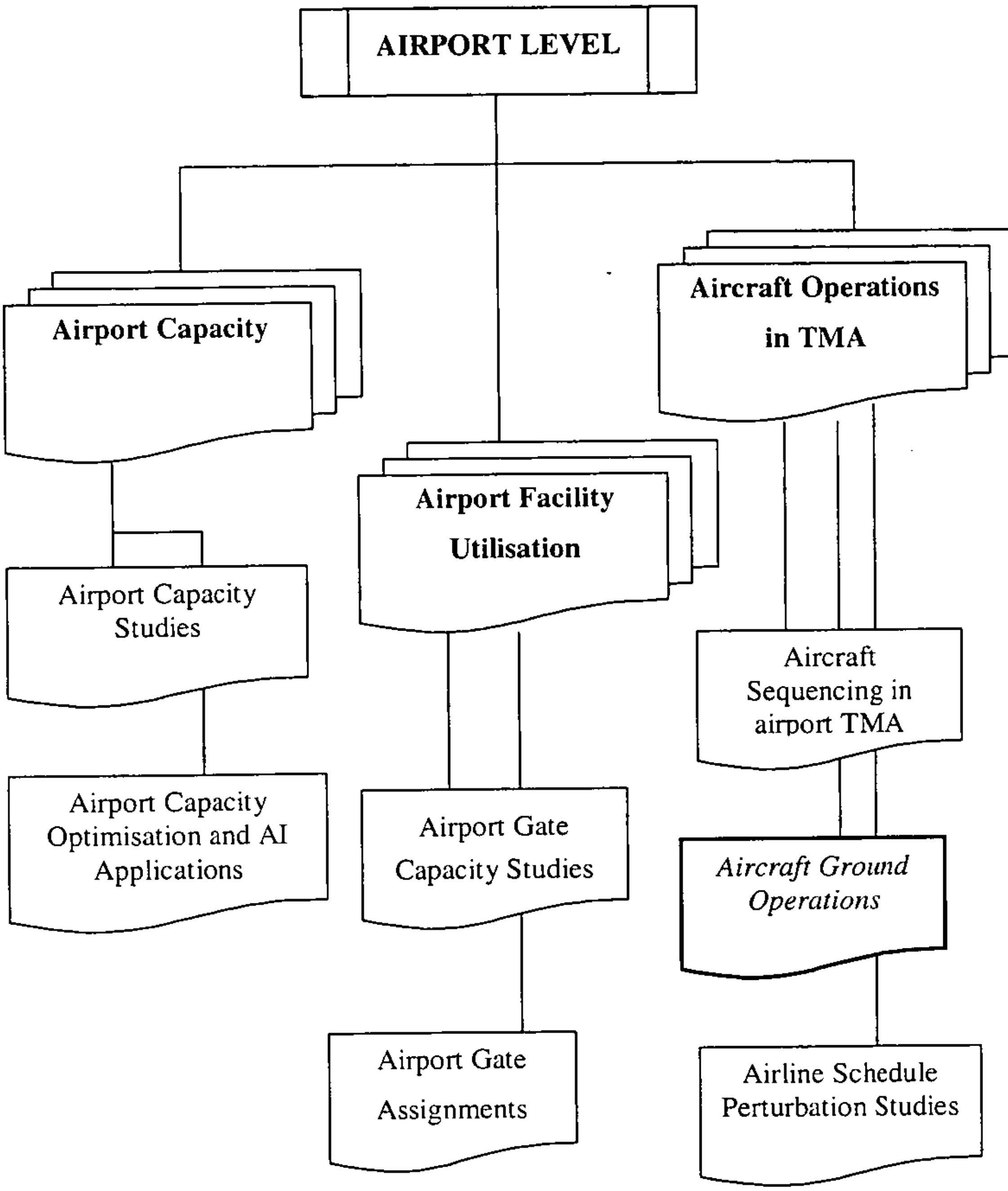

FIGURE 2.2 Literature review structure on the airport level

Chapter 3 Figures

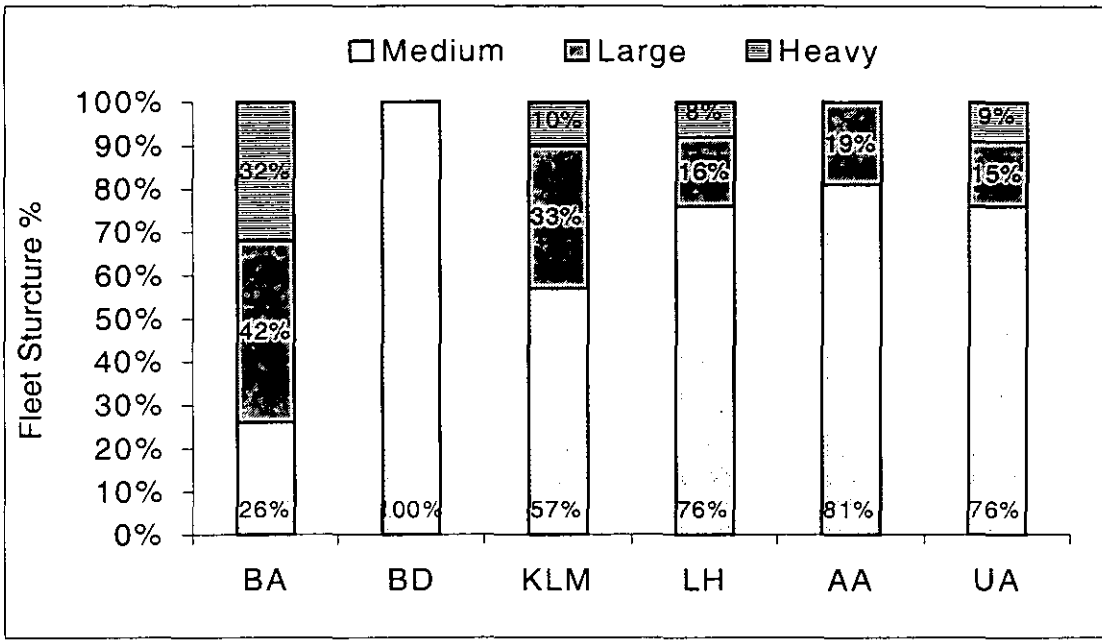

FIGURE 3.1 Aircraft types of major airlines

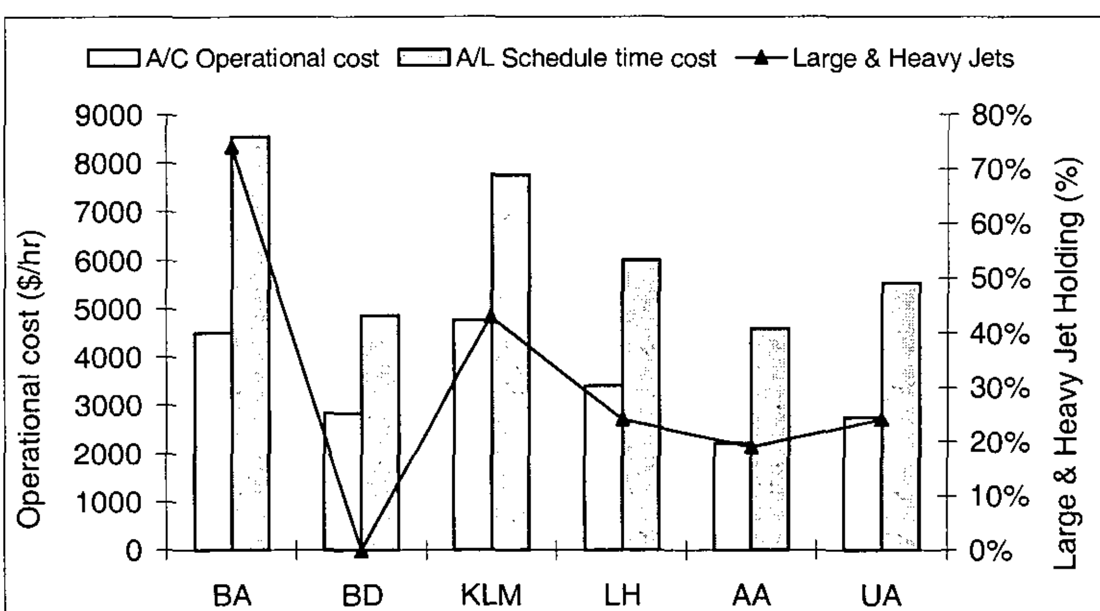

FIGURE 3.2 Comparison of operational costs and aircraft fleet usage

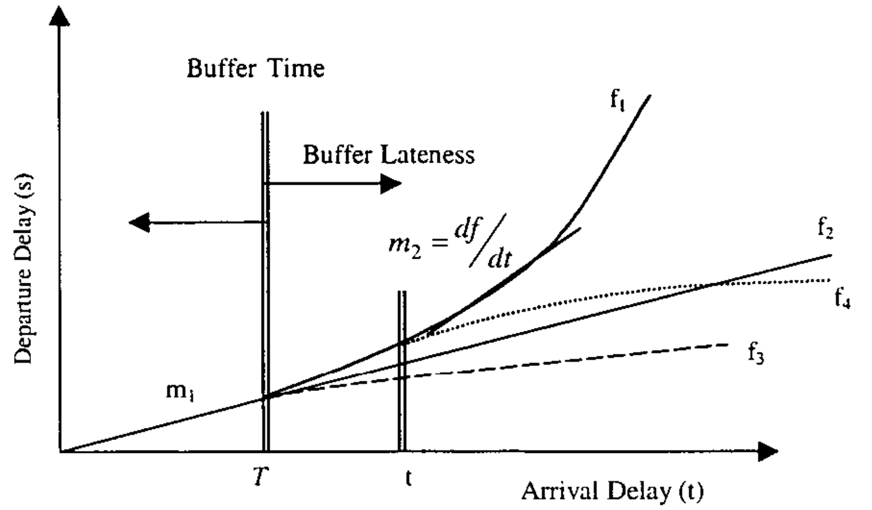

FIGURE 3.3 Development of departure delay due to arrival lateness

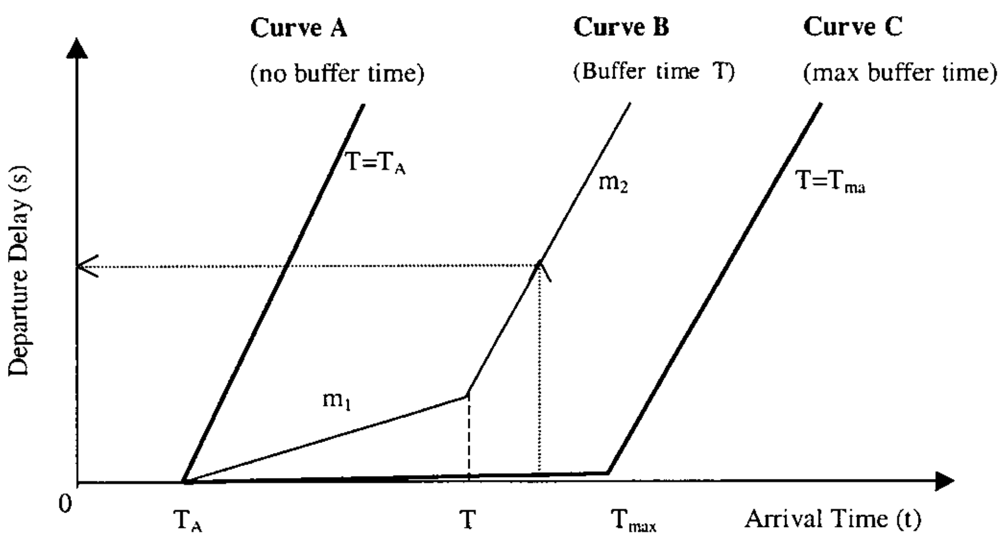

FIGURE 3.4 Relationships between departure time (*s*) and arrival time (*t*) of a turnaround aircraft

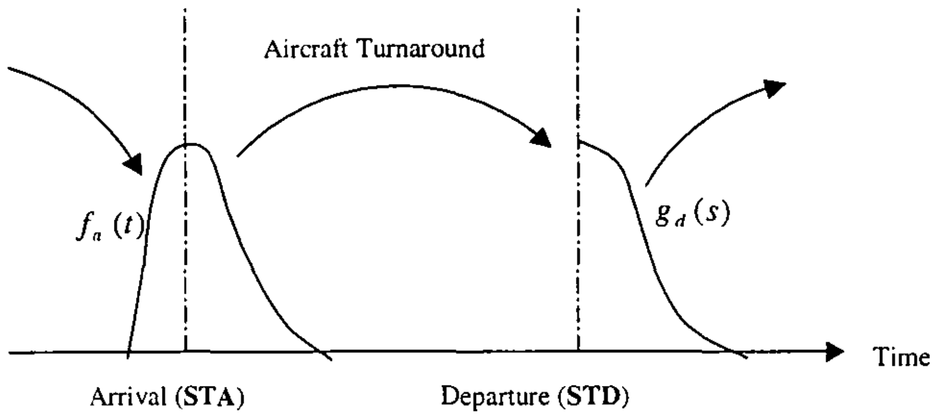

FIGURE 3.5 Relationships between arrival PDFs and departure PDFs

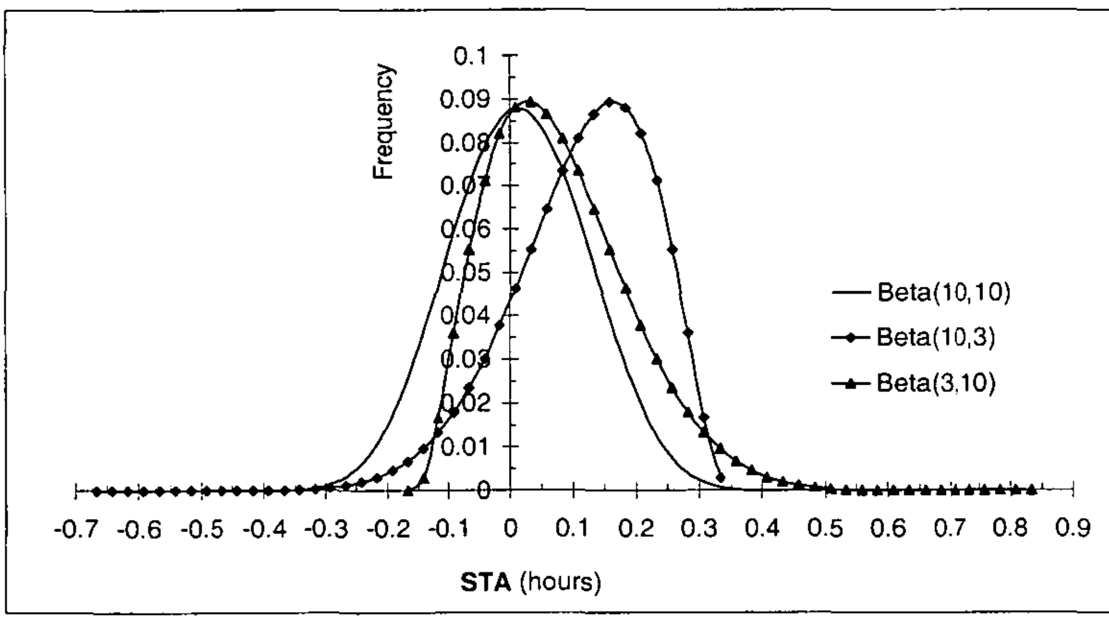

FIGURE 3.6 Aircraft arrival time deviation from STA

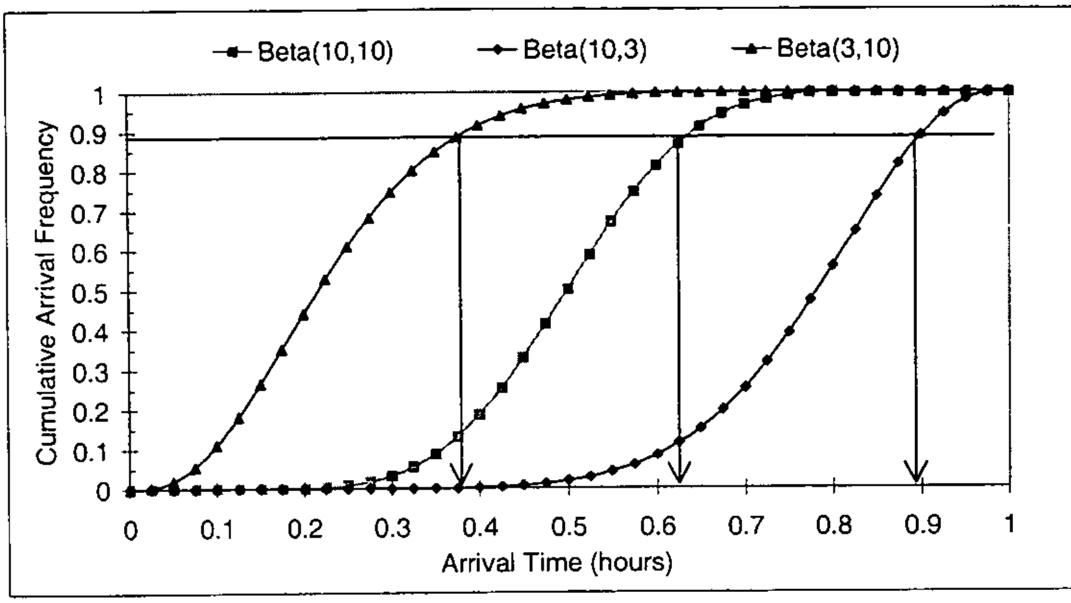

FIGURE 3.7 Cumulative arrival punctuality performance for Beta functions

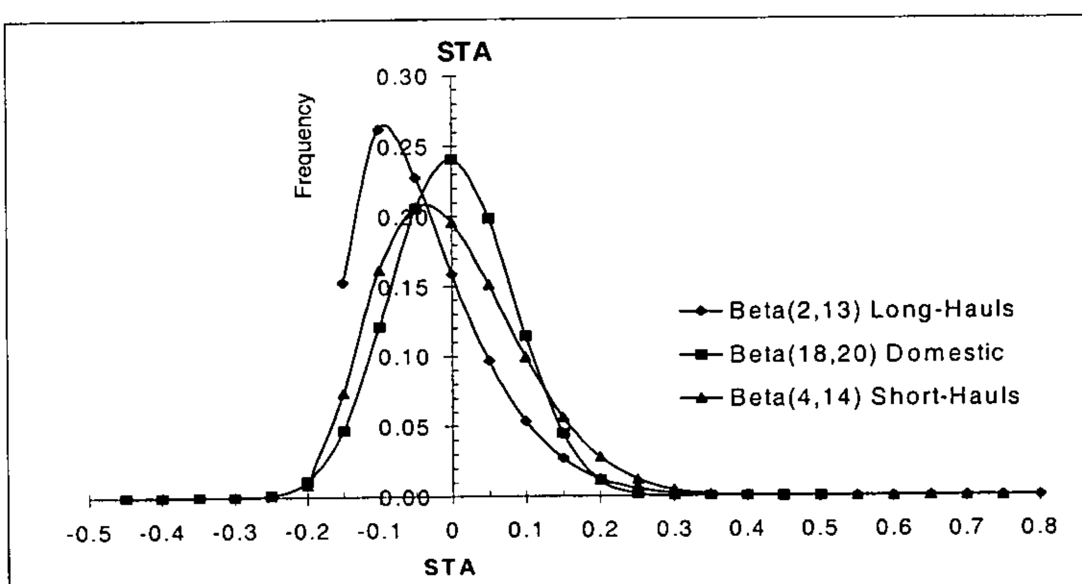

FIGURE 3.8 Aircraft arrival time distributions from flight punctuality data

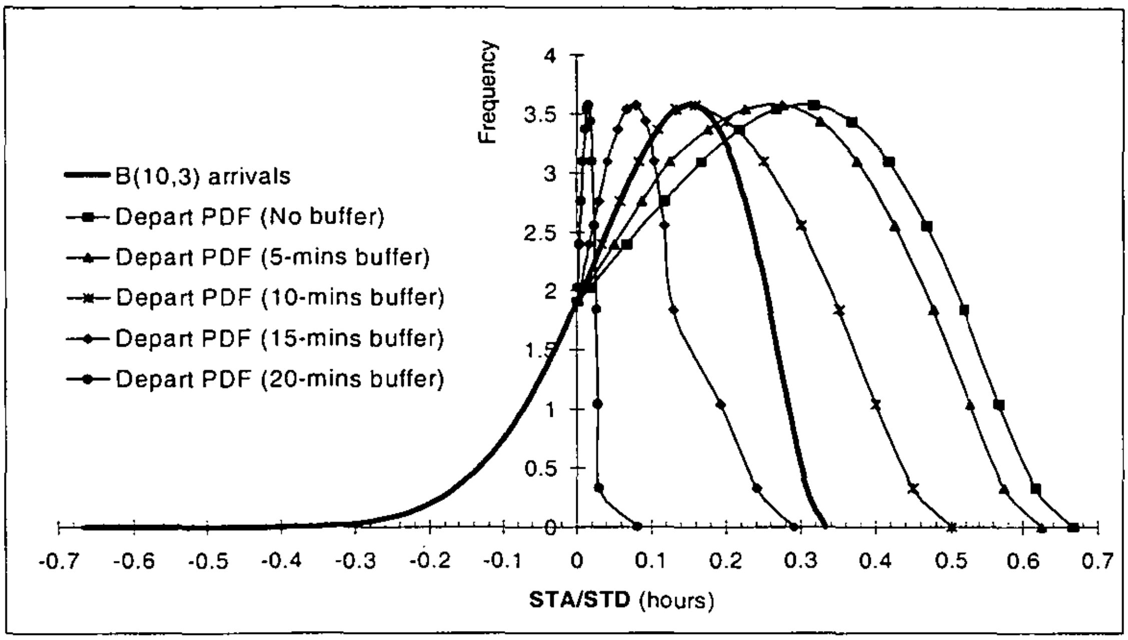

FIGURE 3.9 Departure time distributions corresponding to various punctuality buffers

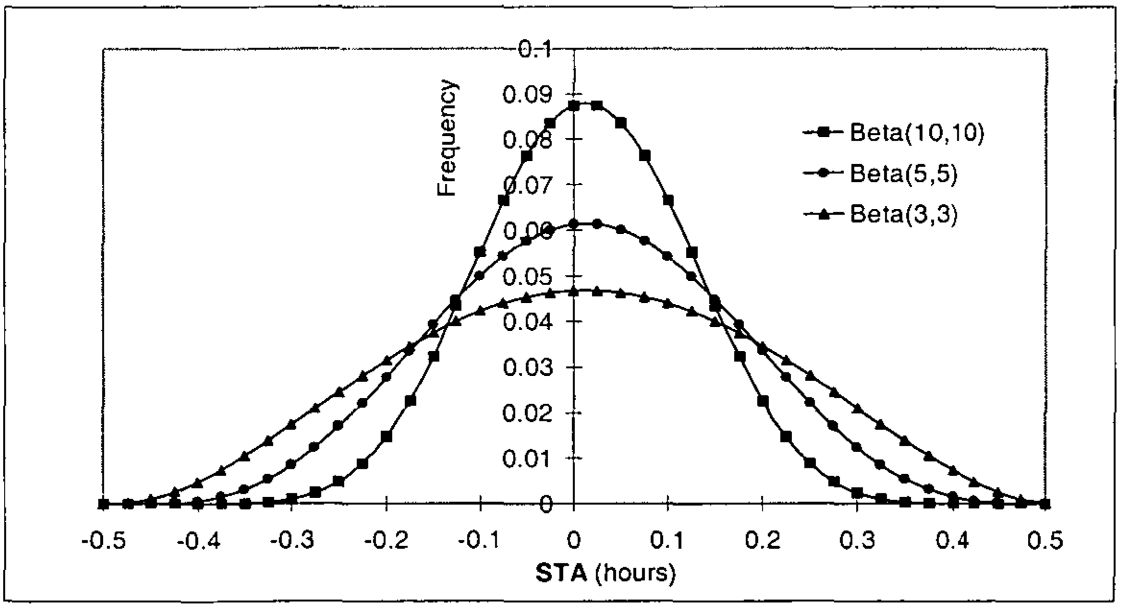

FIGURE 3.10 PDFs of Beta(10,10), Beta(5,5) and Beta(3,3) functions

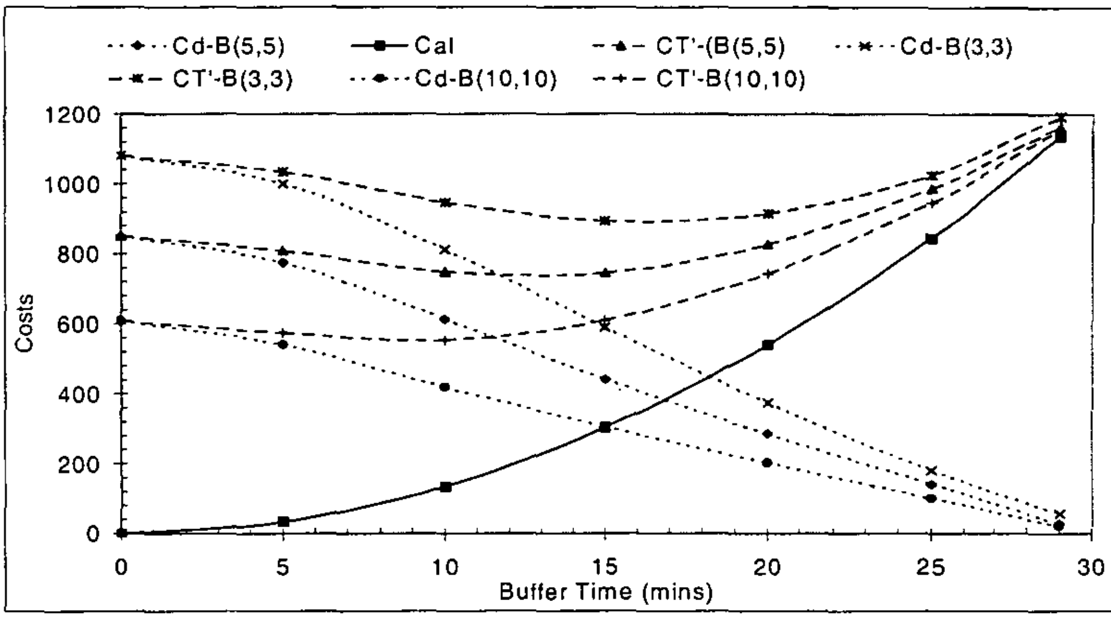

FIGURE 3.11 Influence of aircraft arrival PDFs on model outputs

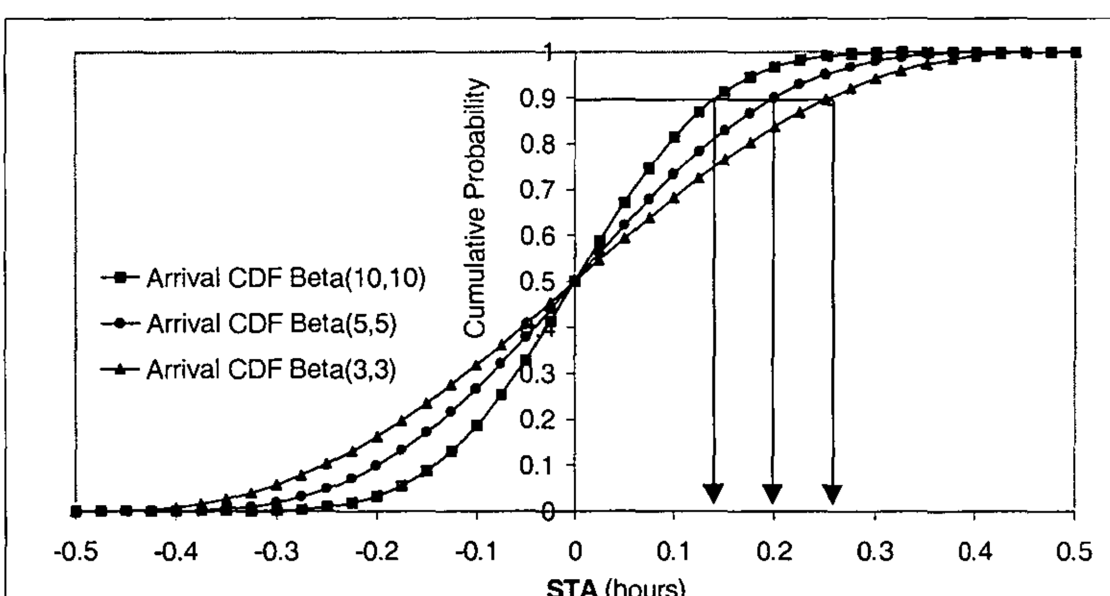

FIGURE 3.12 CDFs of Beta(10,10), Beta(5,5) and Beta(3,3) functions

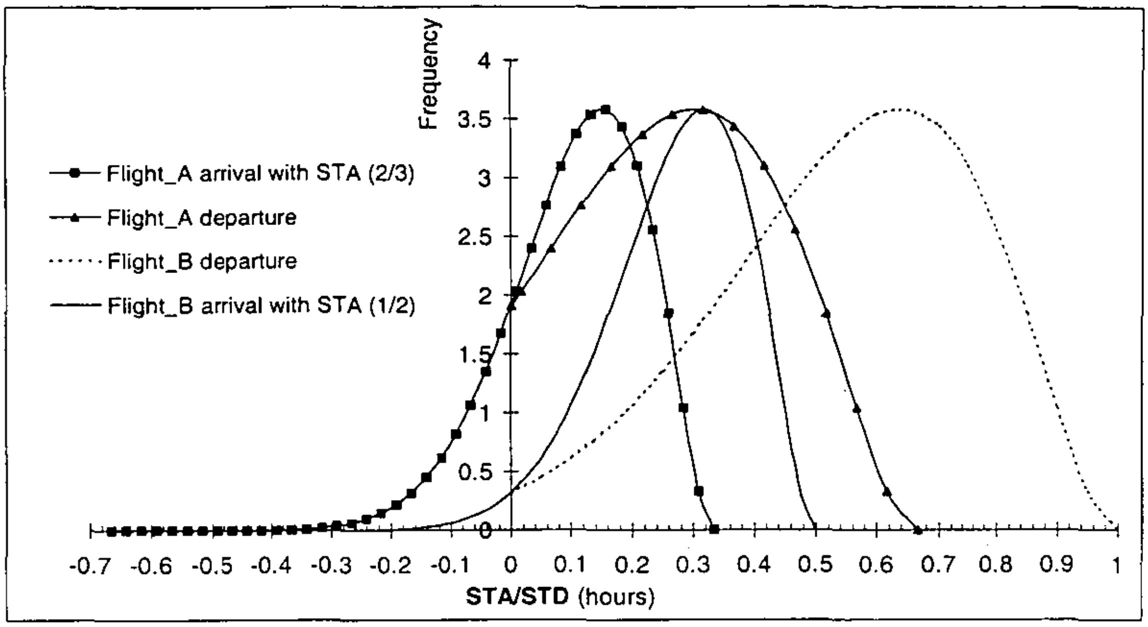

FIGURE 3.13 Influence of arrival punctuality of inbound aircraft on departure PDFs

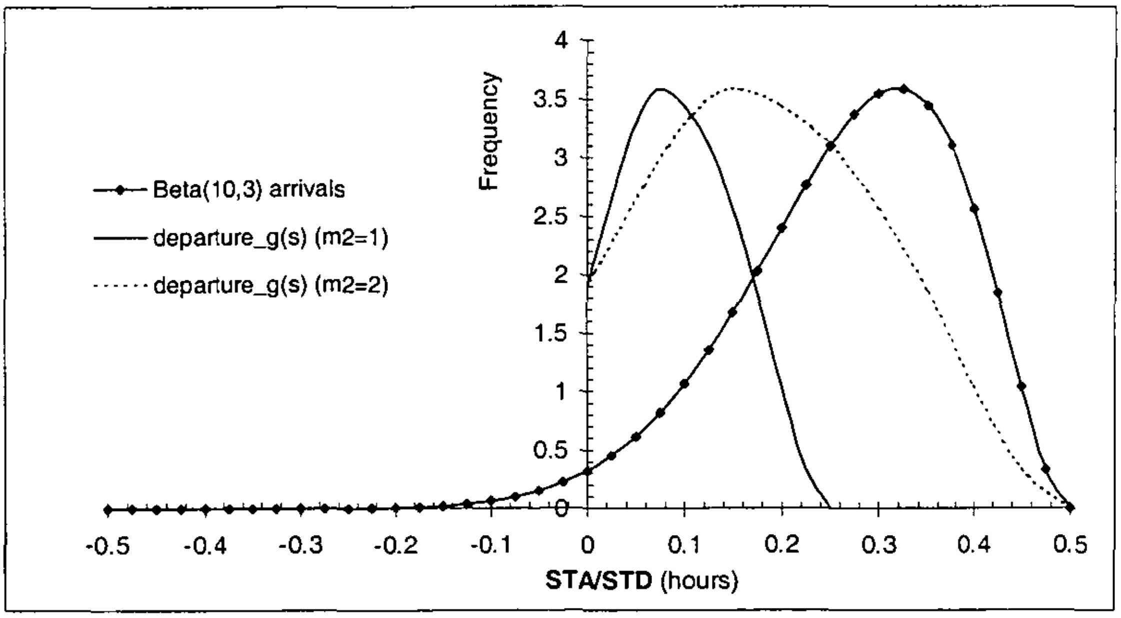

FIGURE 3.14 Influence of ground service efficiency on departure punctuality of a turnaround aircraft

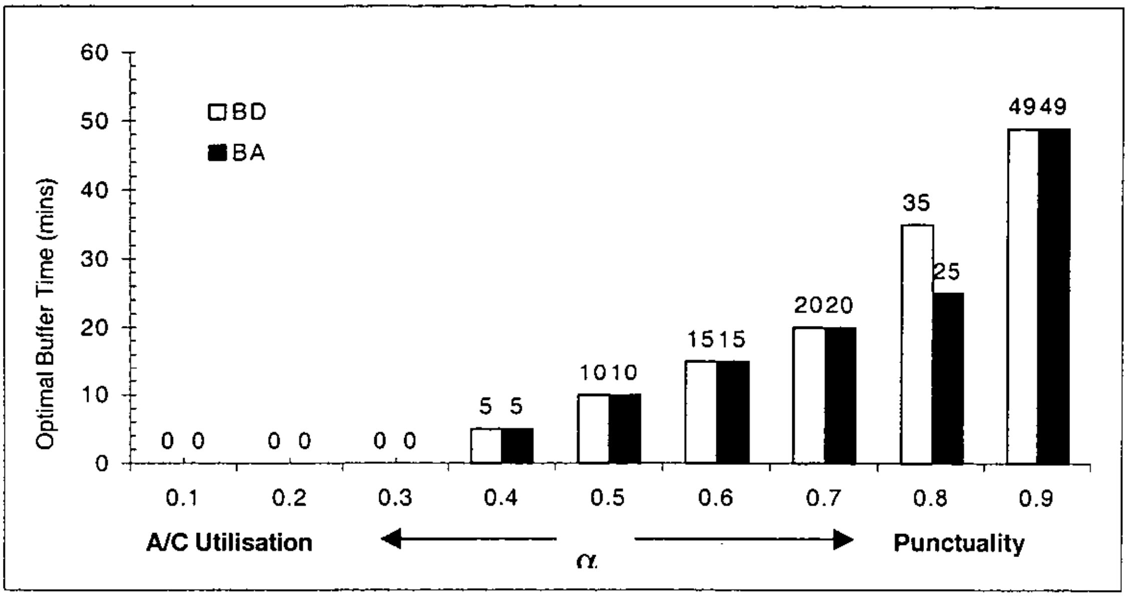

FIGURE 3.15 Influence of airline scheduling strategy on the use of schedule buffer time

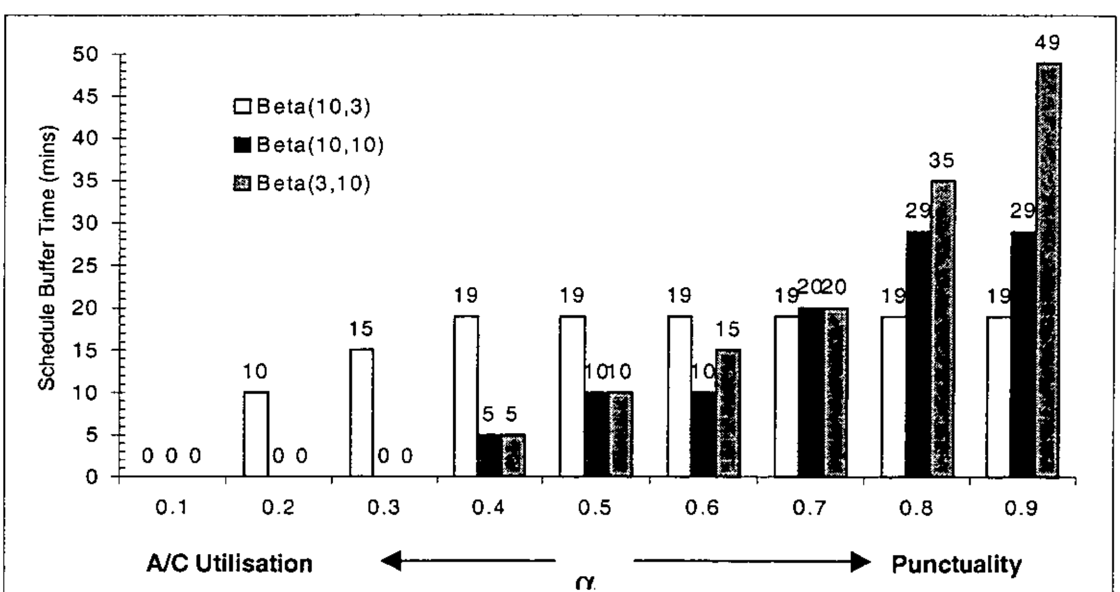

FIGURE 3.16 Requirements of schedule buffer time for different scheduling strategies of airlines

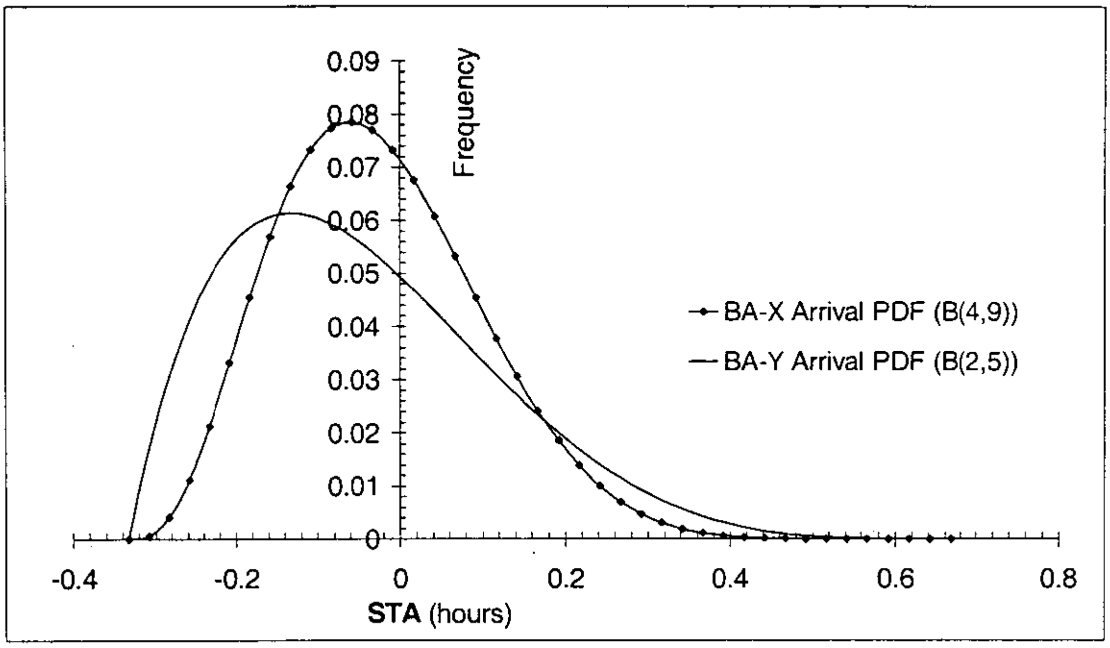

FIGURE 3.17 Arrival PDFs of BA-X and BA-Y

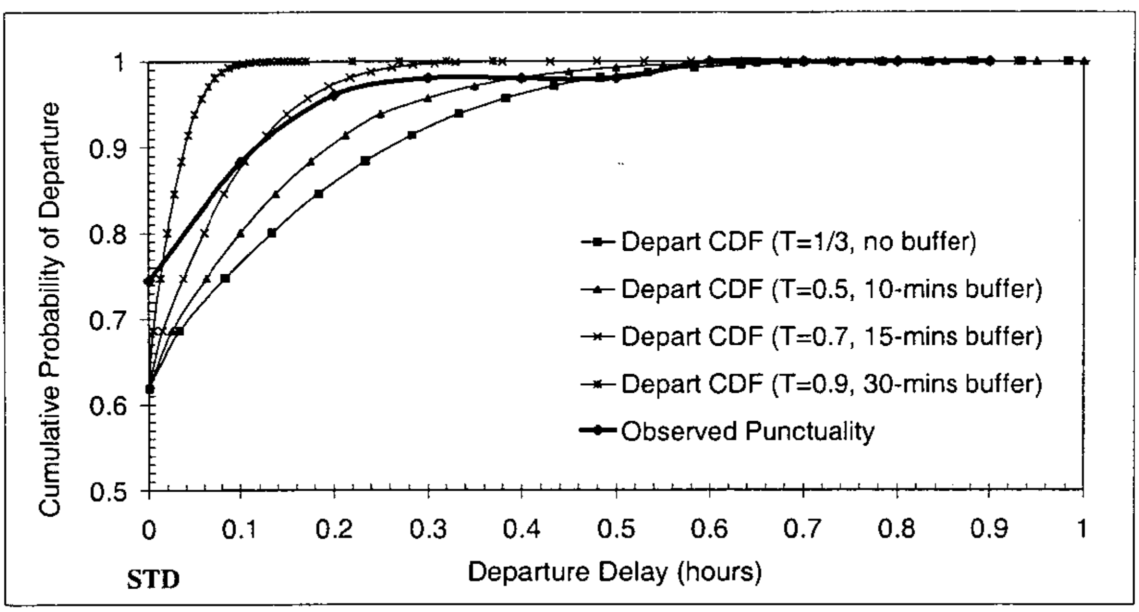

FIGURE 3.18 Departure punctuality of BA-X from observations and simulations

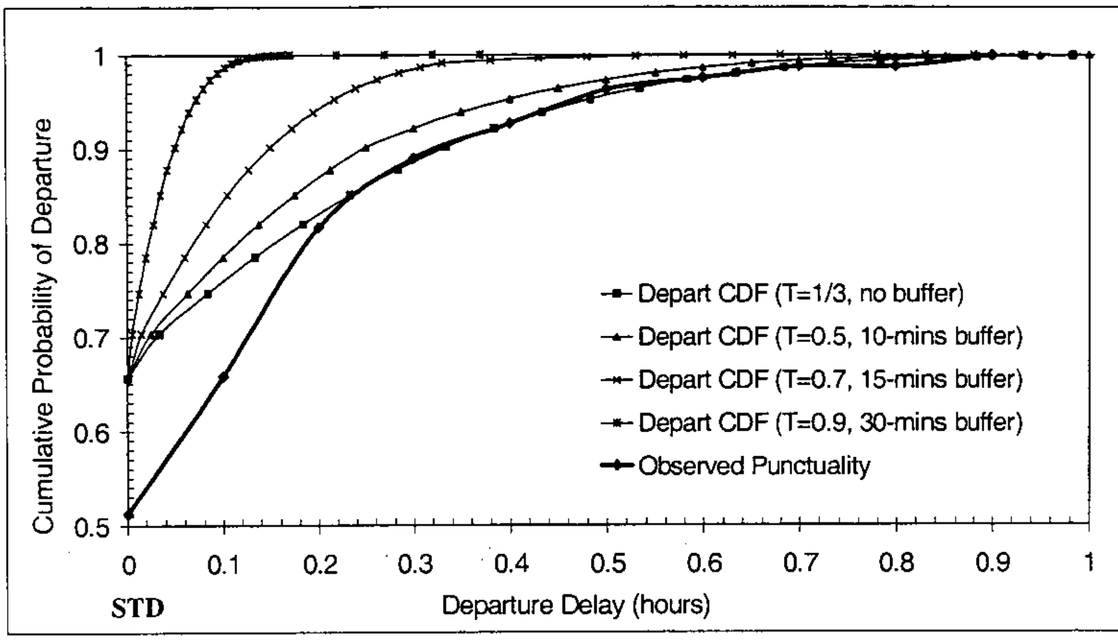

FIGURE 3.19 Departure punctuality of BA-Y from observations and simulations

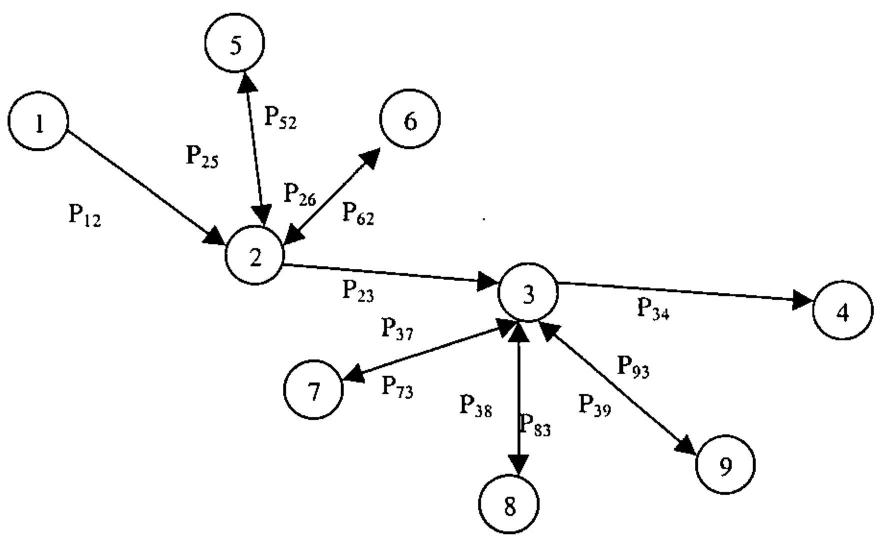

FIGURE 3.20 State transition behaviour for cargo & baggage processing flow

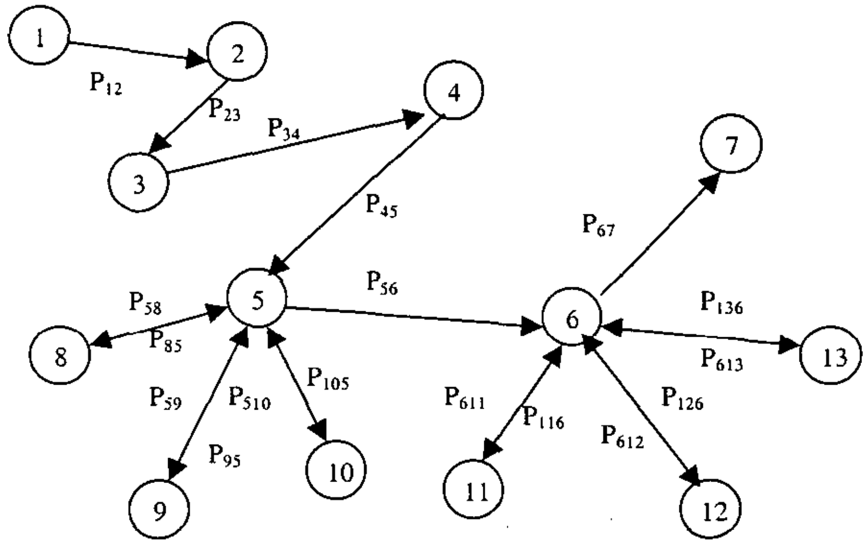

FIGURE 3.21 State transition behaviour for passengers/crews/cabin cleaning processing flow

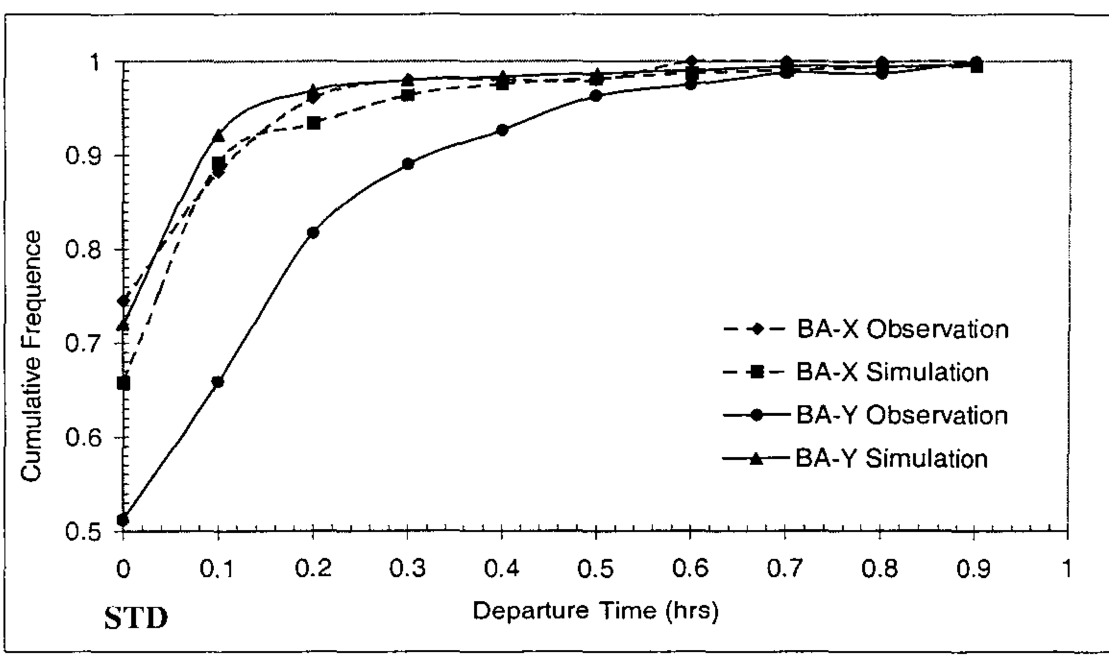

FIGURE 3.22 Turnaround performance and simulation results of BA-X and BA-Y

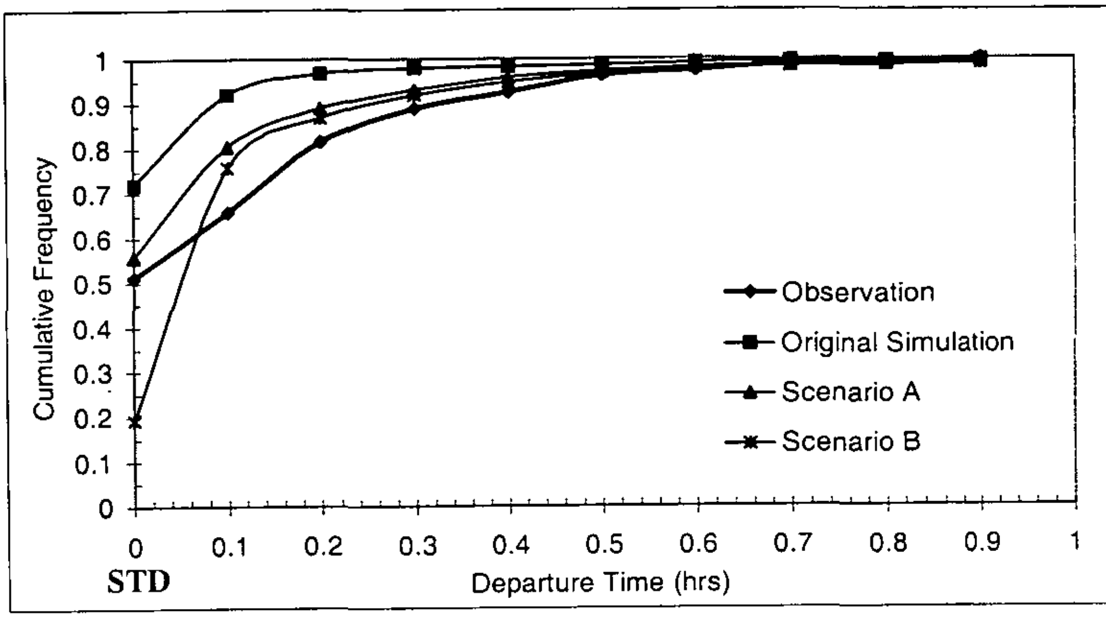

FIGURE 3.23 Scenario analysis of BA-Y

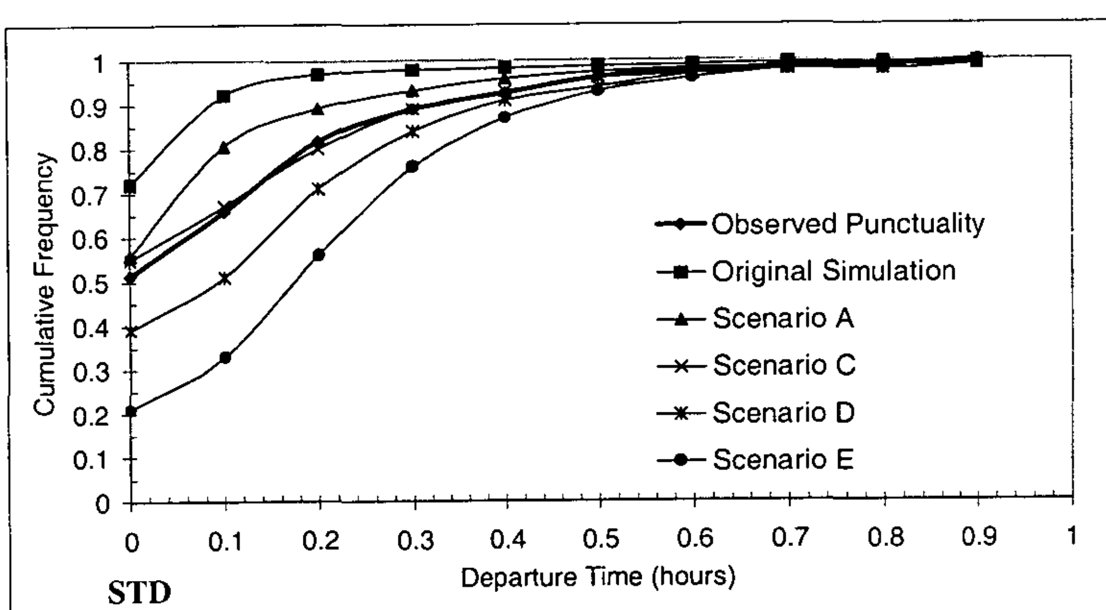

FIGURE 3.24 Long turnaround time scenario analysis of BA-Y

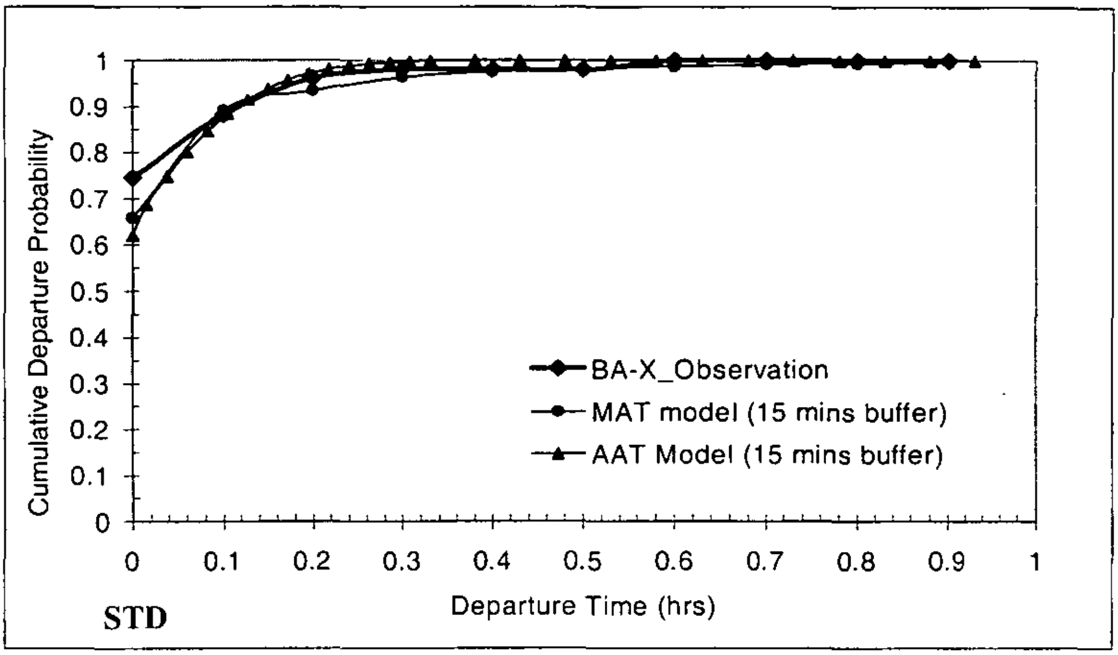

FIGURE 3.25 Punctuality performance of BA-X compared with simulation results

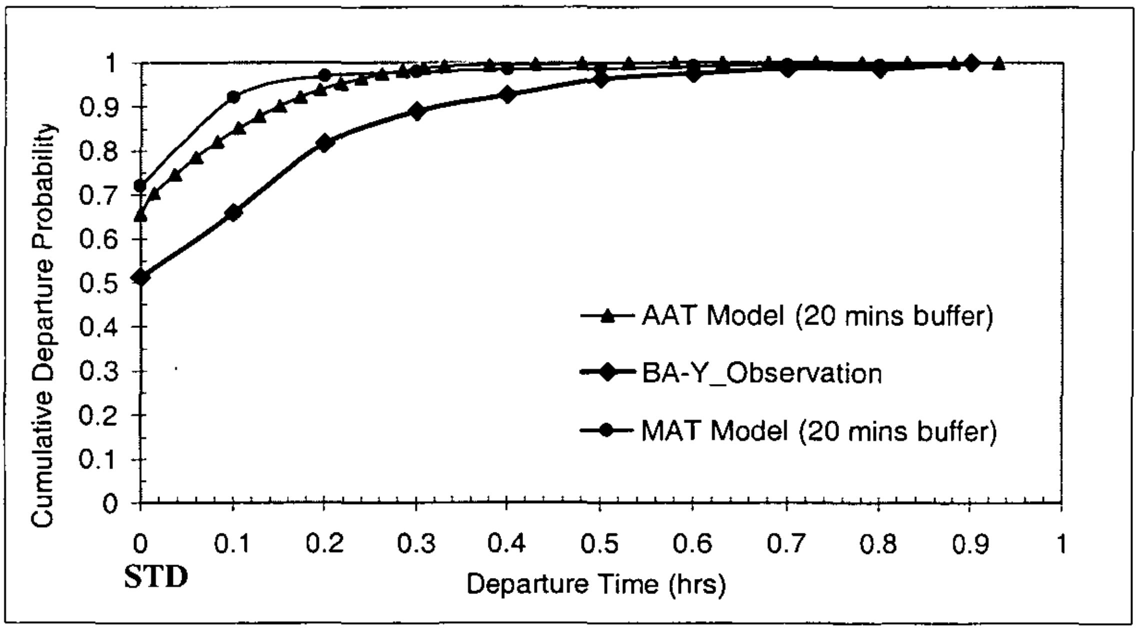

FIGURE 3.26 Punctuality performance of BA-Y compared with simulation results

Chapter 4 Figures

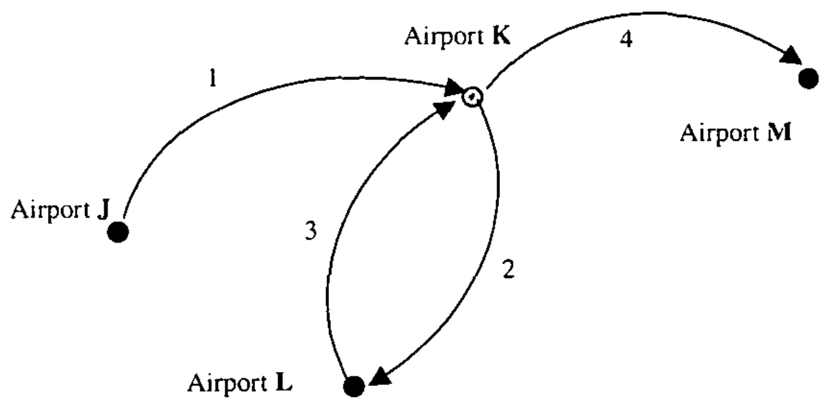

FIGURE 4.1 Aircraft Rotation in a Network of Airports

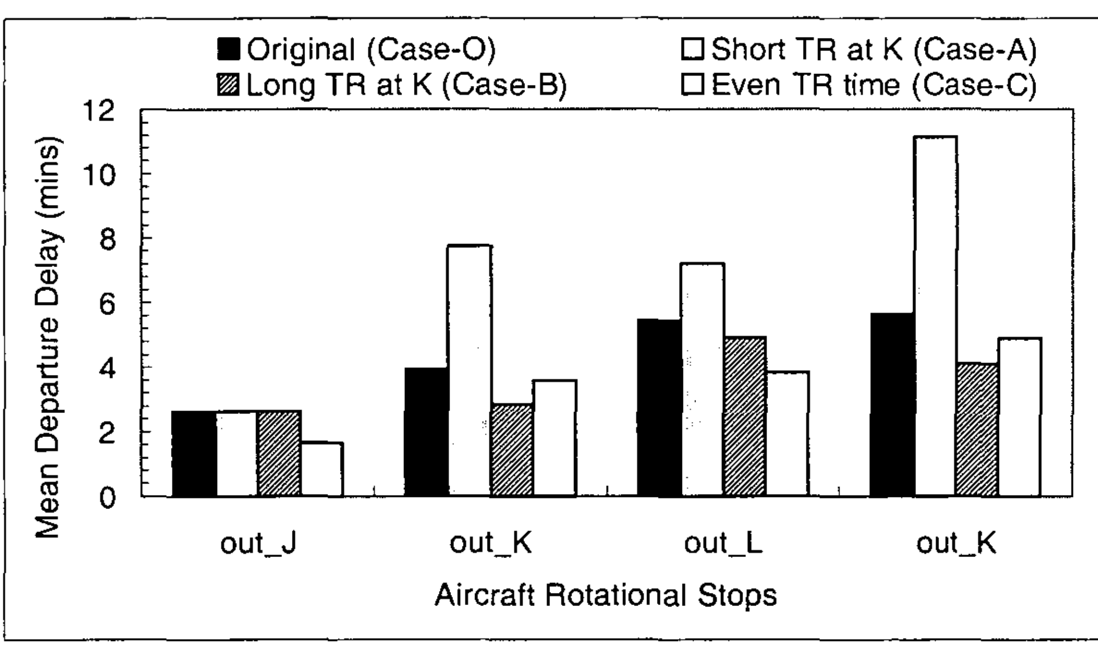

FIGURE 4.2 Influence of Turnaround Time on Departure Delays

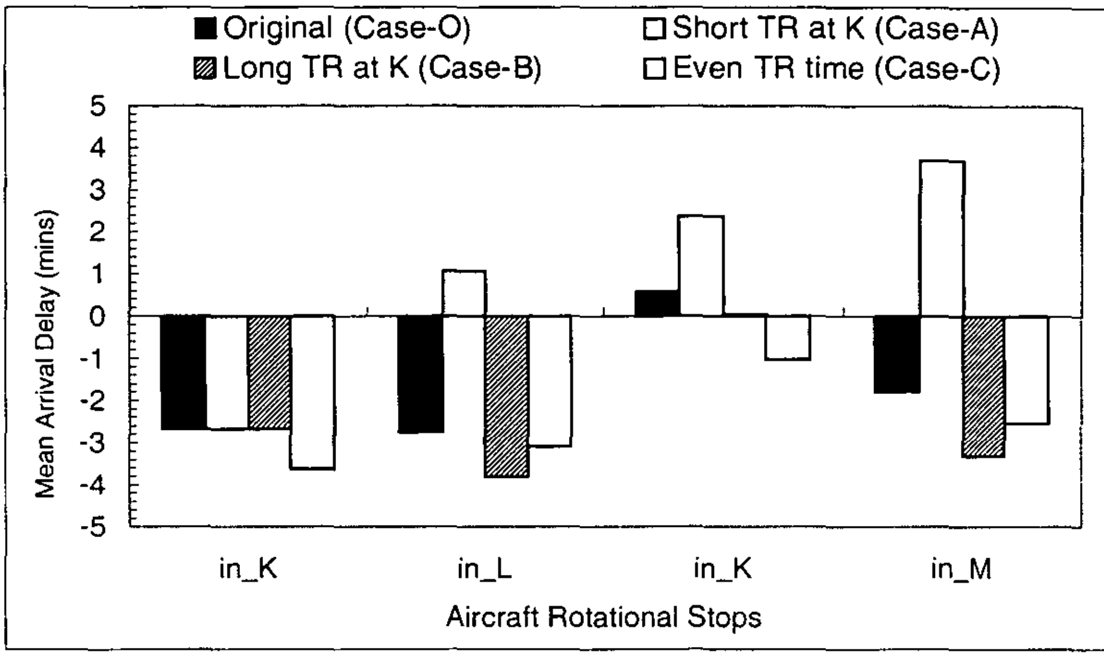

FIGURE 4.3 Influence of Turnaround Time on Arrival Delays

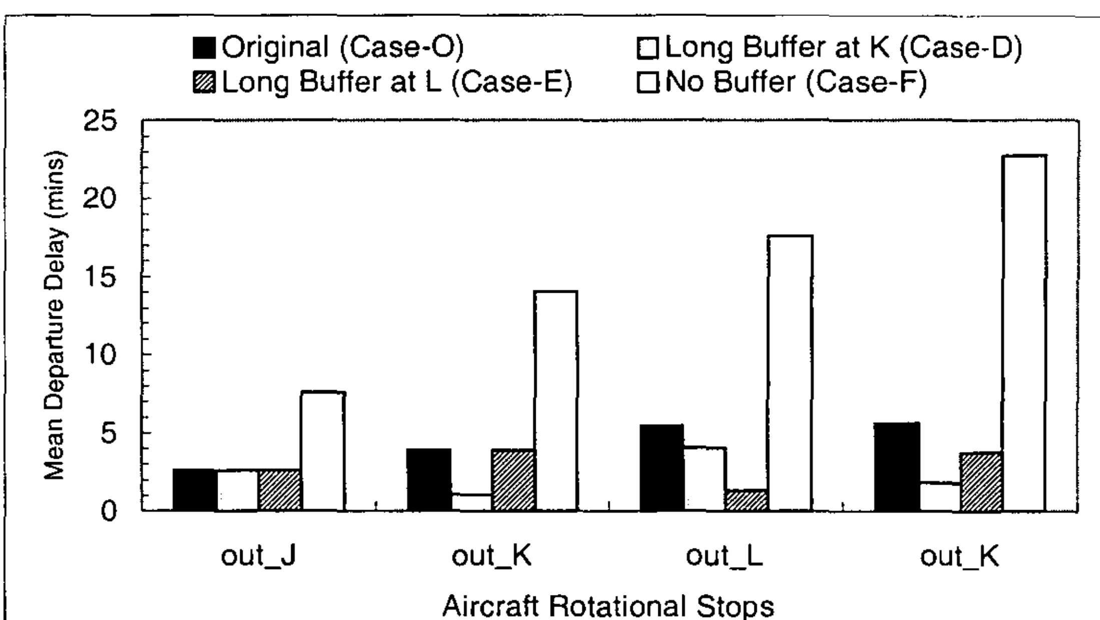

FIGURE 4.4 Influence of Long Schedule Break Time on Departure Delays

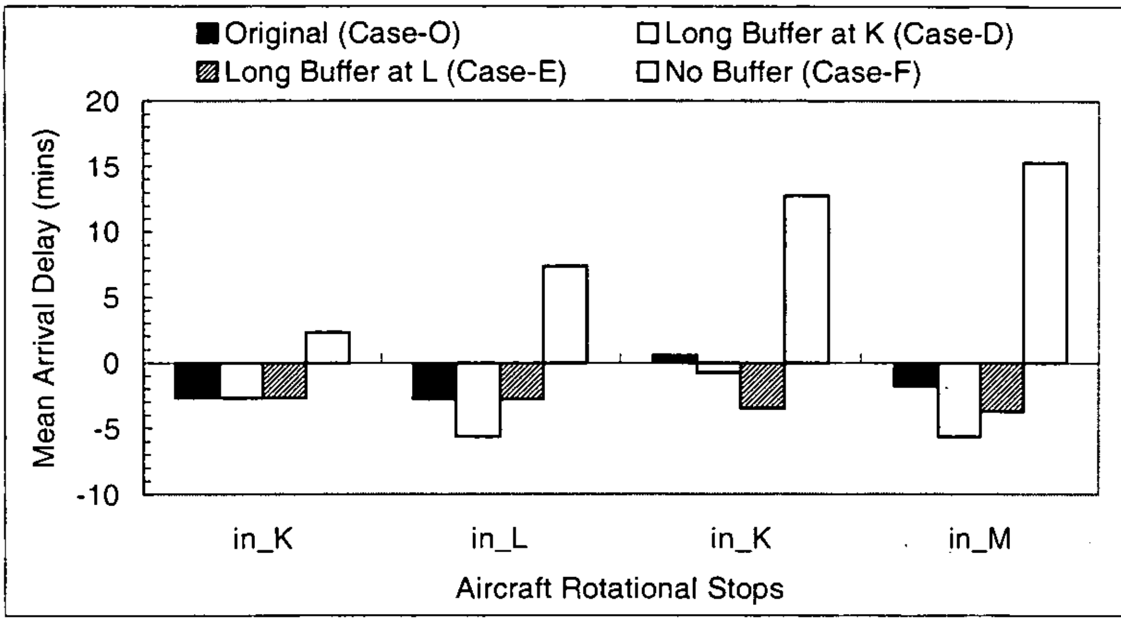

FIGURE 4.5 Influence of Long Schedule Break Time on Arrival Delays

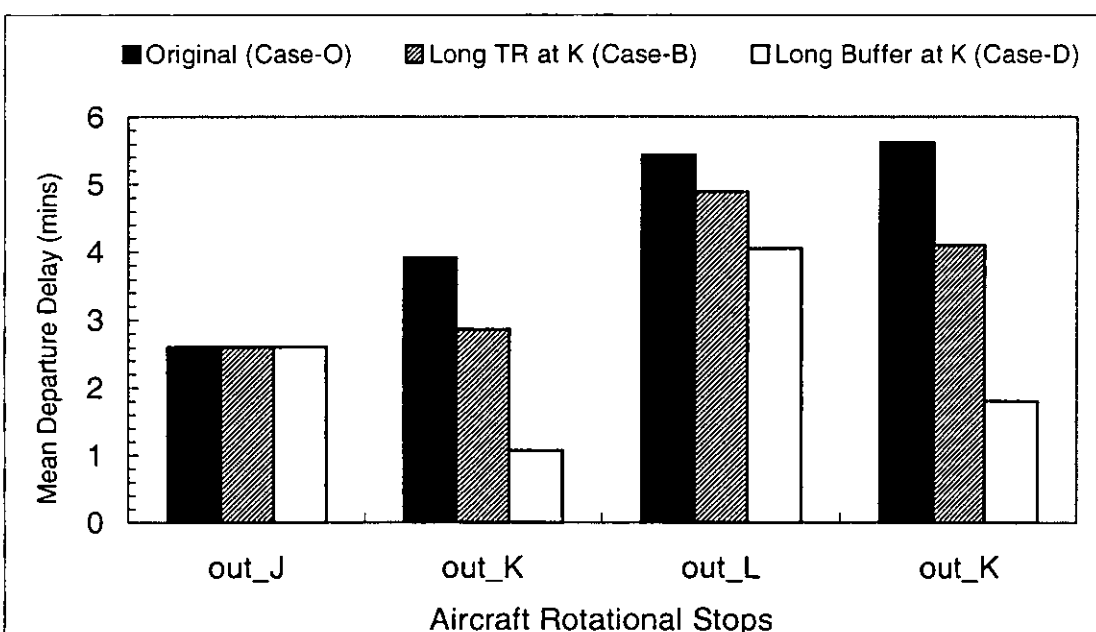

FIGURE 4.6 Influence of the Length of Turnaround Time at Airport K on Departure Delays

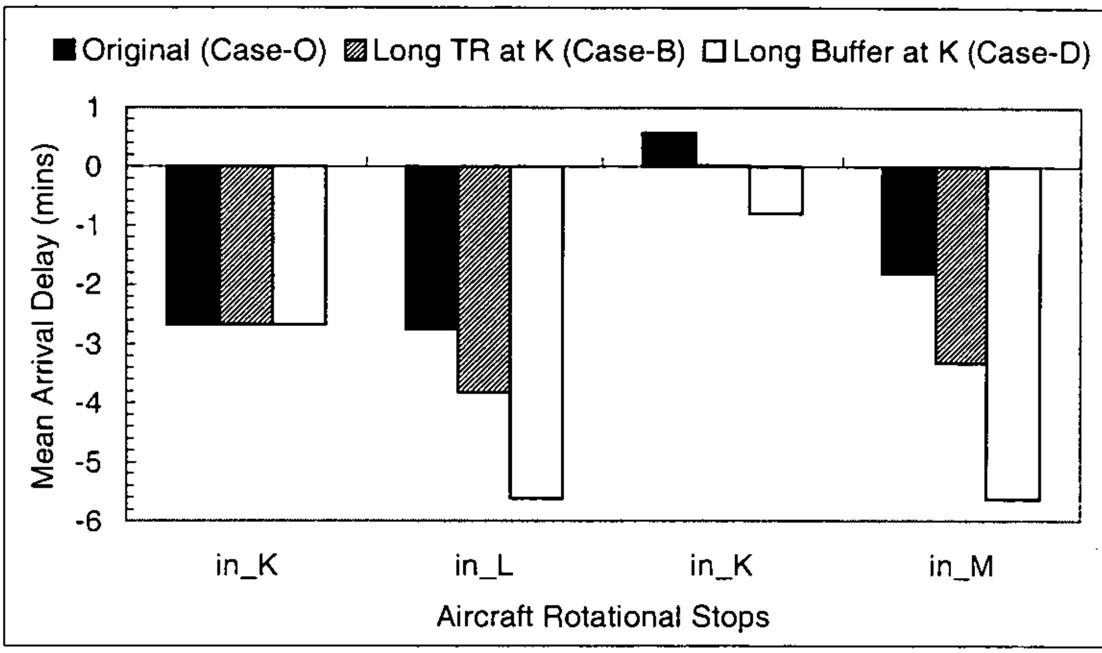

FIGURE 4.7 Influence of the Length of Turnaround Time at Airport K on Arrival Delays

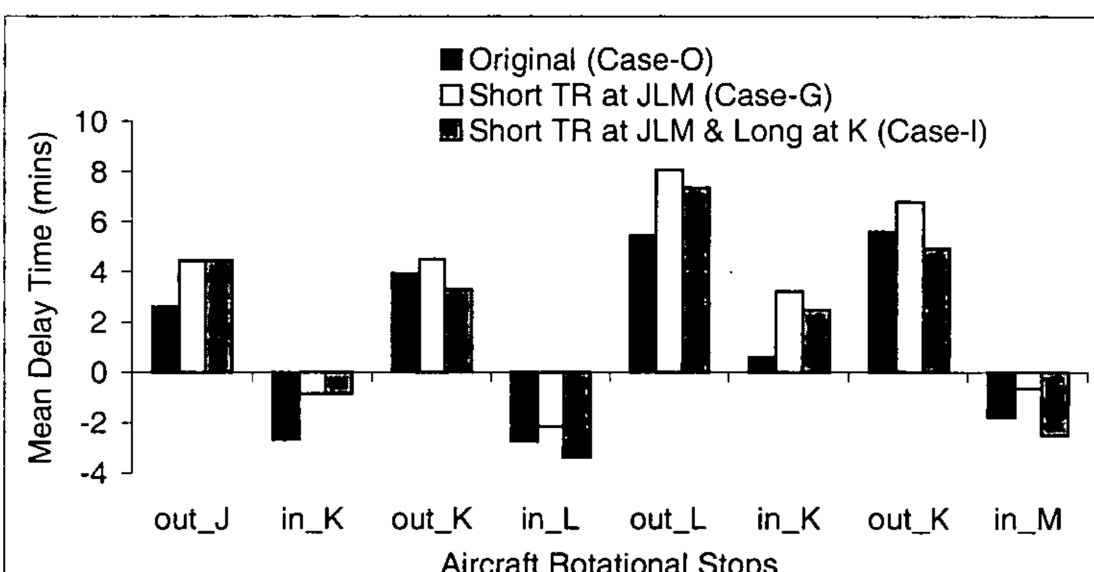

FIGURE 4.8 Short Turnaround at Spoke Airports and Long Turnaround Time at the Hub Airport

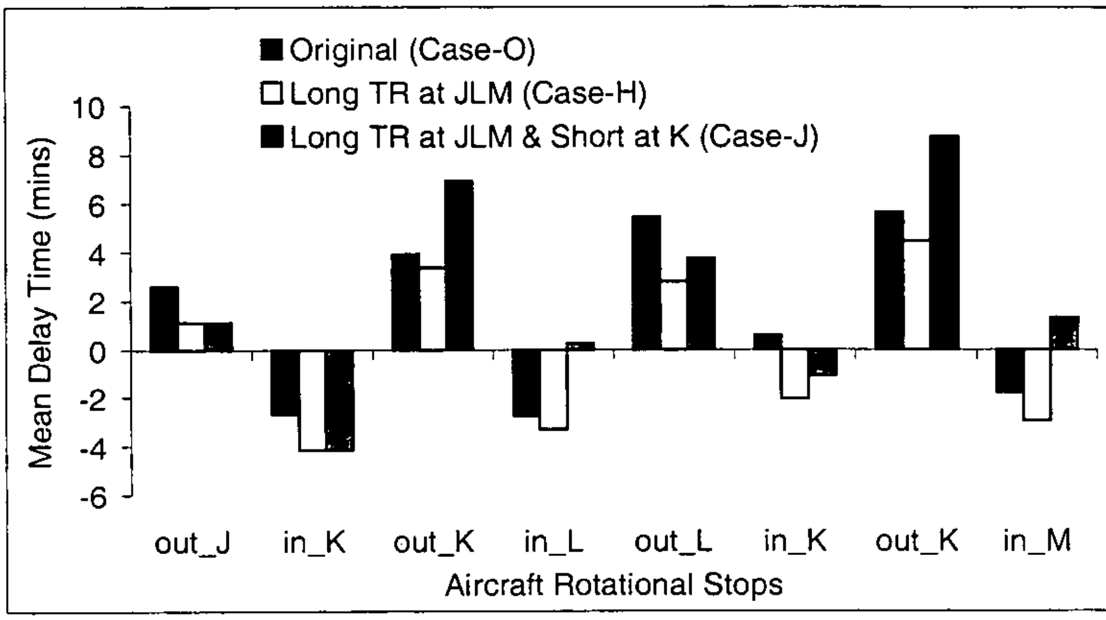

FIGURE 4.9 Long Turnaround Time at Spoke Airports and Short Turnaround Time at the Hub Airport

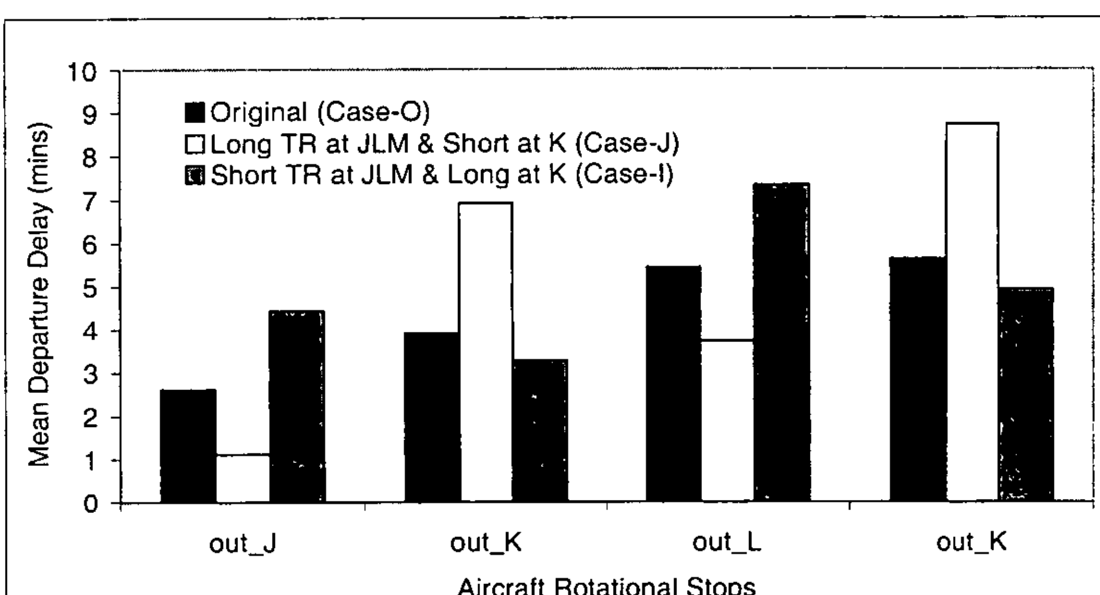

FIGURE 4.10 Influence of Scheduling Strategies of hubbing Aircraft on Departure Punctuality

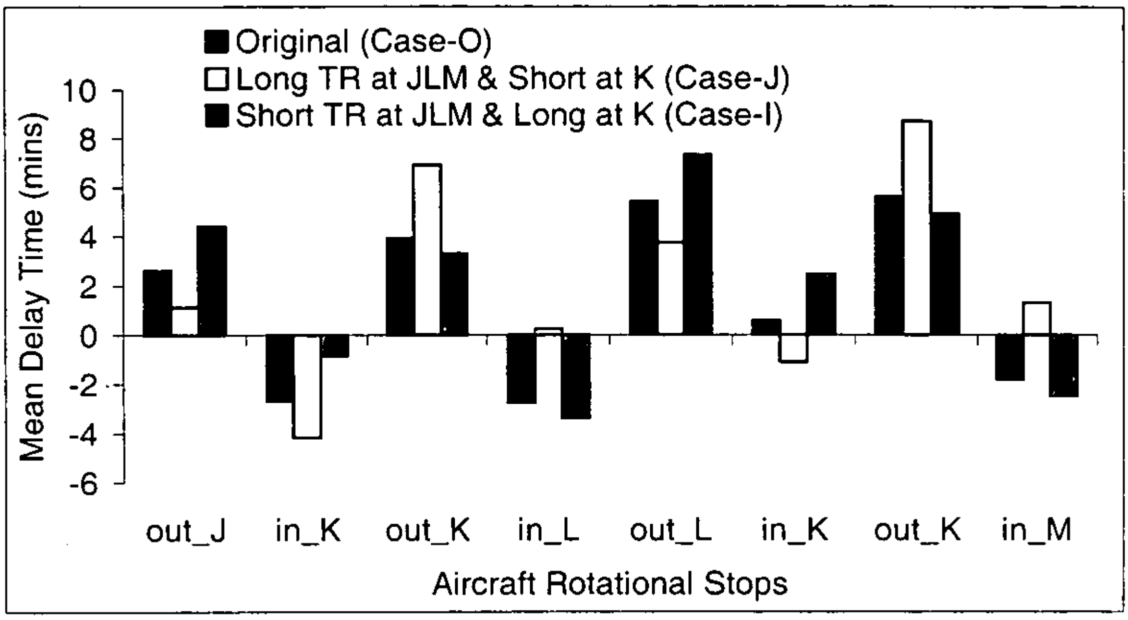

FIGURE 4.11 Influence of Scheduling Strategies of hubbing Aircraft on Aircraft Rotational Punctuality

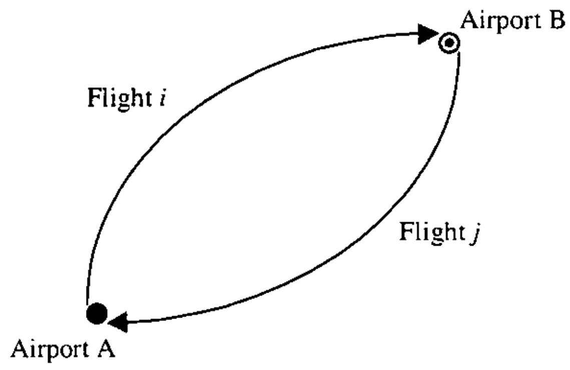

FIGURE 4.12 Turnaround operations between Airport A and B

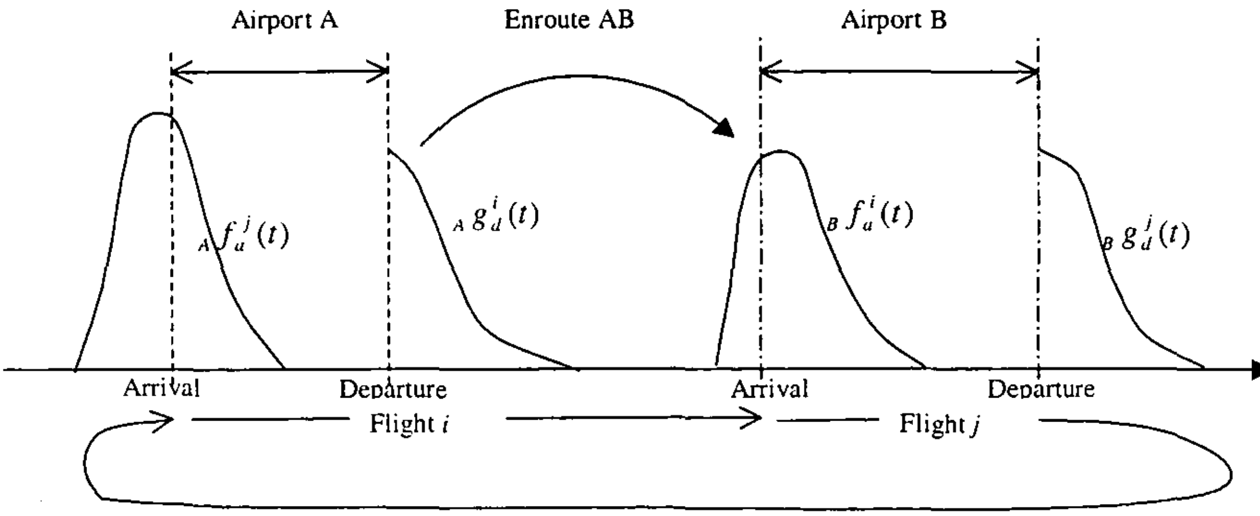

FIGURE 4.13 Arrival and departure PDFs for turnaround aircraft between Airport A and B

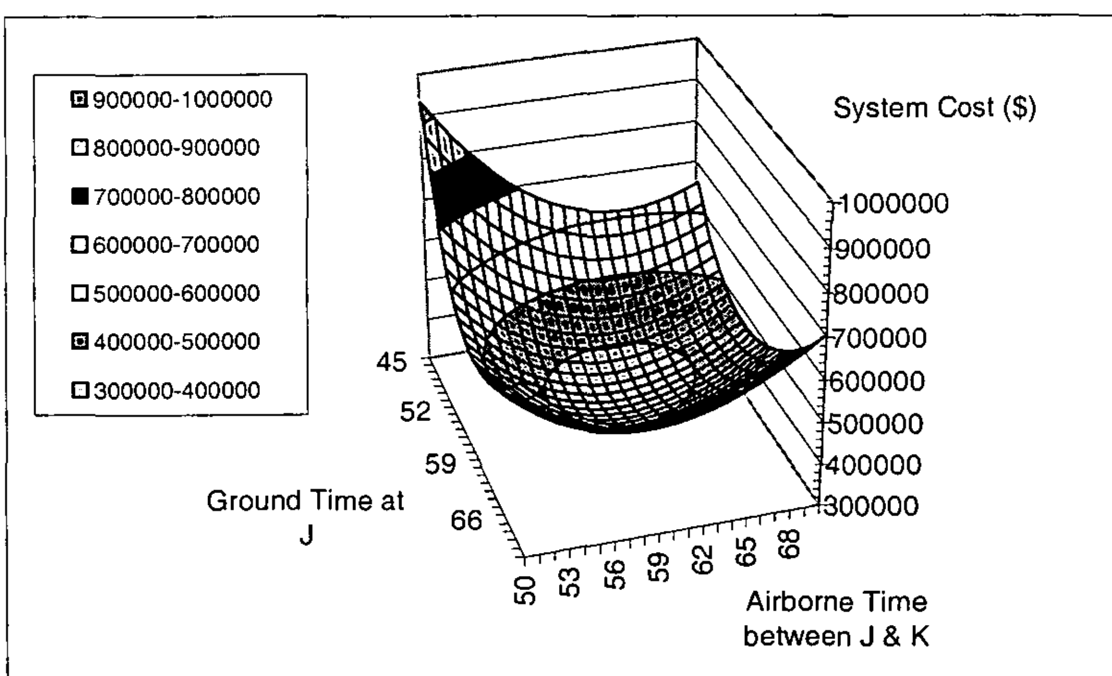

FIGURE 4.14 Optimisation of schedule time of Leg_JK

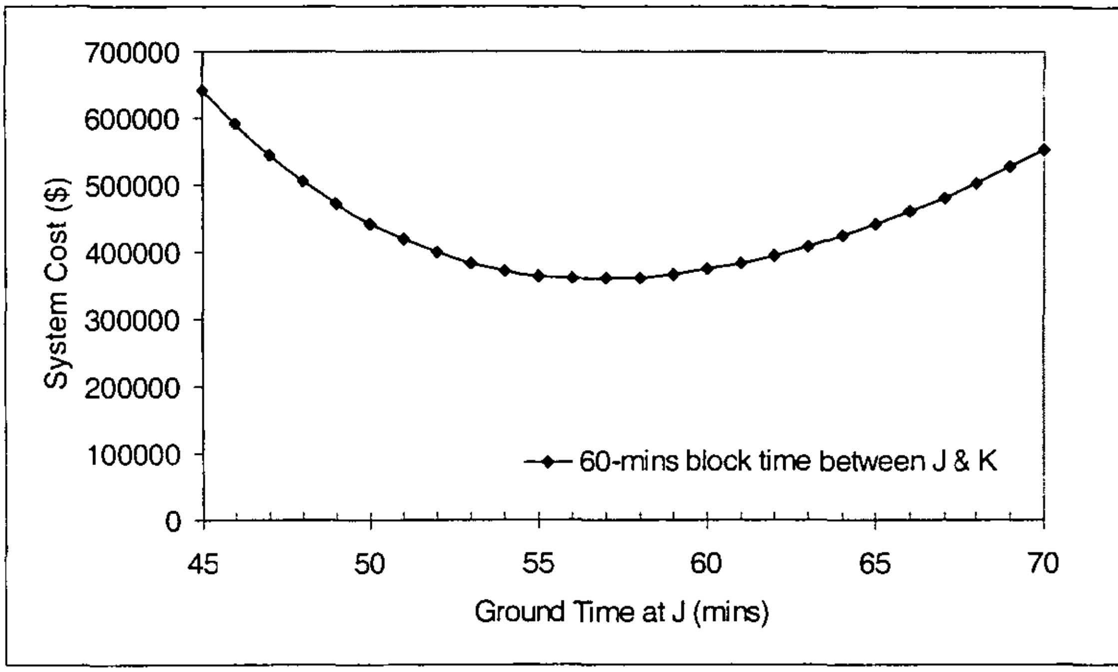

FIGURE 4.15 Cross section of the system cost envelope with 60-minute block time

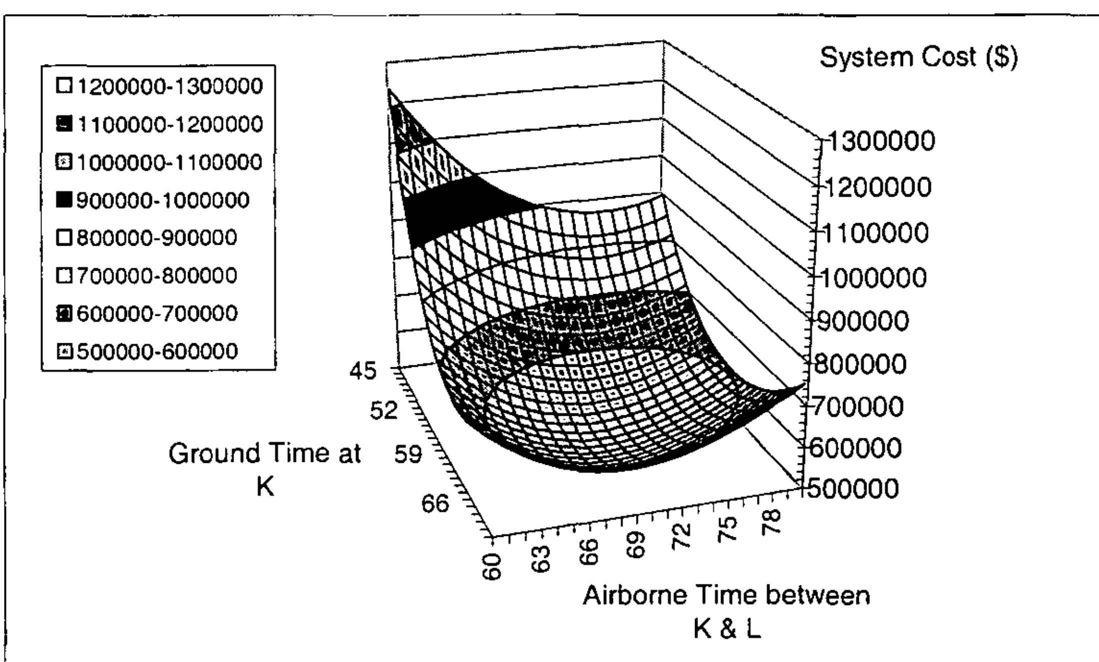

FIGURE 4.16 Optimisation of schedule time of Leg_KL

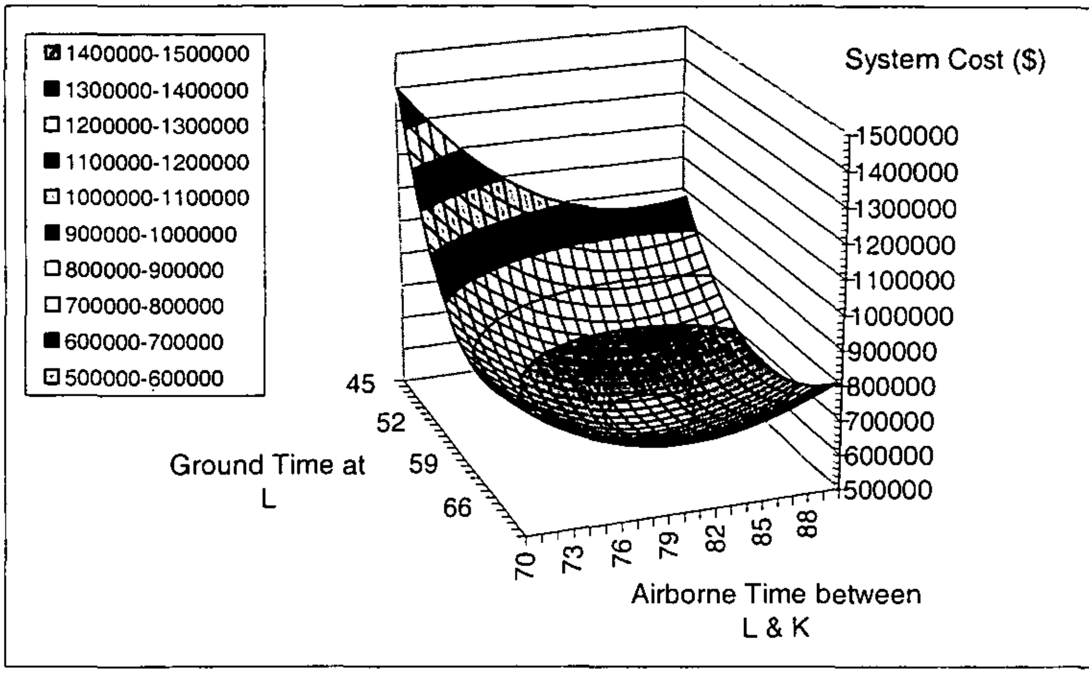

FIGURE 4.17 Optimisation of schedule time of Leg_LK

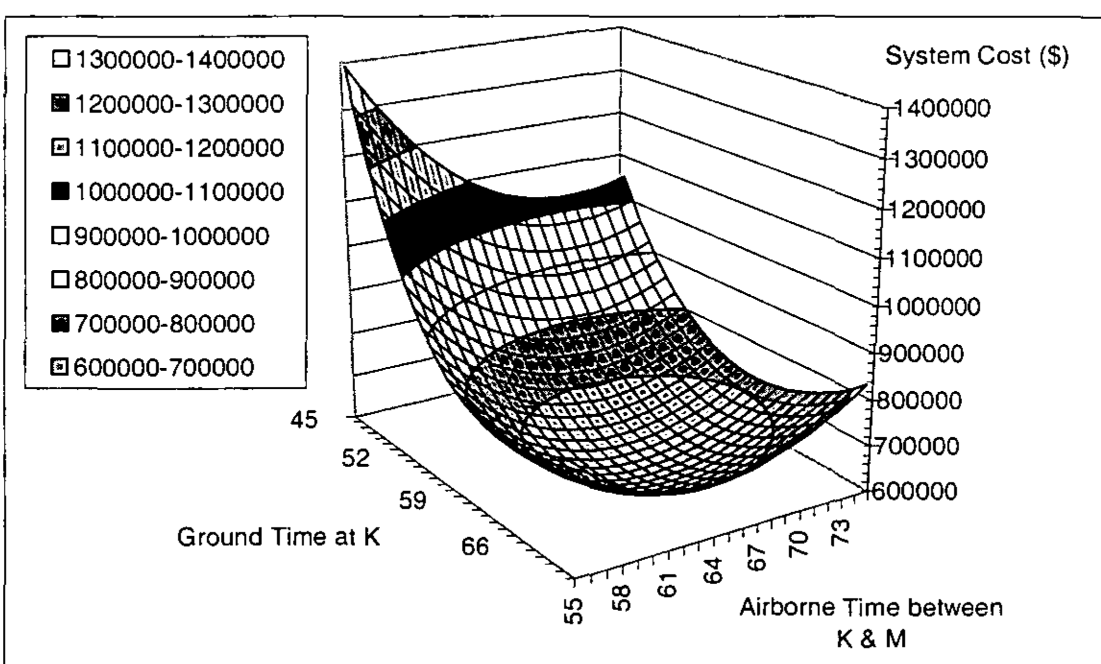

FIGURE 4.18 Optimisation of schedule time of Leg_KM

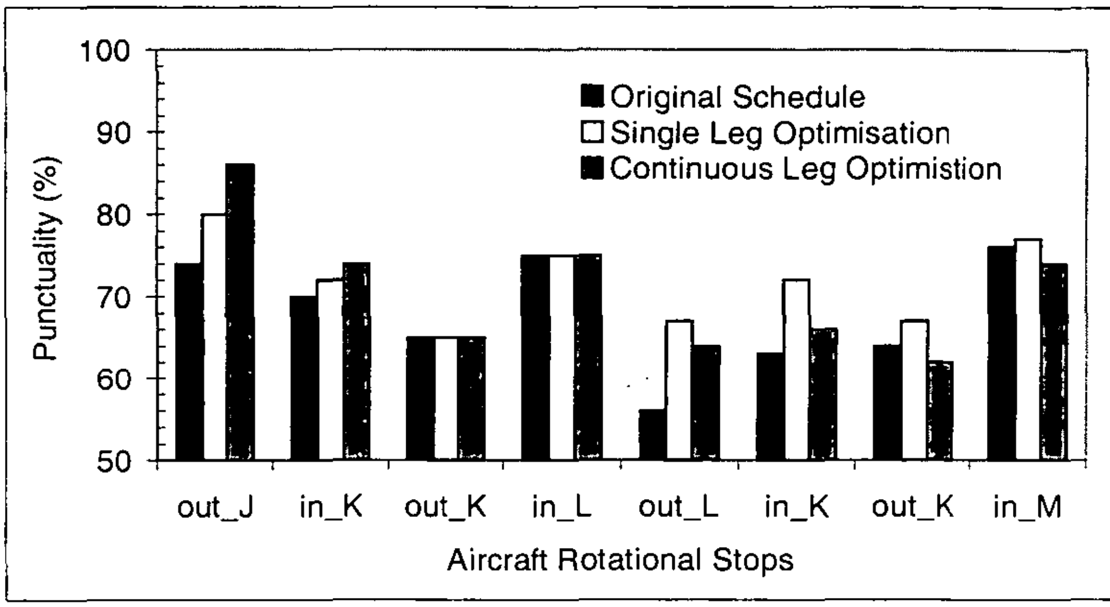

FIGURE 4.19 Improvements of schedule punctuality after optimisation

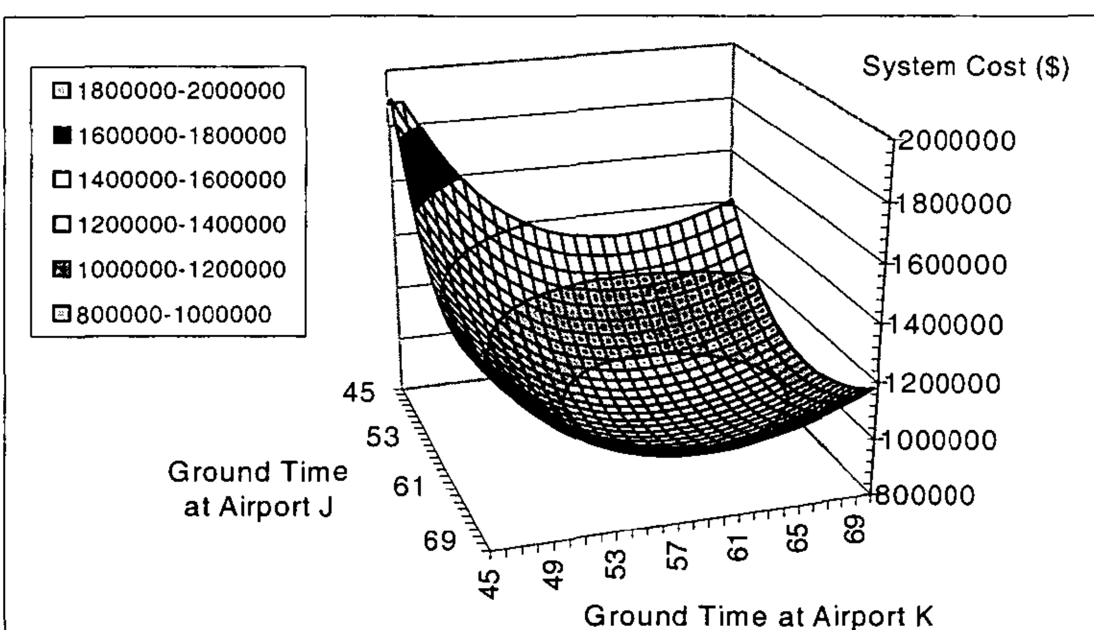

FIGURE 4.20 Optimisation of turnaround time at airport J and K

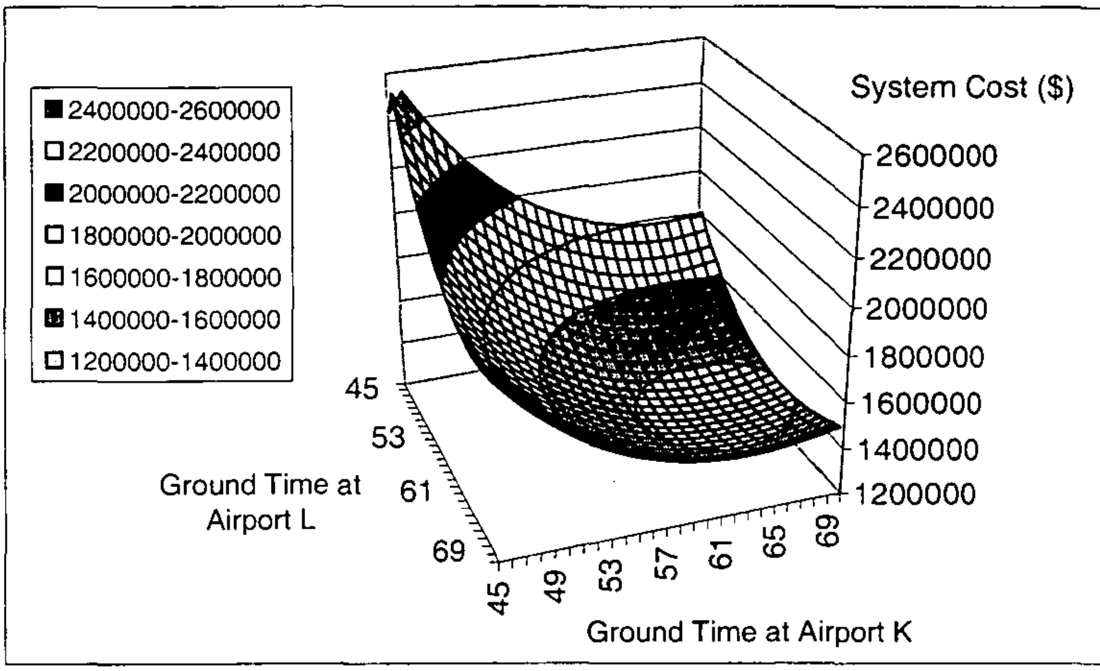

FIGURE 4.21 Optimisation of turnaround time at airport K and L

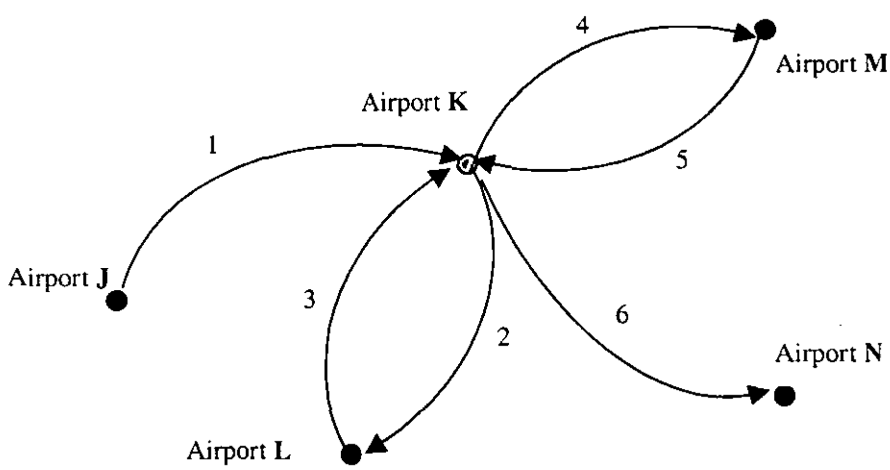

FIGURE 4.22 Rotation of Aircraft_A of Airline R

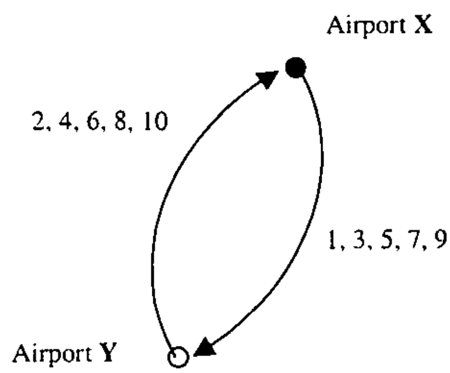

FIGURE 4.23 Rotation of Aircraft_B of Airline P

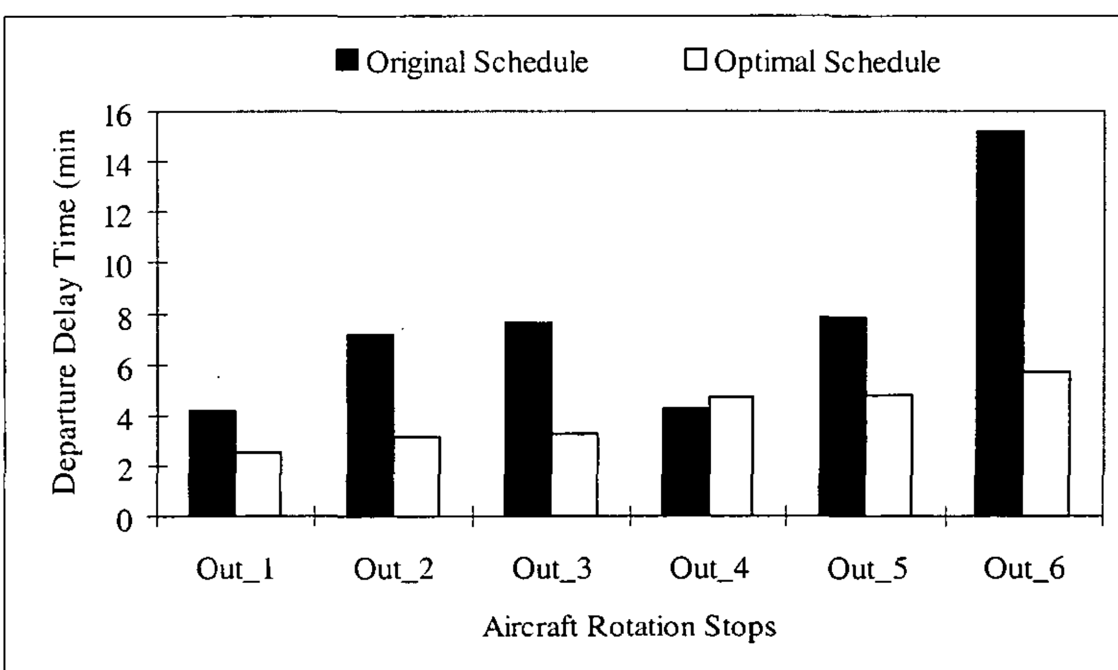

FIGURE 4.24 Outbound punctuality of the rotation of Aircraft_A

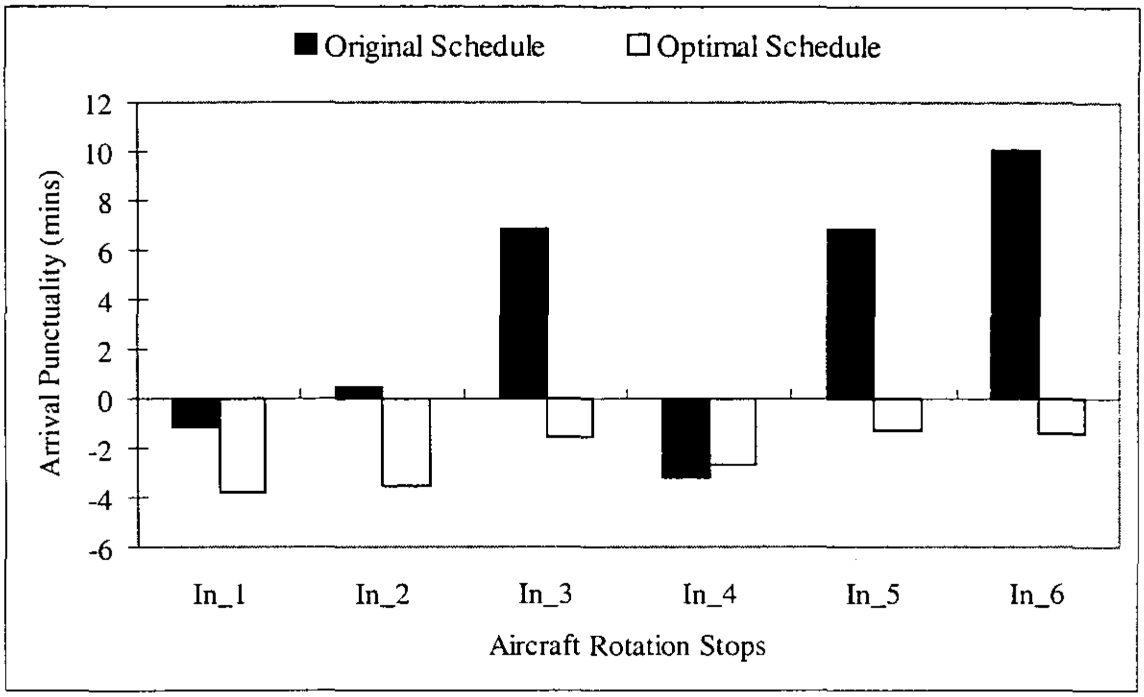

FIGURE 4.25 Inbound punctuality of the rotation of Aircraft_A

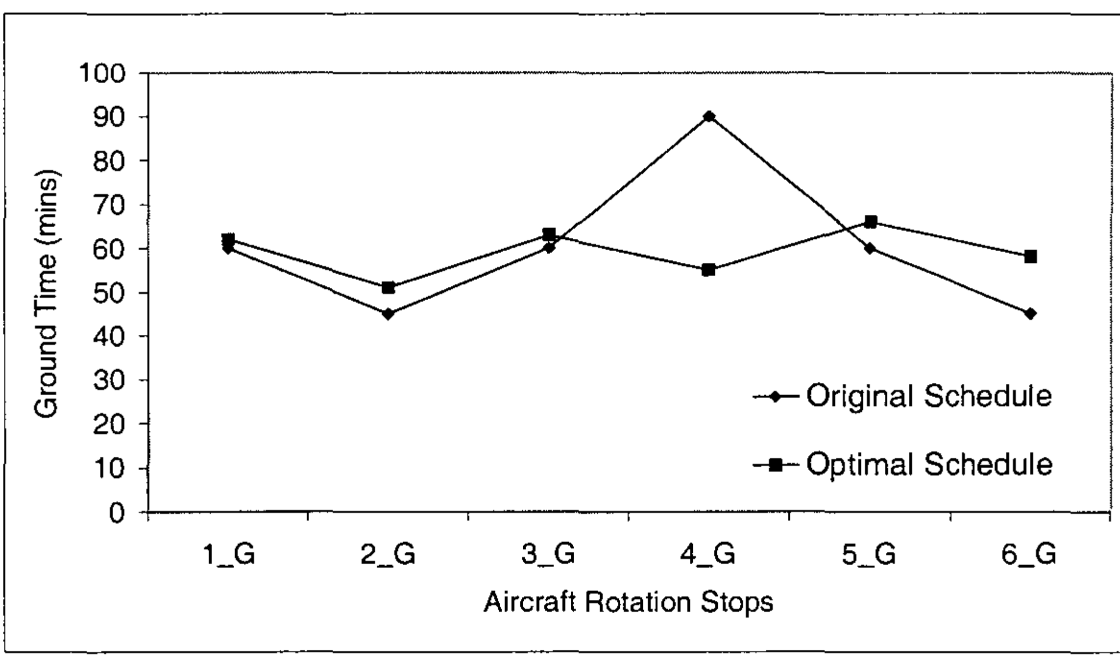

FIGURE 4.26 Scheduled ground time in two case of Aircraft_A

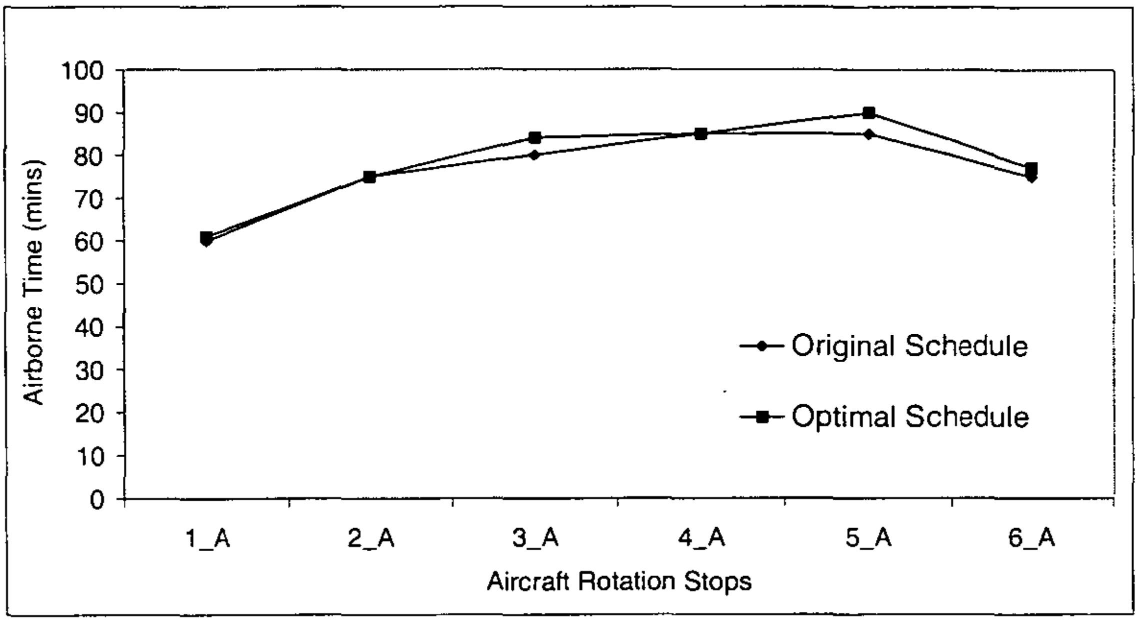

FIGURE 4.27 Scheduled airborne time in two cases of Aircraft_A

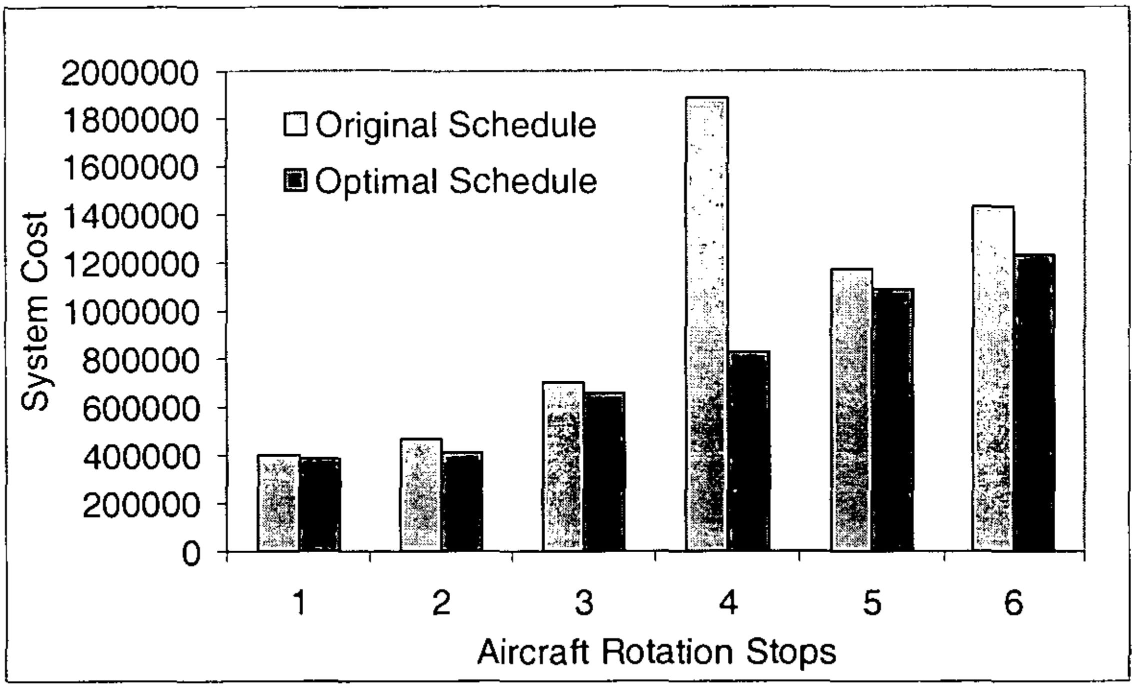

FIGURE 4.28 Comparison of system costs in the original case and the optimal case of Aircraft_A

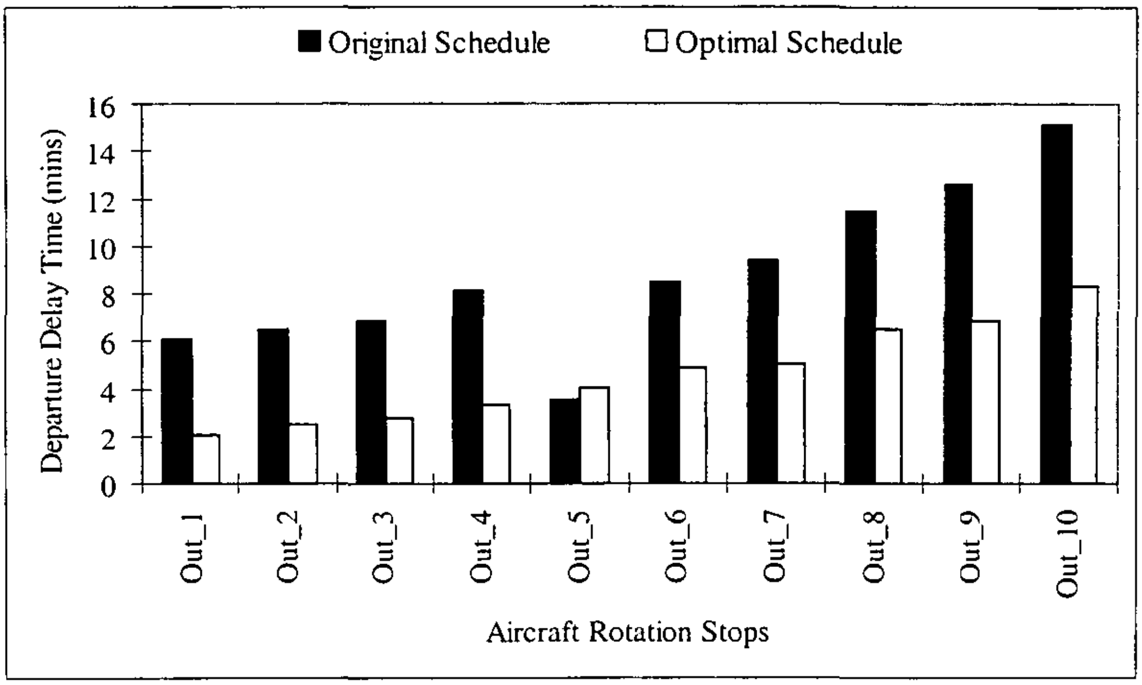

FIGURE 4.29 Outbound punctuality of the rotation of Aircraft_B of Airline P

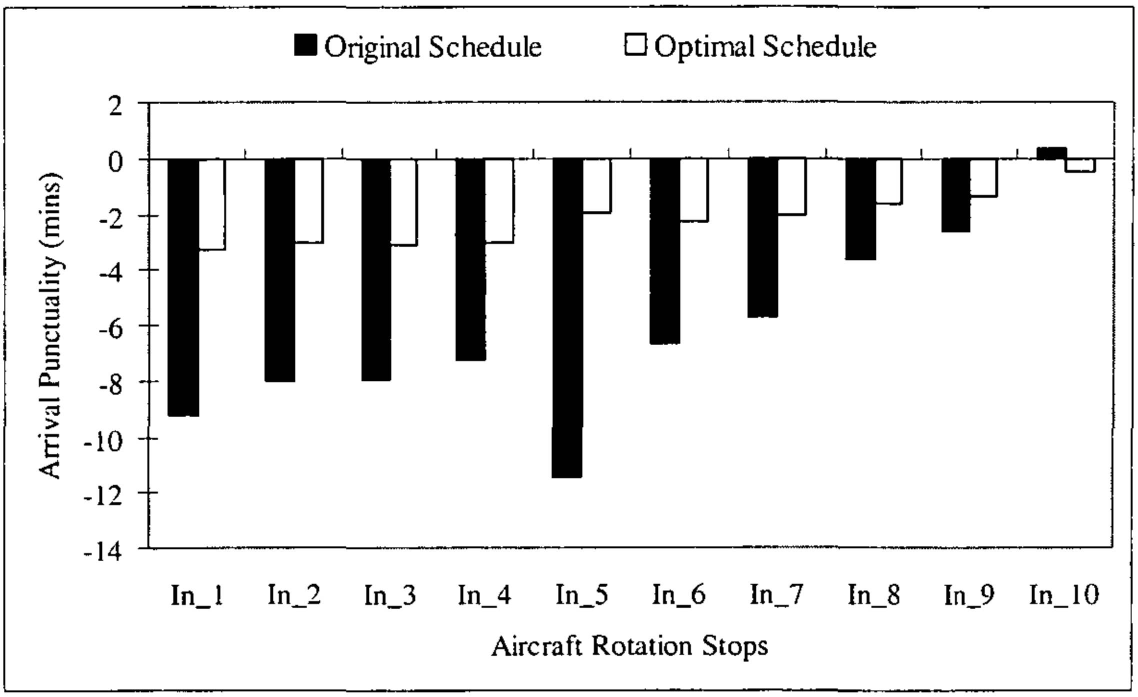

FIGURE 4.30 Inbound punctuality of the rotation of Aircraft_B of Airline P

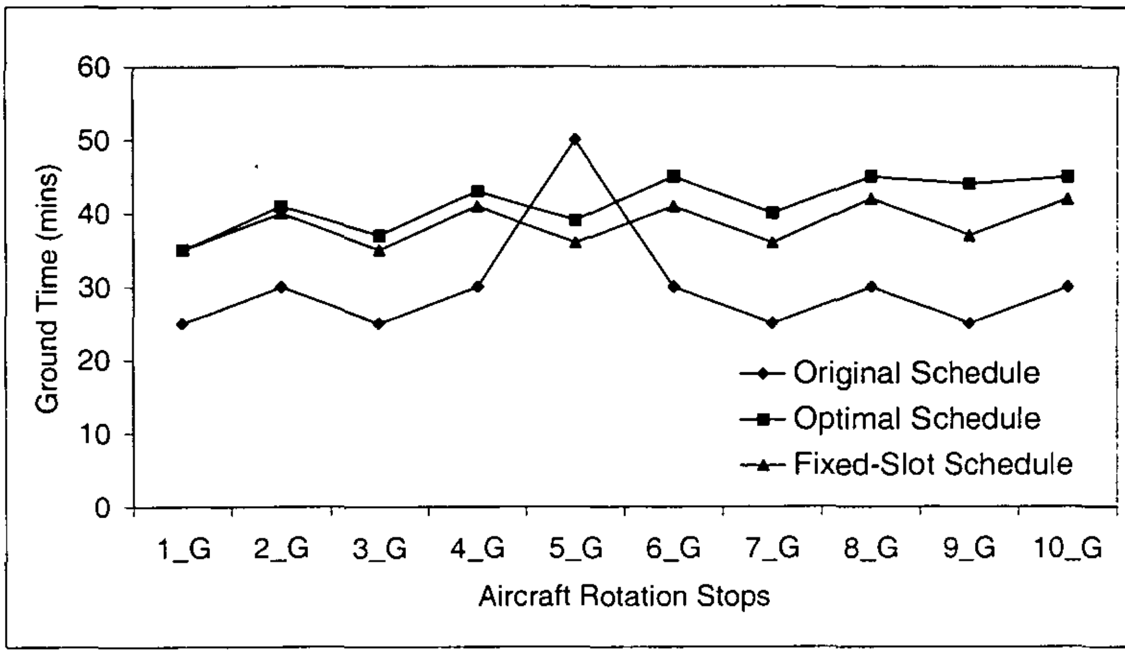

FIGURE 4.31 Scheduled ground time of Aircraft_B in different rotation schedules

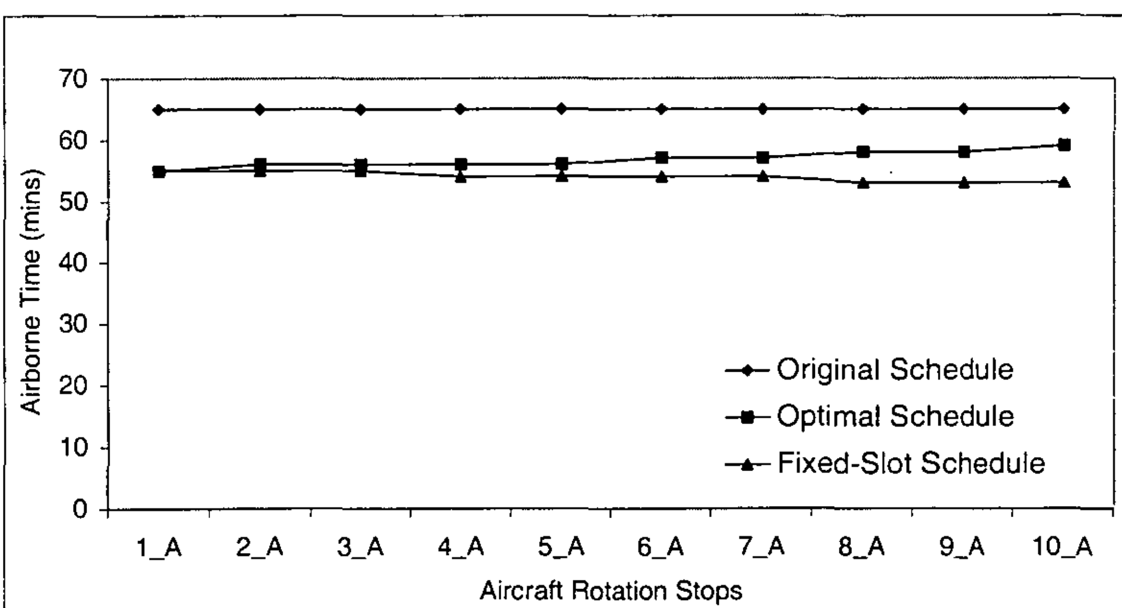

FIGURE 4.32 Scheduled airborne time of Aircraft_B in different rotation schedules

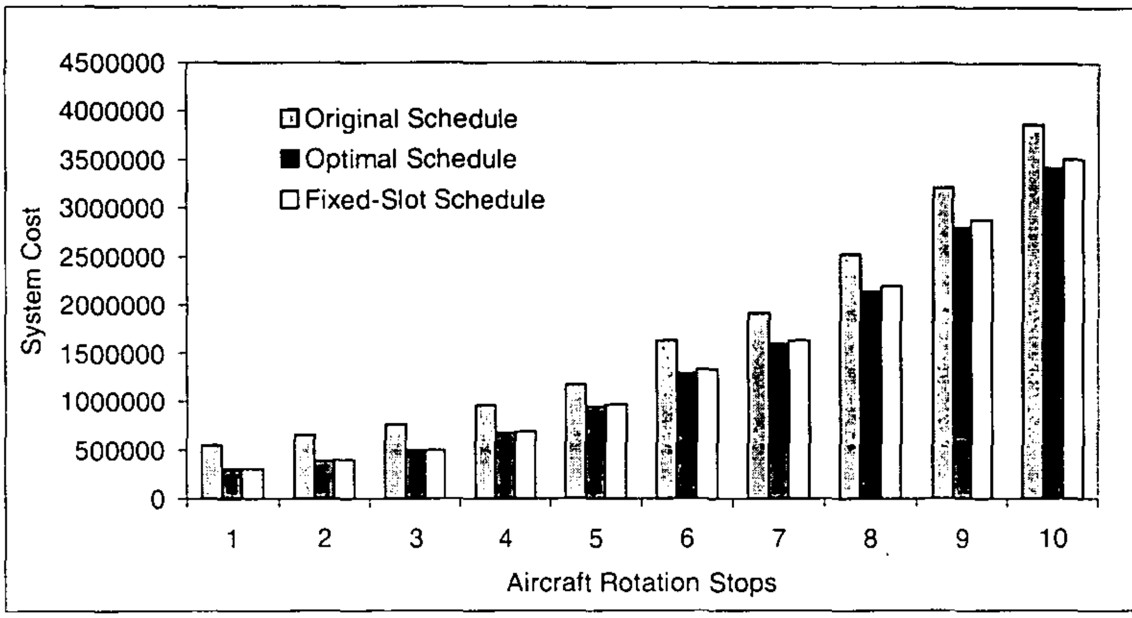

FIGURE 4.33 Comparison of system cost of Aircraft_B in different rotation schedules

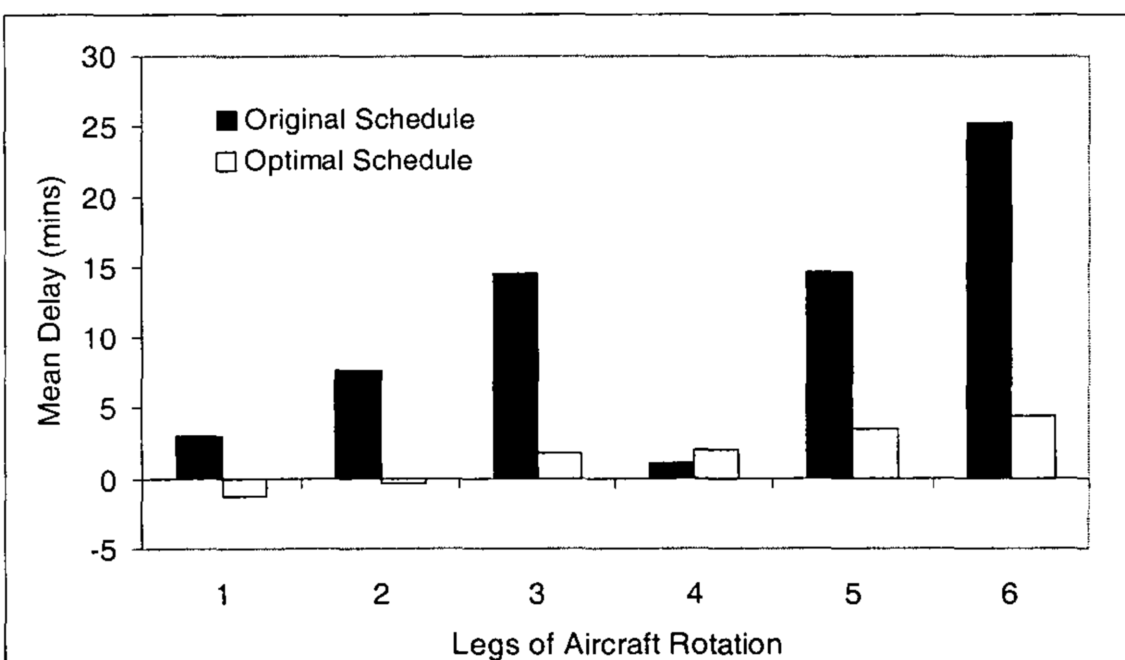

FIGURE 4.34 Mean delay of legs in the rotation of Aircraft_A

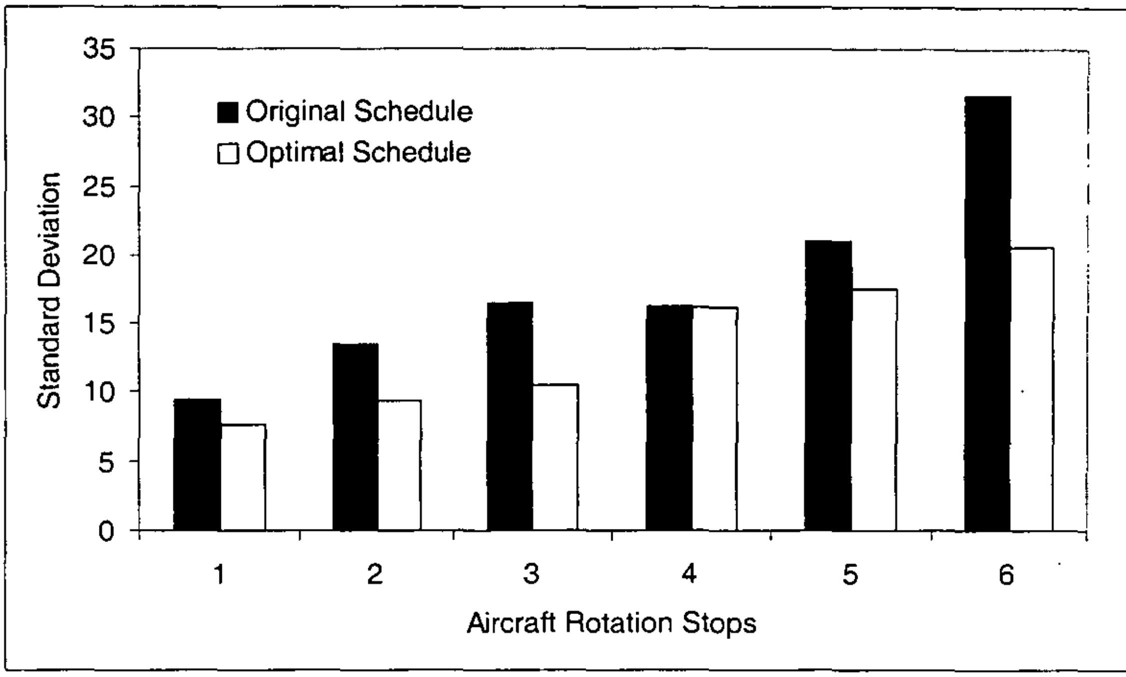

FIGURE 4.35 Standard deviation of departure time of Aircraft_A

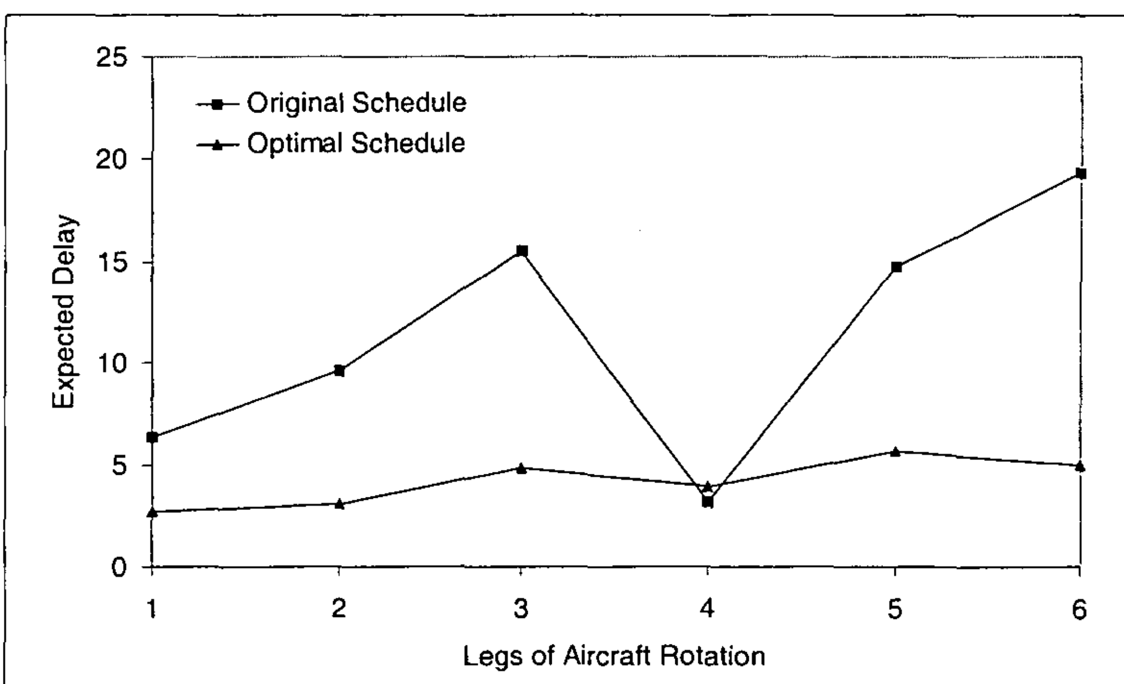

FIGURE 4.36 Expected delay of legs in the rotation of Aircraft_A

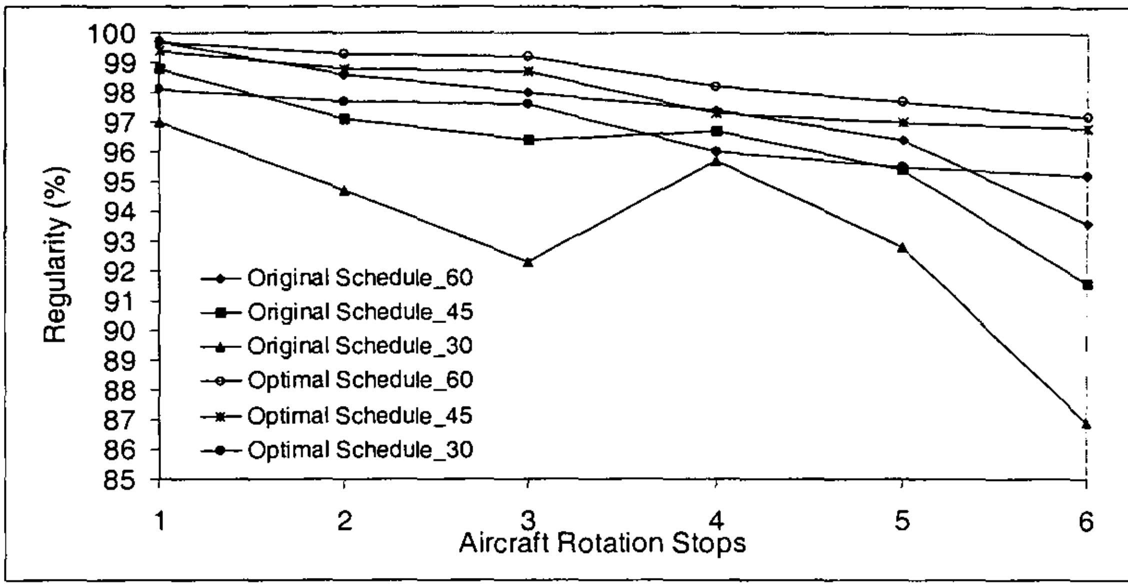

FIGURE 4.37 Schedule regularity of Aircraft_A in different operational scenarios

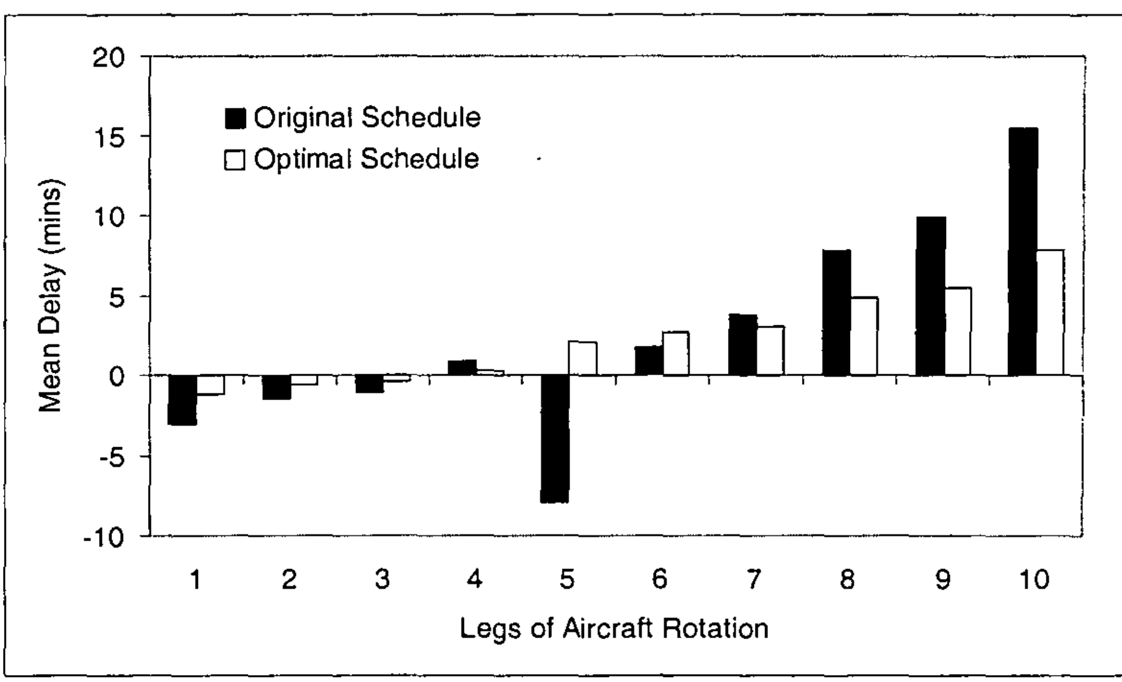

FIGURE 4.38 Mean delay of legs in the rotation of Aircraft_B

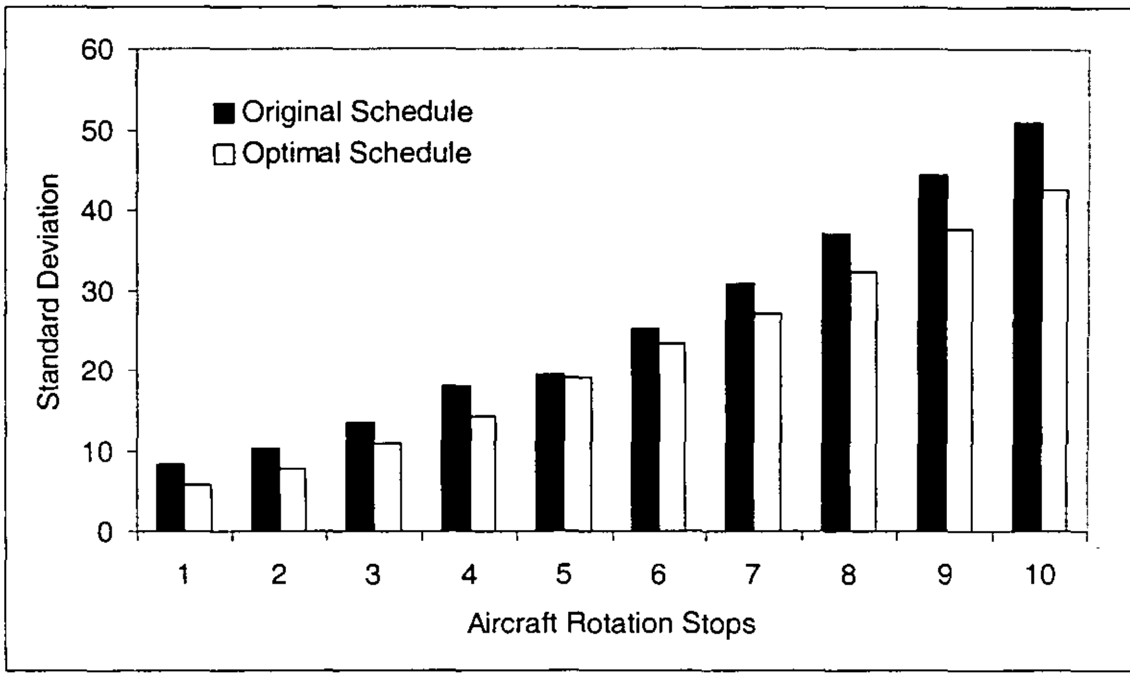

FIGURE 4.39 Standard deviation of departure time in the rotation of Aircraft_B

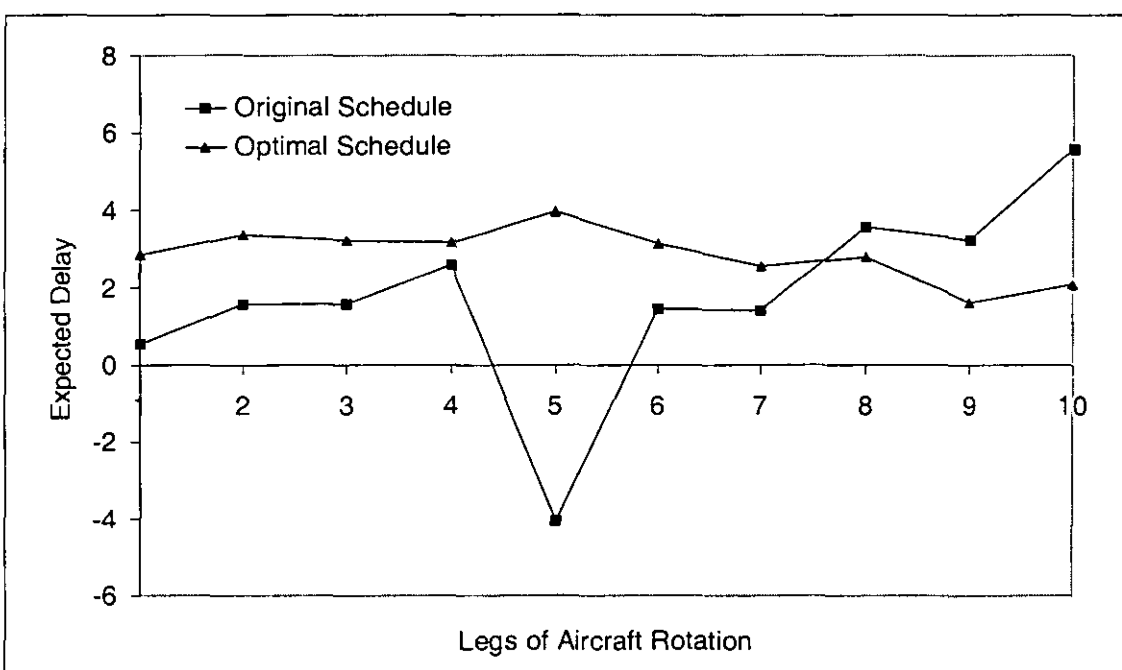

FIGURE 4.40 Expected delay of legs in the rotation of Aircraft_B

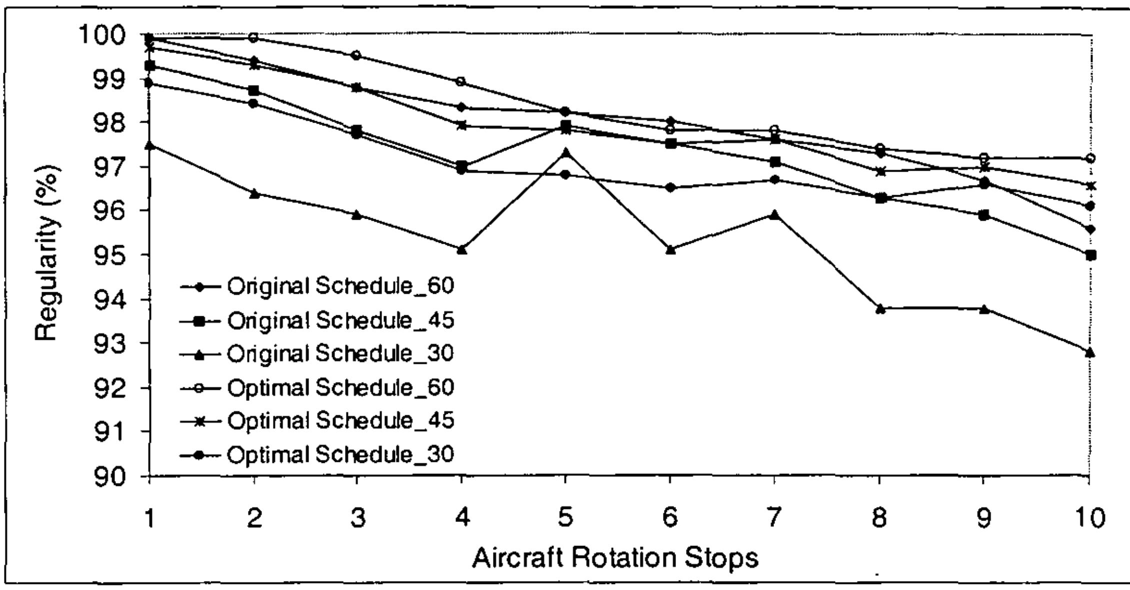

FIGURE 4.41 Schedule regularity of Aircraft_B in different scenarios

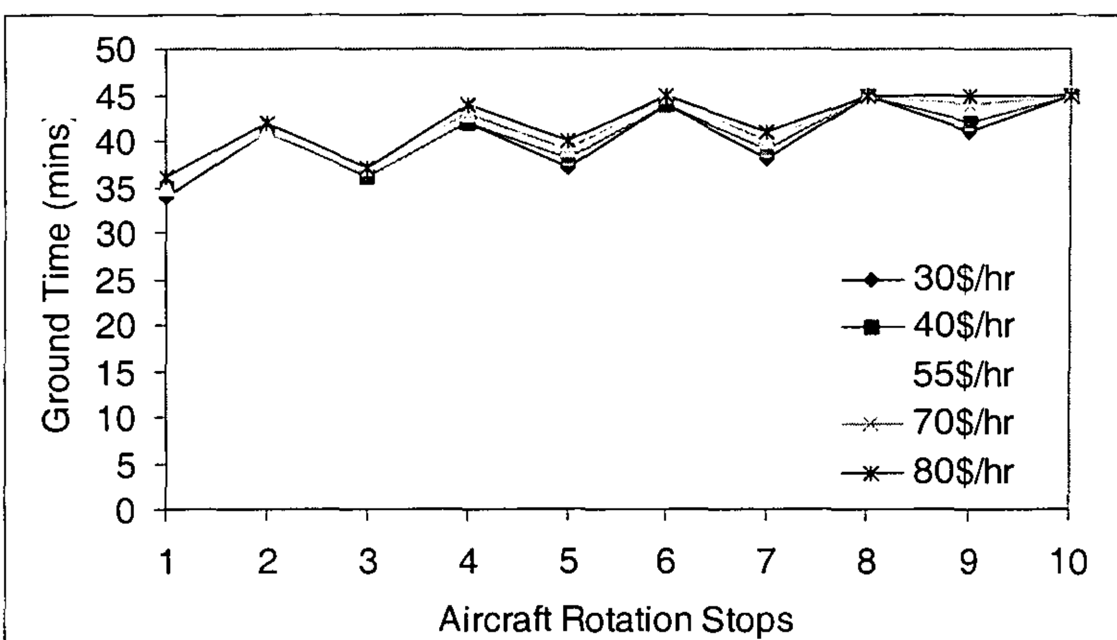

FIGURE 4.42 Ground time allocation – sensitivity analysis to the unit delay cost of a passenger

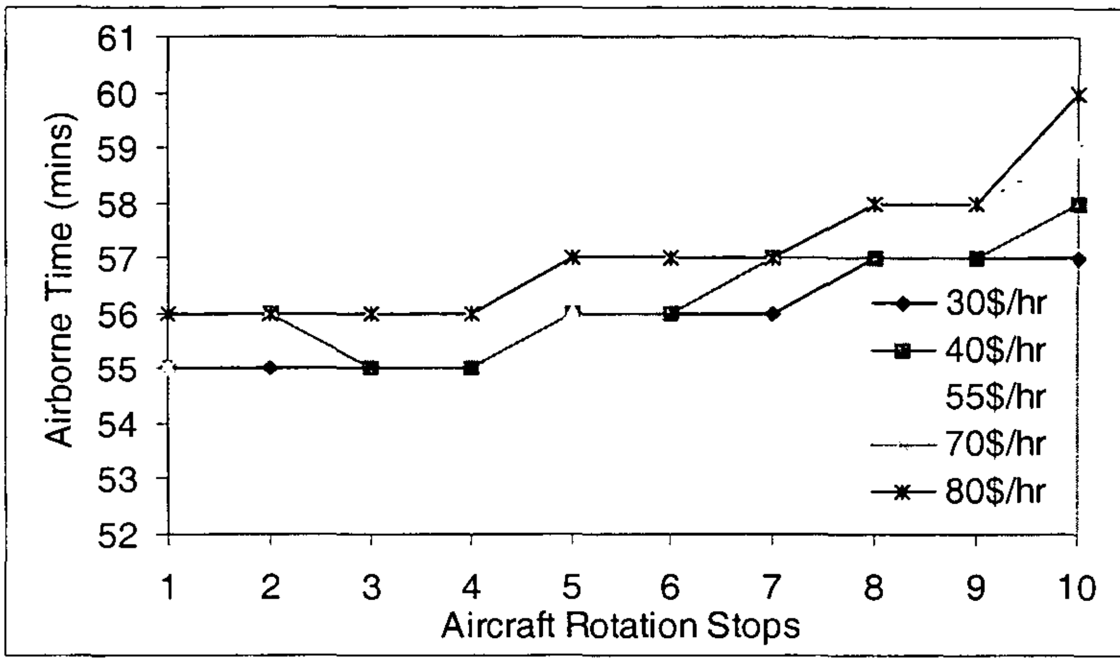

FIGURE 4.43 Airborne time allocation – sensitivity analysis to the unit delay cost of a passenger

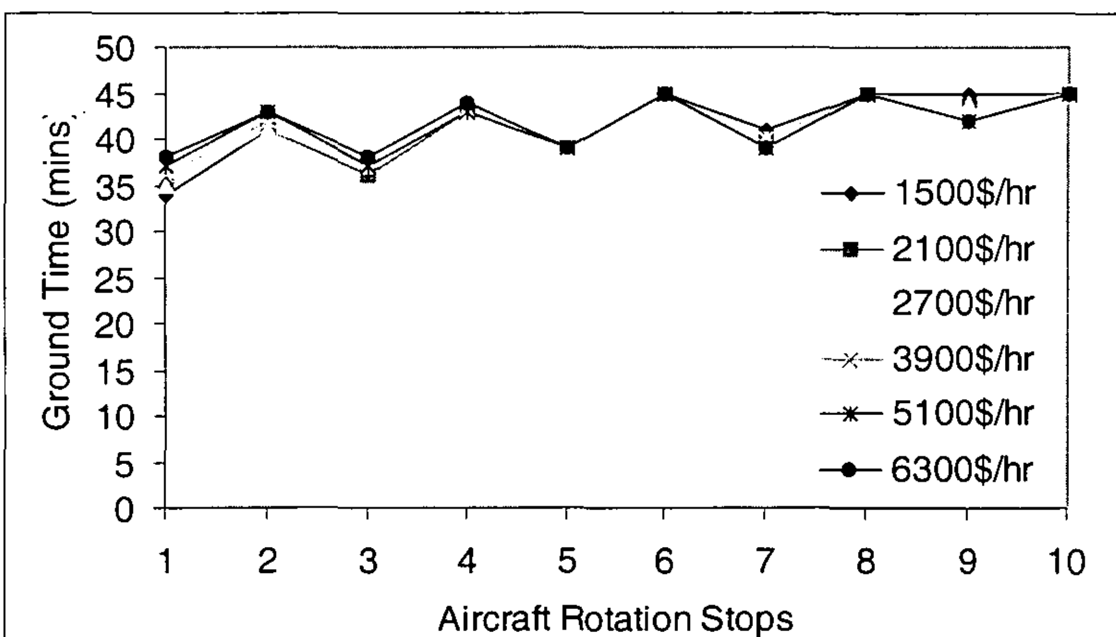

FIGURE 4.44 Ground time allocation – sensitivity analysis to the unit delay cost of an aircraft

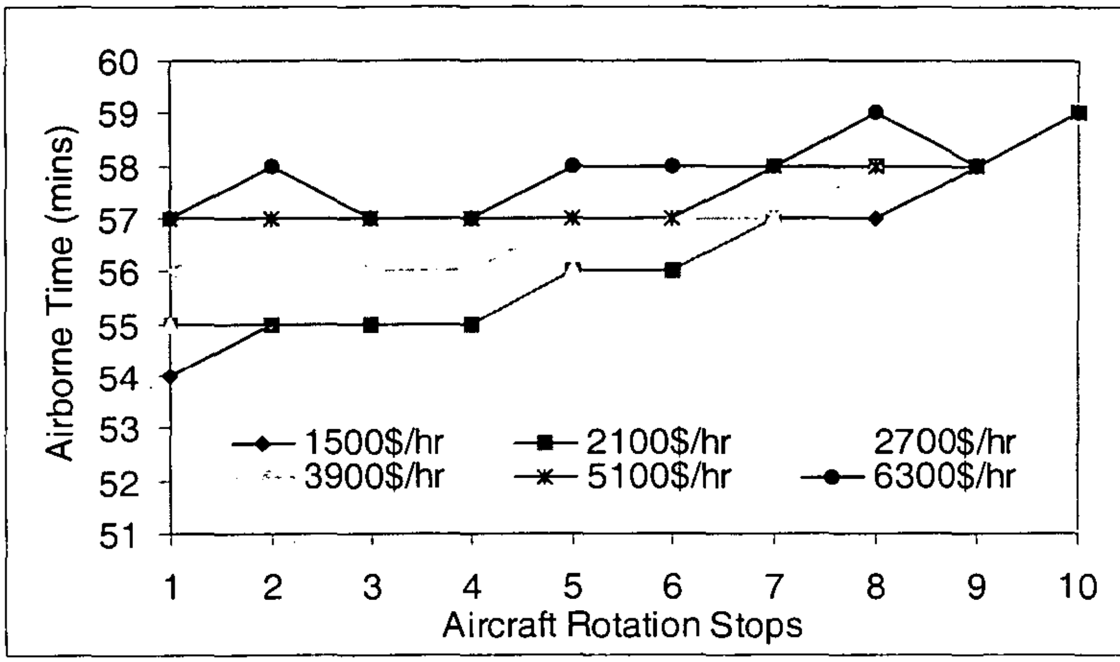

FIGURE 4.45 Airborne time allocation – sensitivity analysis to the unit delay cost of an aircraft

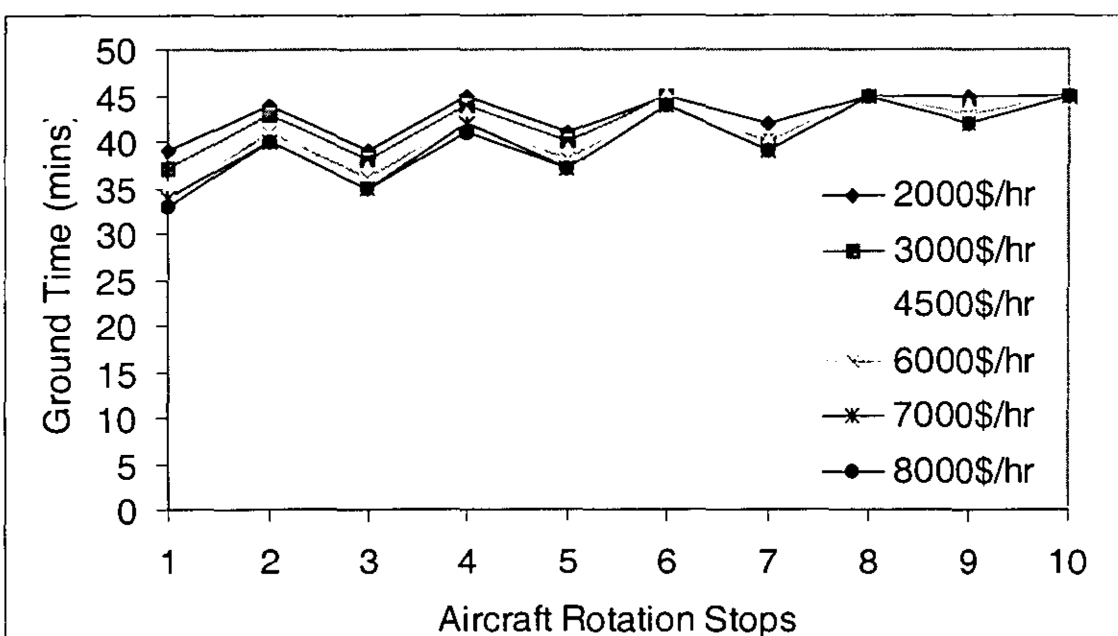

FIGURE 4.46 Ground time allocation – sensitivity analysis to the unit cost of schedule time

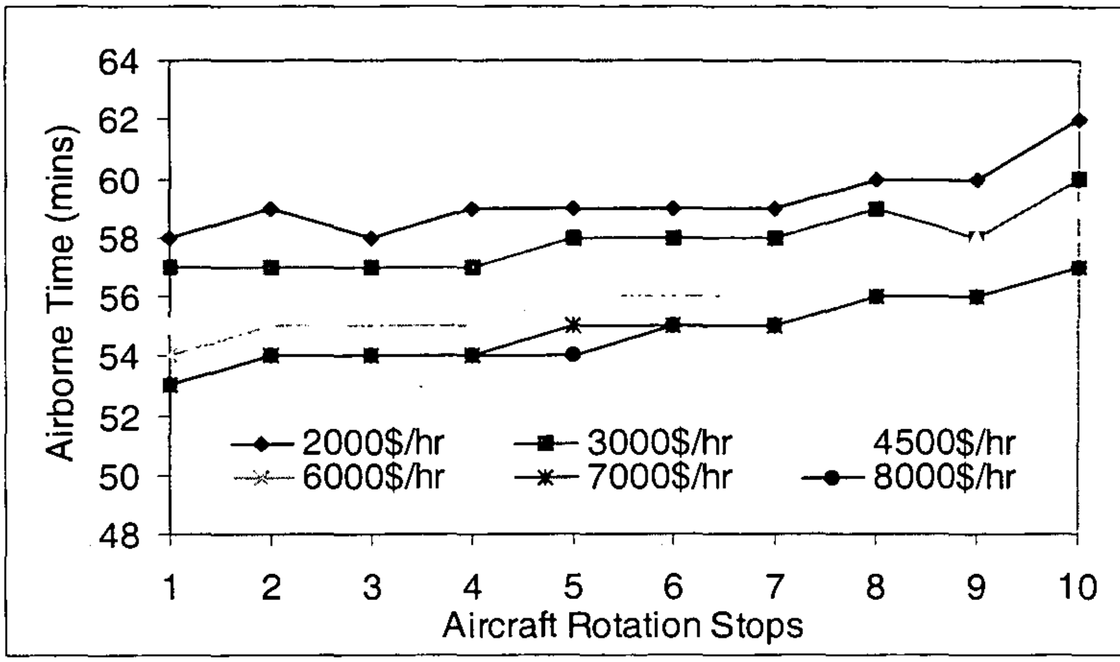

FIGURE 4.47 Airborne time allocation – sensitivity analysis to the unit cost of schedule time

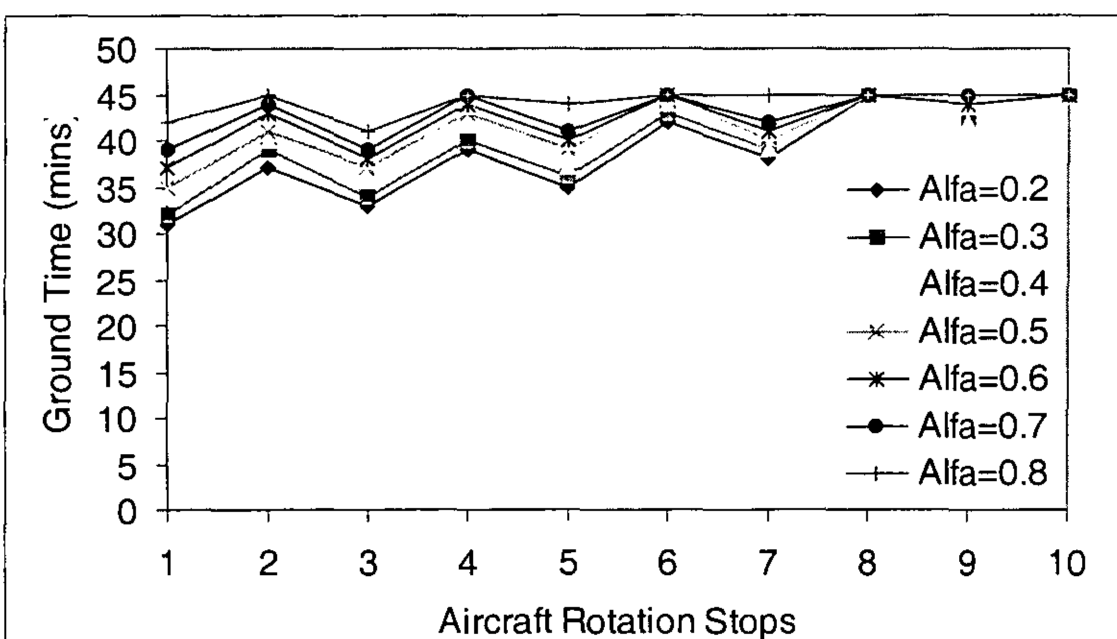

FIGURE 4.48 Ground time allocation – sensitivity analysis to weight factors in model optimisation

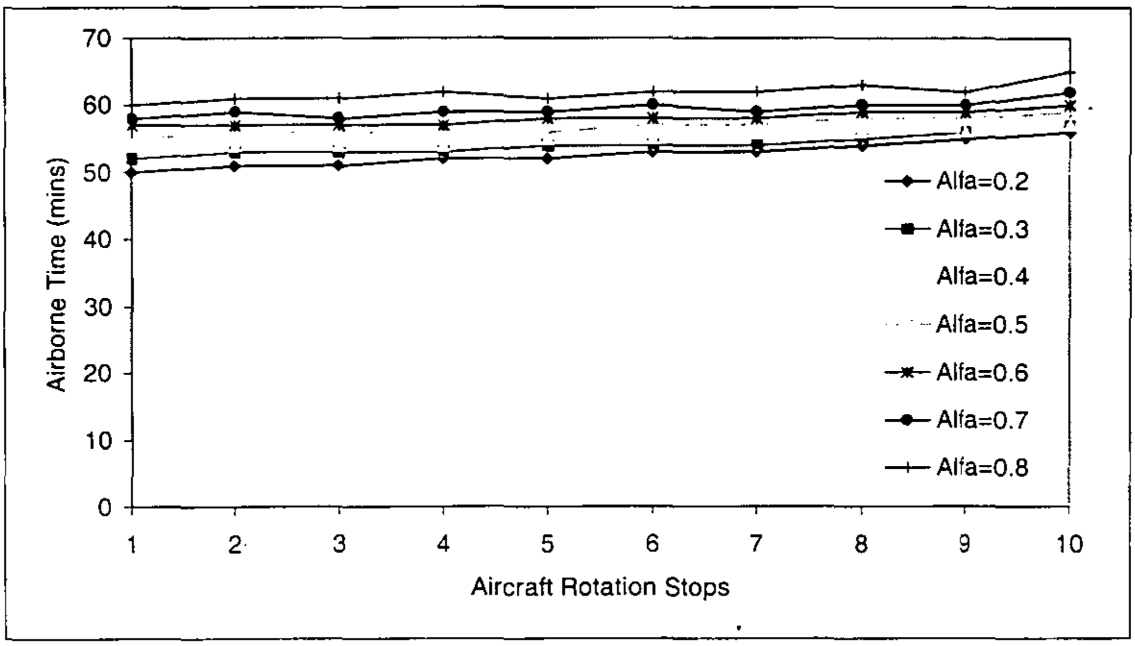

FIGURE 4.49 Airborne time allocation – sensitivity analysis to weight factors in model optimisation

Chapter 5 Figures

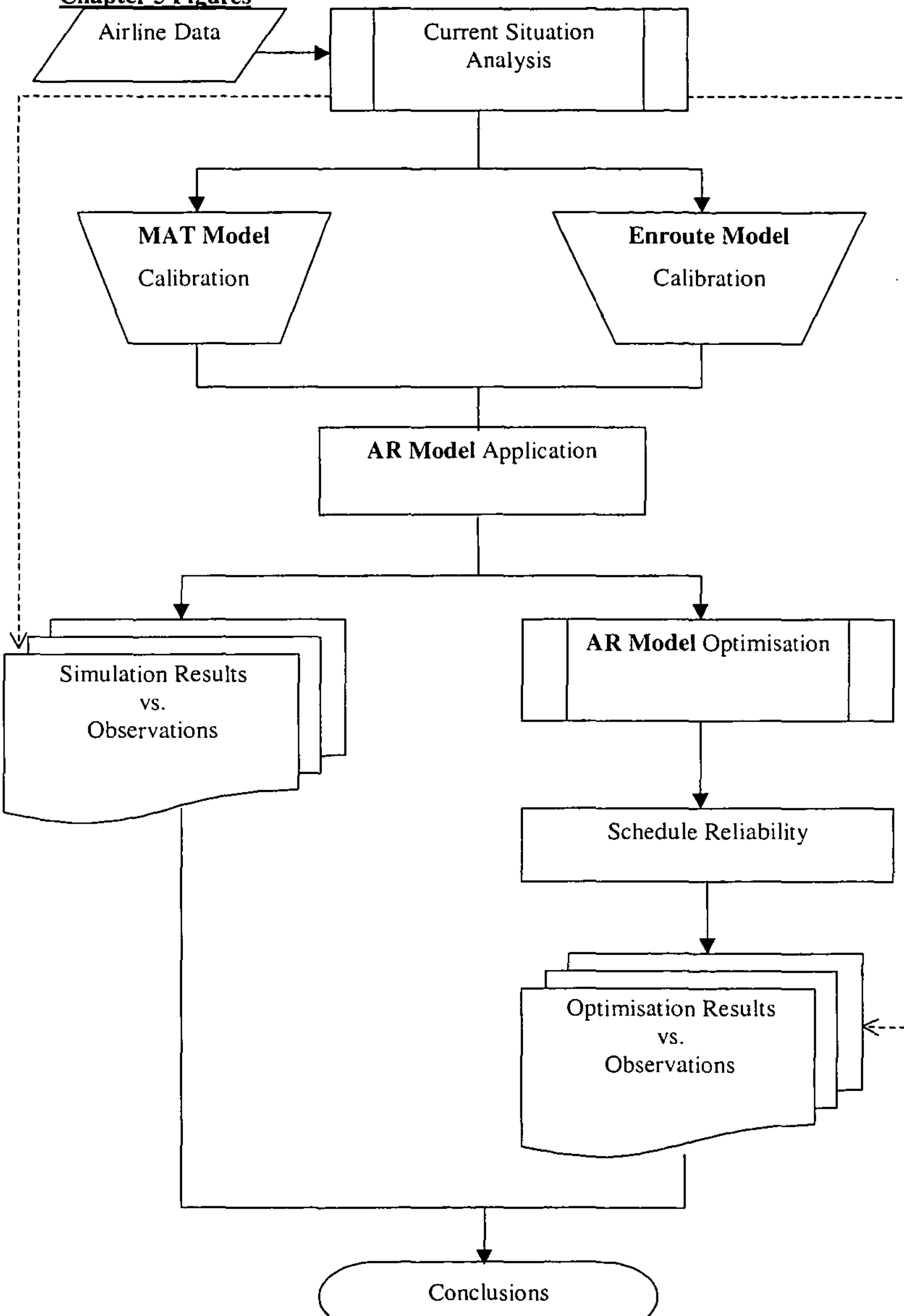

FIGURE 5.1 Flow chart of case study- EasyJet

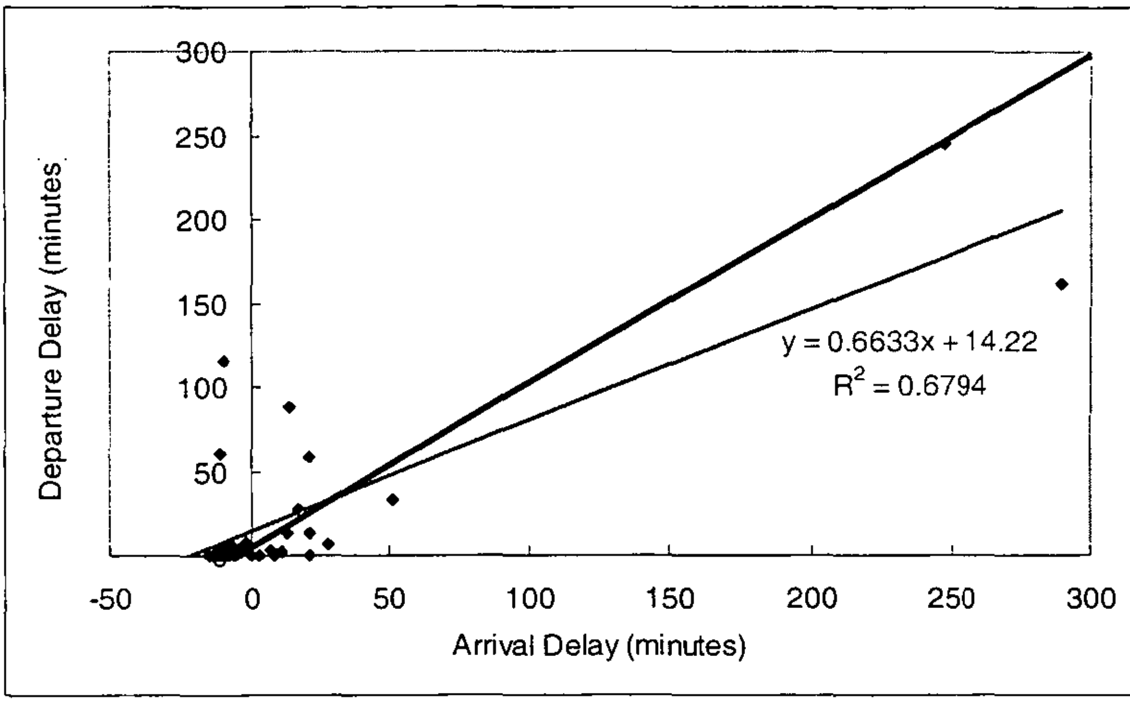

FIGURE 5.2 Turnaround efficiency of EZY207 at LTN Airport

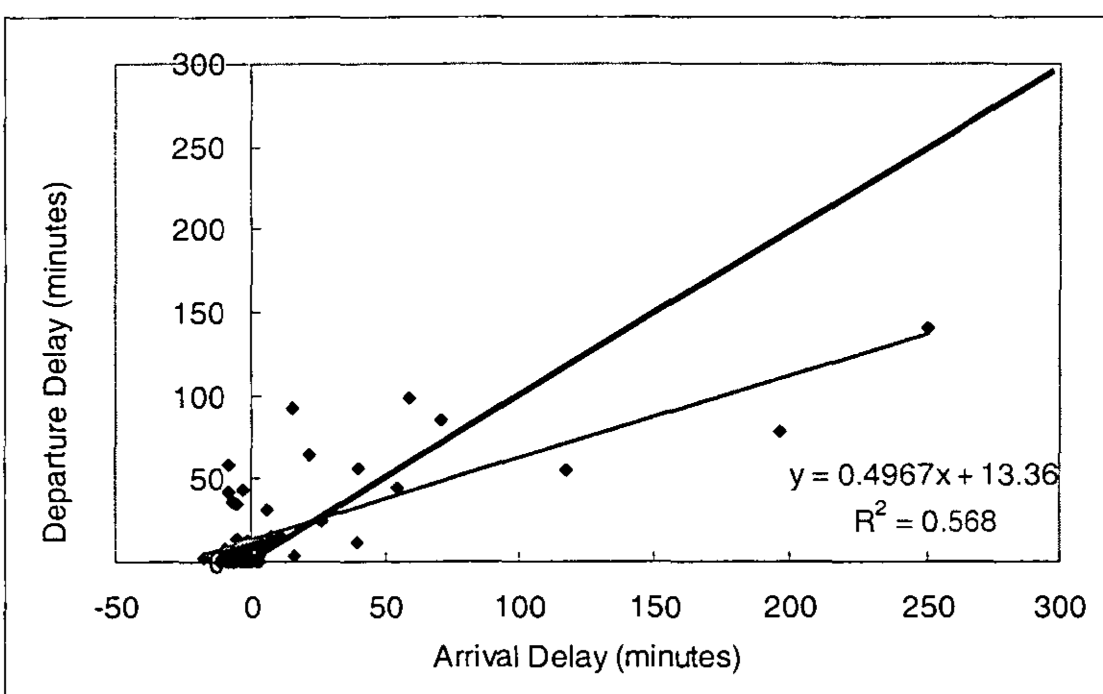

FIGURE 5.3 Turnaround efficiency of EZY209 at LTN Airport

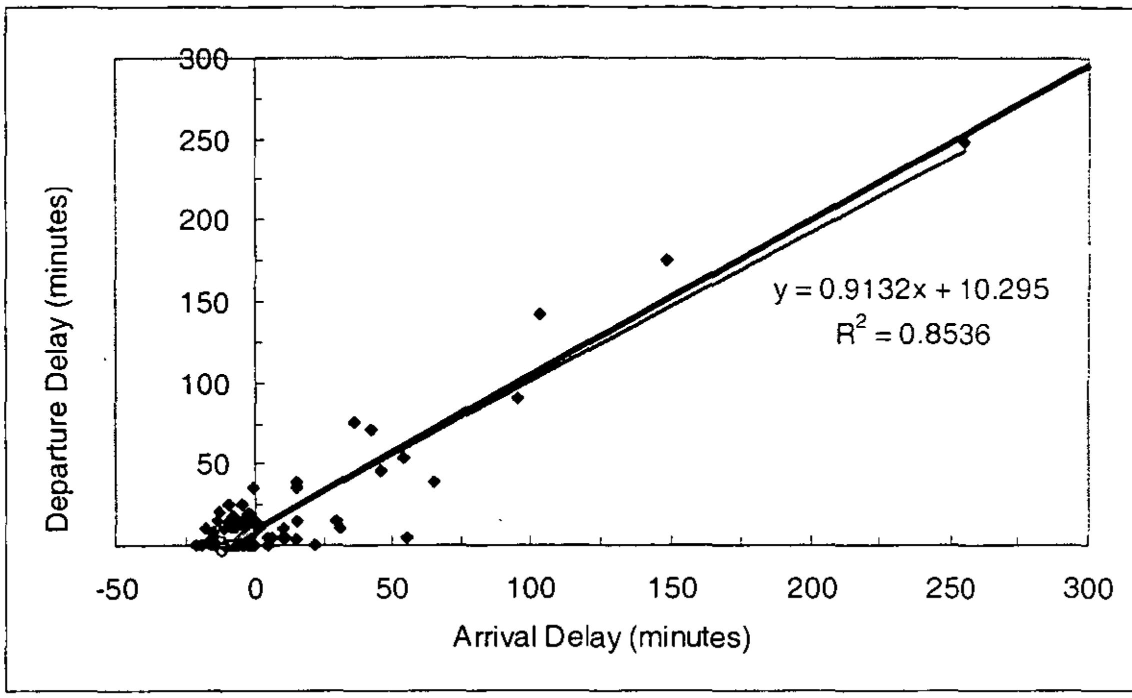

FIGURE 5.4 Turnaround Efficiency of EZY202 at AMS Airport

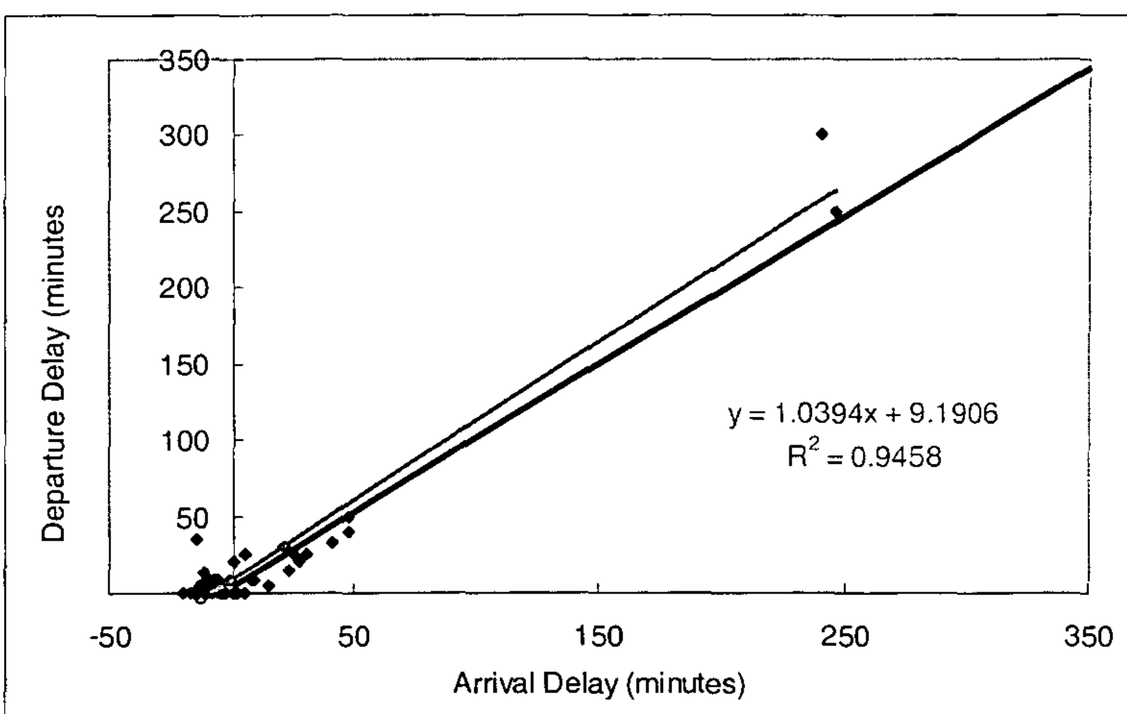

FIGURE 5.5 Turnaround Efficiency of EZY204 at AMS Airport

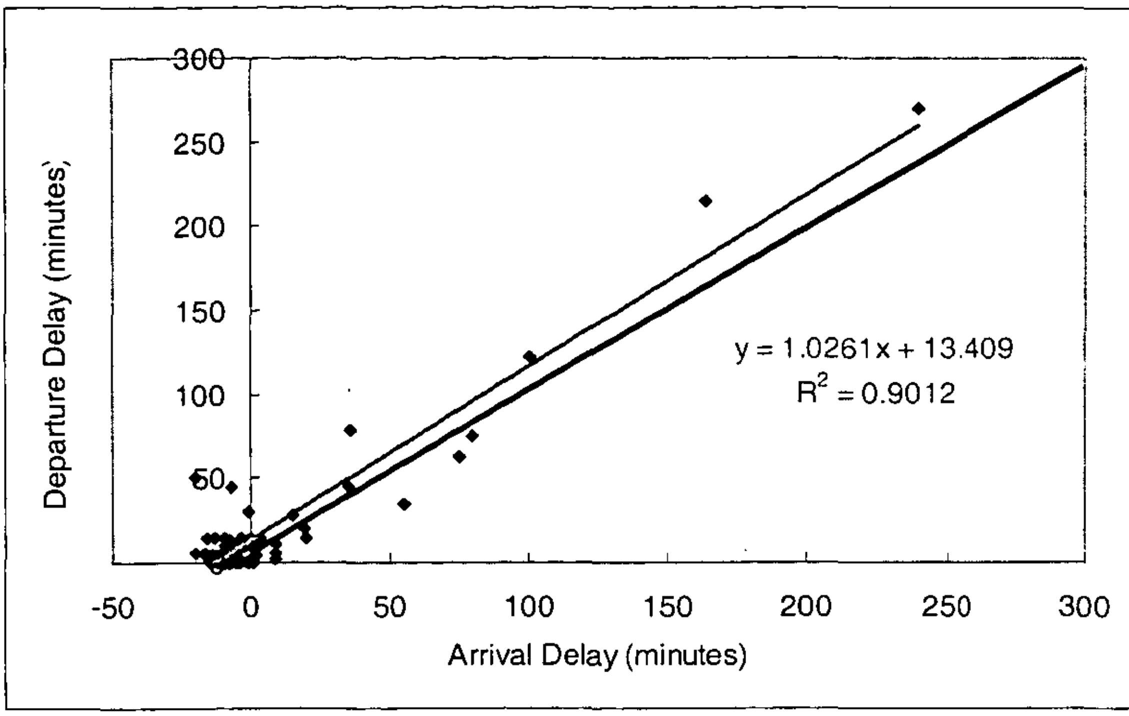

FIGURE 5.6 Turnaround Efficiency of EZY206 at AMS Airport

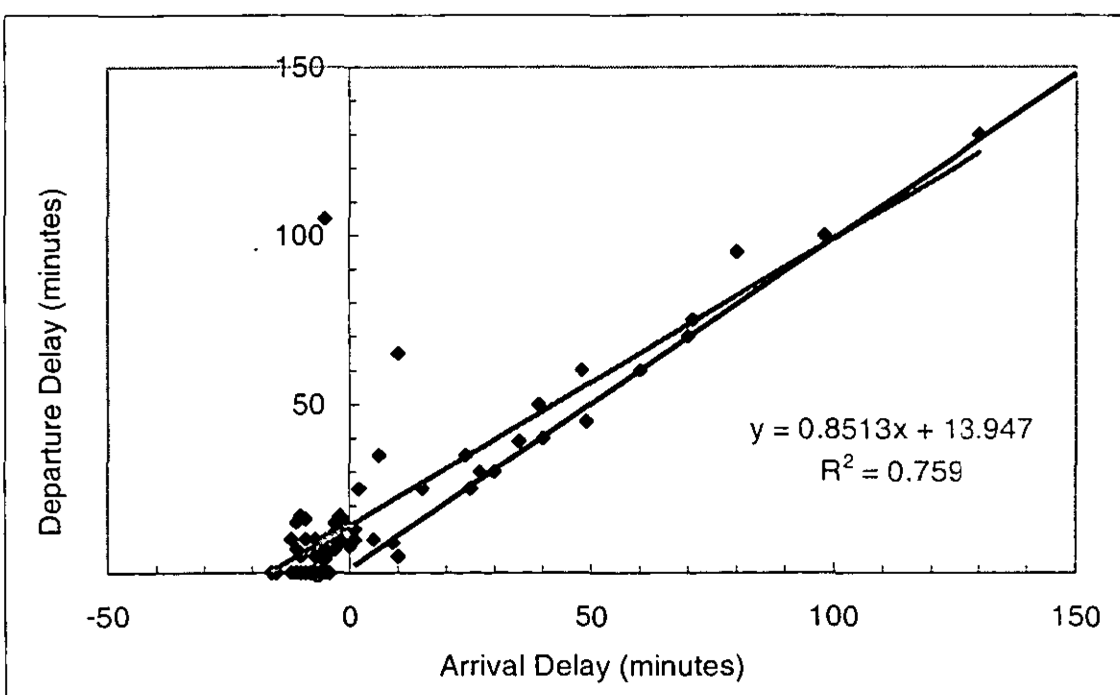

FIGURE 5.7 Turnaround Efficiency of EZY208 at AMS Airport

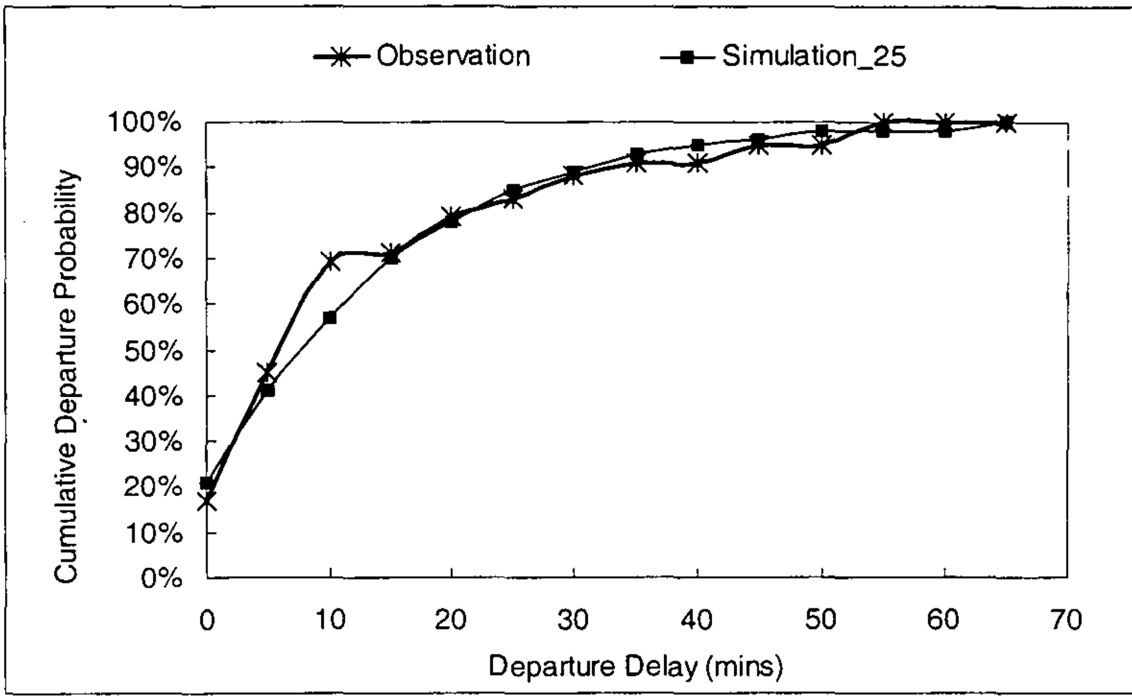

FIGURE 5.8 MAT model application to the turnaround operation of EZY203 at LTN

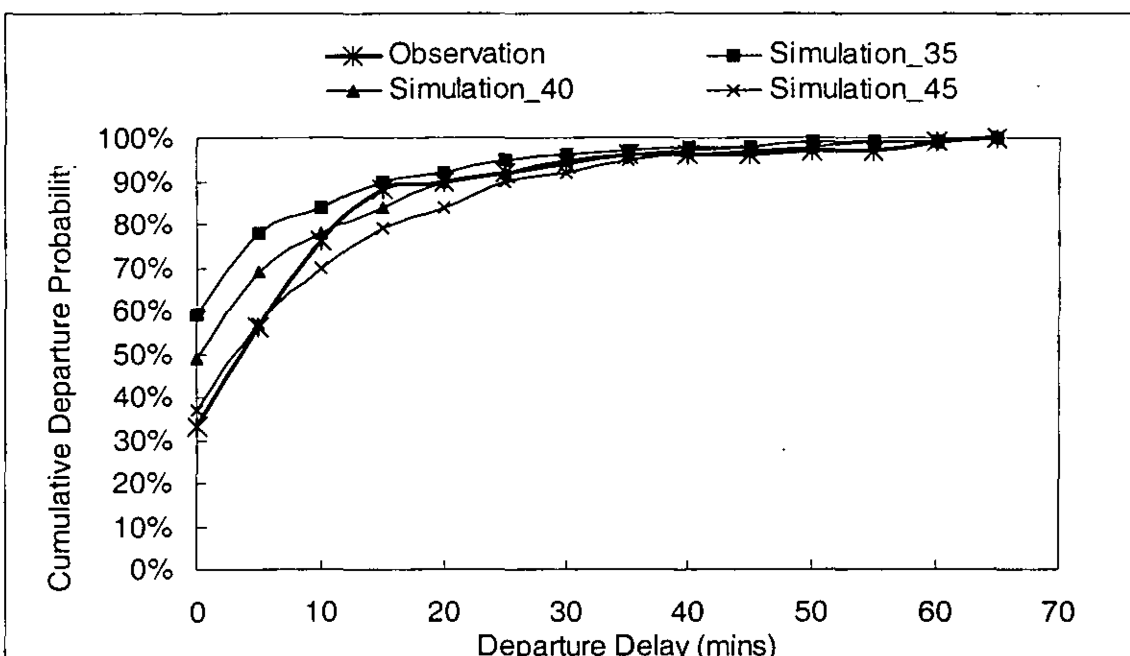

FIGURE 5.9 MAT model application to the turnaround operation of EZY207 at LTN

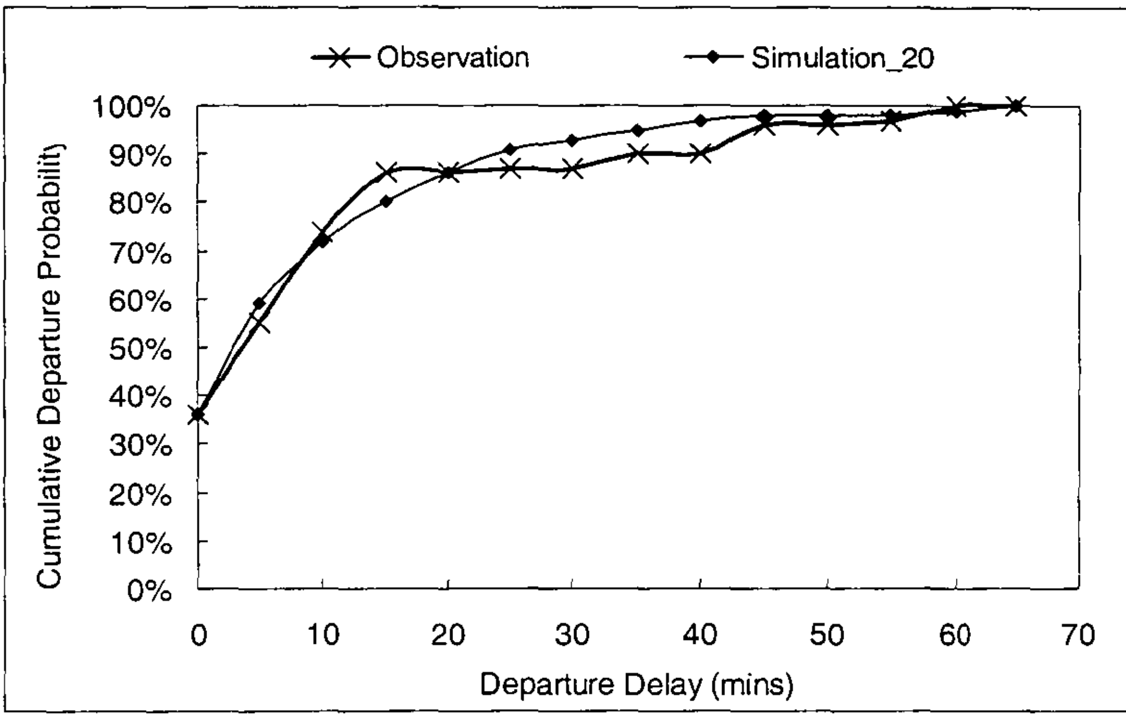

FIGURE 5.10 MAT model application to the turnaround operation of EZY209 at LTN

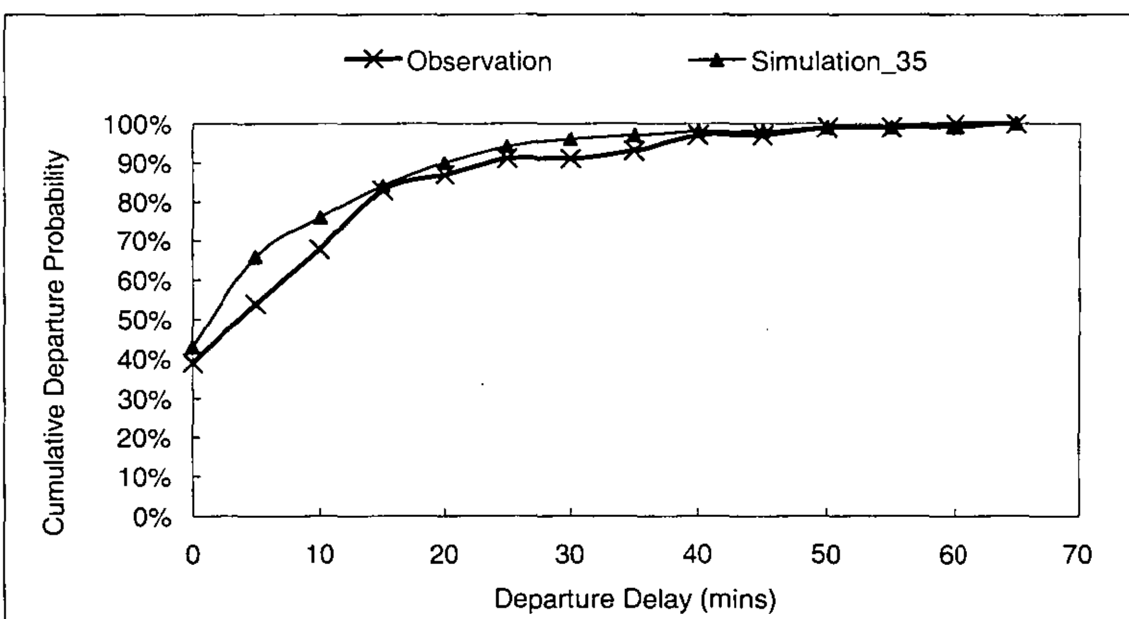

FIGURE 5.11 MAT model application to the turnaround operation of EZY202 at AMS

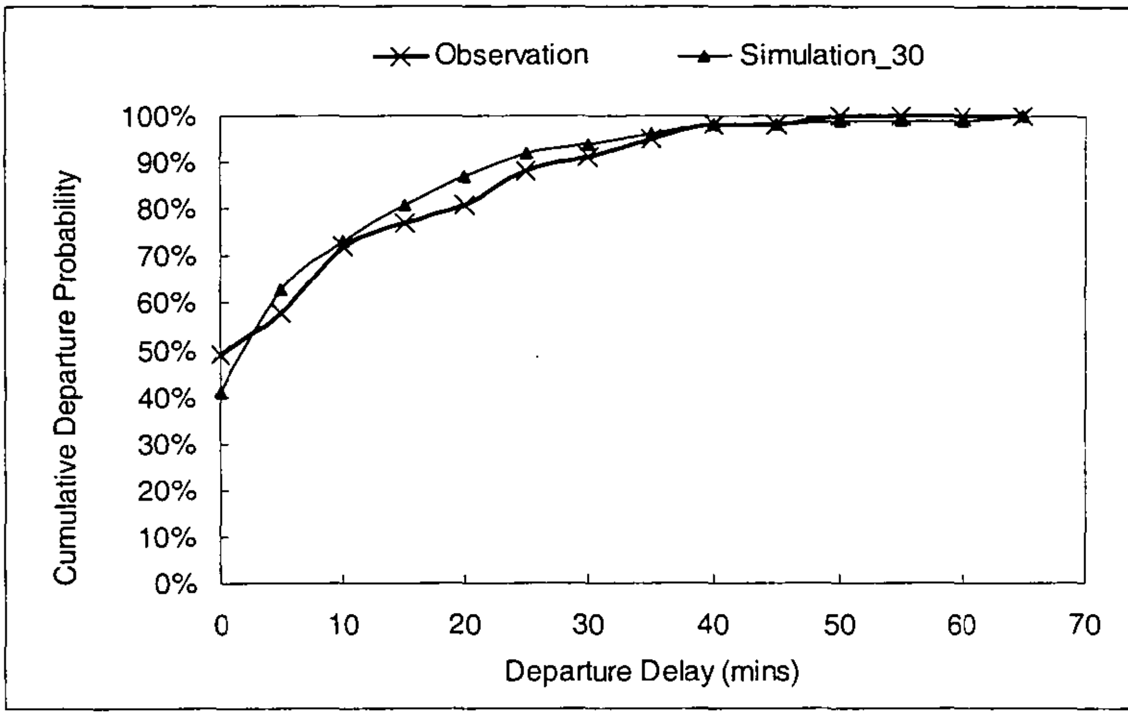

FIGURE 5.12 MAT model application to the turnaround operation of EZY204 at AMS

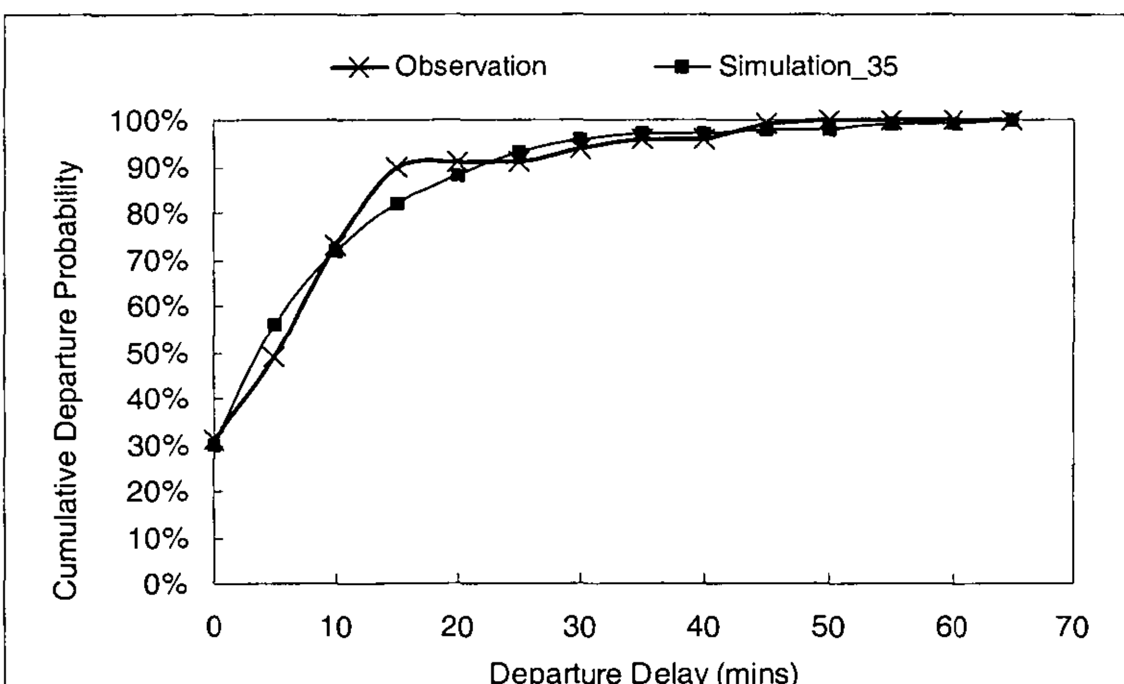

FIGURE 5.13 MAT model application to the turnaround operation of EZY206 at AMS

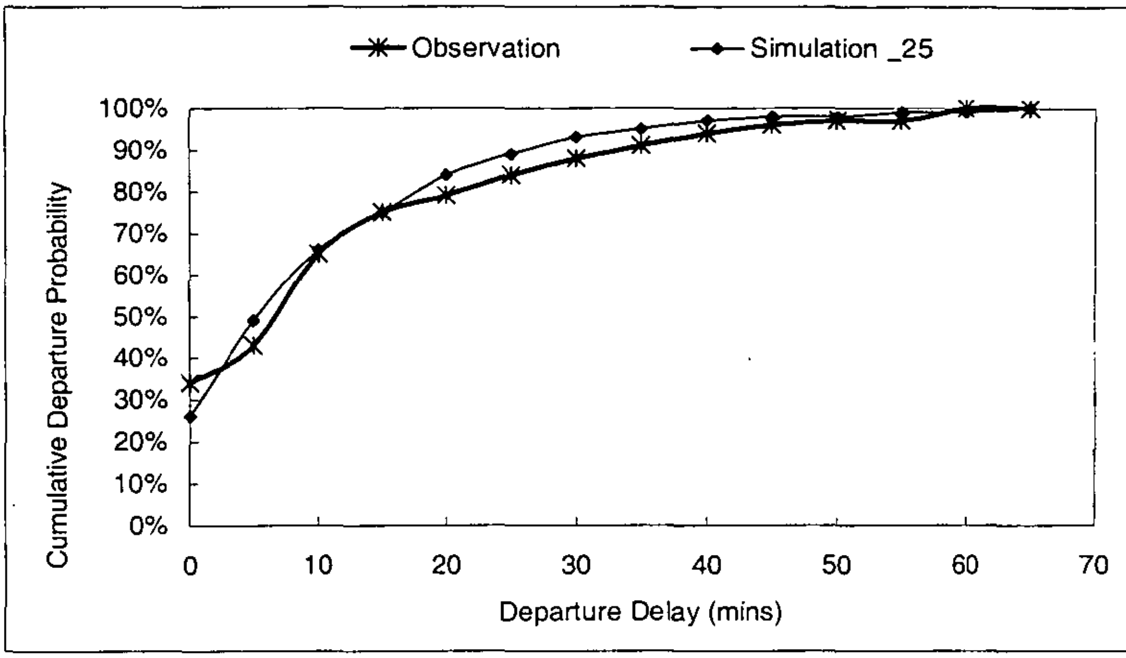

FIGURE 5.14 MAT model application to the turnaround operation of EZY208 at AMS

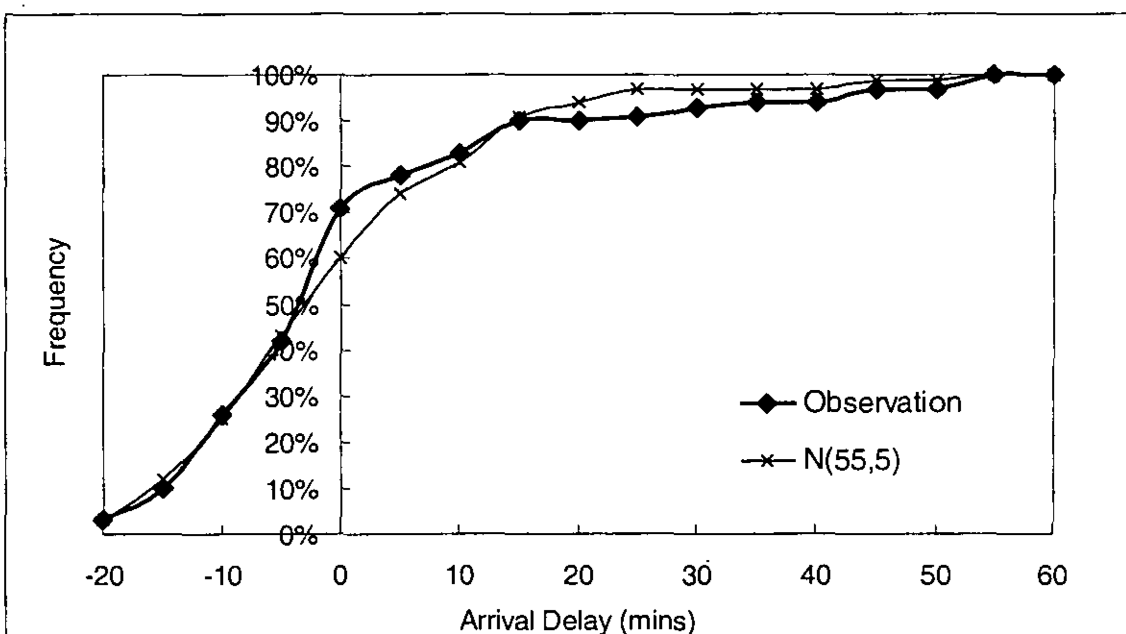

FIGURE 5.15 Enroute model application to EZY201 from LTN to AMS

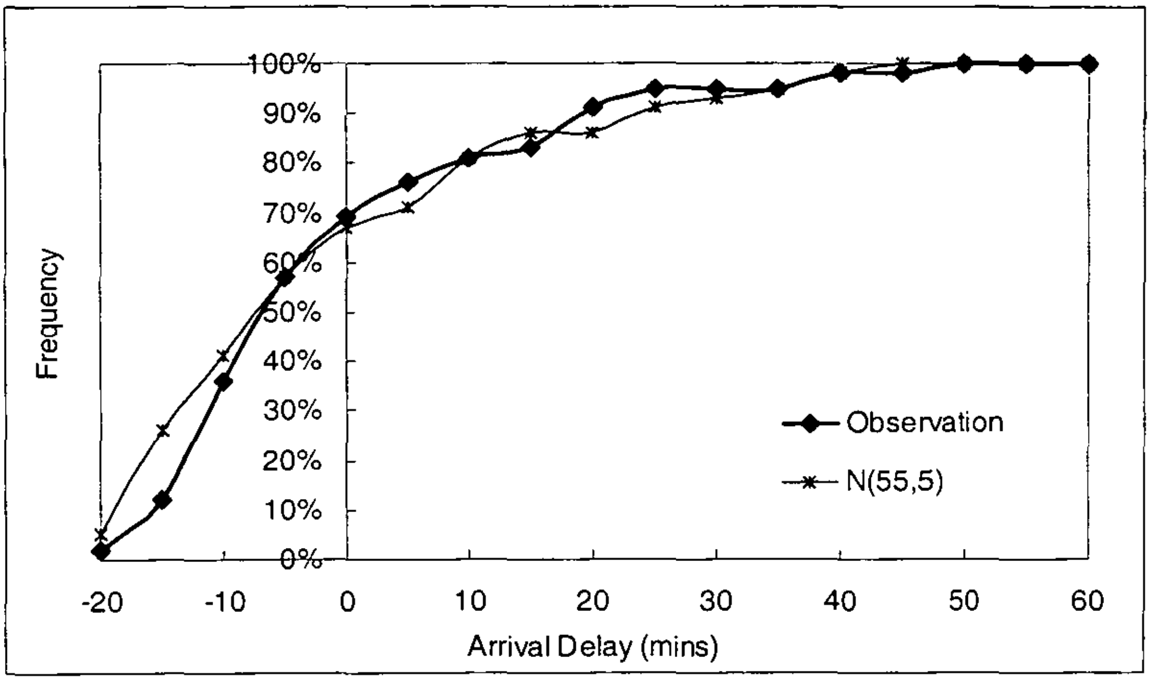

FIGURE 5.16 Enroute model application to EZY203 from LTN to AMS

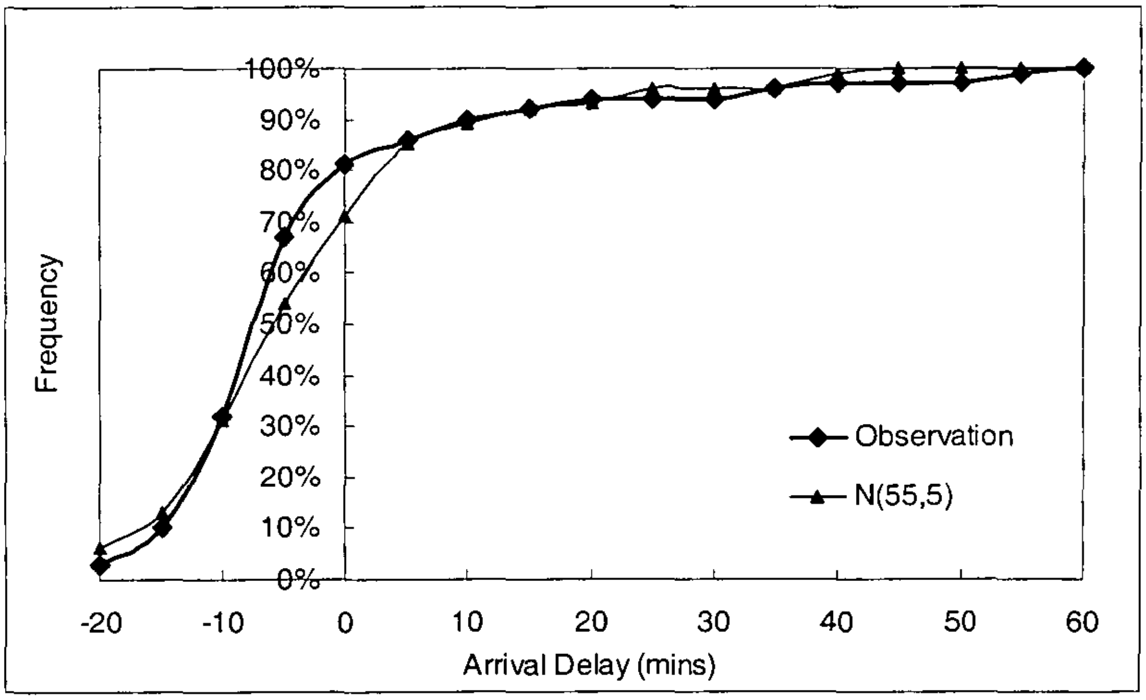

FIGURE 5.17 Enroute model application to EZY207 from LTN to AMS

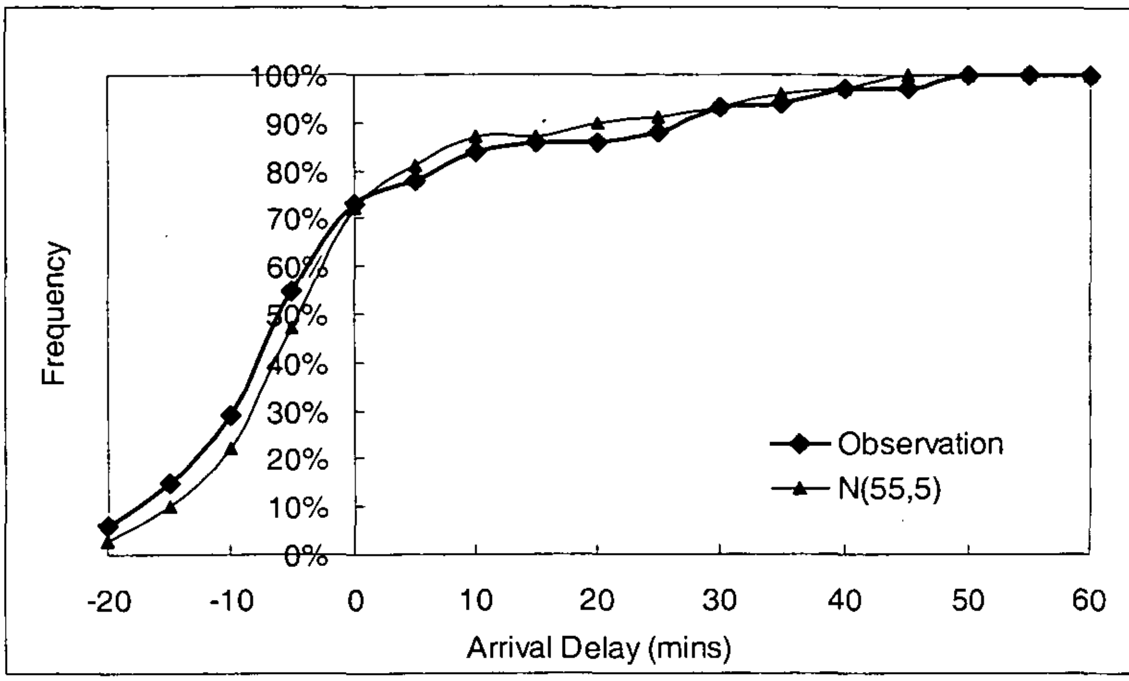

FIGURE 5.18 Enroute model application to EZY209 from LTN to AMS

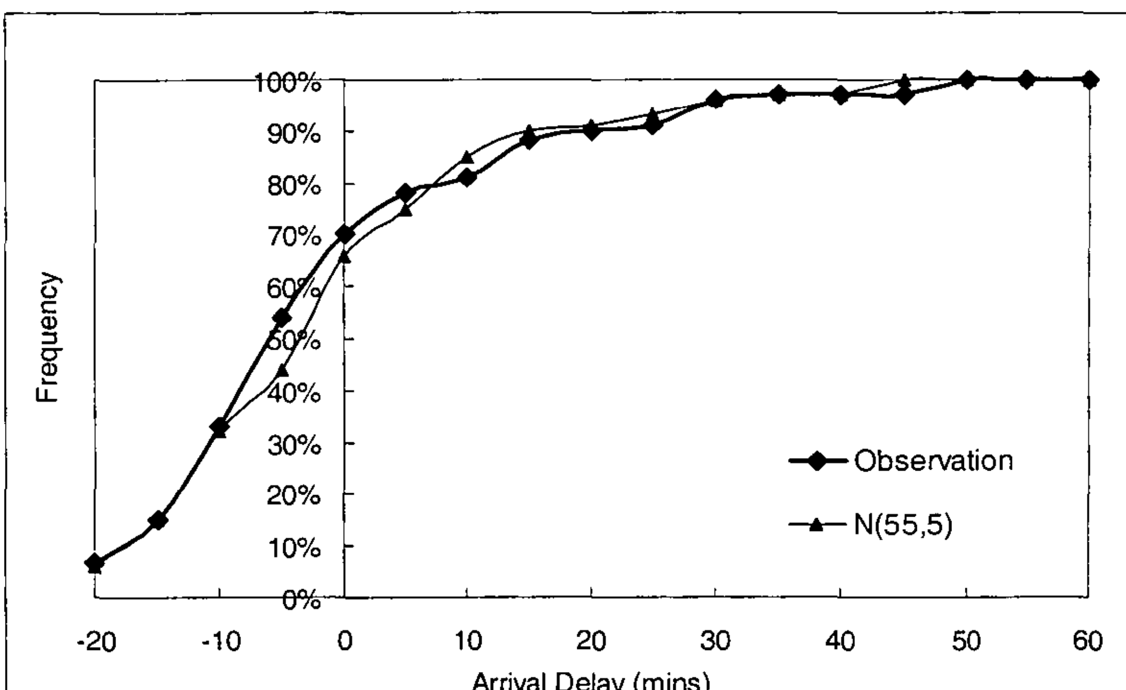

FIGURE 5.19 Enroute model application to EZY202 from AMS to LTN

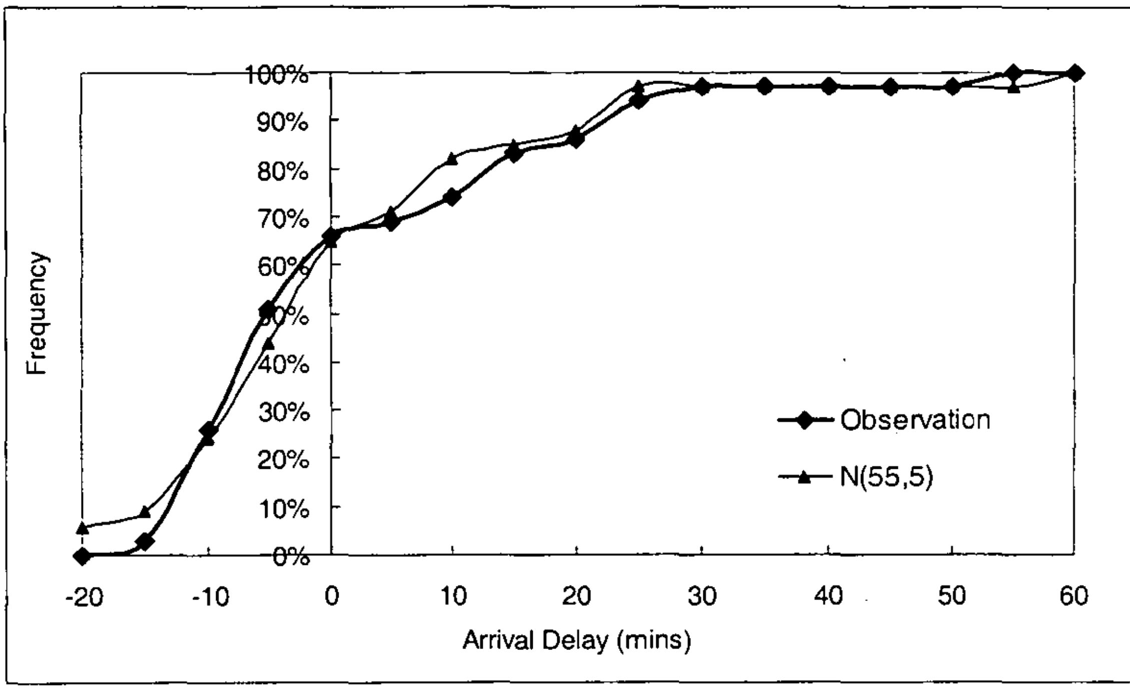

FIGURE 5.20 Enroute model application to EZY204 from AMS to LTN

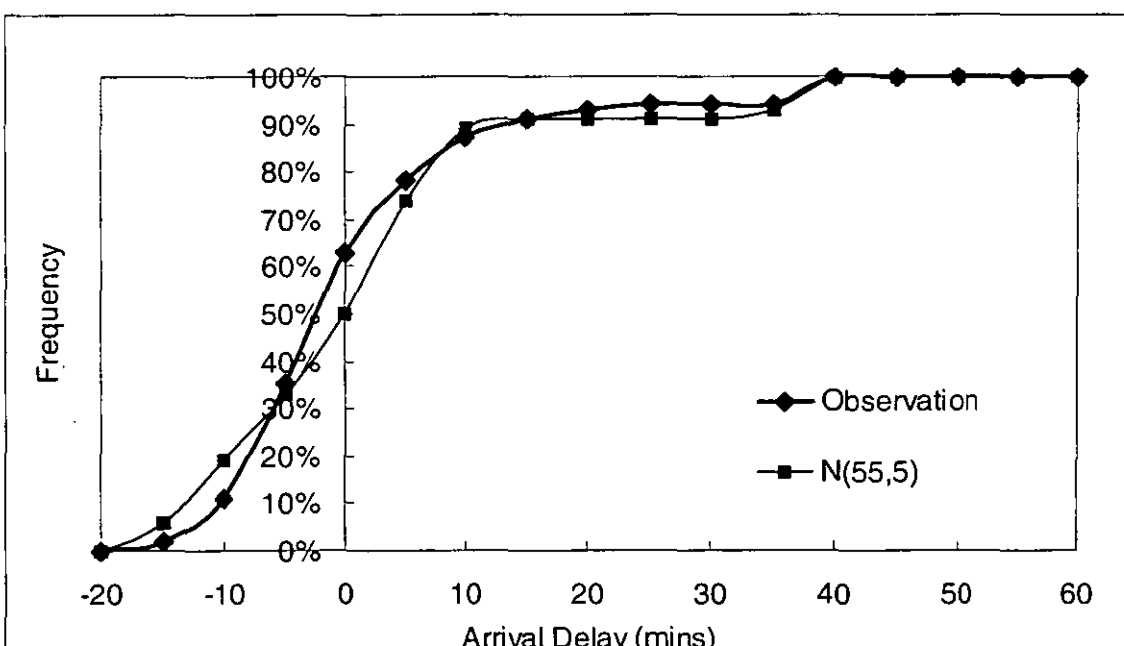

FIGURE 5.21 Enroute model application to EZY206 from AMS to LTN

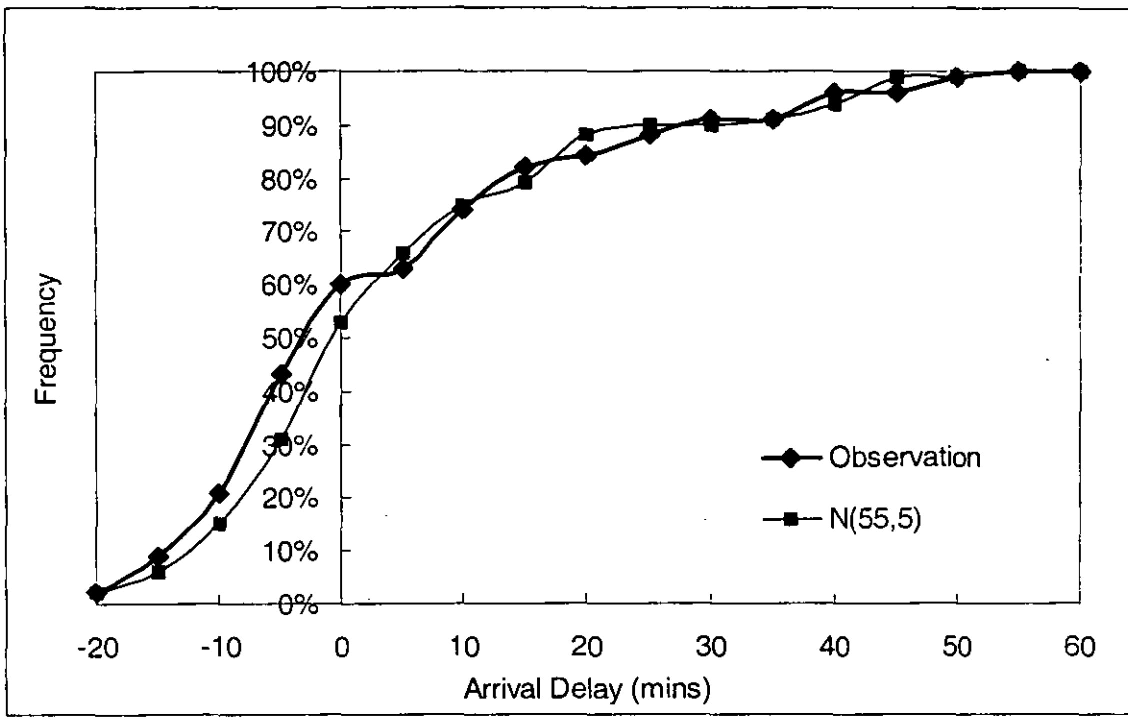

FIGURE 5.22 Enroute model application to EZY208 from AMS to LTN

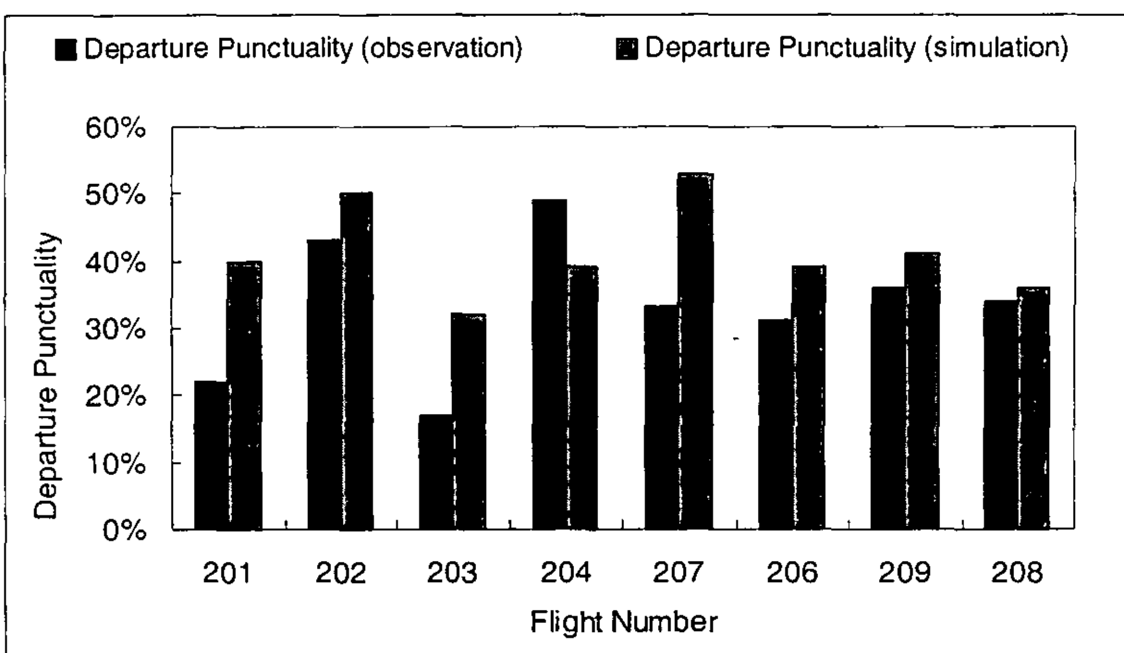

FIGURE 5.23 Comparison of departure punctuality between observation and simulation results

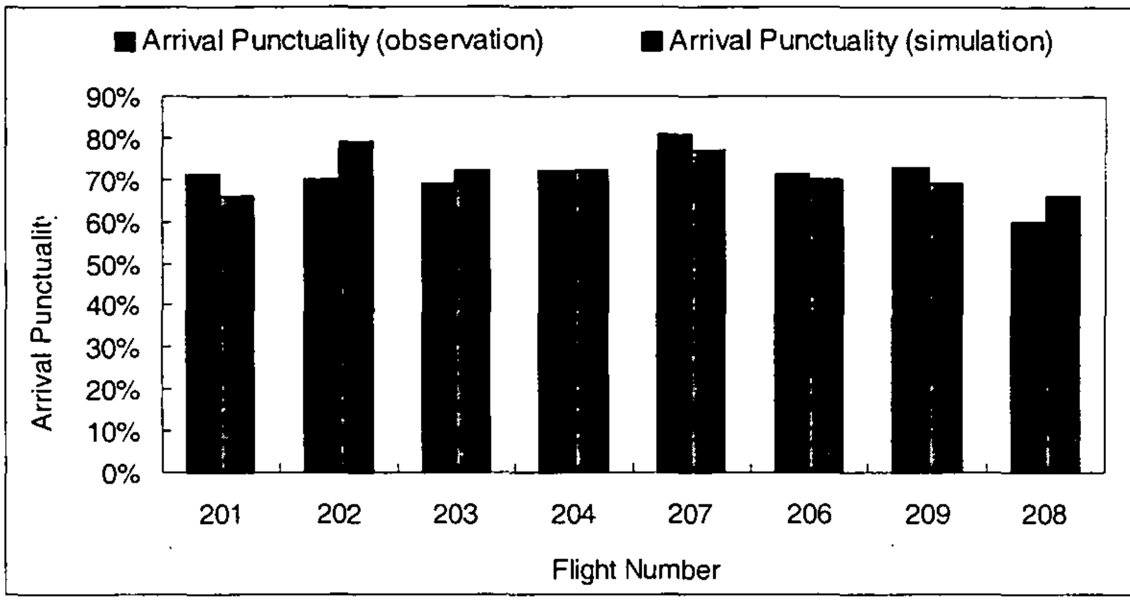

FIGURE 5.24 Comparison of arrival punctuality between observation and simulation results

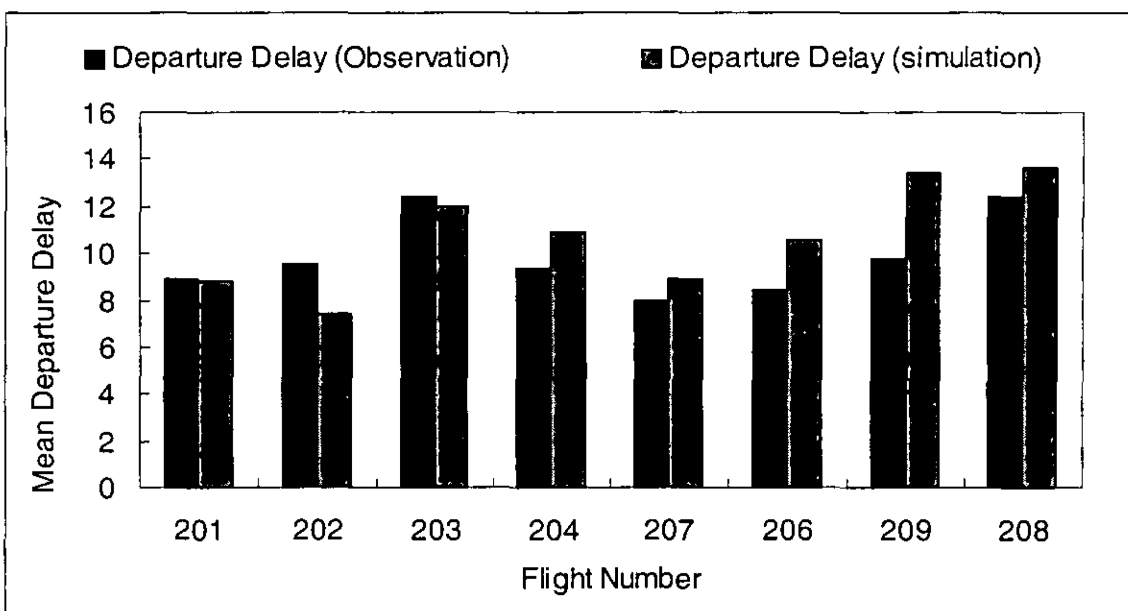

FIGURE 5.25 Comparison of mean departure delay between observation and simulation results

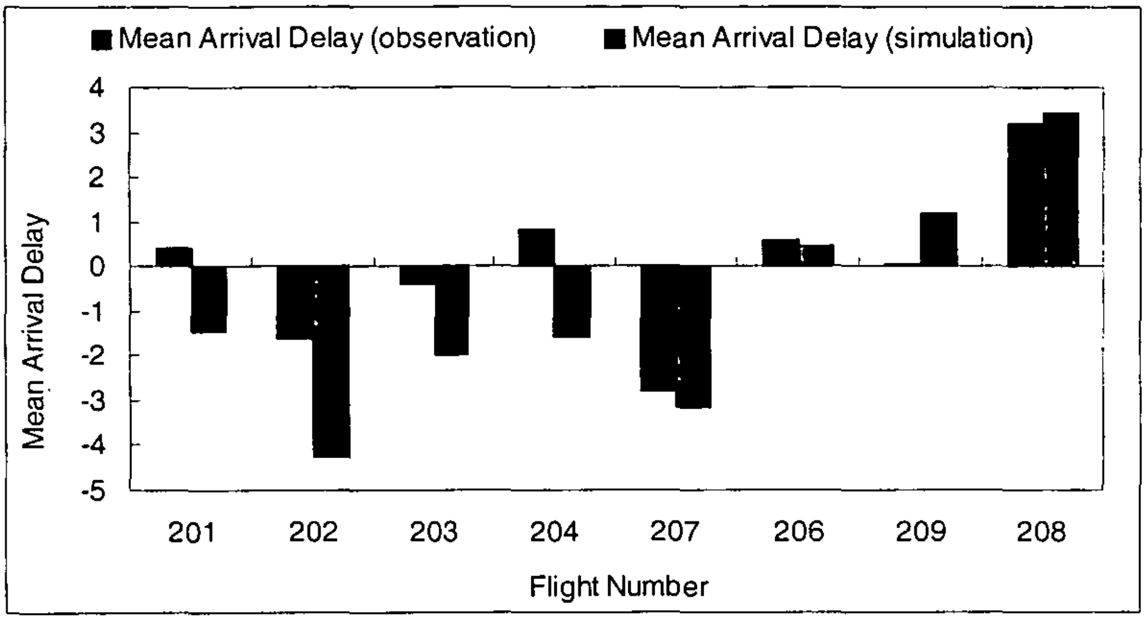

FIGURE 5.26 Comparison of mean arrival delay between observation and simulation results

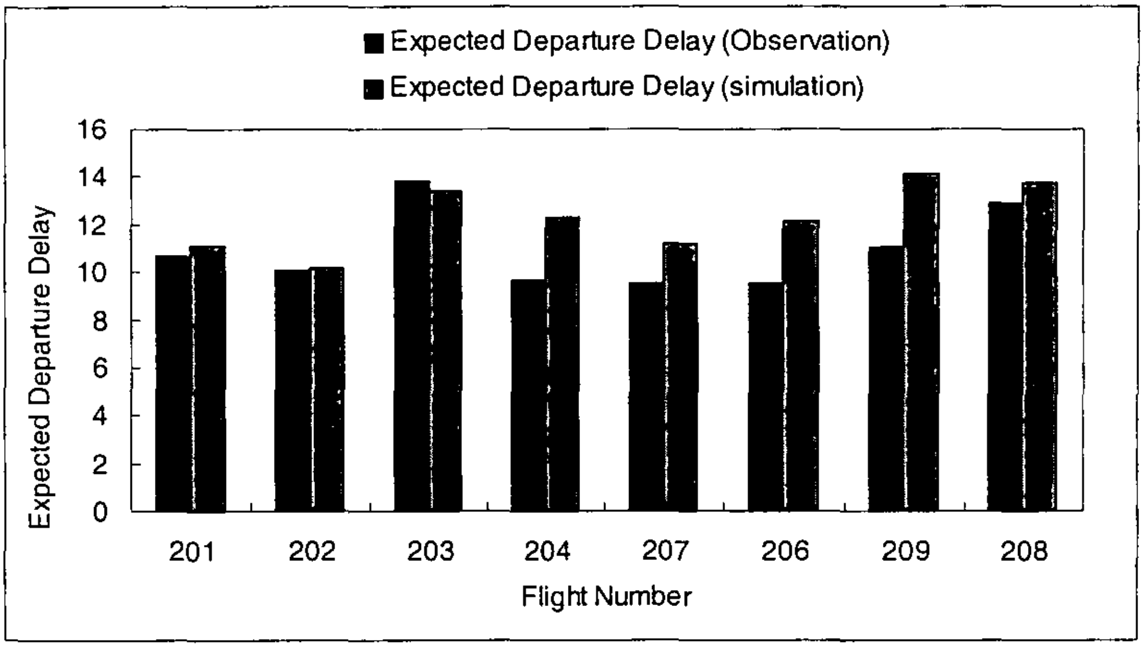

FIGURE 5.27 Comparison of expected departure delay between observation and simulation results

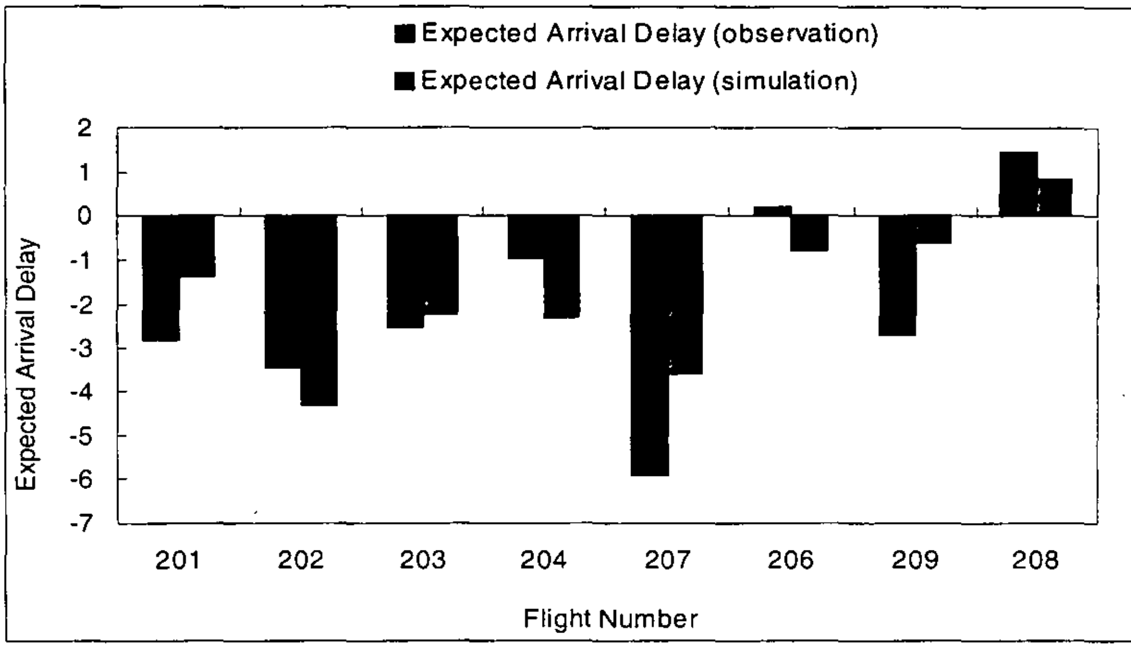

FIGURE 5.28 Comparison of expected arrival delay between observation and simulation results

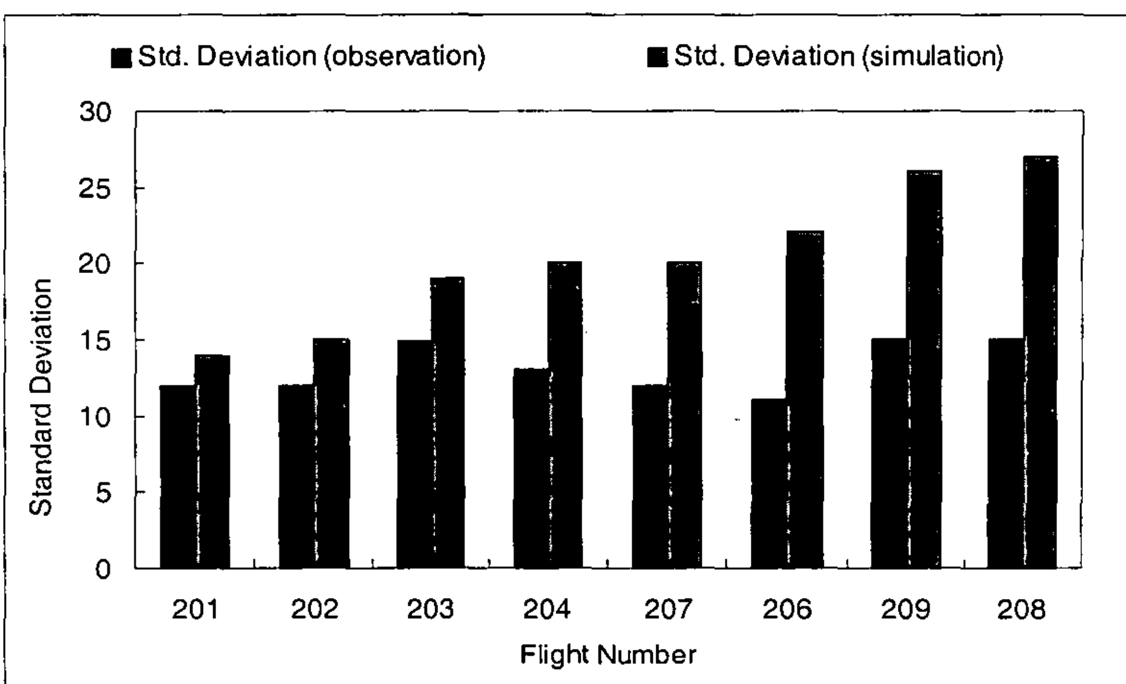

FIGURE 5.29 Comparison of standard deviation of departure delay between observation and simulation results

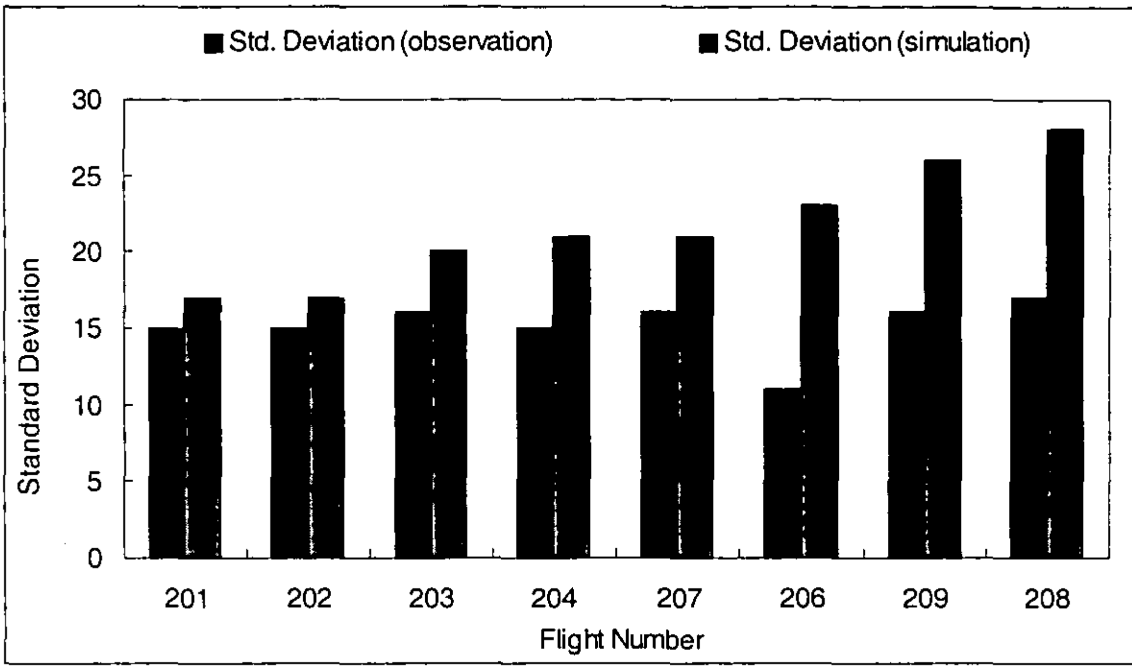

FIGURE 5.30 Comparison of standard deviation of arrival delay between observation and simulation results

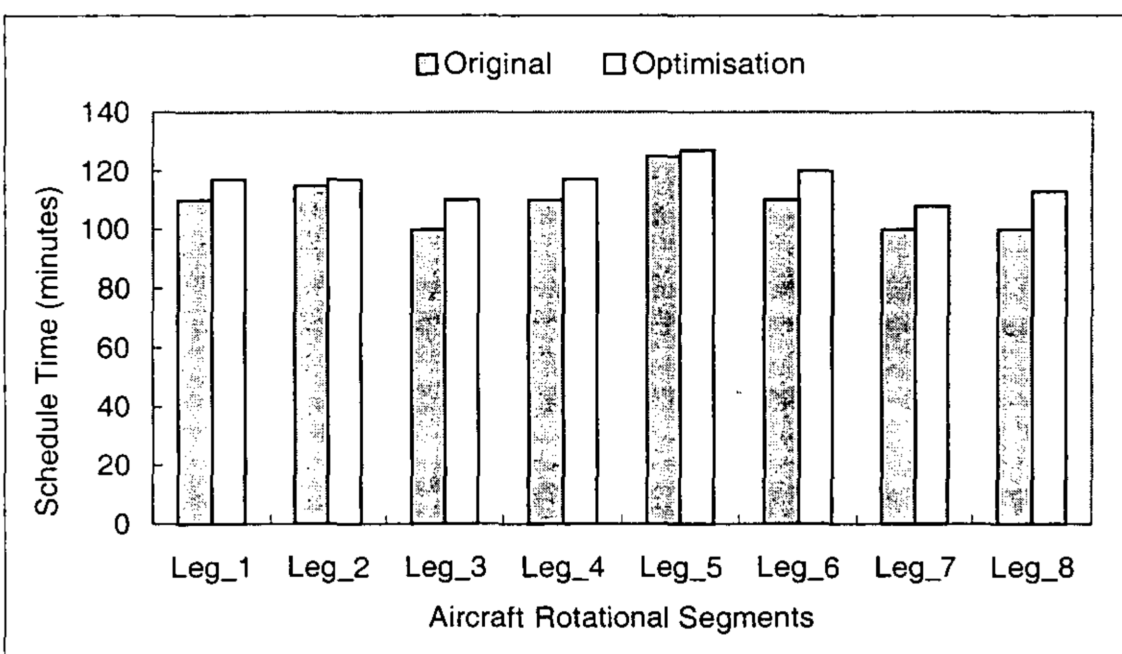

FIGURE 5.31 Comparison of scheduled leg-time in aircraft rotations between the optimisation and the original schedule

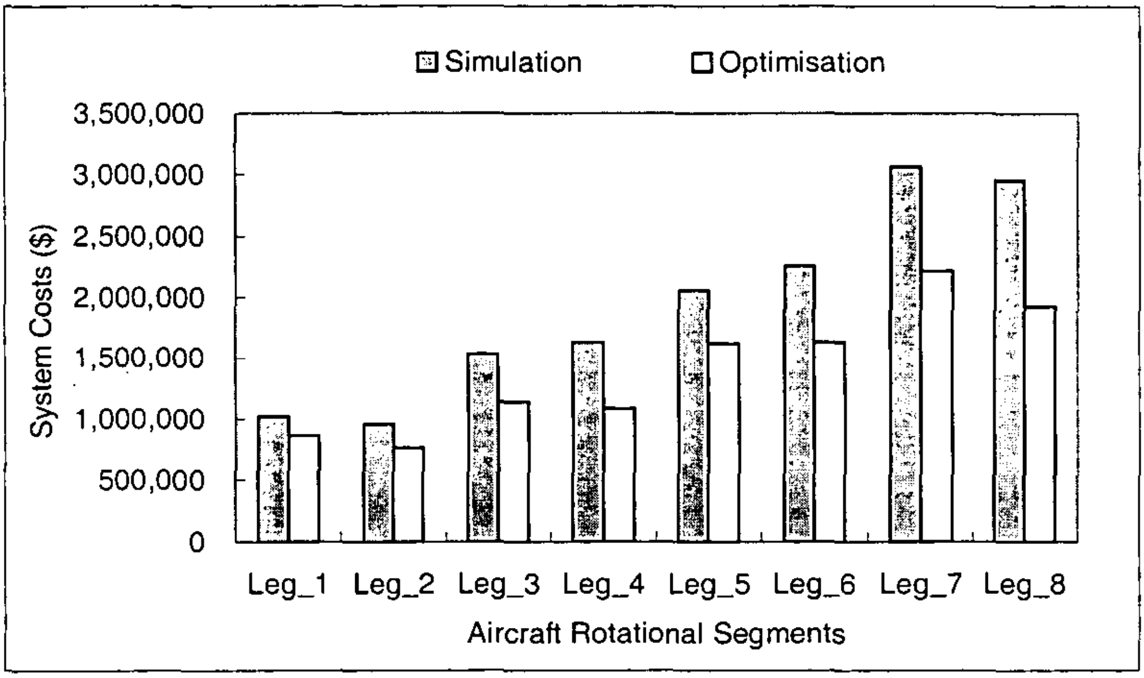

FIGURE 5.32 Comparison of system costs between optimisation and simulation results

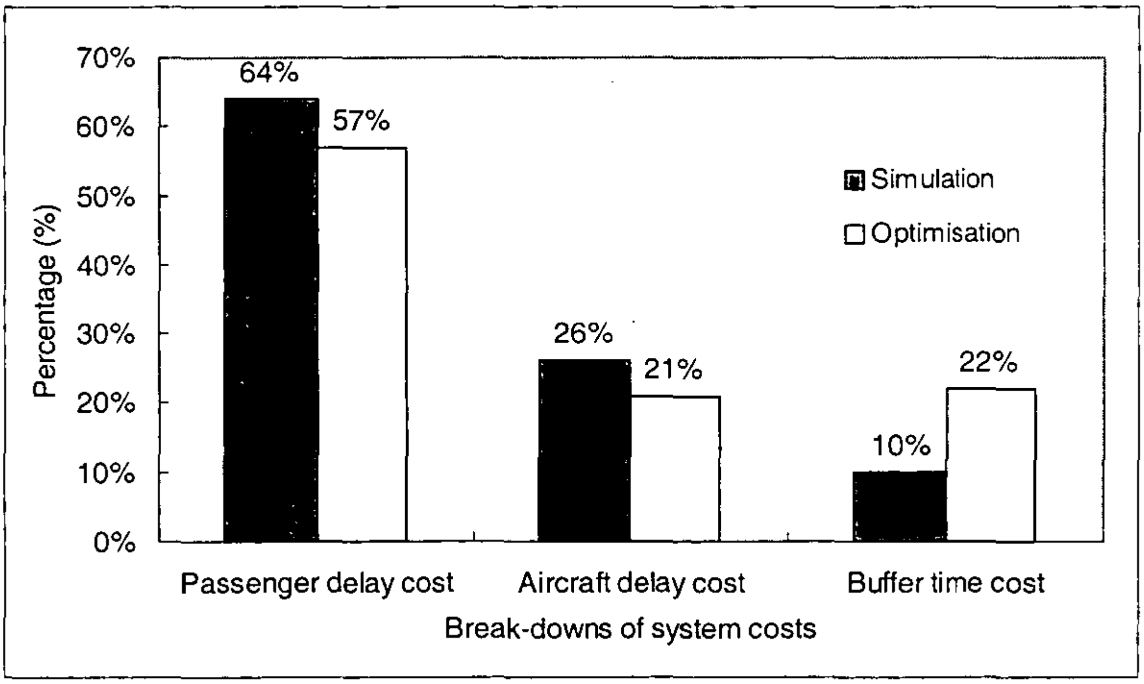

FIGURE 5.33 Comparison of break-downs of system costs between optimisation and simulation results

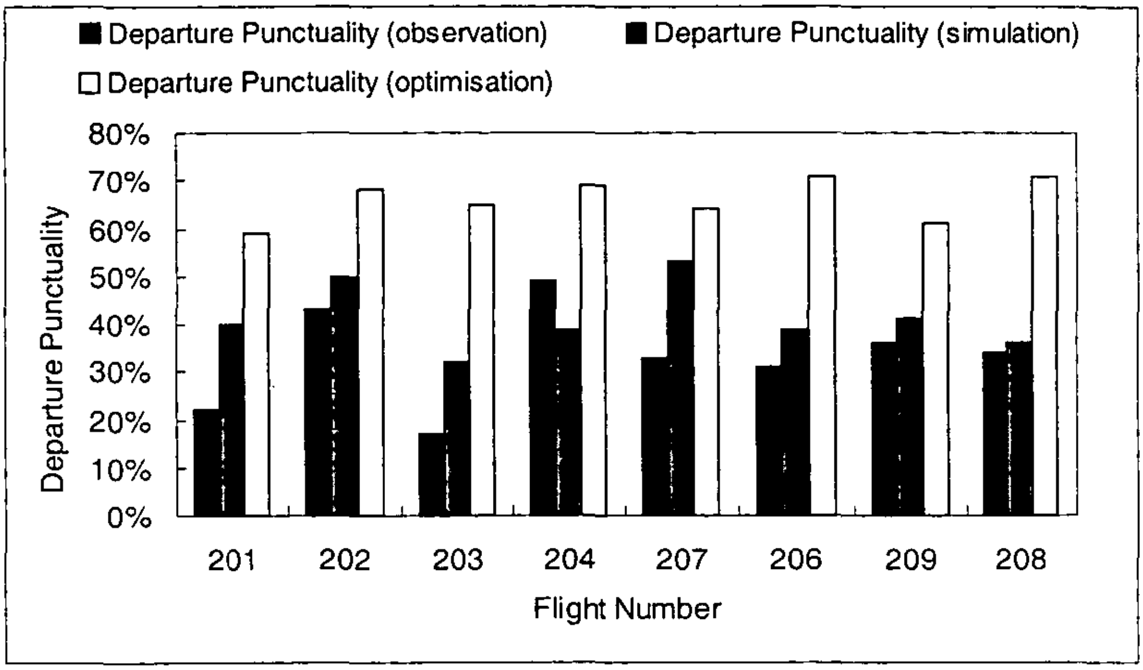

FIGURE 5.34 Comparison of departure punctuality between optimisation, simulation and observation

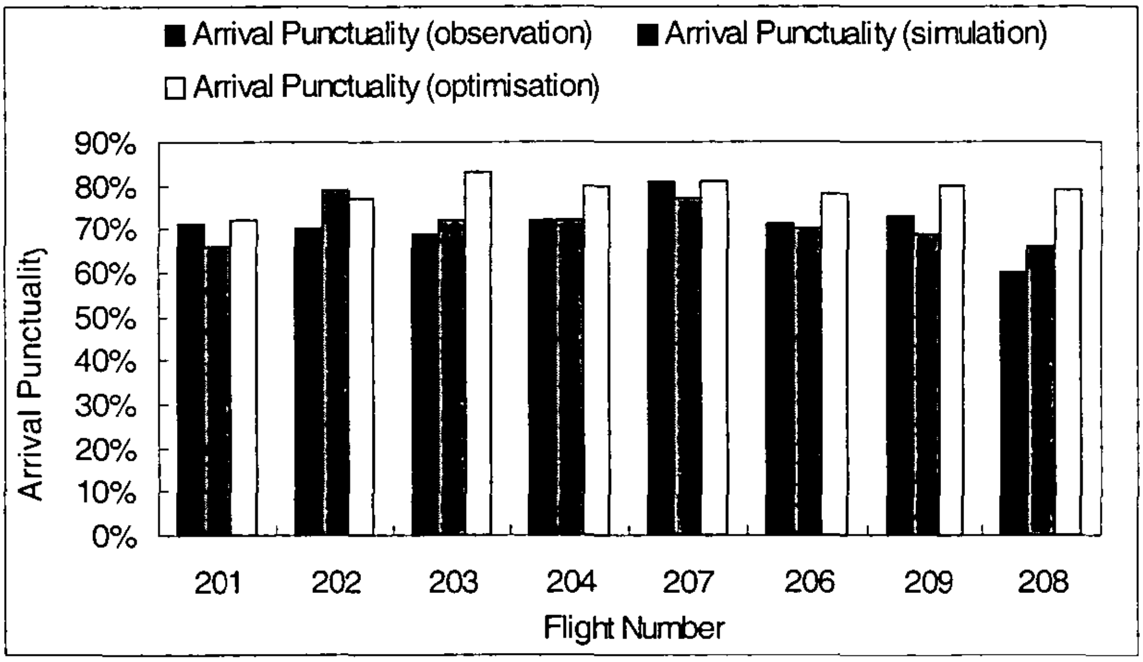

FIGURE 5.35 Comparison of arrival punctuality between optimisation, simulation and observation

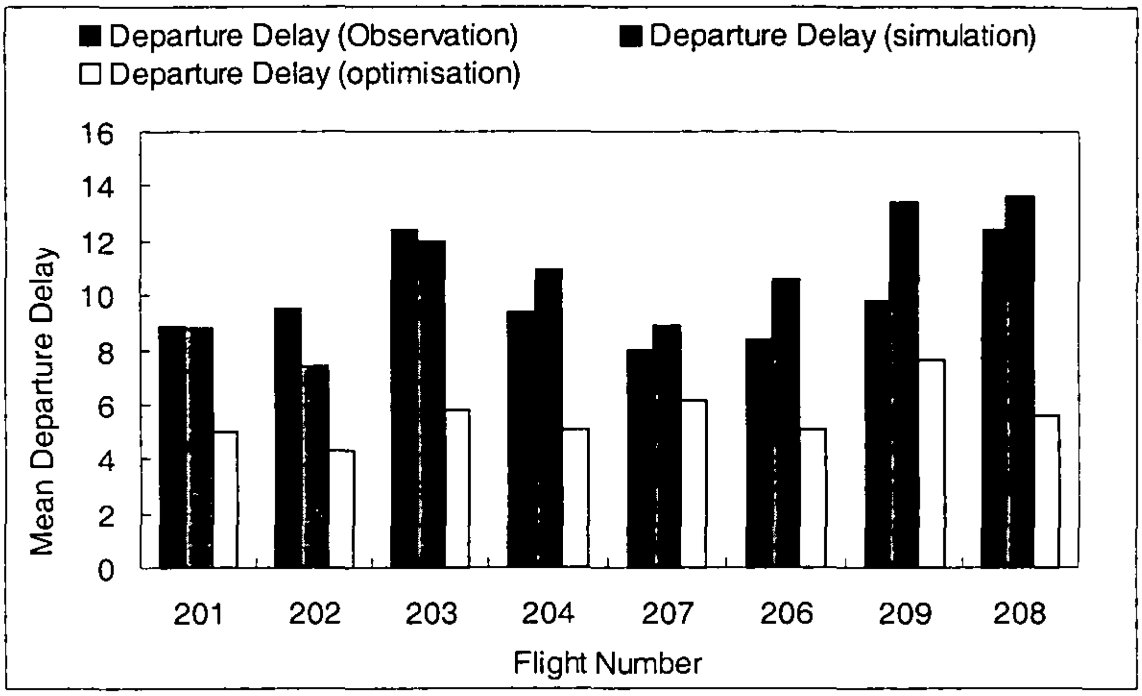

FIGURE 5.36 Comparison of mean departure delay between optimisation, simulation and observation

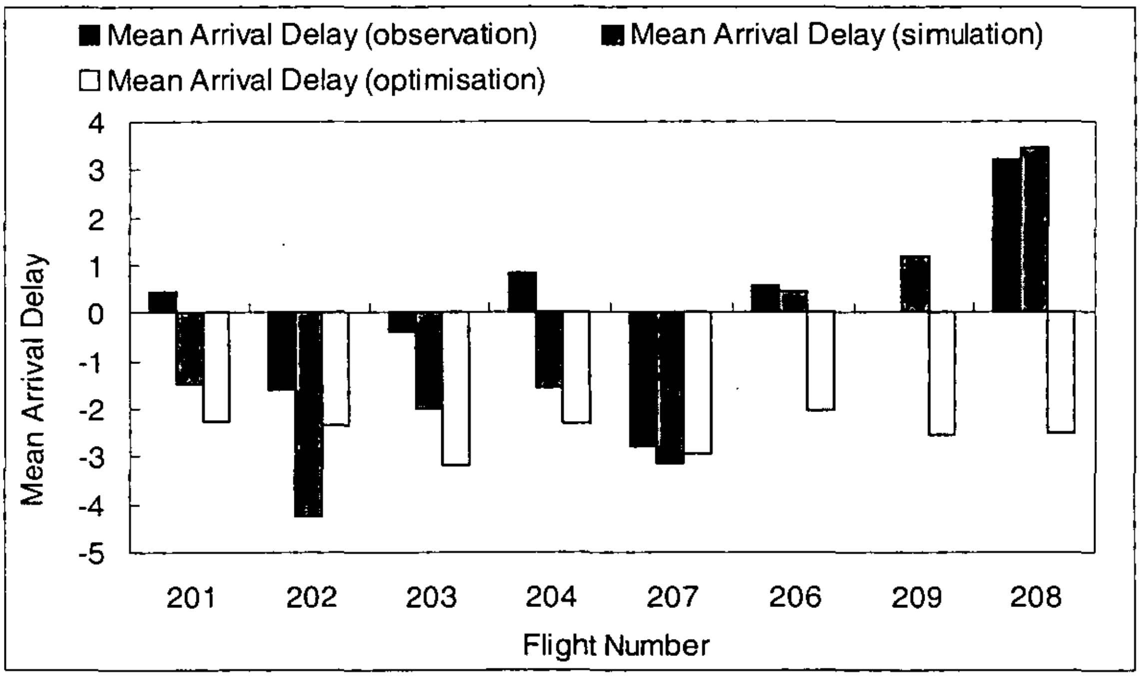

FIGURE 5.37 Comparison of mean arrival delay between optimisation, simulation and observation

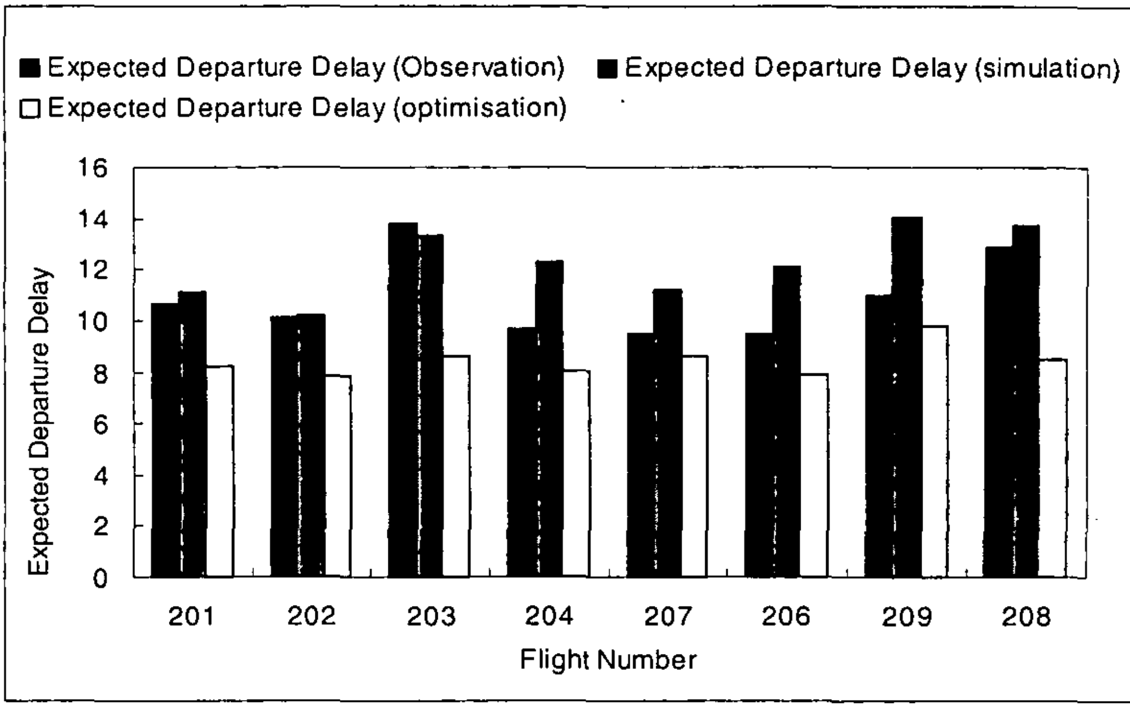

FIGURE 5.38 Comparison of expected departure delay between optimisation, simulation and observation

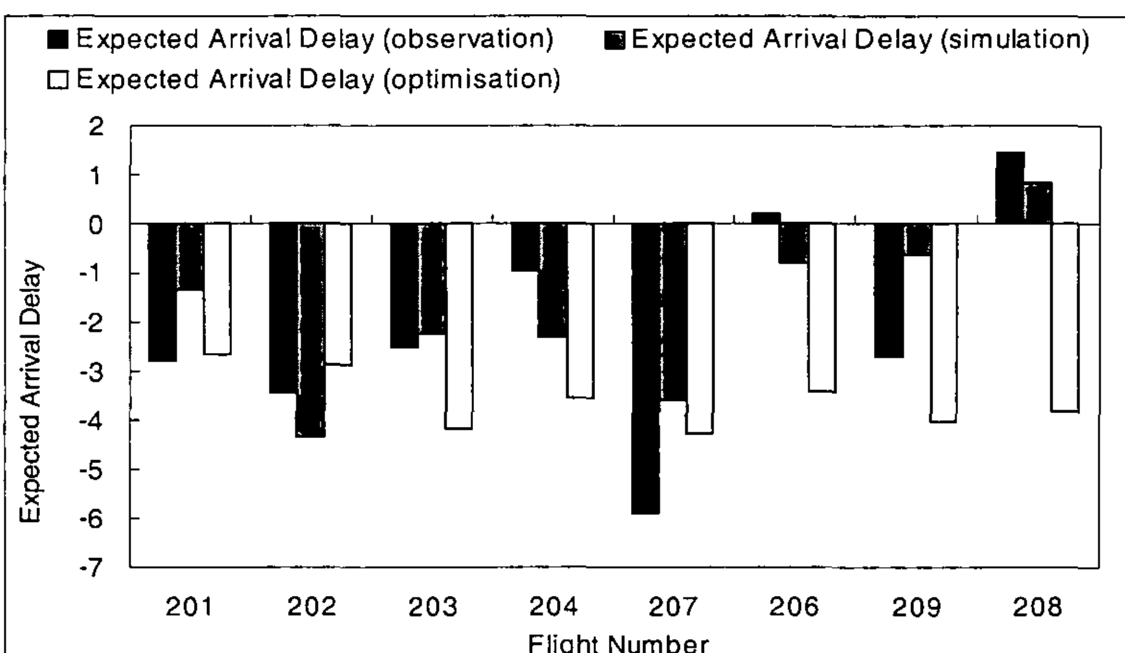

FIGURE 5.39 Comparison of expected arrival delay between optimisation, simulation and observation

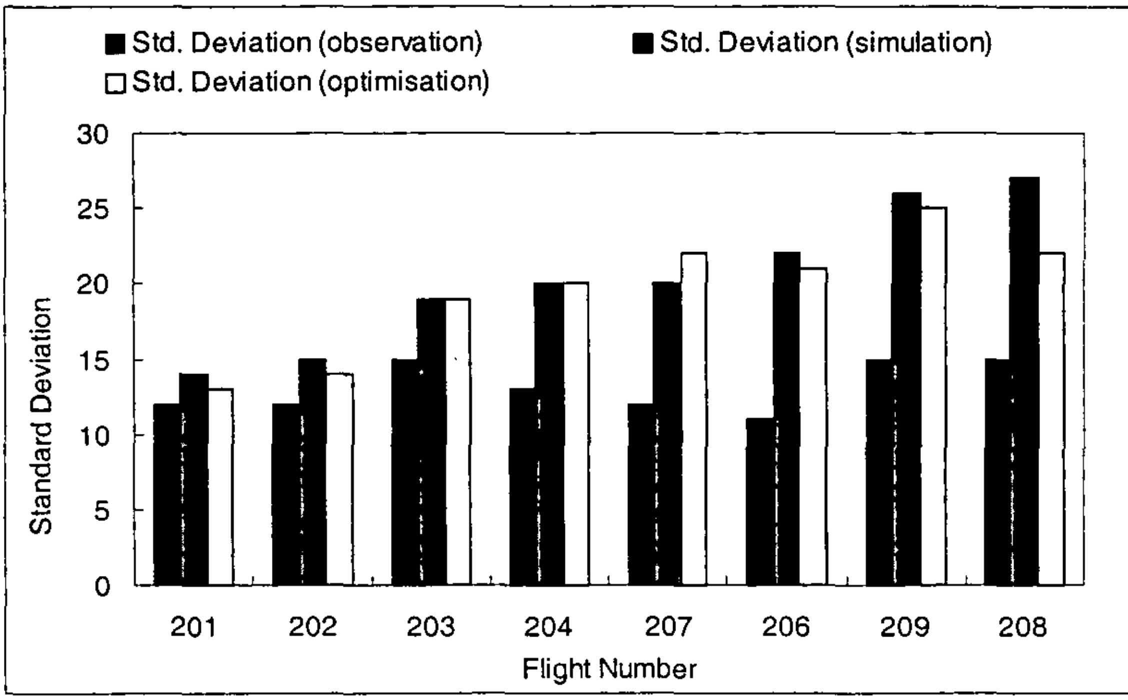

FIGURE 5.40 Comparison of standard deviation of departure delay between optimisation, simulation and observation

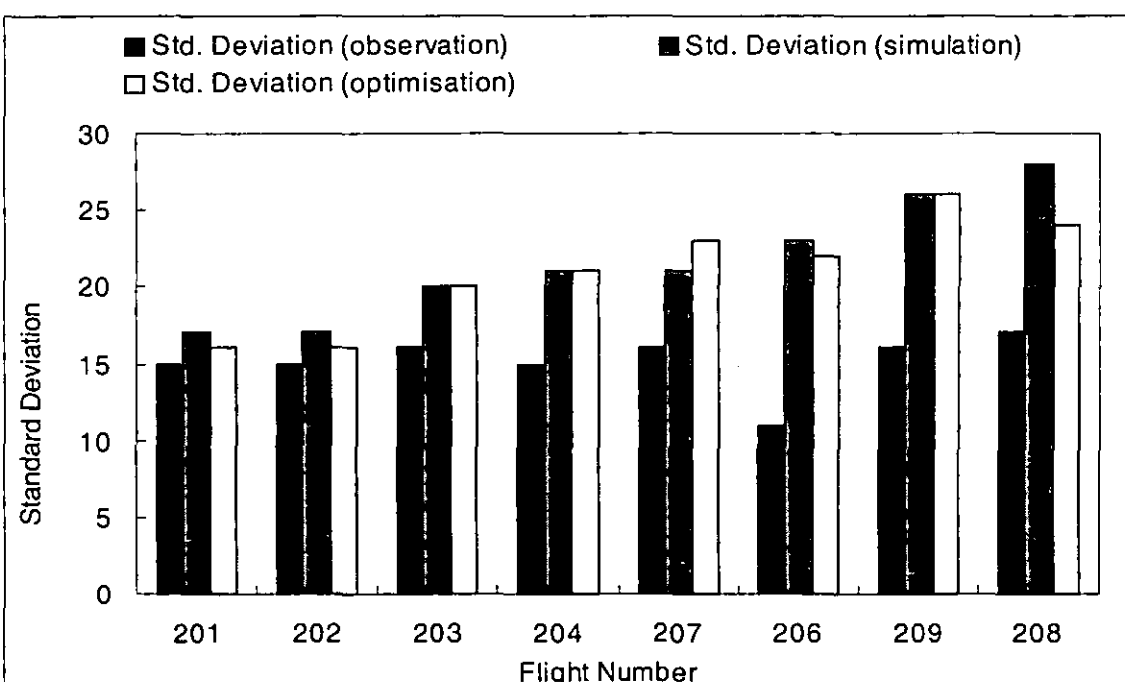

FIGURE 5.41 Comparison of standard deviation of arrival delay between optimisation, simulation and observation

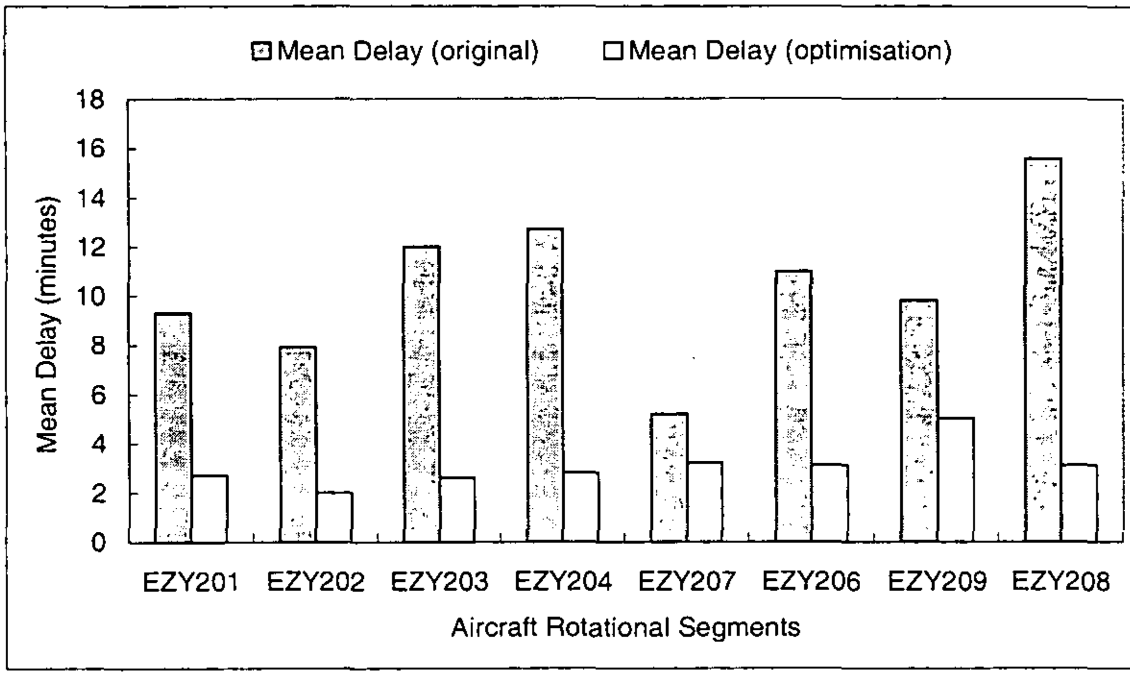

FIGURE 5.42 Mean delay of segments in aircraft rotation (schedule reliability analysis)

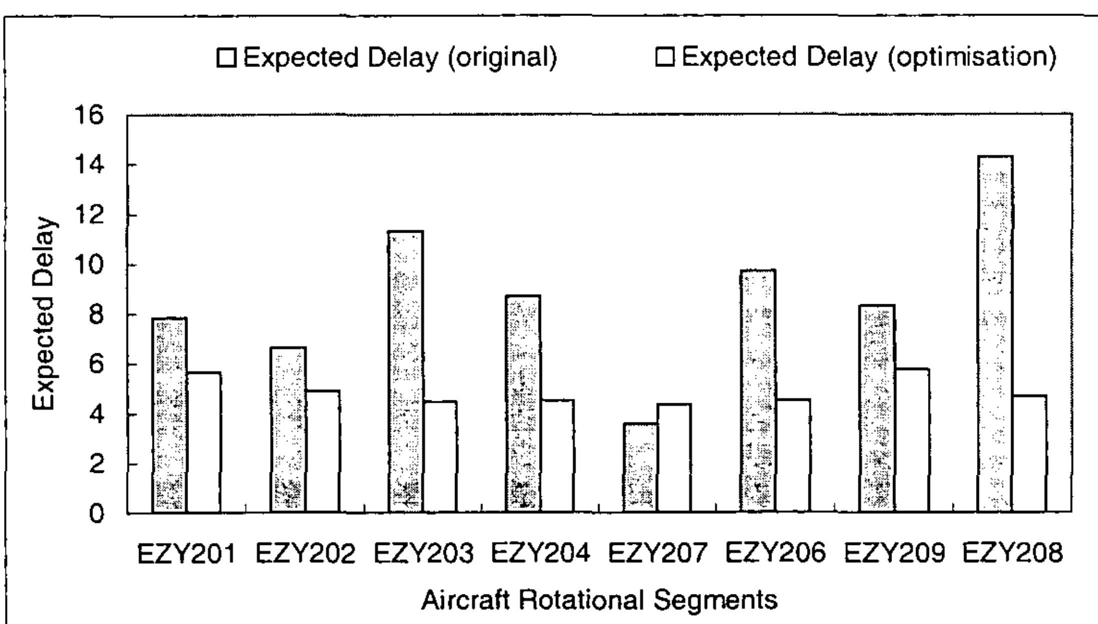

FIGURE 5.43 Expected delay of segments in aircraft rotation (schedule reliability analysis)

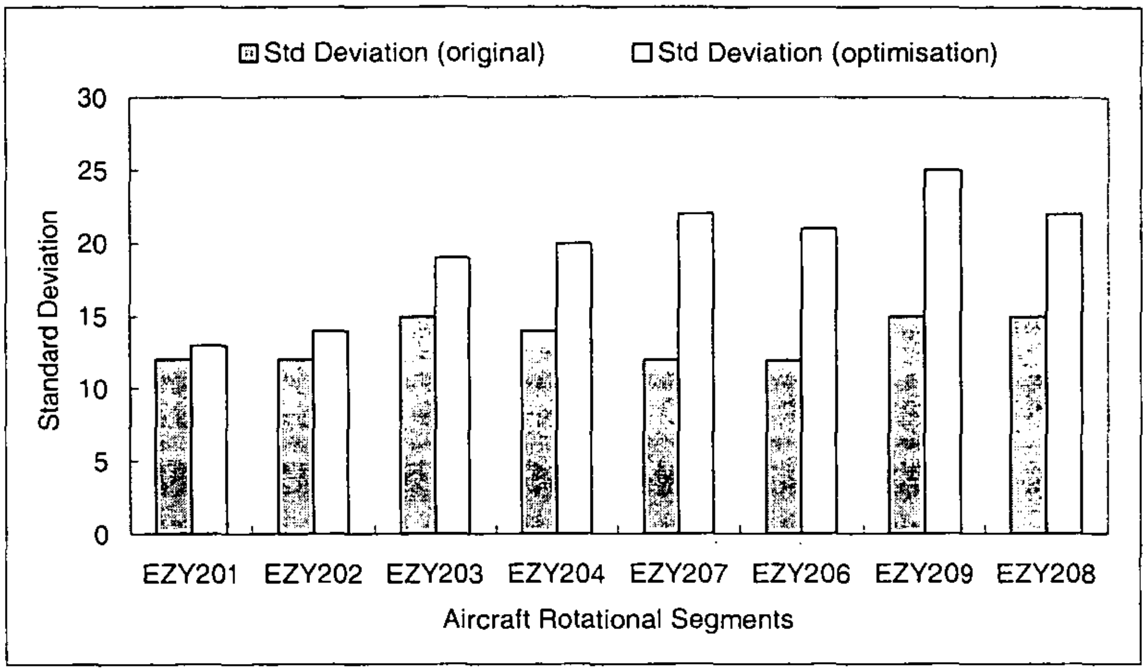

FIGURE 5.44 Standard deviation of departure delay in aircraft rotation (schedule reliability analysis)

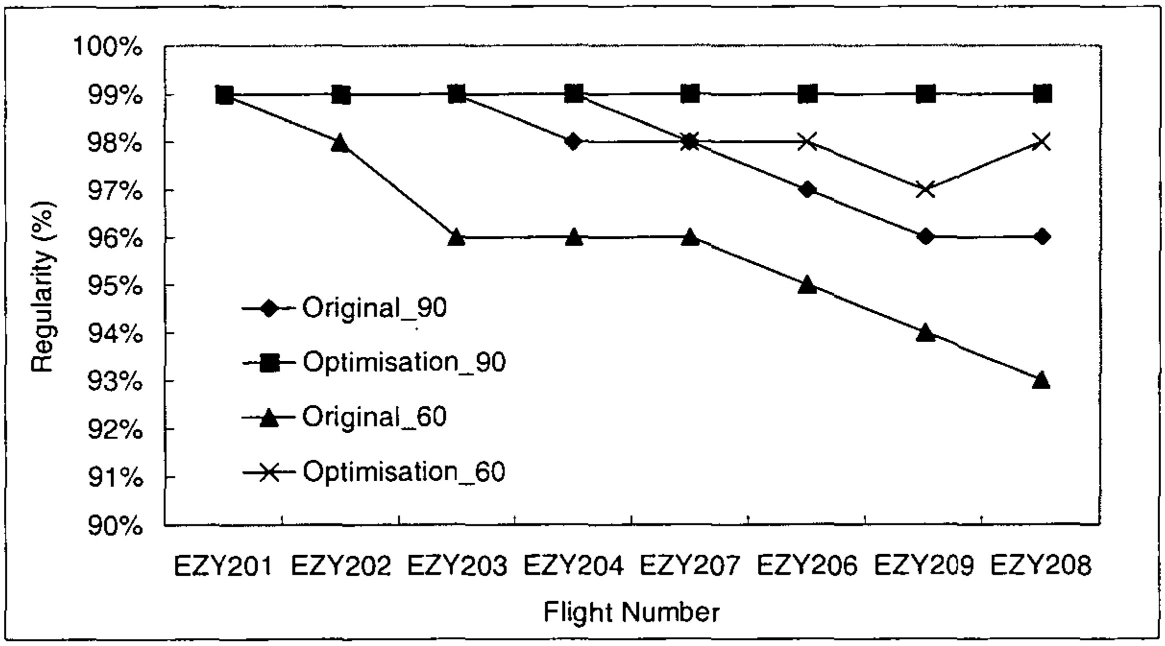

FIGURE 5.45 Schedule regularity R_{REG_90} and R_{REG_60} in aircraft rotation (schedule reliability analysis)

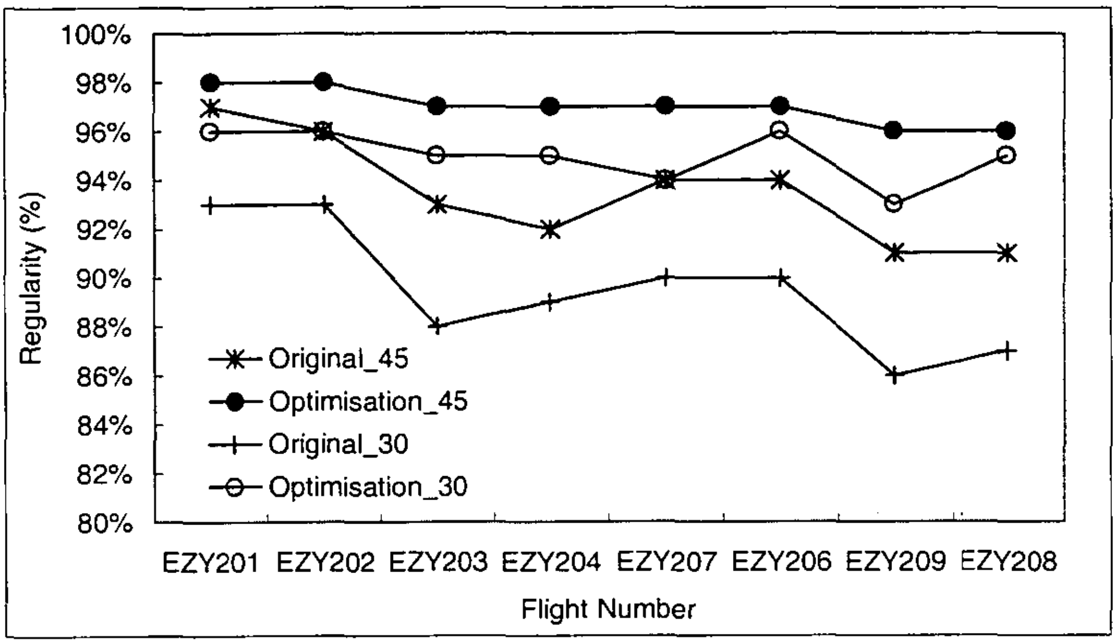

FIGURE 5.46 Schedule regularity R_{REG_45} and R_{REG_30} in aircraft rotation (schedule reliability analysis)

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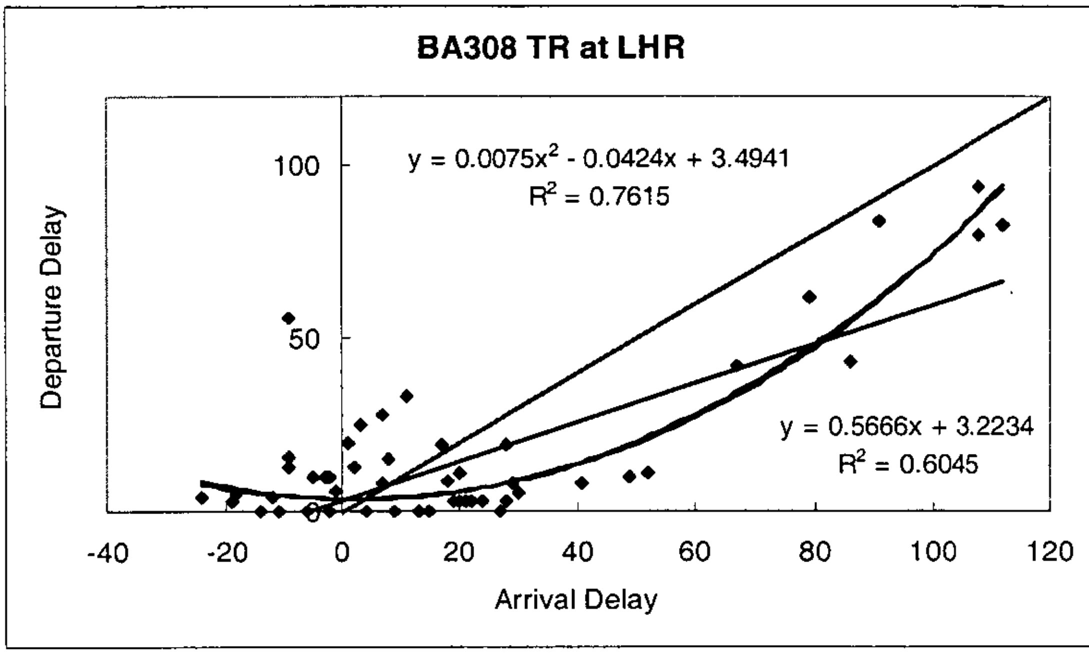

FIGURE 6.1 Turnaround efficiency of BA308 at LHR

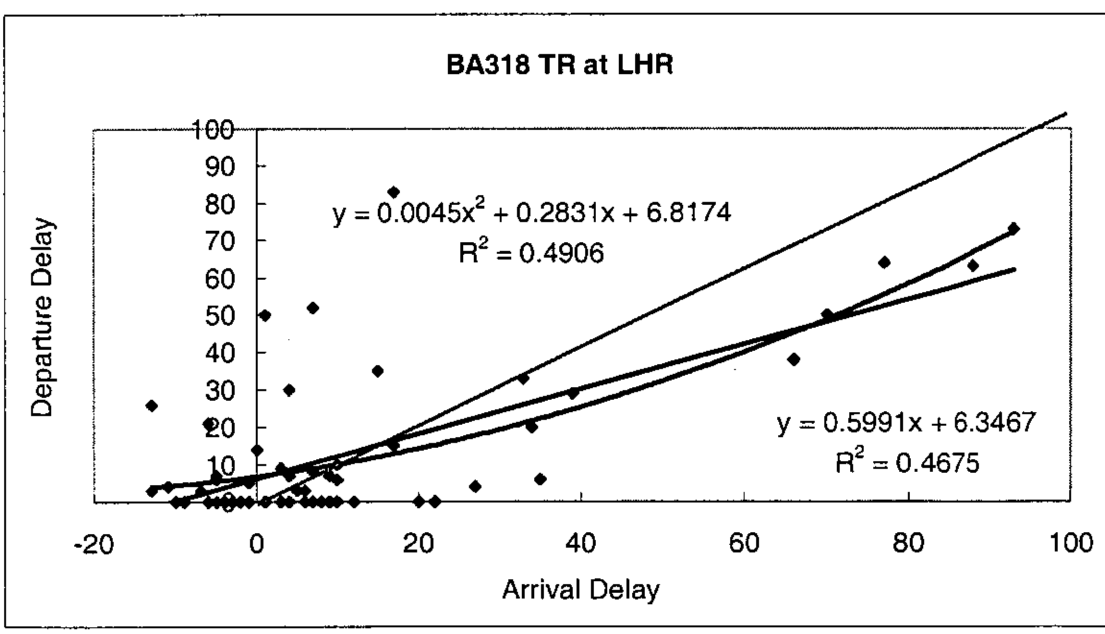

FIGURE 6.2 Turnaround efficiency of BA318 at LHR

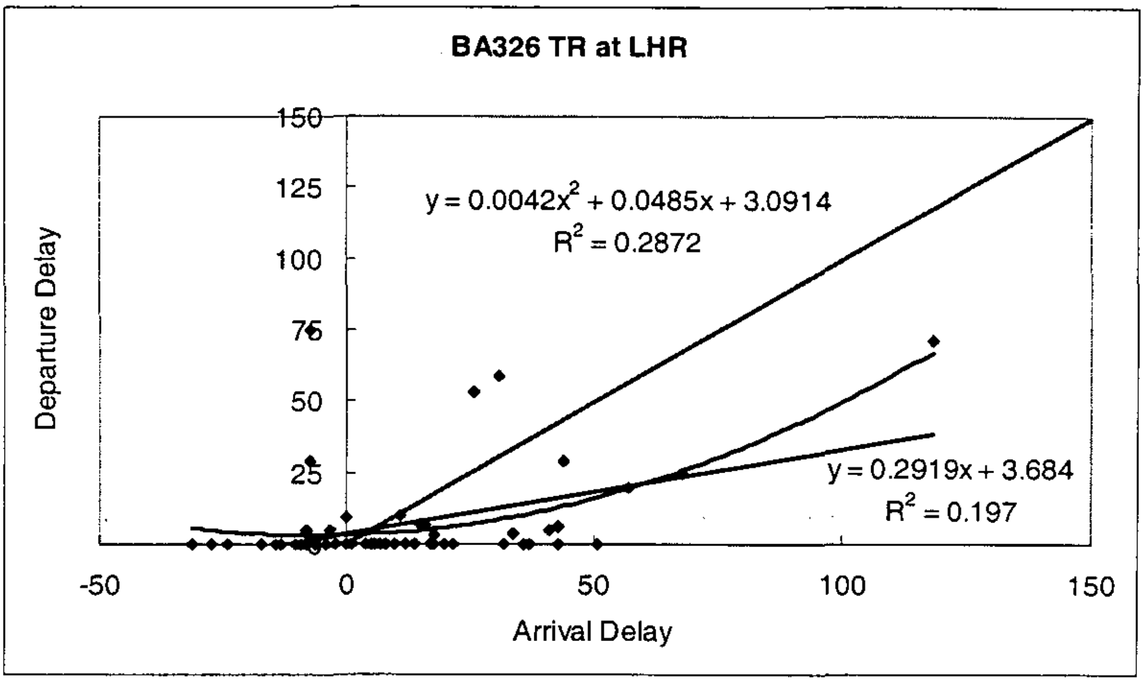

FIGURE 6.3 Turnaround efficiency of BA326 at LHR

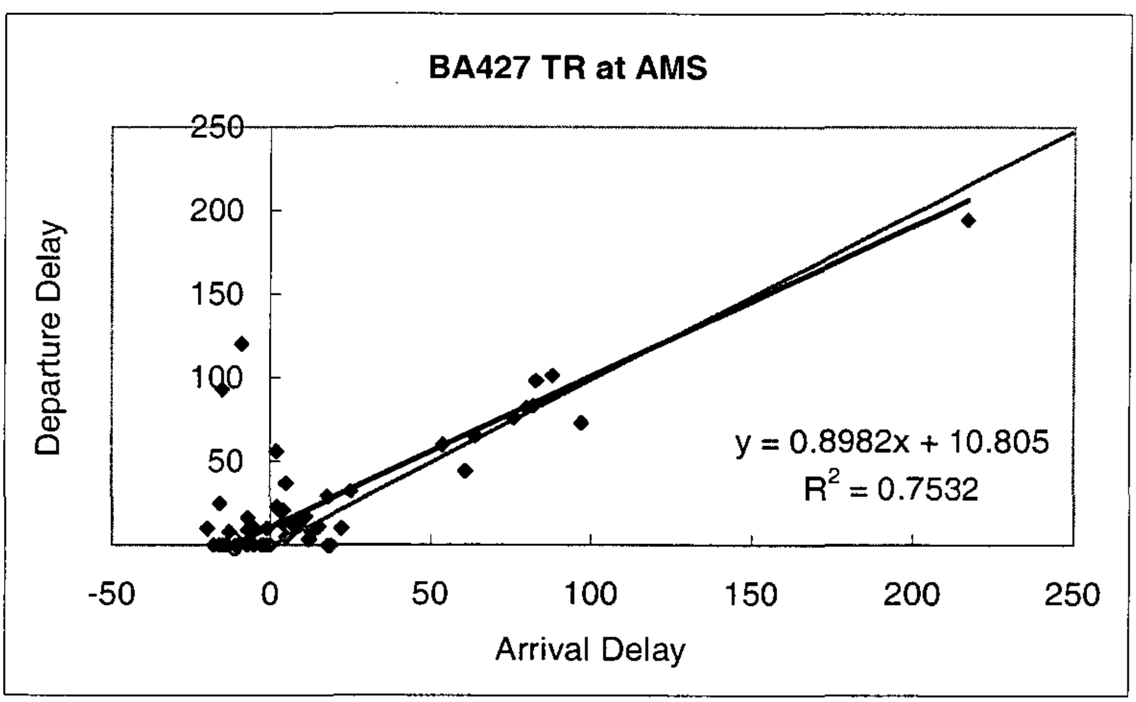

FIGURE 6.4 Turnaround efficiency of BA427 at AMS

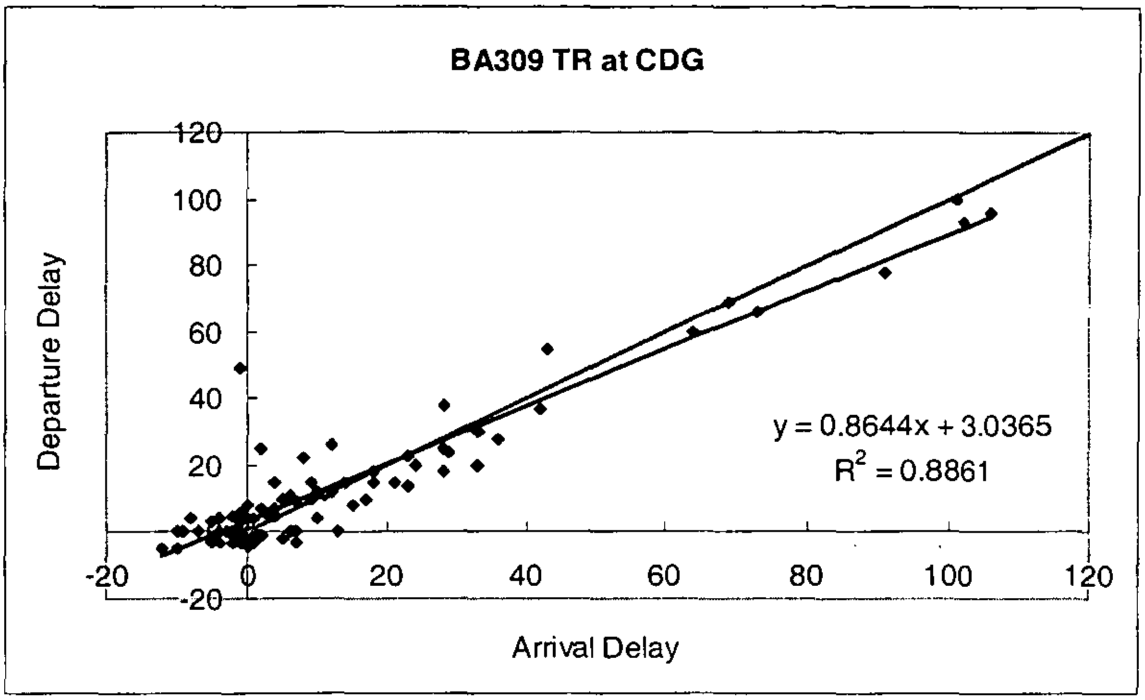

FIGURE 6.5 Turnaround efficiency of BA309 at CDG

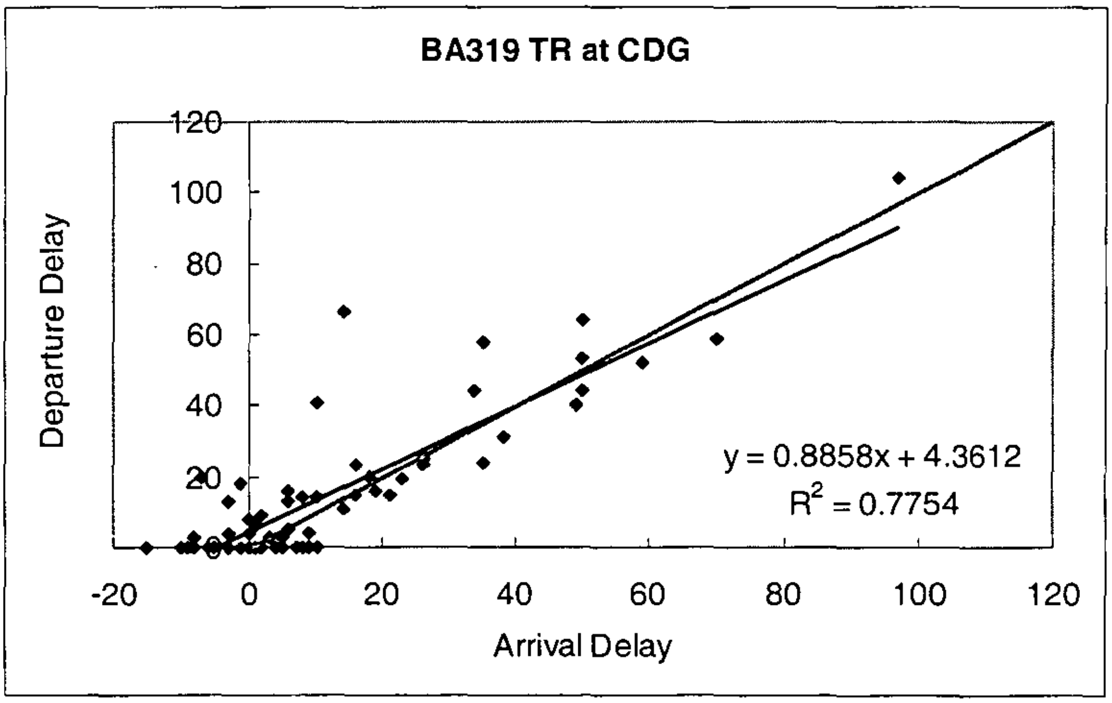

FIGURE 6.6 Turnaround efficiency of BA319 at CDG

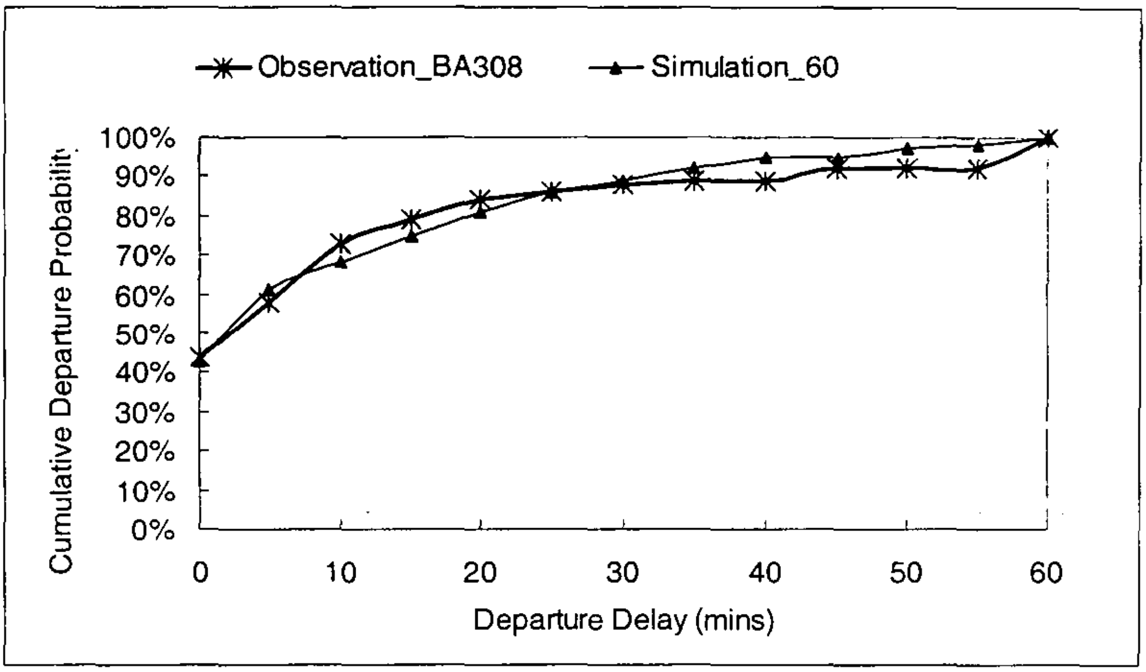

FIGURE 6.7 MAT model application to BA308 at LHR

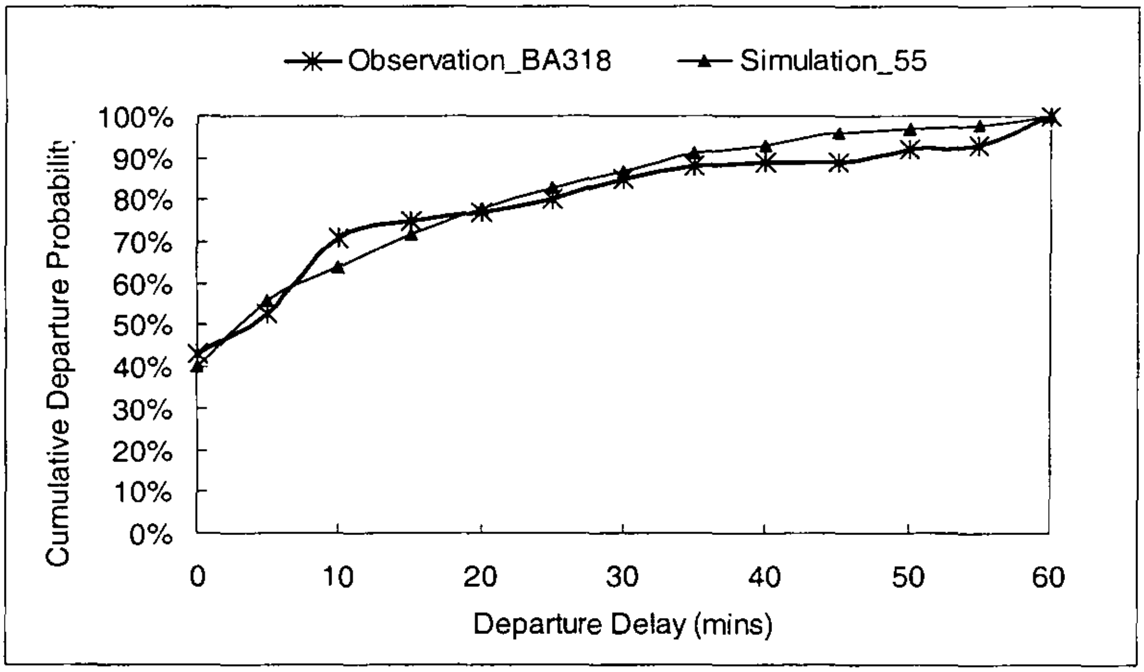

FIGURE 6.8 MAT model application to BA318 at LHR

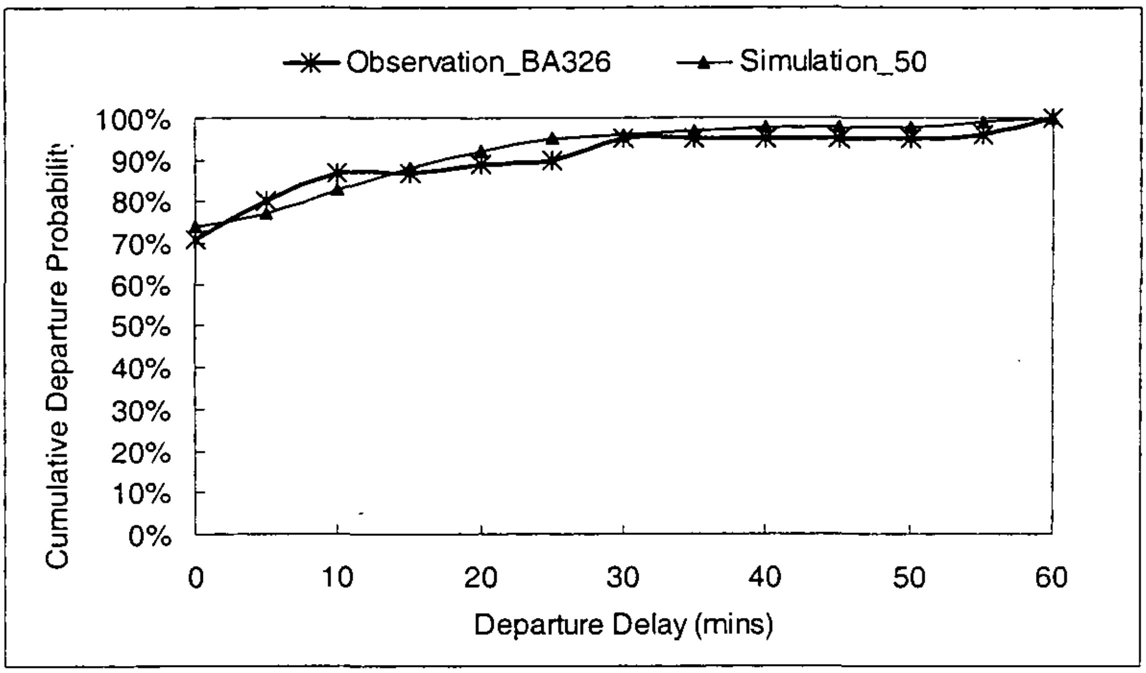

FIGURE 6.9 MAT model application to BA326 at LHR

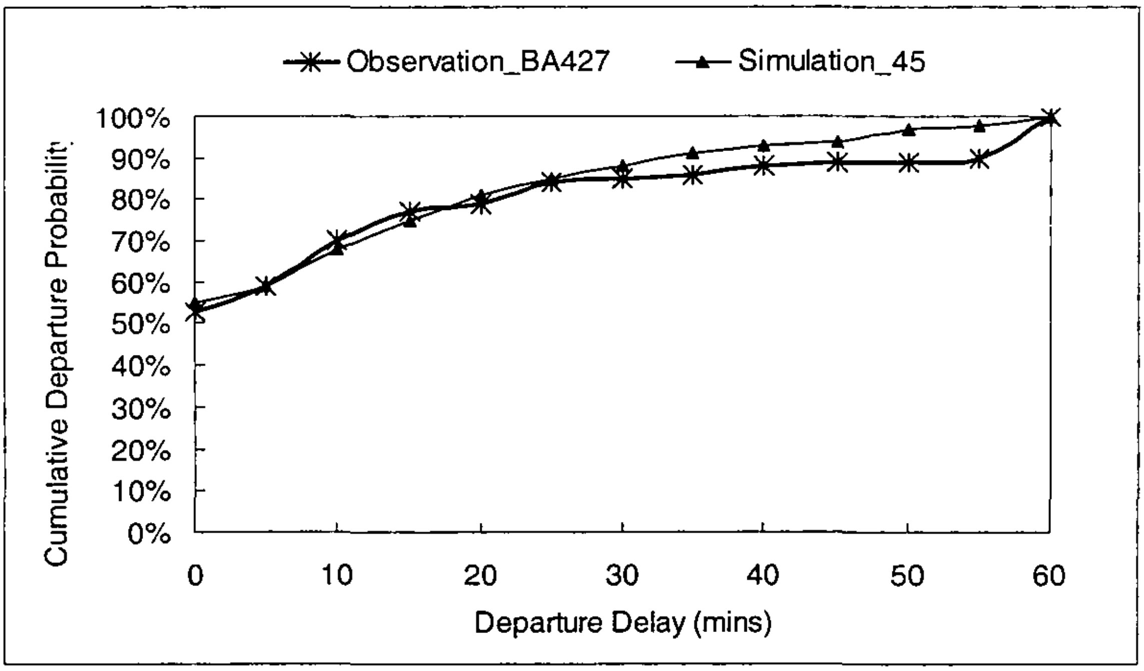

FIGURE 6.10 MAT model application to BA427 at AMS

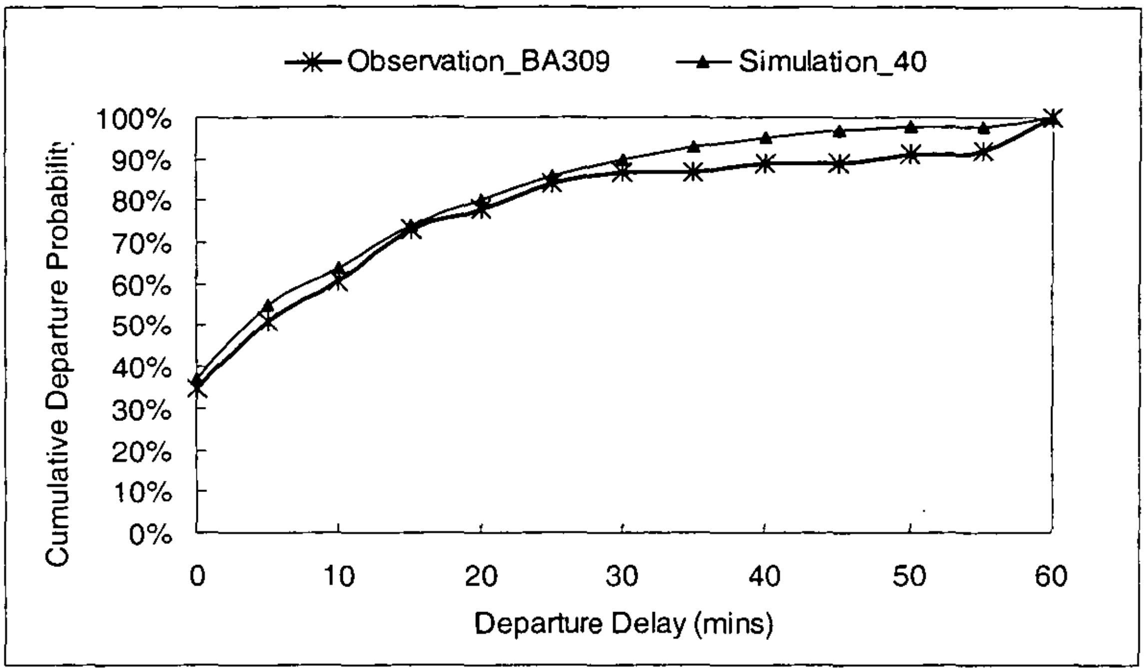

FIGURE 6.11 MAT model application to BA309 at CDG

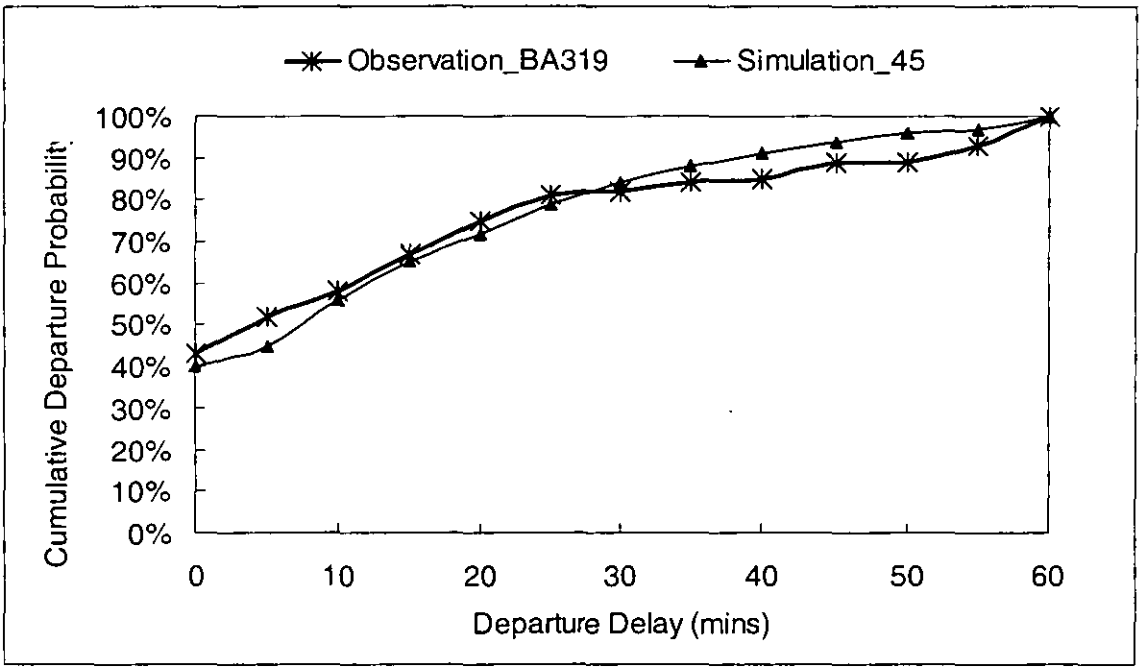

FIGURE 6.12 MAT model application to BA319 at CDG

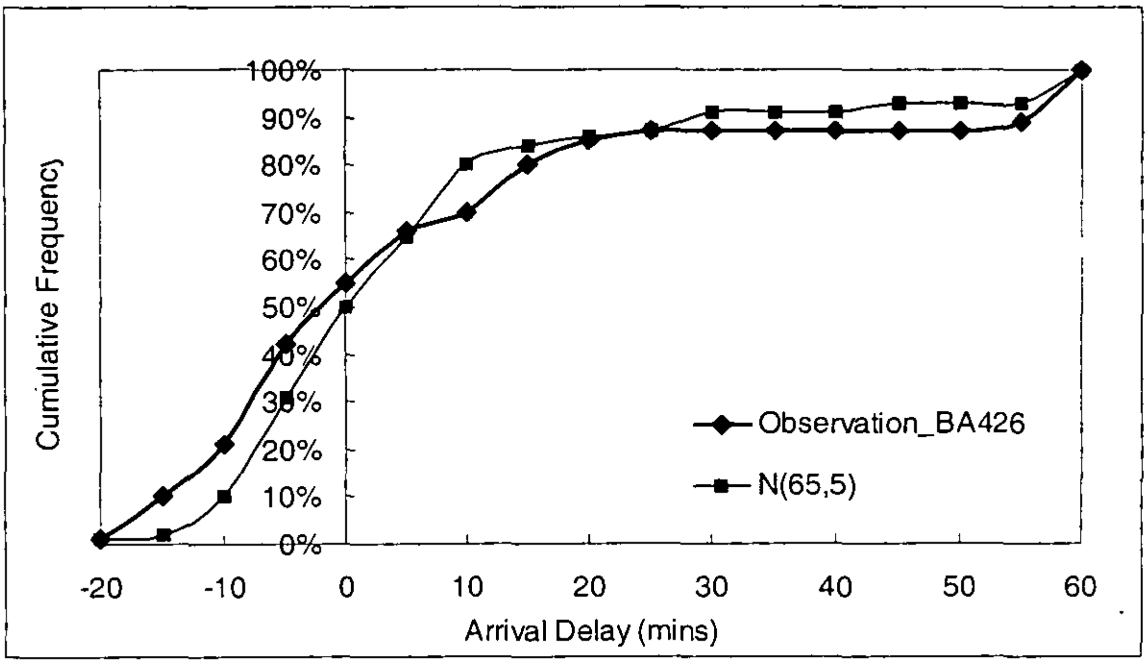

FIGURE 6.13 Enroute model application to BA426 from LHR to AMS

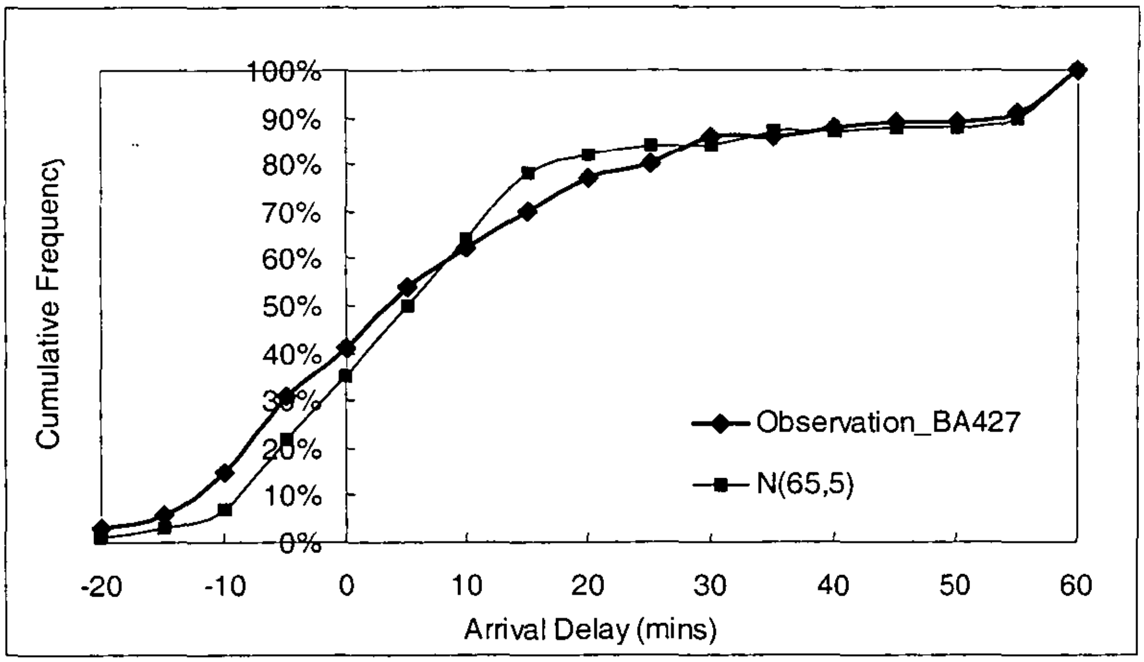

FIGURE 6.14 Enroute model application to BA427 from AMS to LHR

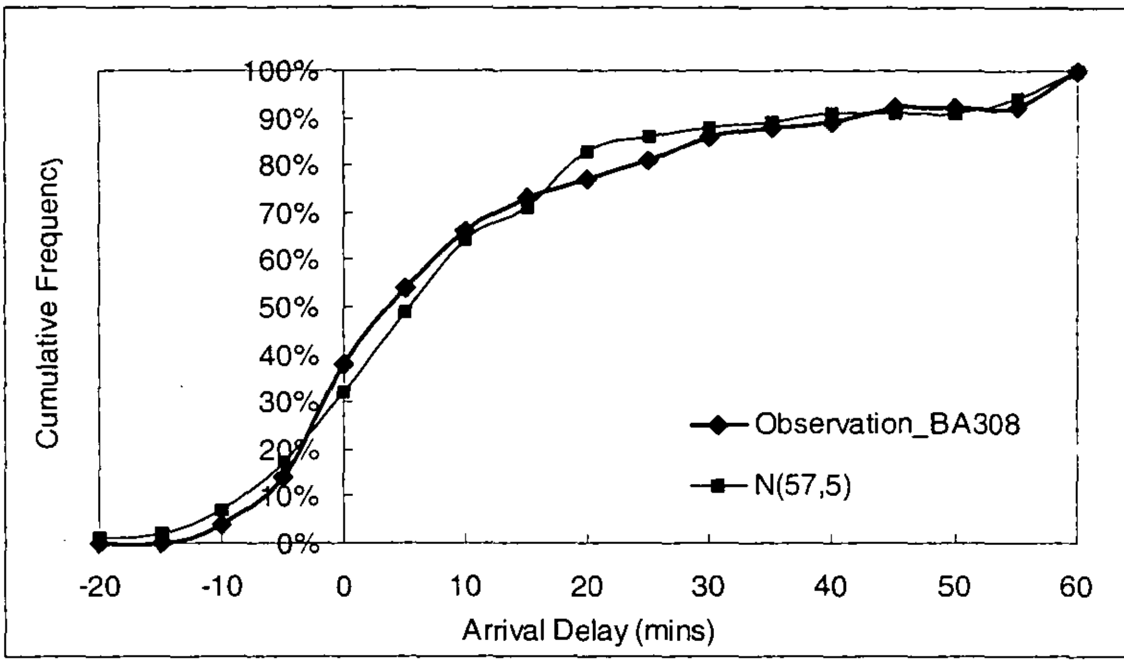

FIGURE 6.15 Enroute model application to BA308 from LHR to CDG

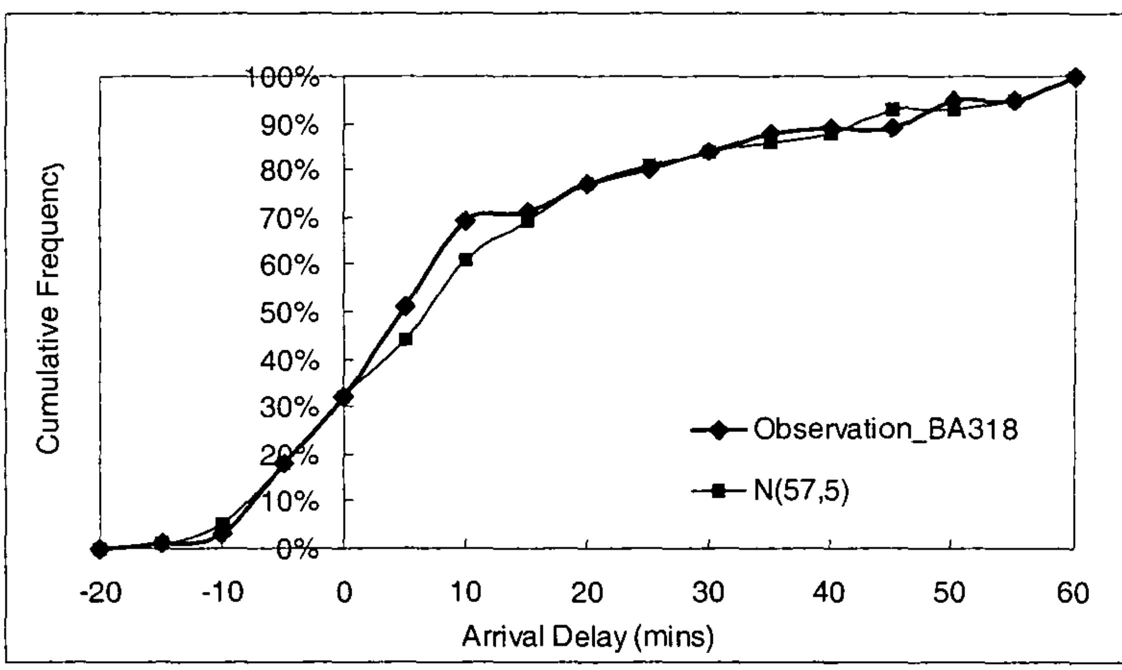

FIGURE 6.16 Enroute model application to BA318 from LHR to CDG

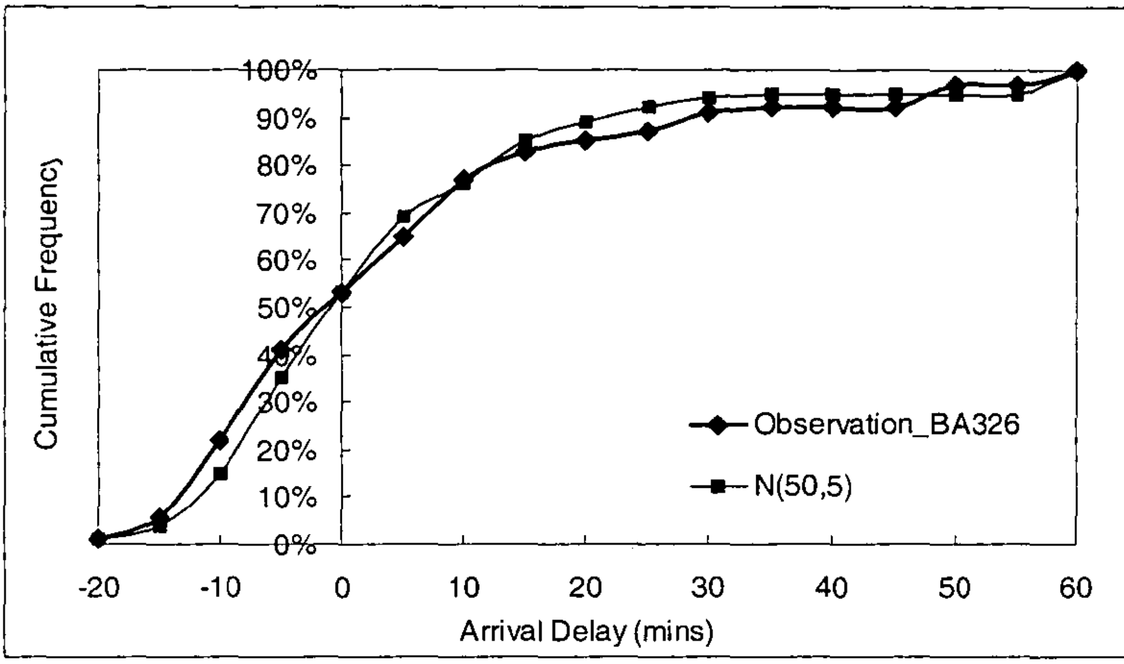

FIGURE 6.17 Enroute model application to BA326 from LHR to CDG

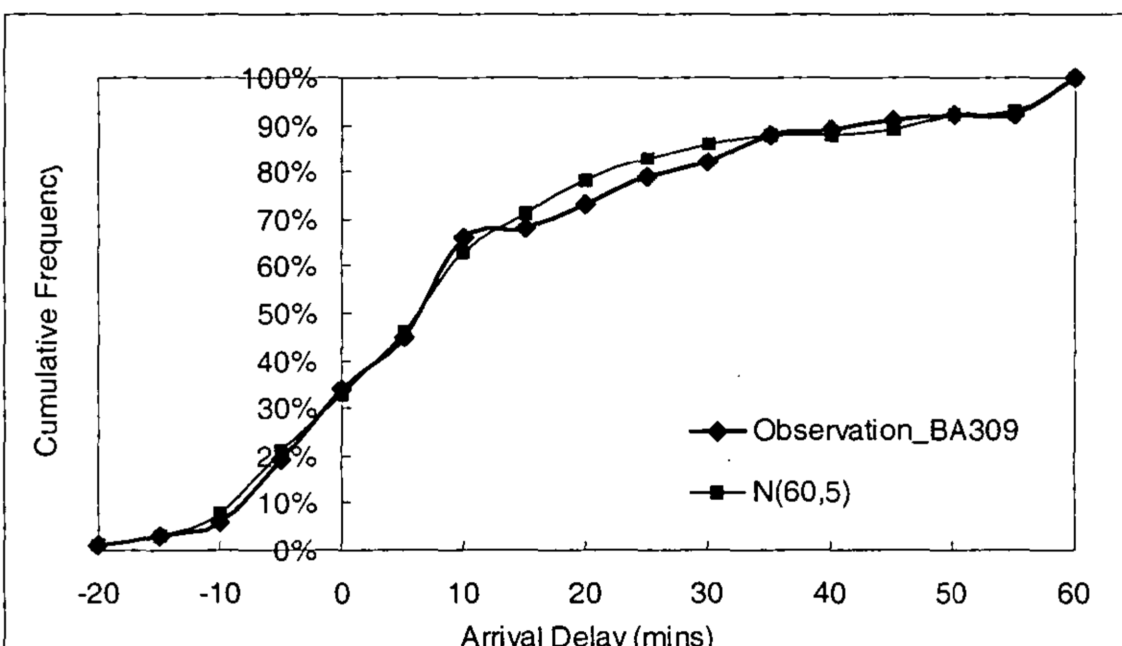

FIGURE 6.18 Enroute model application to BA309 from CDG to LHR

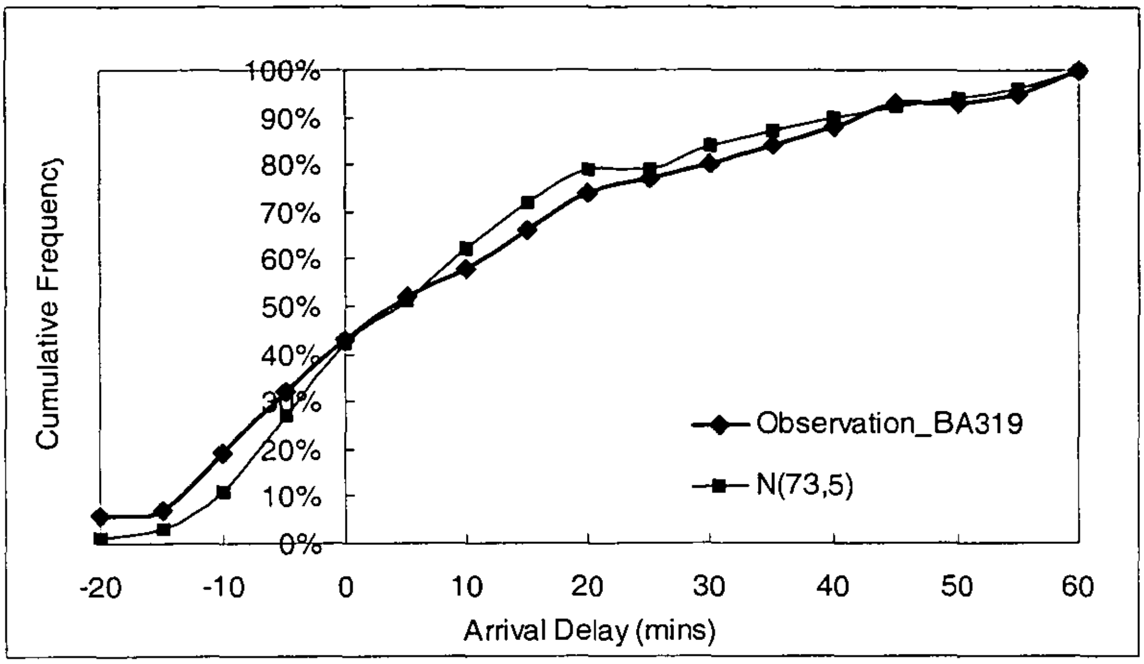

FIGURE 6.19 Enroute model application to BA319 from CDG to LHR

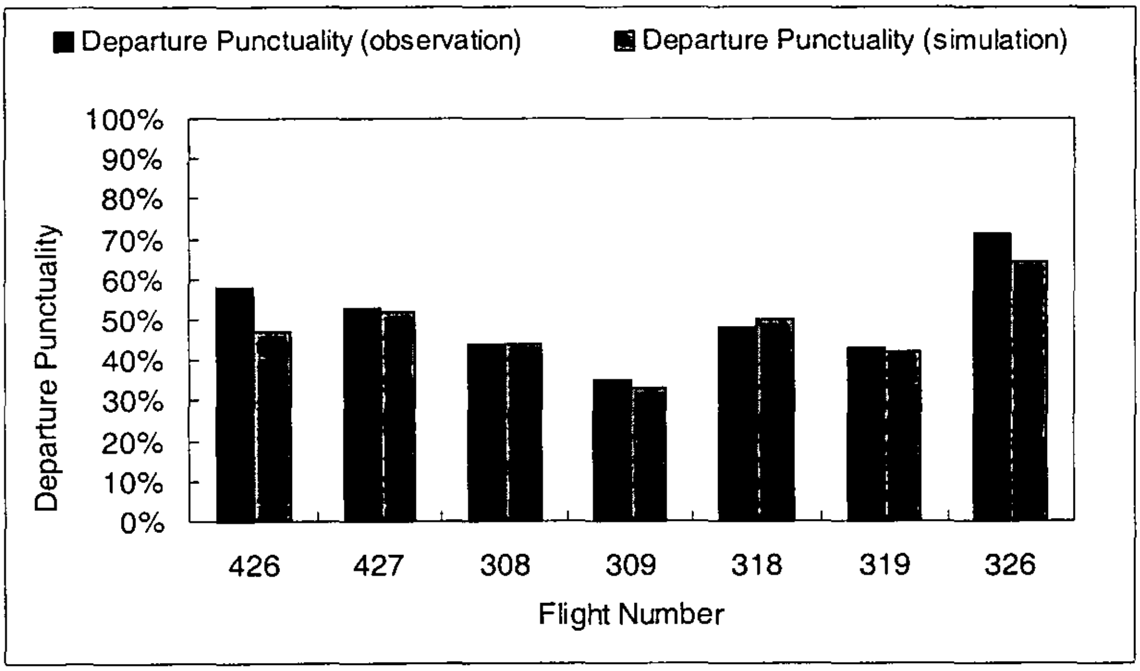

FIGURE 6.20 Comparison of departure punctuality between observation and simulation data

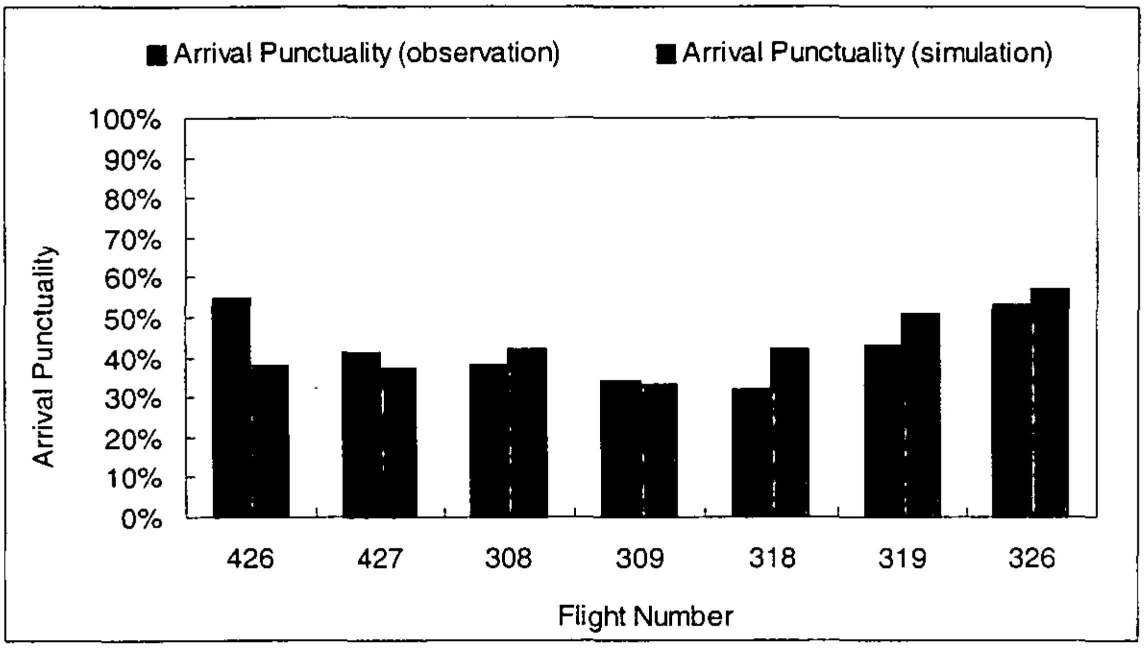

FIGURE 6.21 Comparison of arrival punctuality between observation and simulation data

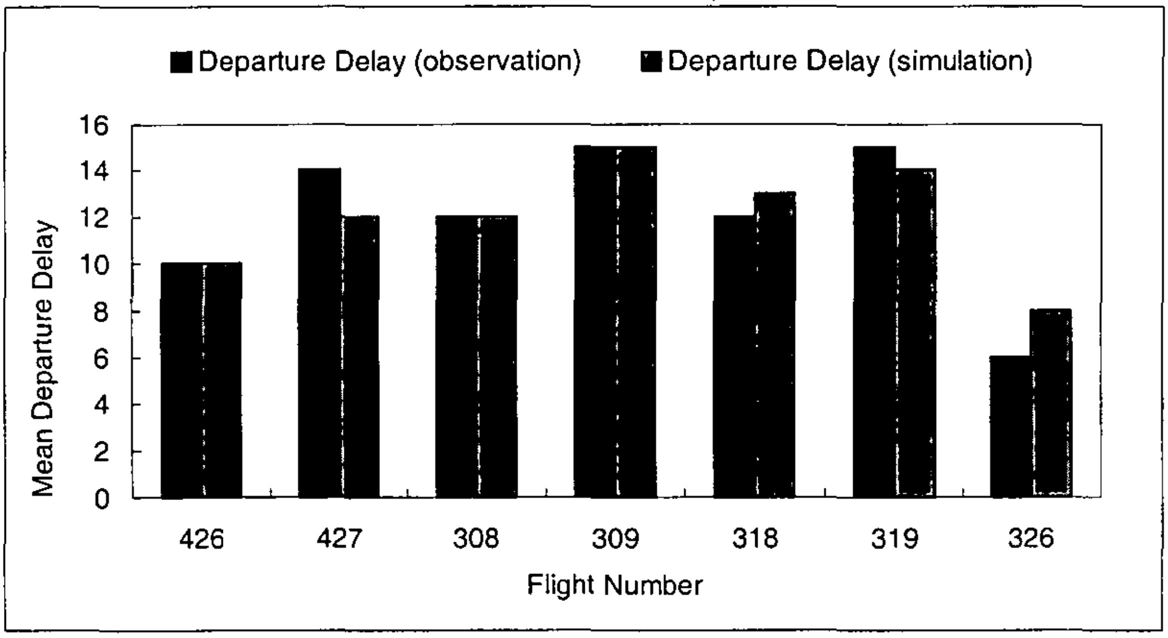

FIGURE 6.22 Comparison of mean departure delay between observation and simulation results

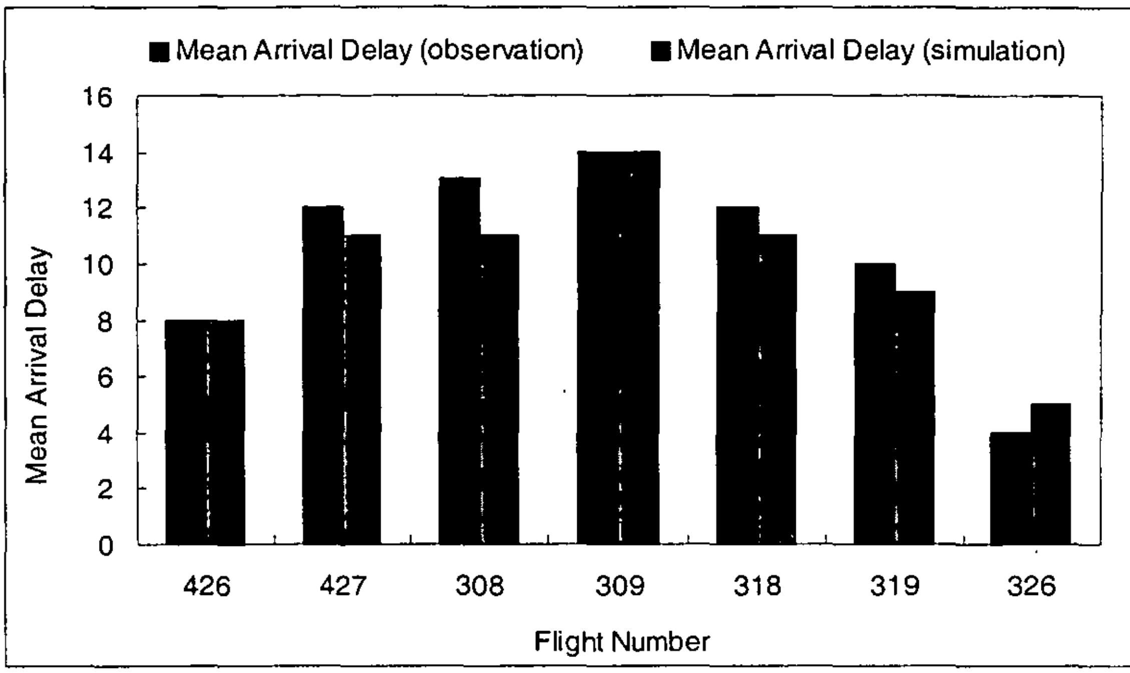

FIGURE 6.23 Comparison of mean arrival delay between observation and simulation results

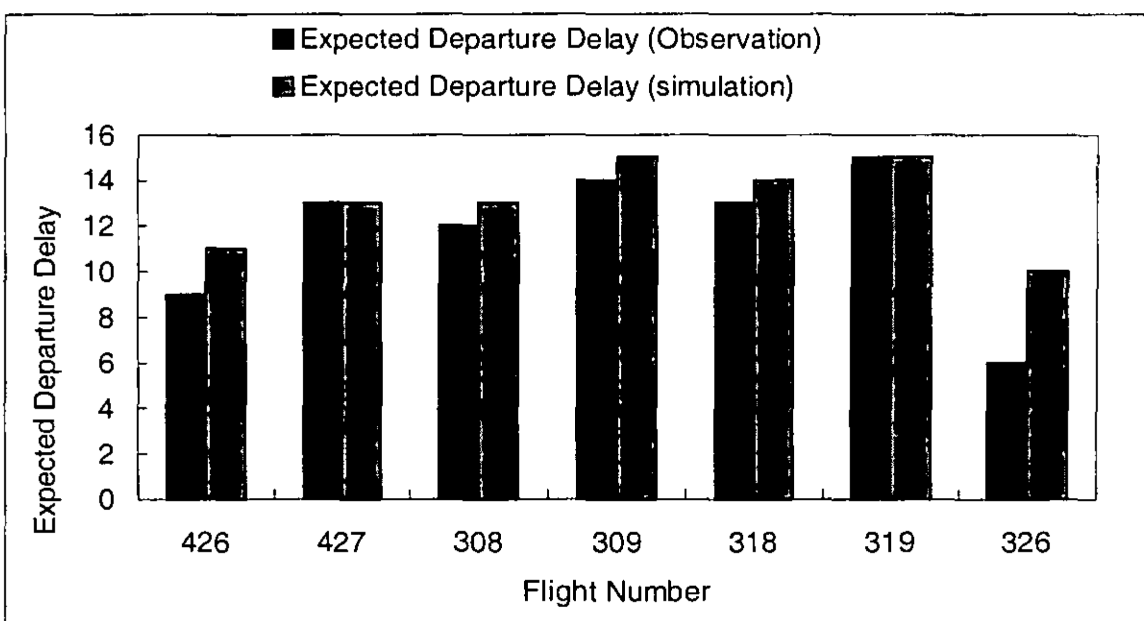

FIGURE 6.24 Comparison of expected departure delay between observation and simulation results

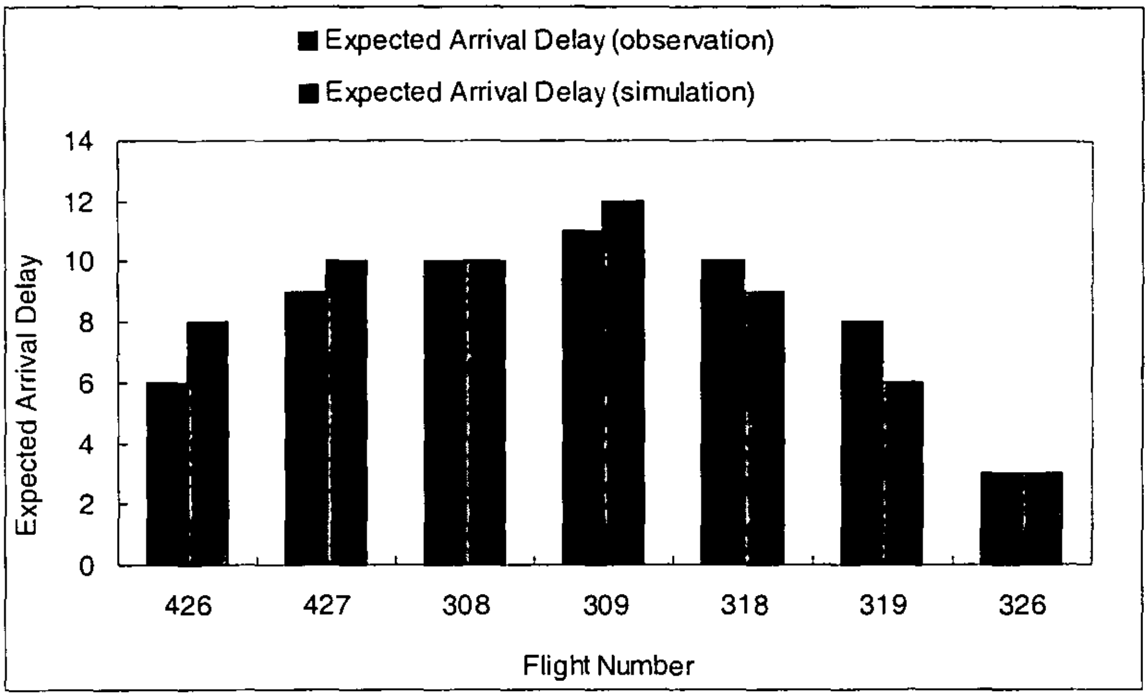

FIGURE 6.25 Comparison of expected arrival delay between observation and simulation results

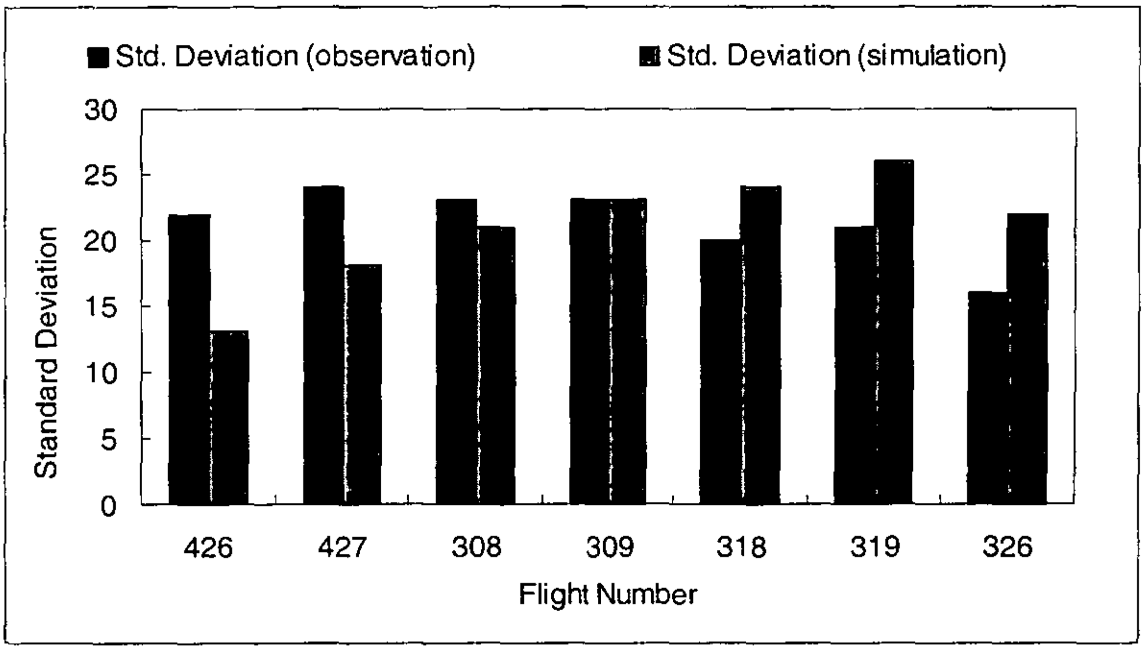

FIGURE 6.26 Comparison of standard deviation of departure delay between observation and simulation results

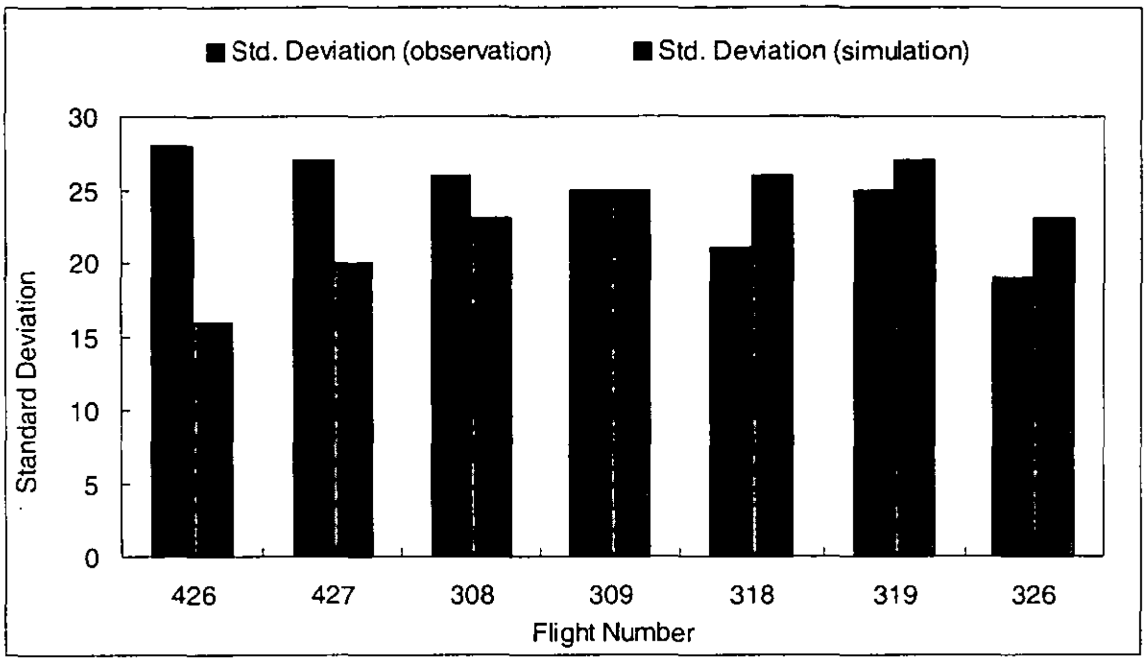

FIGURE 6.27 Comparison of standard deviation of arrival delay between observation and simulation results

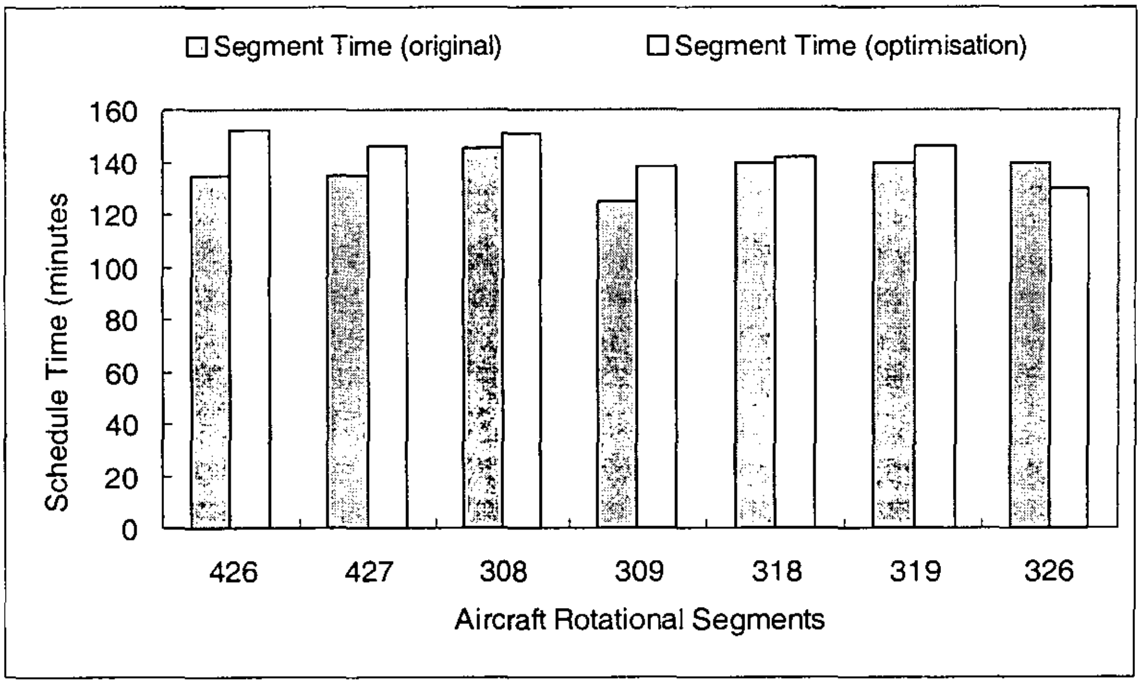

FIGURE 6.28 Comparison of scheduled leg time in aircraft rotation schedule between the optimisation case and the original case

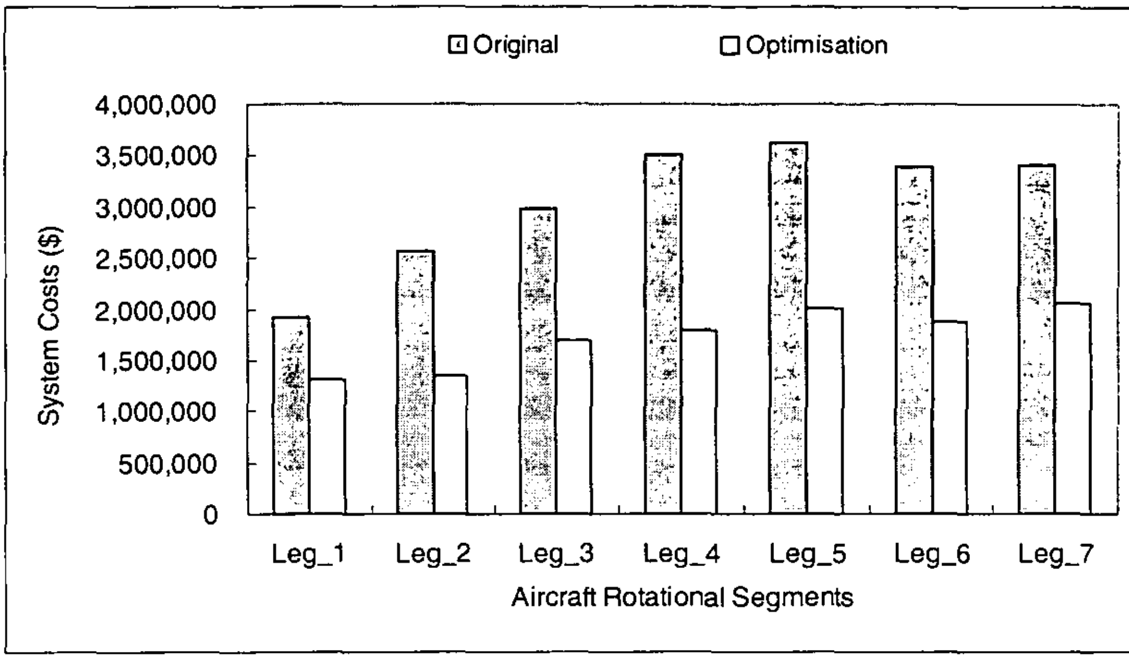

FIGURE 6.29 Comparison of system costs between the optimisation case and the original case

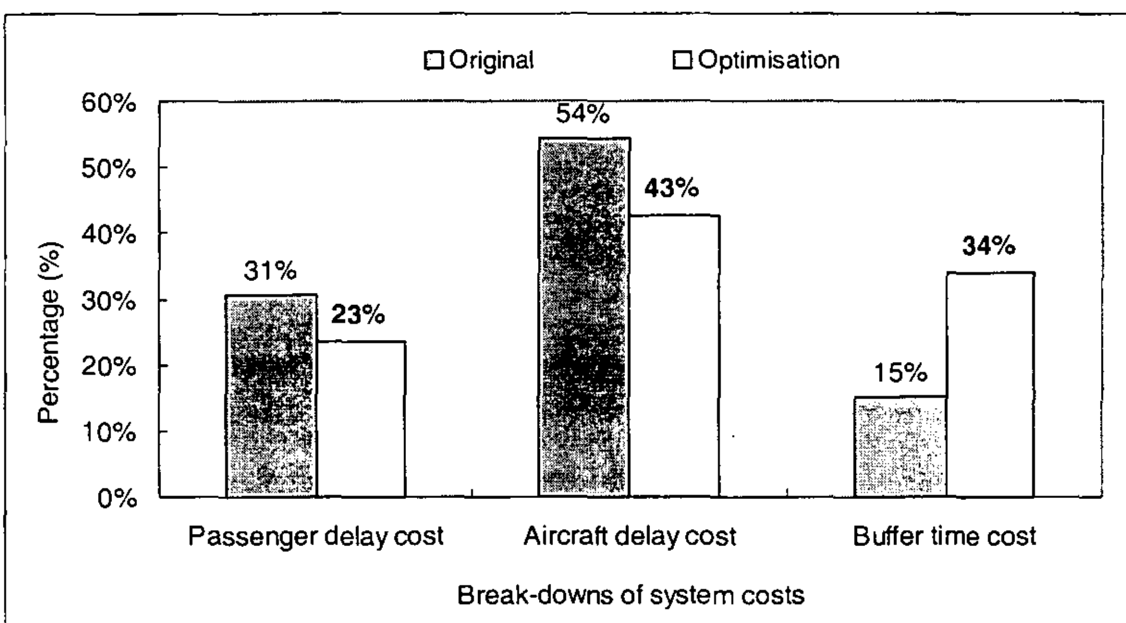

FIGURE 6.30 Comparison of break-downs of system cost before and after schedule optimisation

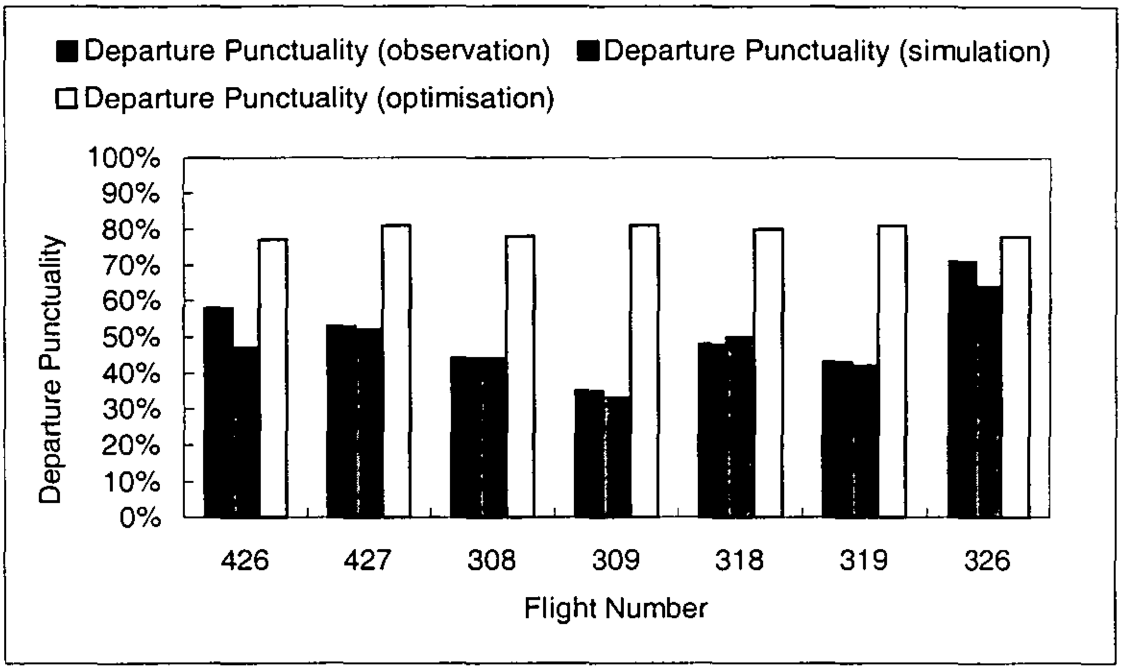

FIGURE 6.31 Comparison of departure punctuality between optimisation, simulation and observation

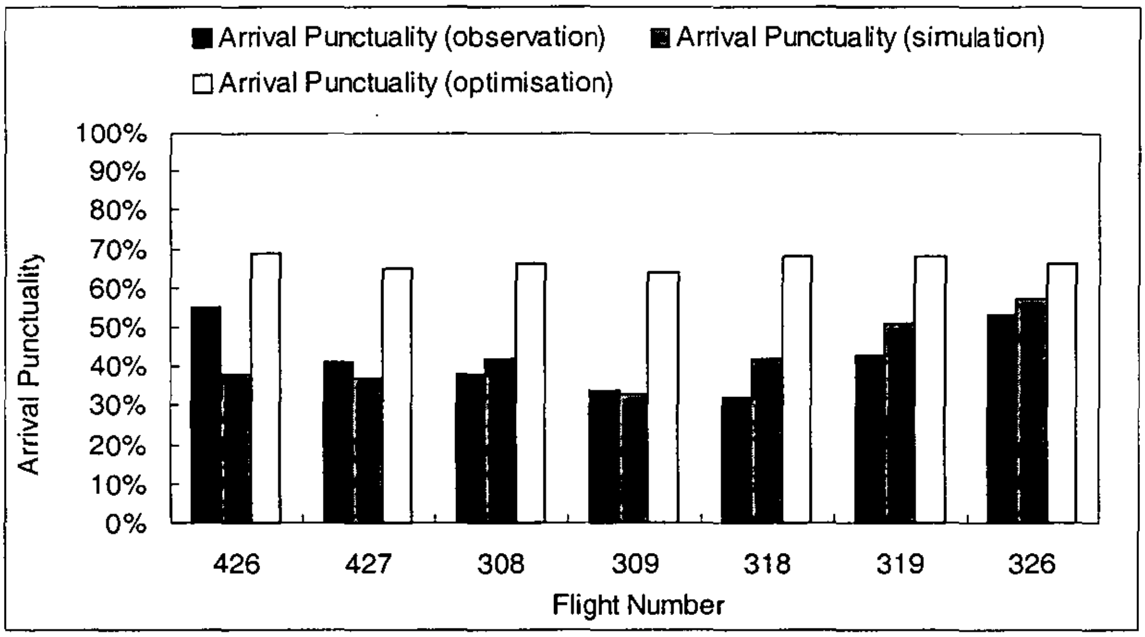

FIGURE 6.32 Comparison of arrival punctuality between optimisation, simulation and observation

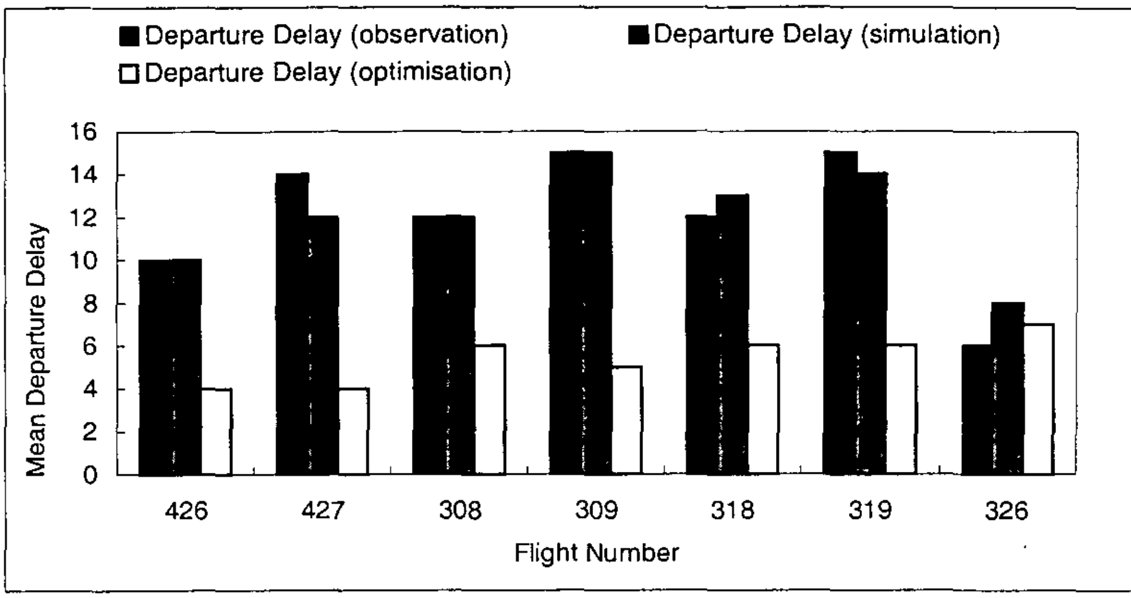

FIGURE 6.33 Comparison of mean departure delay between optimisation, simulation and observation

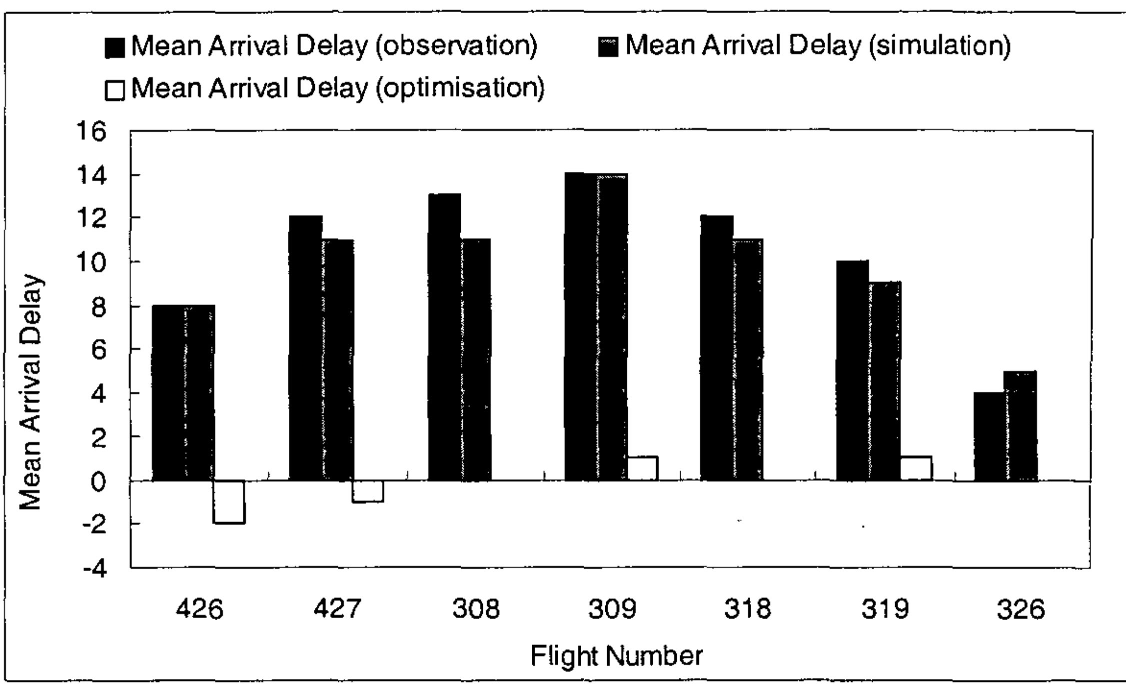

FIGURE 6.34 Comparison of mean arrival delay between optimisation, simulation and observation

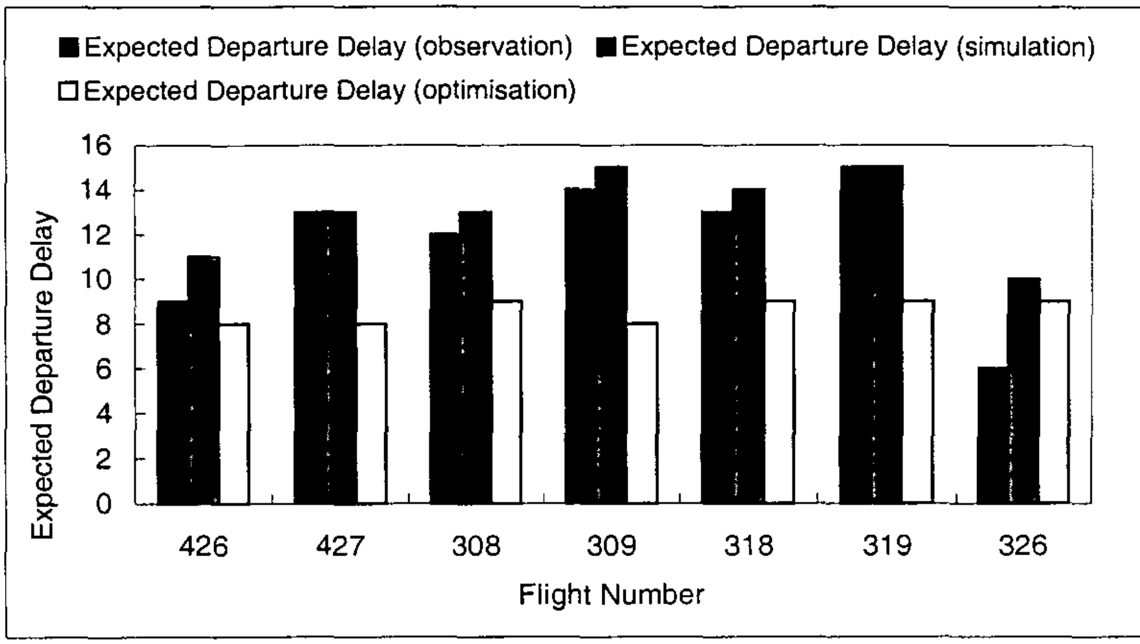

FIGURE 6.35 Comparison of expected departure delay between optimisation, simulation and observation

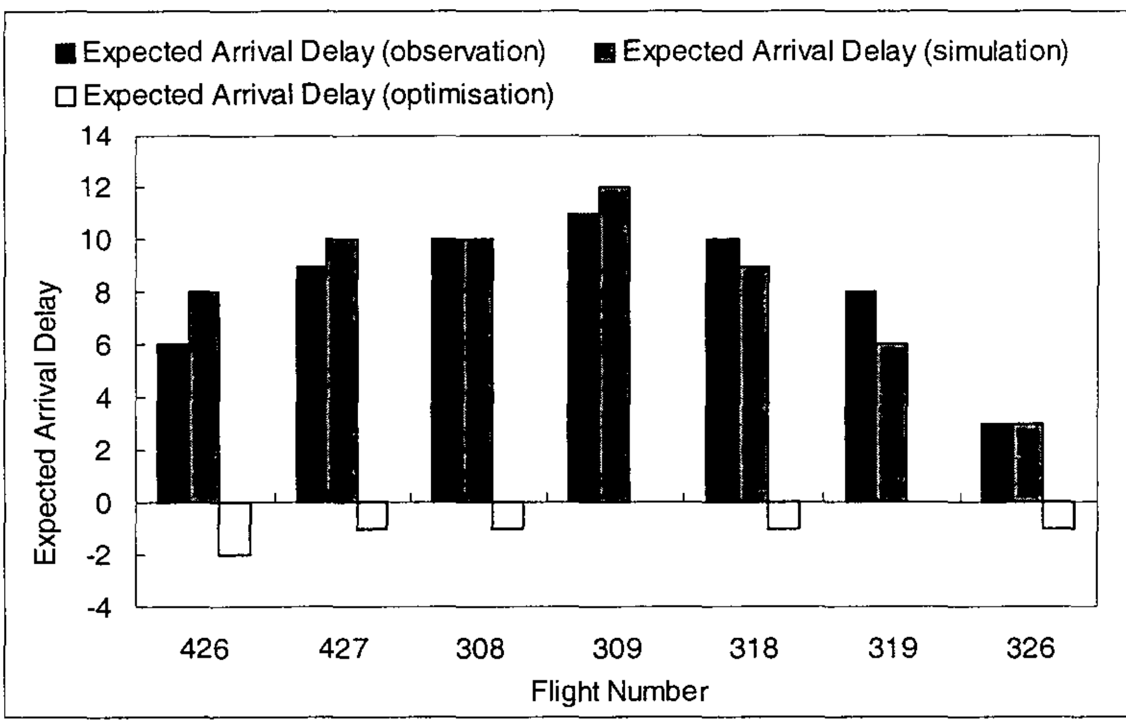

FIGURE 6.36 Comparison of expected arrival delay between optimisation, simulation and observation

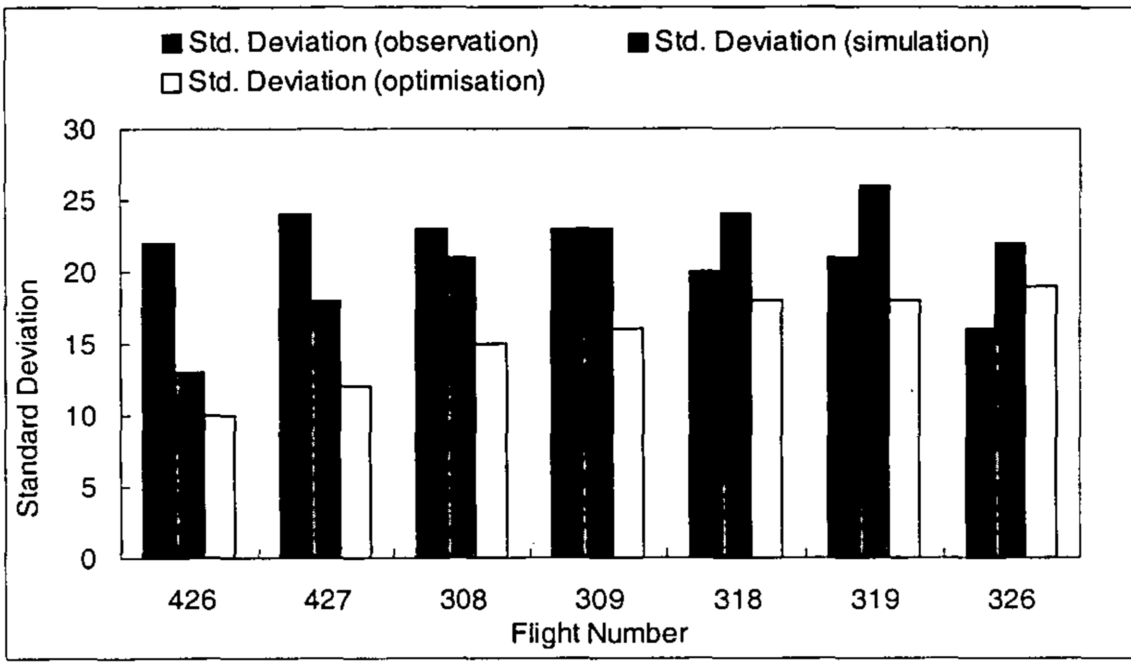

FIGURE 6.37 Comparison of standard deviation of departure delay between optimisation, simulation and observation

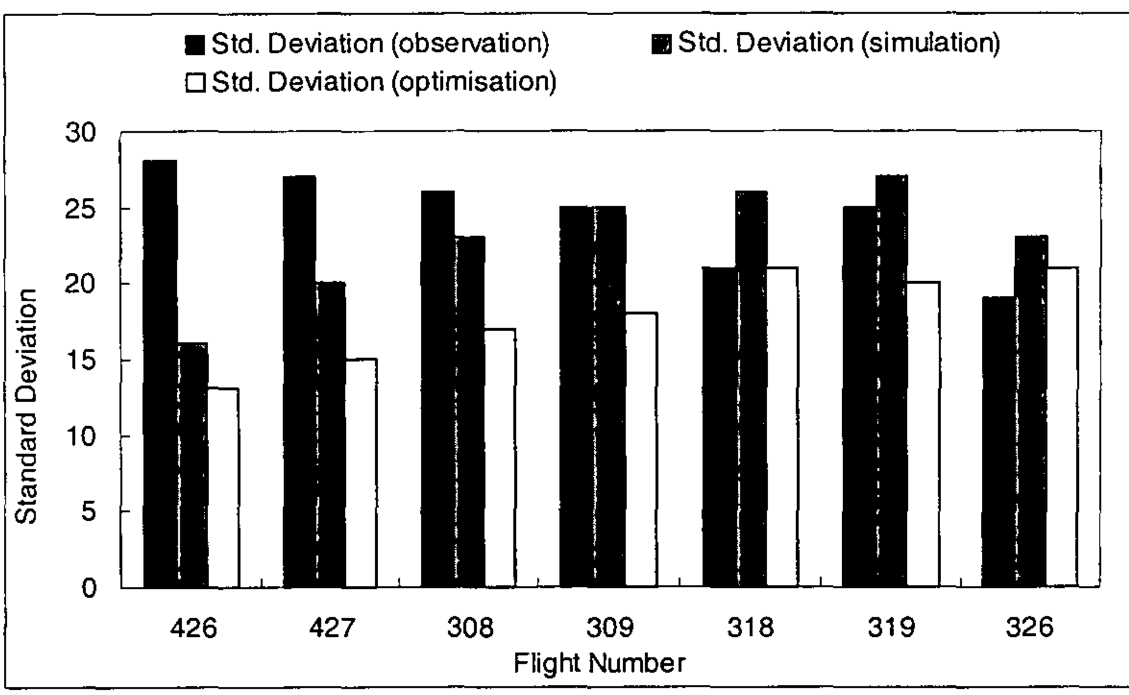

FIGURE 6.38 Comparison of standard deviation of arrival delay between optimisation, simulation and observation

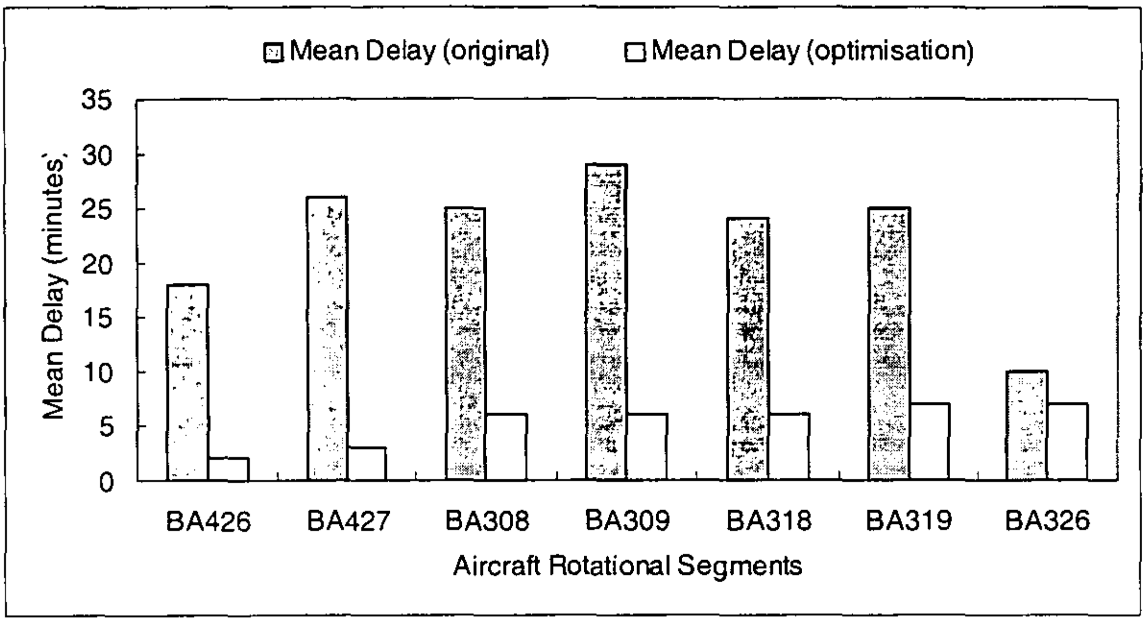

FIGURE 6.39 Mean delay of segments in aircraft rotation (schedule reliability analysis)

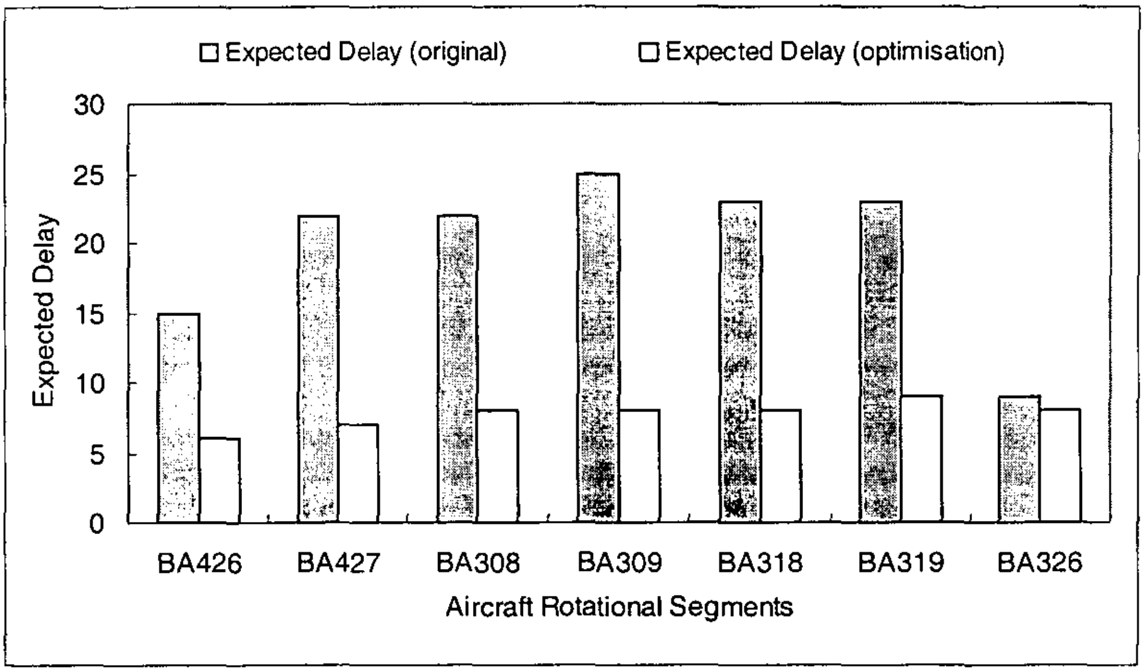

FIGURE 6.40 Expected delay of segments in aircraft rotation (schedule reliability analysis)

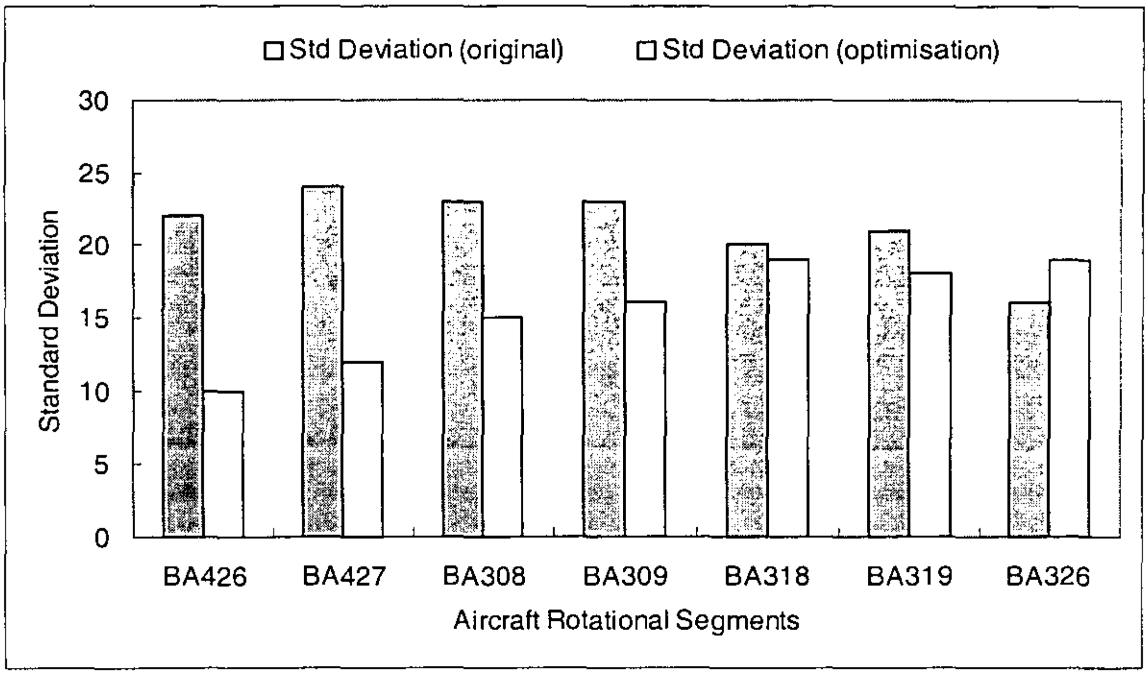

FIGURE 6.41 Standard deviation of departure delay in aircraft rotation (schedule reliability analysis)

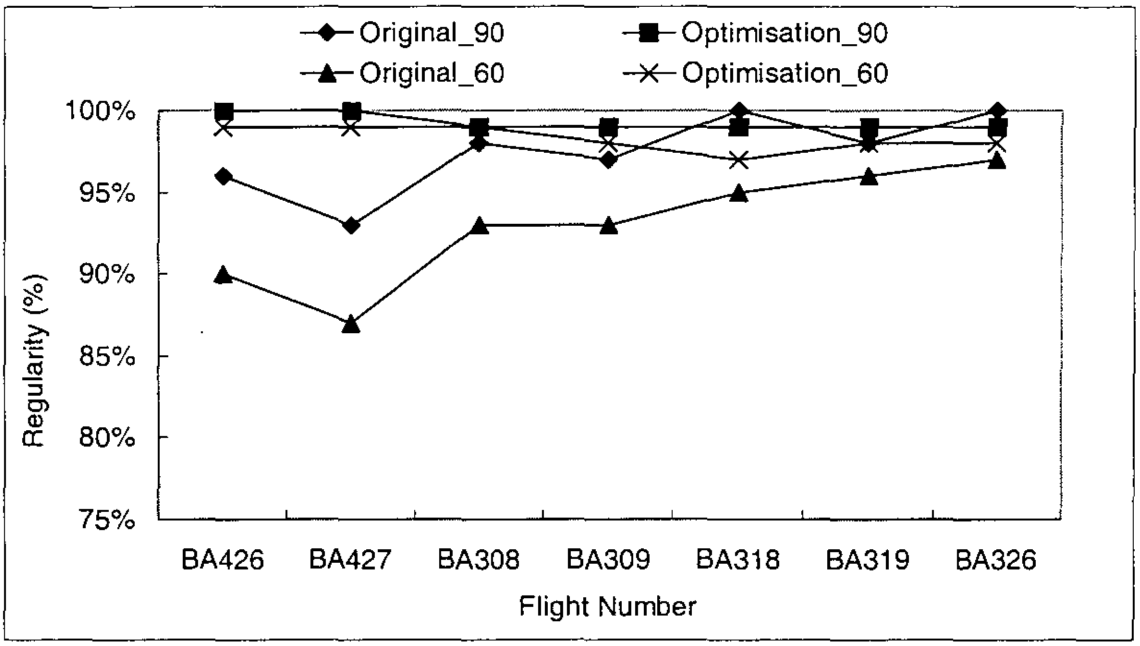

FIGURE 6.42 Schedule regularity in aircraft rotation (R_{REG_90} and R_{REG_60} ; schedule reliability analysis)

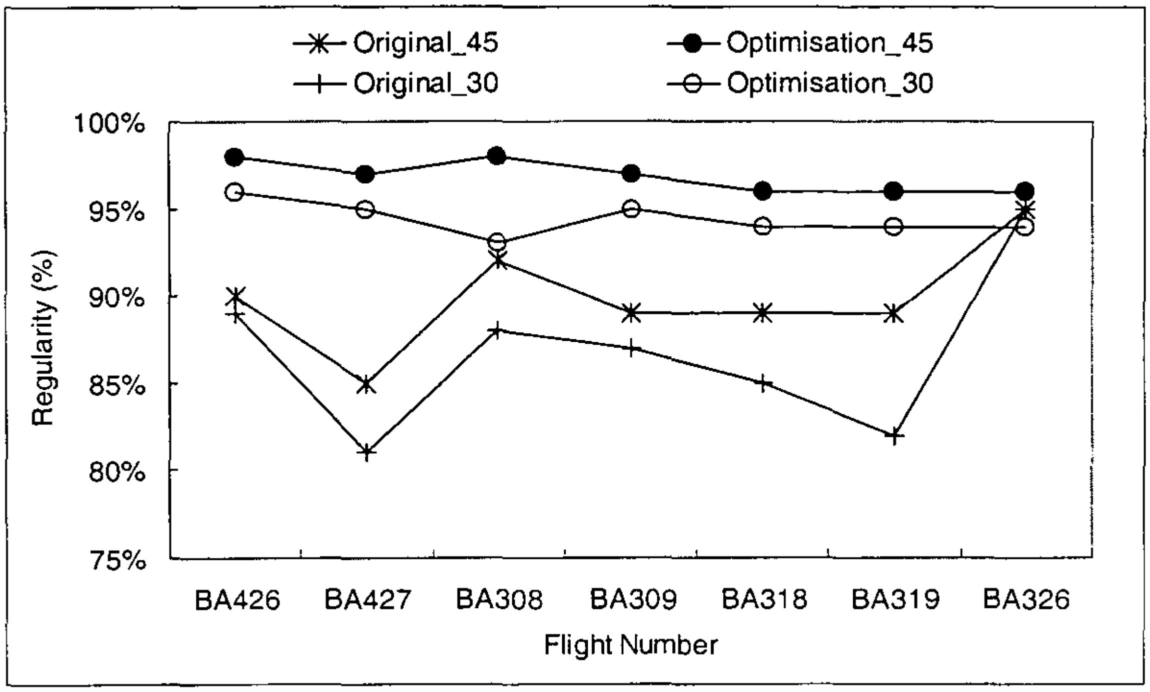

FIGURE 6.43 Schedule regularity in aircraft rotation (R_{REG_45} and R_{REG_30} ; schedule reliability analysis)

APPENDIX [I]

SIMULATION PROGRAMMES

MAT MODEL PROGRAMME CODES

```
PROGRAM AIRPORT
IMPLICIT NONE

INTEGER :: N,I,J,E_FLAG,E_CNT,ios,TSG,TG
INTEGER, DIMENSION(1000) :: FLT,A = (/ (0,I=1,1000) /)


REAL, DIMENSION(1000) :: ARR_D,DEPT_D,C_OPS,C_TME = (/ (0,I=1,1000) /)
REAL, DIMENSION(1000) :: P_OPS,ATC_D,P_TME = (/ (0,I=1,1000) /)
REAL, DIMENSION(1000) :: E_TME,B,OPS_D,OPS_TME,OUT_D = (/ (0,I=1,1000) /)


!programme starts here
!simulation size=1000 flights
!scheduled ground time (TSG)= 65 mins
!mean ground service time (TG)= 45 mins

 N=1000
  TSG=80
  TG=50


!generation of TR time by calling subroutines
!CARGO, PASSENGER, AND DISRUPTION
!not subroutine arguments
!output files
!CARGO      --> yc_time.txt
!PASSENGER  --> yp_time.txt
!DISRUPTION --> ye_out.txt

   CALL CARGO
   CALL PASSENGER
   CALL DISRUPTION

!read in simulation results from yc_time.txt, yp_time.txt and ye_out.txt
!re-open CARGO output files for data processing purposes

   OPEN(UNIT=20,FILE="yc_time.txt",STATUS="OLD",IOSTAT=ios)
     REWIND 20
   100 FORMAT(I5,F10.5,F10.5,F10.5,F10.5)

   DO I=1,N
     READ(UNIT=20,FMT=100) FLT(I),ARR_D(I),C_OPS(I), &
                   DEPT_D(I),C_TME(I)
   END DO
```

```
!re-open PAX output files for data processing purposes

 OPEN(UNIT=40,FILE="yp_time.txt",STATUS="OLD",IOSTAT=ios)
 REWIND 40
 200 FORMAT(15X,F10.5,10X,F10.5,F10.5)

 DO I=1,N
   READ(UNIT=40,FMT=200) P_OPS(I),ATC_D(I),P_TME(I)
 END DO


!re-open EVENT output files for data processing purposes
!flag vlaue E_FLAG is used to assign event time to corresponding
!flights and store event time in E_TME(*)
!read data until "ios" <0 (end of file), then EXIT

   OPEN(UNIT=50,FILE="ye_out.txt",STATUS="OLD",IOSTAT=ios)
   REWIND 50
     300 FORMAT(I5,25X,F10.5)

   E_FLAG=1
   DO
     READ(UNIT=50,FMT=300,IOSTAT=ios) A(E_FLAG),B(E_FLAG)
     E_FLAG=E_FLAG+1
     IF ( ios < 0 ) EXIT
   END DO

!E_FLAG is used as a flag pointer for A(*) B(*) data processing
!E_CNT is used as a flag value to count the no of re-occurrence

   E_FLAG=1
   DO I=1,N
     E_CNT=1
     IF ( I == A(E_FLAG) ) THEN
       DO J=1,4
         IF ( A(E_FLAG+J) == A(E_FLAG) ) THEN
           E_CNT=E_CNT+1
         END IF
       END DO
             !end of count, re-occurrence no= E_CNT
             !start to process data
             !there are 4 cases (max of 4 events)
       IF ( E_CNT == 1 ) THEN
         E_TME(I)=B(E_FLAG)
         E_FLAG=E_FLAG+1
       ELSE IF ( E_CNT == 2 ) THEN
         E_TME(I)=MAX( B(E_FLAG),B(E_FLAG+1) )
         E_FLAG=E_FLAG+E_CNT
       ELSE IF ( E_CNT == 3 ) THEN
         E_TME(I)=MAX( B(E_FLAG),B(E_FLAG+1),B(E_FLAG+2) )
```

```
        E_FLAG=E_FLAG+E_CNT
      ELSE
        E_TME(I)=MAX( B(E_FLAG),B(E_FLAG+1),B(E_FLAG+2),B(E_FLAG+3) )
        E_FLAG=E_FLAG+E_CNT
      END IF
    END IF
  END DO

!open a new file yap_or.txt to store simulation flight data
!data includes
!       flight no.
!       arrival delay
!       operation time
!       operational delay
!       ATC delay
!       outbound delay (dept delay + Ops delay + ATC delay)
!       scheduled ground time (TSG=65 mins)
!       mean TR service time (TG, mena of Ops time)

  OPEN(UNIT=60,FILE="yap_or.txt",STATUS="OLD",IOSTAT=ios)
  WRITE(UNIT=60,FMT=400) "FLT","IN_D","OPS_TME","OPS_D", &
               "ATC_D","OUT_D","TSG","TG"
  400 FORMAT(A5,A10,A10,A10,A10,A10,A5,A5)
  500 FORMAT(I5,F10.2,F10.2,F10.2,F10.2,F10.2,I5,I5)


  DO I=1,N
    OPS_TME(I)=MAX( C_OPS(I),P_OPS(I),E_TME(I) )
    OPS_D(I)=OPS_TME(I)+ARR_D(I)-TSG
      IF ( OPS_D(I) < 0 ) THEN
        OPS_D(I)=0
      END IF
    OUT_D(I)=OPS_D(I)+DEPT_D(I)+ATC_D(I)

    WRITE(UNIT=60,FMT=500) I,ARR_D(I),OPS_TME(I),OPS_D(I), &
               ATC_D(I),OUT_D(I),TSG,TG
  END DO



ENDFILE 60
CLOSE (60)

PRINT *,"############## AIRPORT TR SIMULATION IS DONE!! ##### ^_^ Rich"

END PROGRAM AIRPORT
```

ENROUTE MODEL PROGRAMME CODES

```
PROGRAM ENROUTE

IMPLICIT NONE

INTEGER :: N,I,ios

REAL*8 ER_FLTME(1000),TMA_DLY(84)
REAL*8 NSEED_1,ESEED_1,B_1
REAL :: FL_V_1,FL_M_1,B_TME_1
REAL :: IN_D
REAL :: OUT_D_1(84),IN_D_1(84)


 N=78
 B_TME_1=60
 NSEED_1=395428951
 FL_V_1=5
 FL_M_1=50
 ESEED_1=345071507
 B_1=7


 ! READ DEPARTURE DELAY TIME OF BAxxx FROM xxx_dept.txt FILE


OPEN(UNIT=60,FILE="326_dept.txt",STATUS="OLD",POSITION="REWIND",IOSTAT=ios)

   DO I=1,N
     READ (UNIT=60,FMT='(F3.0)') OUT_D_1(I)
   END DO


!Enroute travel time is simulated by a Normal distribution
!with FL_V (standard deviation) and FL_M (mean flight time)
!output array ER_FLTME(N)

   PRINT *,"GENERATING ENROUTE FLIGHT TIME ARRAY"

     CALL NORMAL(NSEED_1,N,FL_V_1,FL_M_1,ER_FLTME)

!TMA congestion delay is simulated by an Exponential
!distribution with mean congestion time B minutes

     PRINT *,"GENERATING TMA CONGESTION DELAY"


       CALL EXP(ESEED_1,N,B_1,TMA_DLY)
```

```
!calculation of inbound delay from
!deaprture delay at origin a/p,
!enroute delay=(flight time+tma delay)-block time
!inbound delay=dept_delay+enroute_delay

    DO I=1,N
     IN_D_1(I)=OUT_D_1(I)+ER_FLTME(I)+TMA_DLY(I)-B_TME_1
    END DO

!output results to er_i.txt for operations of a flight
!              xxx_arr.txt for operational results of all flights
! IN_D =0 IS ONLY FOR RECORDS. TO REPLACE NEGATIVE ARRIVAL DELAYS IN
OUTPUTS....

   400 FORMAT(5A10)
      IN_D=0

   OPEN(UNIT=150,FILE="326_arr.txt",STATUS="OLD",IOSTAT=ios)
      WRITE(UNIT=150,FMT=400)
"OUT_DLY","ER_FLTME","TMA_DLY","IN_DLY","IN_D_P"

   DO I=1,N
       IF ( IN_D_1(I) < 0 ) THEN
      WRITE(UNIT=150,FMT='(5F10.0)')
OUT_D_1(I),ER_FLTME(I),TMA_DLY(I),IN_D_1(I),IN_D
         ELSE
      WRITE(UNIT=150,FMT='(5F10.0)')
OUT_D_1(I),ER_FLTME(I),TMA_DLY(I),IN_D_1(I),IN_D_1(I)
         END IF
    END DO
    ENDFILE 150


 PRINT *,"PROGRAME ENROUTE IS RUNNING WELL!!"

 CLOSE (UNIT=60)
 CLOSE (UNIT=150)


 END PROGRAM ENROUTE
```

AIRCRAFT ROTATION MODEL PROGRAMME CODES

```
PROGRAM APNETWORK
 USE erdelay
 IMPLICIT NONE

 INTEGER :: N,I,APN,ios
 INTEGER :: TSG_1,TG_1,TSG_2,TG_2,TSG_3,TG_3,TSG_4,TG_4
 INTEGER :: TSG_5,TG_5,TSG_6,TG_6,TSG_7,TG_7


!programme starts here
!simulation size (N)=1000 flights
!input scheduled TR time (TSG) and mean service tiem (TG)
!from schedule data file "sched.txt"


 OPEN(UNIT=4000,FILE="sched.txt",STATUS="OLD",IOSTAT=ios)
  READ(UNIT=4000,FMT='(10X,I4)') N
  READ(UNIT=4000,FMT='(10X,I2)') TSG_1
  READ(UNIT=4000,FMT='(10X,I2)') TG_1
  READ(UNIT=4000,FMT='(10X,I2)') TSG_2
  READ(UNIT=4000,FMT='(10X,I2)') TG_2
  READ(UNIT=4000,FMT='(10X,I2)') TSG_3
  READ(UNIT=4000,FMT='(10X,I2)') TG_3
  READ(UNIT=4000,FMT='(10X,I2)') TSG_4
  READ(UNIT=4000,FMT='(10X,I2)') TG_4
  READ(UNIT=4000,FMT='(10X,I2)') TSG_5
  READ(UNIT=4000,FMT='(10X,I2)') TG_5
  READ(UNIT=4000,FMT='(10X,I2)') TSG_6
  READ(UNIT=4000,FMT='(10X,I2)') TG_6
  READ(UNIT=4000,FMT='(10X,I2)') TSG_7
  READ(UNIT=4000,FMT='(10X,I2)') TG_7
 CLOSE (UNIT=4000)

!running simulation subroutines: airport & enroute for 10 T/Rs
!by calling subroutines 10 times
!APN == the airport codes



!###########################1
  APN=1
  CALL AIRPORT(N,TSG_1,TG_1,APN)
  CALL ENROUTE(N,APN)

!###########################2
  APN=APN+1

  CALL AIRPORT(N,TSG_2,TG_2,APN)
```

```
  CALL ENROUTE(N,APN)
!##########################3
  APN=APN+1

  CALL AIRPORT(N,TSG_3,TG_3,APN)
  CALL ENROUTE(N,APN)
!##########################4
  APN=APN+1

  CALL AIRPORT(N,TSG_4,TG_4,APN)
  CALL ENROUTE(N,APN)
!##########################5
  APN=APN+1

  CALL AIRPORT(N,TSG_5,TG_5,APN)
  CALL ENROUTE(N,APN)
!##########################6
  APN=APN+1

  CALL AIRPORT(N,TSG_6,TG_6,APN)
  CALL ENROUTE(N,APN)
!##########################7
  APN=APN+1

  CALL AIRPORT(N,TSG_7,TG_7,APN)
  CALL ENROUTE(N,APN)

!output simulation results to net_or.txt

 OPEN(UNIT=250,FILE="net_or.txt",STATUS="OLD",IOSTAT=ios)

 DO I=1,N
   WRITE(UNIT=250,FMT='(I5,14F10.2)') I,OUT_D_1(I),IN_D_1(I), &
                       OUT_D_2(I),IN_D_2(I), &
                       OUT_D_3(I),IN_D_3(I), &
                       OUT_D_4(I),IN_D_4(I), &
                       OUT_D_5(I),IN_D_5(I), &
                       OUT_D_6(I),IN_D_6(I), &
                       OUT_D_7(I),IN_D_7(I)
 END DO

 ENDFILE 250
 CLOSE (UNIT=250)


PRINT *,"----------->>PROGRAMME APNETWORK IS DONE!!<<----    {^_^} "

END PROGRAM APNETWORK
```

AIRCRAFT ROTATION OPTIMISATION PROGRAMME CODES

```
PROGRAM APNETWORK
 USE erdelay
 IMPLICIT NONE

 INTEGER :: N,I,K,APN,ios,FLAG
 INTEGER :: TSG_1,TG_1,TSG_2,TG_2,TSG_3,TG_3,TSG_4,TG_4
 INTEGER :: TSG_5,TG_5,TSG_6,TG_6,TSG_7,TG_7
 INTEGER :: TSG_MAX_1,TSG_MAX_2,TSG_MAX_3,TSG_MAX_4,TSG_MAX_5
 INTEGER :: TSG_MAX_6,TSG_MAX_7
 INTEGER :: OPM_I_1,OPM_I_2,OPM_I_3,OPM_I_4,OPM_I_5,OPM_I_6
 INTEGER :: OPM_I_7

 REAL :: J
 REAL :: OPM_J_1,OPM_J_2,OPM_J_3,OPM_J_4,OPM_J_5,OPM_J_6
 REAL :: OPM_J_7
 REAL :: ALFA_A,ALFA_AB,BETA_A,BETA_AB
 REAL :: UC_P,UC_A_G,UC_A_A,UC_B
 REAL :: B_MAX_1,B_MAX_2,B_MAX_3,B_MAX_4,B_MAX_5,B_MAX_6
 REAL :: B_MAX_7
 REAL :: B_TME_1,B_TME_2,B_TME_3,B_TME_4,B_TME_5,B_TME_6
 REAL :: B_TME_7

 REAL :: CT_1,CT_2,CT_3,CT_4,CT_5,CT_6,CT_7
 REAL :: MIN_CT_1,MIN_CT_2,MIN_CT_3,MIN_CT_4,MIN_CT_5,MIN_CT_6
 REAL :: MIN_CT_7
 REAL, DIMENSION(1000) :: CDP_1,CDA_1,CAP_1 = (/ (0,I=1,1000) /)
 REAL, DIMENSION(1000) :: CAA_1,CBA_1,CBAB_1,CI_1 = (/ (0,I=1,1000) /)
 REAL, DIMENSION(1000) :: CDP_2,CDA_2,CAP_2 = (/ (0,I=1,1000) /)
 REAL, DIMENSION(1000) :: CAA_2,CBA_2,CBAB_2,CI_2 = (/ (0,I=1,1000) /)
 REAL, DIMENSION(1000) :: CDP_3,CDA_3,CAP_3 = (/ (0,I=1,1000) /)
 REAL, DIMENSION(1000) :: CAA_3,CBA_3,CBAB_3,CI_3 = (/ (0,I=1,1000) /)
 REAL, DIMENSION(1000) :: CDP_4,CDA_4,CAP_4 = (/ (0,I=1,1000) /)
 REAL, DIMENSION(1000) :: CAA_4,CBA_4,CBAB_4,CI_4 = (/ (0,I=1,1000) /)
 REAL, DIMENSION(1000) :: CDP_5,CDA_5,CAP_5 = (/ (0,I=1,1000) /)
 REAL, DIMENSION(1000) :: CAA_5,CBA_5,CBAB_5,CI_5 = (/ (0,I=1,1000) /)
 REAL, DIMENSION(1000) :: CDP_6,CDA_6,CAP_6 = (/ (0,I=1,1000) /)
 REAL, DIMENSION(1000) :: CAA_6,CBA_6,CBAB_6,CI_6 = (/ (0,I=1,1000) /)
 REAL, DIMENSION(1000) :: CDP_7,CDA_7,CAP_7 = (/ (0,I=1,1000) /)
 REAL, DIMENSION(1000) :: CAA_7,CBA_7,CBAB_7,CI_7 = (/ (0,I=1,1000) /)


!programme starts here
!simulation size (N)=1000 flights
!input scheduled TR time (TSG) and mean service tiem (TG)
!from schedule data file "sched.txt" & "route_va.txt"
```

```
 OPEN(UNIT=4000,FILE="sched.txt",STATUS="OLD",IOSTAT=ios)
  READ(UNIT=4000,FMT='(10X,I4)') N
  READ(UNIT=4000,FMT='(10X,I2)') TSG_1
  READ(UNIT=4000,FMT='(10X,I2)') TG_1
  READ(UNIT=4000,FMT='(10X,I2)') TSG_MAX_1
  READ(UNIT=4000,FMT='(10X,I2)') TSG_2
  READ(UNIT=4000,FMT='(10X,I2)') TG_2
  READ(UNIT=4000,FMT='(10X,I2)') TSG_MAX_2
  READ(UNIT=4000,FMT='(10X,I2)') TSG_3
  READ(UNIT=4000,FMT='(10X,I2)') TG_3
  READ(UNIT=4000,FMT='(10X,I2)') TSG_MAX_3
  READ(UNIT=4000,FMT='(10X,I2)') TSG_4
  READ(UNIT=4000,FMT='(10X,I2)') TG_4
  READ(UNIT=4000,FMT='(10X,I2)') TSG_MAX_4
  READ(UNIT=4000,FMT='(10X,I2)') TSG_5
  READ(UNIT=4000,FMT='(10X,I2)') TG_5
  READ(UNIT=4000,FMT='(10X,I2)') TSG_MAX_5
  READ(UNIT=4000,FMT='(10X,I2)') TSG_6
  READ(UNIT=4000,FMT='(10X,I2)') TG_6
  READ(UNIT=4000,FMT='(10X,I2)') TSG_MAX_6
  READ(UNIT=4000,FMT='(10X,I2)') TSG_7
  READ(UNIT=4000,FMT='(10X,I2)') TG_7
  READ(UNIT=4000,FMT='(10X,I2)') TSG_MAX_7
 CLOSE (UNIT=4000)

!Input optimisation parameters from "route_va.txt"

 OPEN(UNIT=4100,FILE="route_va.txt",STATUS="OLD",IOSTAT=ios)

  READ(UNIT=4100,FMT='(10X,F2.0)') B_TME_1
  READ(UNIT=4100,FMT='(10X,F2.0)') B_MAX_1
  READ(UNIT=4100,FMT='(10X,F2.0)') B_TME_2
  READ(UNIT=4100,FMT='(10X,F2.0)') B_MAX_2
  READ(UNIT=4100,FMT='(10X,F2.0)') B_TME_3
  READ(UNIT=4100,FMT='(10X,F2.0)') B_MAX_3
  READ(UNIT=4100,FMT='(10X,F2.0)') B_TME_4
  READ(UNIT=4100,FMT='(10X,F2.0)') B_MAX_4
  READ(UNIT=4100,FMT='(10X,F2.0)') B_TME_5
  READ(UNIT=4100,FMT='(10X,F2.0)') B_MAX_5
  READ(UNIT=4100,FMT='(10X,F2.0)') B_TME_6
  READ(UNIT=4100,FMT='(10X,F2.0)') B_MAX_6
  READ(UNIT=4100,FMT='(10X,F2.0)') B_TME_7
  READ(UNIT=4100,FMT='(10X,F2.0)') B_MAX_7
  READ(UNIT=4100,FMT='(10X,F3.1)') UC_P
  READ(UNIT=4100,FMT='(10X,F3.0)') UC_A_G
  READ(UNIT=4100,FMT='(10X,F3.0)') UC_A_A
  READ(UNIT=4100,FMT='(10X,F3.1)') UC_B
  READ(UNIT=4100,FMT='(10X,F3.1)') ALFA_A
  READ(UNIT=4100,FMT='(10X,F3.1)') BETA_A
  READ(UNIT=4100,FMT='(10X,F3.1)') ALFA_AB
```

```
  READ(UNIT=4100,FMT='(10X,F3.1)') BETA_AB
 CLOSE(UNIT=4100)

!running simulation subroutines: airport & enroute for 10 T/Rs
!by calling subroutines 10 times
!APN == the airport codes

!open file "results.txt to save optimisation results which
!were previously printed on output screen.

OPEN(UNIT=270,FILE="results.txt",STATUS="OLD",IOSTAT=ios)


!############################ A/P_1
   APN=1
   CALL CARGO(APN)
   CALL PASSENGER(APN)
   CALL DISRUPTION(APN)
   CALL FLIGHT(N,APN)


!Start optimisation and system cost calculations

OPEN(UNIT=6000,FILE="route_c1.txt",STATUS="OLD",IOSTAT=ios)

 FLAG=1

 DO J=B_TME_1,B_MAX_1
  DO I=TG_1,TSG_MAX_1

    CALL AIRPORT(N,I,TG_1,APN)
    CALL ENROUTE(N,APN,J)

     CT_1=0.
     DO K=1,N
      !Cost (CT) calculations
      CDP_1(K)=UC_P*0.5*OUT_D_1(K)**2
      CDA_1(K)=UC_A_G*OUT_D_1(K)
      CBA_1(K)=UC_B*0.5*(I-TG_1)**2

      IF ( IN_D_1(K) <= 0. ) THEN
         CAP_1(K)=0.
         CAA_1(K)=0.
         CBAB_1(K)=UC_B*0.5*(J-B_TME_1)**2
      ELSE
         CAP_1(K)=UC_P*0.5*IN_D_1(K)**2
         CAA_1(K)=UC_A_A*IN_D_1(K)
         CBAB_1(K)=UC_B*0.5*(J-B_TME_1)**2
      END IF
```

```
    CI_1(K)=ALFA_A*( CDP_1(K)+CDA_1(K) )+BETA_A*CBA_1(K)+ &
        ALFA_AB*( CAP_1(K)+CAA_1(K) )+BETA_AB*CBAB_1(K)

    CT_1=CT_1+CI_1(K)

   END DO

!Output cost values to "route_ci.txt" and reference data to BOUT_D_i(*)

    IF (I == 25 .AND. J == 65) THEN
      !outbound and inbound delay time of the original case
      CALL APOR(N,I,TG_1,APN)
      CALL ER(N,APN,J)
       DO K=1,N
         BOUT_D_1(K)=OUT_D_1(K)
         BIN_D_1(K)=IN_D_1(K)
       END DO
    END IF


    WRITE(UNIT=6000,FMT='(I5,F5.0,F15.0)') I,J,CT_1

! Global cost minimum search

    IF (FLAG == 1) THEN
      MIN_CT_1=CT_1
      OPM_I_1=I
      OPM_J_1=J
    ELSE IF (CT_1 <= MIN_CT_1) THEN
        MIN_CT_1=CT_1
        OPM_I_1=I
        OPM_J_1=J
    END IF

    FLAG=FLAG+1
  END DO
 END DO

!Generate inbound delay time of the global minimum case

  CALL AIRPORT(N,OPM_I_1,TG_1,APN)
  CALL ENROUTE(N,APN,OPM_J_1)

   PRINT *,"Leg_",APN
   PRINT *,"The optimal TSG is", OPM_I_1
   PRINT *,"The optimal B_TME is", OPM_J_1
   PRINT *,"The minimum cost is", MIN_CT_1

!output to results.txt
```

```
WRITE(UNIT=270,FMT='(A10,I10)') "Leg_",APN
WRITE(UNIT=270,FMT='(A30,I10)') "The optimal TSG is", OPM_I_1
WRITE(UNIT=270,FMT='(A30,F10.0)') "The optimal B_TME is", OPM_J_1
WRITE(UNIT=270,FMT='(A30,F10.0)') "The minimum cost is", MIN_CT_1


ENDFILE 6000
CLOSE(UNIT=6000)

!########################### A/P_2
   APN=2
   CALL CARGO(APN)
   CALL PASSENGER(APN)
   CALL DISRUPTION(APN)
   CALL FLIGHT(N,APN)


!Start optimisation and system cost calculations

OPEN(UNIT=6100,FILE="route_c2.txt",STATUS="OLD",IOSTAT=ios)

 FLAG=1

 DO J=B_TME_2,B_MAX_2
  DO I=TG_2,TSG_MAX_2

    CALL AIRPORT(N,I,TG_2,APN)
    CALL ENROUTE(N,APN,J)

     CT_2=0.
     DO K=1,N
      !Cost (CT) calculations
      CDP_2(K)=UC_P*0.5*OUT_D_2(K)**2
      CDA_2(K)=UC_A_G*OUT_D_2(K)
      CBA_2(K)=UC_B*0.5*(I-TG_2)**2

      IF ( IN_D_2(K) <= 0. ) THEN
         CAP_2(K)=0.
         CAA_2(K)=0.
         CBAB_2(K)=UC_B*0.5*(J-B_TME_2)**2
      ELSE
         CAP_2(K)=UC_P*0.5*IN_D_2(K)**2
         CAA_2(K)=UC_A_A*IN_D_2(K)
         CBAB_2(K)=UC_B*0.5*(J-B_TME_2)**2
      END IF

      CI_2(K)=ALFA_A*( CDP_2(K)+CDA_2(K) )+BETA_A*CBA_2(K)+ &
          ALFA_AB*( CAP_2(K)+CAA_2(K) )+BETA_AB*CBAB_2(K)

      CT_2=CT_2+CI_2(K)
```

```
    END DO

!Output cost values to "route_ci.txt" and reference data to BOUT_D_i(*)


      IF (I == 30 .AND. J == 65) THEN
        !outbound and inbound delay time of the original case
        CALL APOR(N,I,TG_2,APN)
        CALL ER(N,APN,J)
         DO K=1,N
           BOUT_D_2(K)=OUT_D_2(K)
           BIN_D_2(K)=IN_D_2(K)
         END DO
      END IF


      WRITE(UNIT=6100,FMT='(I5,F5.0,F15.0)') I,J,CT_2

! Global cost minimum search

     IF (FLAG == 1) THEN
       MIN_CT_2=CT_2
       OPM_I_2=I
       OPM_J_2=J
     ELSE IF (CT_2 <= MIN_CT_2) THEN
         MIN_CT_2=CT_2
         OPM_I_2=I
         OPM_J_2=J
     END IF

     FLAG=FLAG+1
  END DO
 END DO

!Generate inbound delay time of the global minimum case

  CALL AIRPORT(N,OPM_I_2,TG_2,APN)
  CALL ENROUTE(N,APN,OPM_J_2)

    PRINT *,"Leg_",APN
    PRINT *,"The optimal TSG is", OPM_I_2
    PRINT *,"The optimal B_TME is", OPM_J_2
    PRINT *,"The minimum cost is", MIN_CT_2

 !output to results.txt

 WRITE(UNIT=270,FMT='(A10,I10)') "Leg_",APN
 WRITE(UNIT=270,FMT='(A30,I10)') "The optimal TSG is", OPM_I_2
 WRITE(UNIT=270,FMT='(A30,F10.0)') "The optimal B_TME is", OPM_J_2
```

```
WRITE(UNIT=270,FMT='(A30,F10.0)') "The minimum cost is", MIN_CT_2


ENDFILE 6100
CLOSE(UNIT=6100)


!########################## A/P_3
  APN=3
  CALL CARGO(APN)
  CALL PASSENGER(APN)
  CALL DISRUPTION(APN)
  CALL FLIGHT(N,APN)


!Start optimisation and system cost calculations

OPEN(UNIT=6200,FILE="route_c3.txt",STATUS="OLD",IOSTAT=ios)

 FLAG=1

 DO J=B_TME_3,B_MAX_3
  DO I=TG_3,TSG_MAX_3

    CALL AIRPORT(N,I,TG_3,APN)
    CALL ENROUTE(N,APN,J)

     CT_3=0.
     DO K=1,N
      !Cost (CT) calculations
      CDP_3(K)=UC_P*0.5*OUT_D_3(K)**2
      CDA_3(K)=UC_A_G*OUT_D_3(K)
      CBA_3(K)=UC_B*0.5*(I-TG_3)**2

      IF ( IN_D_3(K) <= 0. ) THEN
         CAP_3(K)=0.
         CAA_3(K)=0.
         CBAB_3(K)=UC_B*0.5*(J-B_TME_3)**2
      ELSE
         CAP_3(K)=UC_P*0.5*IN_D_3(K)**2
         CAA_3(K)=UC_A_A*IN_D_3(K)
         CBAB_3(K)=UC_B*0.5*(J-B_TME_3)**2
      END IF

      CI_3(K)=ALFA_A*( CDP_3(K)+CDA_3(K) )+BETA_A*CBA_3(K)+ &
          ALFA_AB*( CAP_3(K)+CAA_3(K) )+BETA_AB*CBAB_3(K)

      CT_3=CT_3+CI_3(K)

     END DO
```

```
!Output cost values to "route_ci.txt" and reference data to BOUT_D_i(*)


      IF (I == 25 .AND. J == 65) THEN
        !outbound and inbound delay time of the original case
        CALL APOR(N,I,TG_3,APN)
        CALL ER(N,APN,J)
         DO K=1,N
           BOUT_D_3(K)=OUT_D_3(K)
           BIN_D_3(K)=IN_D_3(K)
         END DO
      END IF


      WRITE(UNIT=6200,FMT='(I5,F5.0,F15.0)') I,J,CT_3

! Global cost minimum search

     IF (FLAG == 1) THEN
       MIN_CT_3=CT_3
       OPM_I_3=I
       OPM_J_3=J
     ELSE IF (CT_3 <= MIN_CT_3) THEN
         MIN_CT_3=CT_3
         OPM_I_3=I
         OPM_J_3=J
     END IF

     FLAG=FLAG+1
  END DO
 END DO

!Generate inbound delay time of the global minimum case

  CALL AIRPORT(N,OPM_I_3,TG_3,APN)
  CALL ENROUTE(N,APN,OPM_J_3)

    PRINT *,"Leg_",APN
    PRINT *,"The optimal TSG is", OPM_I_3
    PRINT *,"The optimal B_TME is", OPM_J_3
    PRINT *,"The minimum cost is", MIN_CT_3

!output to results.txt

WRITE(UNIT=270,FMT='(A10,I10)') "Leg_",APN
WRITE(UNIT=270,FMT='(A30,I10)') "The optimal TSG is", OPM_I_3
WRITE(UNIT=270,FMT='(A30,F10.0)') "The optimal B_TME is", OPM_J_3
WRITE(UNIT=270,FMT='(A30,F10.0)') "The minimum cost is", MIN_CT_3
```

```
ENDFILE 6200
CLOSE(UNIT=6200)

!########################### A/P_4
  APN=4
  CALL CARGO(APN)
  CALL PASSENGER(APN)
  CALL DISRUPTION(APN)
  CALL FLIGHT(N,APN)


!Start optimisation and system cost calculations

OPEN(UNIT=6300,FILE="route_c4.txt",STATUS="OLD",IOSTAT=ios)

 FLAG=1

 DO J=B_TME_4,B_MAX_4
  DO I=TG_4,TSG_MAX_4

    CALL AIRPORT(N,I,TG_4,APN)
    CALL ENROUTE(N,APN,J)

     CT_4=0.
     DO K=1,N
      !Cost (CT) calculations
      CDP_4(K)=UC_P*0.5*OUT_D_4(K)**2
      CDA_4(K)=UC_A_G*OUT_D_4(K)
      CBA_4(K)=UC_B*0.5*(I-TG_4)**2

      IF ( IN_D_4(K) <= 0. ) THEN
         CAP_4(K)=0.
         CAA_4(K)=0.
         CBAB_4(K)=UC_B*0.5*(J-B_TME_4)**2
      ELSE
         CAP_4(K)=UC_P*0.5*IN_D_4(K)**2
         CAA_4(K)=UC_A_A*IN_D_4(K)
         CBAB_4(K)=UC_B*0.5*(J-B_TME_4)**2
      END IF

      CI_4(K)=ALFA_A*( CDP_4(K)+CDA_4(K) )+BETA_A*CBA_4(K)+ &
          ALFA_AB*( CAP_4(K)+CAA_4(K) )+BETA_AB*CBAB_4(K)

      CT_4=CT_4+CI_4(K)

     END DO

 !Output cost values to "route_ci.txt" and reference data to BOUT_D_i(*)
```

```
      IF (I == 30 .AND. J == 65) THEN
        !outbound and inbound delay time of the original case
        CALL APOR(N,I,TG_4,APN)
        CALL ER(N,APN,J)
          DO K=1,N
            BOUT_D_4(K)=OUT_D_4(K)
            BIN_D_4(K)=IN_D_4(K)
          END DO
      END IF


      WRITE(UNIT=6300,FMT='(I5,F5.0,F15.0)') I,J,CT_4

! Global cost minimum search

     IF (FLAG == 1) THEN
       MIN_CT_4=CT_4
       OPM_I_4=I
       OPM_J_4=J
     ELSE IF (CT_4 <= MIN_CT_4) THEN
         MIN_CT_4=CT_4
         OPM_I_4=I
         OPM_J_4=J
     END IF

     FLAG=FLAG+1
  END DO
 END DO

!Generate inbound delay time of the global minimum case

  CALL AIRPORT(N,OPM_I_4,TG_4,APN)
  CALL ENROUTE(N,APN,OPM_J_4)

    PRINT *,"Leg_",APN
    PRINT *,"The optimal TSG is", OPM_I_4
    PRINT *,"The optimal B_TME is", OPM_J_4
    PRINT *,"The minimum cost is", MIN_CT_4

!output to results.txt

WRITE(UNIT=270,FMT='(A10,I10)') "Leg_",APN
WRITE(UNIT=270,FMT='(A30,I10)') "The optimal TSG is", OPM_I_4
WRITE(UNIT=270,FMT='(A30,F10.0)') "The optimal B_TME is", OPM_J_4
WRITE(UNIT=270,FMT='(A30,F10.0)') "The minimum cost is", MIN_CT_4


ENDFILE 6300
CLOSE(UNIT=6300)
```

```
!########################### A/P_5
  APN=5
  CALL CARGO(APN)
  CALL PASSENGER(APN)
  CALL DISRUPTION(APN)
  CALL FLIGHT(N,APN)


!Start optimisation and system cost calculations

OPEN(UNIT=6400,FILE="route_c5.txt",STATUS="OLD",IOSTAT=ios)

 FLAG=1

 DO J=B_TME_5,B_MAX_5
  DO I=TG_5,TSG_MAX_5

    CALL AIRPORT(N,I,TG_5,APN)
    CALL ENROUTE(N,APN,J)

     CT_5=0.
     DO K=1,N
      !Cost (CT) calculations
      CDP_5(K)=UC_P*0.5*OUT_D_5(K)**2
      CDA_5(K)=UC_A_G*OUT_D_5(K)
      CBA_5(K)=UC_B*0.5*(I-TG_5)**2

      IF ( IN_D_5(K) <= 0. ) THEN
         CAP_5(K)=0.
         CAA_5(K)=0.
         CBAB_5(K)=UC_B*0.5*(J-B_TME_5)**2
      ELSE
         CAP_5(K)=UC_P*0.5*IN_D_5(K)**2
         CAA_5(K)=UC_A_A*IN_D_5(K)
         CBAB_5(K)=UC_B*0.5*(J-B_TME_5)**2
      END IF

      CI_5(K)=ALFA_A*( CDP_5(K)+CDA_5(K) )+BETA_A*CBA_5(K)+ &
          ALFA_AB*( CAP_5(K)+CAA_5(K) )+BETA_AB*CBAB_5(K)

      CT_5=CT_5+CI_5(K)

     END DO

 !Output cost values to "route_ci.txt" and reference data to BOUT_D_i(*)


      IF (I == 50 .AND. J == 65) THEN
```

```
        !outbound and inbound delay time of the original case
        CALL APOR(N,I,TG_5,APN)
        CALL ER(N,APN,J)
         DO K=1,N
           BOUT_D_5(K)=OUT_D_5(K)
           BIN_D_5(K)=IN_D_5(K)
         END DO
      END IF


      WRITE(UNIT=6400,FMT='(I5,F5.0,F15.0)') I,J,CT_5

! Global cost minimum search

     IF (FLAG == 1) THEN
       MIN_CT_5=CT_5
       OPM_I_5=I
       OPM_J_5=J
     ELSE IF (CT_5 <= MIN_CT_5) THEN
         MIN_CT_5=CT_5
         OPM_I_5=I
         OPM_J_5=J
     END IF

     FLAG=FLAG+1
  END DO
 END DO

!Generate inbound delay time of the global minimum case

  CALL AIRPORT(N,OPM_I_5,TG_5,APN)
  CALL ENROUTE(N,APN,OPM_J_5)

    PRINT *,"Leg_",APN
    PRINT *,"The optimal TSG is", OPM_I_5
    PRINT *,"The optimal B_TME is", OPM_J_5
    PRINT *,"The minimum cost is", MIN_CT_5

!output to results.txt

WRITE(UNIT=270,FMT='(A10,I10)') "Leg_",APN
WRITE(UNIT=270,FMT='(A30,I10)') "The optimal TSG is", OPM_I_5
WRITE(UNIT=270,FMT='(A30,F10.0)') "The optimal B_TME is", OPM_J_5
WRITE(UNIT=270,FMT='(A30,F10.0)') "The minimum cost is", MIN_CT_5


ENDFILE 6400
CLOSE(UNIT=6400)
```

```
!########################## A/P_6
   APN=6
   CALL CARGO(APN)
   CALL PASSENGER(APN)
   CALL DISRUPTION(APN)
   CALL FLIGHT(N,APN)


!Start optimisation and system cost calculations

OPEN(UNIT=6500,FILE="route_c6.txt",STATUS="OLD",IOSTAT=ios)

 FLAG=1

 DO J=B_TME_6,B_MAX_6
  DO I=TG_6,TSG_MAX_6

    CALL AIRPORT(N,I,TG_6,APN)
    CALL ENROUTE(N,APN,J)

     CT_6=0.
     DO K=1,N
      !Cost (CT) calculations
      CDP_6(K)=UC_P*0.5*OUT_D_6(K)**2
      CDA_6(K)=UC_A_G*OUT_D_6(K)
      CBA_6(K)=UC_B*0.5*(I-TG_6)**2

      IF ( IN_D_6(K) <= 0. ) THEN
        CAP_6(K)=0.
        CAA_6(K)=0.
        CBAB_6(K)=UC_B*0.5*(J-B_TME_6)**2
      ELSE
        CAP_6(K)=UC_P*0.5*IN_D_6(K)**2
        CAA_6(K)=UC_A_A*IN_D_6(K)
        CBAB_6(K)=UC_B*0.5*(J-B_TME_6)**2
      END IF

      CI_6(K)=ALFA_A*( CDP_6(K)+CDA_6(K) )+BETA_A*CBA_6(K)+ &
          ALFA_AB*( CAP_6(K)+CAA_6(K) )+BETA_AB*CBAB_6(K)

      CT_6=CT_6+CI_6(K)

     END DO

!Output cost values to "route_ci.txt" and reference data to BOUT_D_i(*)

      IF (I == 30 .AND. J == 65) THEN
        !outbound and inbound delay time of the original case
        CALL APOR(N,I,TG_6,APN)
        CALL ER(N,APN,J)
```

```
        DO K=1,N
          BOUT_D_6(K)=OUT_D_6(K)
          BIN_D_6(K)=IN_D_6(K)
        END DO
      END IF

      WRITE(UNIT=6500,FMT='(I5,F5.0,F15.0)') I,J,CT_6

! Global cost minimum search

     IF (FLAG == 1) THEN
       MIN_CT_6=CT_6
       OPM_I_6=I
       OPM_J_6=J
     ELSE IF (CT_6 <= MIN_CT_6) THEN
         MIN_CT_6=CT_6
         OPM_I_6=I
         OPM_J_6=J
     END IF

     FLAG=FLAG+1
  END DO
 END DO

!Generate inbound delay time of the global minimum case

  CALL AIRPORT(N,OPM_I_6,TG_6,APN)
  CALL ENROUTE(N,APN,OPM_J_6)

    PRINT *,"Leg_",APN
    PRINT *,"The optimal TSG is", OPM_I_6
    PRINT *,"The optimal B_TME is", OPM_J_6
    PRINT *,"The minimum cost is", MIN_CT_6

!output to results.txt

WRITE(UNIT=270,FMT='(A10,I10)') "Leg_",APN
WRITE(UNIT=270,FMT='(A30,I10)') "The optimal TSG is", OPM_I_6
WRITE(UNIT=270,FMT='(A30,F10.0)') "The optimal B_TME is", OPM_J_6
WRITE(UNIT=270,FMT='(A30,F10.0)') "The minimum cost is", MIN_CT_6


ENDFILE 6500
CLOSE(UNIT=6500)


!########################## A/P_7
   APN=7
   CALL CARGO(APN)
   CALL PASSENGER(APN)
```

```
   CALL DISRUPTION(APN)
   CALL FLIGHT(N,APN)


!Start optimisation and system cost calculations

OPEN(UNIT=6600,FILE="route_c7.txt",STATUS="OLD",IOSTAT=ios)

 FLAG=1

 DO J=B_TME_7,B_MAX_7
  DO I=TG_7,TSG_MAX_7

    CALL AIRPORT(N,I,TG_7,APN)
    CALL ENROUTE(N,APN,J)

     CT_7=0.
     DO K=1,N
      !Cost (CT) calculations
      CDP_7(K)=UC_P*0.5*OUT_D_7(K)**2
      CDA_7(K)=UC_A_G*OUT_D_7(K)
      CBA_7(K)=UC_B*0.5*(I-TG_7)**2

      IF ( IN_D_7(K) <= 0. ) THEN
         CAP_7(K)=0.
         CAA_7(K)=0.
         CBAB_7(K)=UC_B*0.5*(J-B_TME_7)**2
      ELSE
         CAP_7(K)=UC_P*0.5*IN_D_7(K)**2
         CAA_7(K)=UC_A_A*IN_D_7(K)
         CBAB_7(K)=UC_B*0.5*(J-B_TME_7)**2
      END IF

      CI_7(K)=ALFA_A*( CDP_7(K)+CDA_7(K) )+BETA_A*CBA_7(K)+ &
          ALFA_AB*( CAP_7(K)+CAA_7(K) )+BETA_AB*CBAB_7(K)

      CT_7=CT_7+CI_7(K)

     END DO

!Output cost values to "route_ci.txt" and reference data to BOUT_D_i(*)

      IF (I == 25 .AND. J == 65) THEN
        !outbound and inbound delay time of the original case
        CALL APOR(N,I,TG_7,APN)
        CALL ER(N,APN,J)
         DO K=1,N
           BOUT_D_7(K)=OUT_D_7(K)
           BIN_D_7(K)=IN_D_7(K)
         END DO
```

```
    END IF

    WRITE(UNIT=6600,FMT='(I5,F5.0,F15.0)') I,J,CT_7

! Global cost minimum search

   IF (FLAG == 1) THEN
     MIN_CT_7=CT_7
     OPM_I_7=I
     OPM_J_7=J
   ELSE IF (CT_7 <= MIN_CT_7) THEN
       MIN_CT_7=CT_7
       OPM_I_7=I
       OPM_J_7=J
   END IF

   FLAG=FLAG+1
 END DO
END DO

!Generate inbound delay time of the global minimum case

 CALL AIRPORT(N,OPM_I_7,TG_7,APN)
 CALL ENROUTE(N,APN,OPM_J_7)

   PRINT *,"Leg_",APN
   PRINT *,"The optimal TSG is", OPM_I_7
   PRINT *,"The optimal B_TME is", OPM_J_7
   PRINT *,"The minimum cost is", MIN_CT_7

!output to results.txt

WRITE(UNIT=270,FMT='(A10,I10)') "Leg_",APN
WRITE(UNIT=270,FMT='(A30,I10)') "The optimal TSG is", OPM_I_7
WRITE(UNIT=270,FMT='(A30,F10.0)') "The optimal B_TME is", OPM_J_7
WRITE(UNIT=270,FMT='(A30,F10.0)') "The minimum cost is", MIN_CT_7


ENDFILE 6600
CLOSE(UNIT=6600)



!>>>>>>>>>>##############################################<<<<<<<<<<
!output original simulation results to net_or.txt

 OPEN(UNIT=250,FILE="net_or.txt",STATUS="OLD",IOSTAT=ios)

  DO I=1,N
```

```
   WRITE(UNIT=250,FMT='(I5,14F10.2)') I,BOUT_D_1(I),BIN_D_1(I), &
                          BOUT_D_2(I),BIN_D_2(I), &
                          BOUT_D_3(I),BIN_D_3(I), &
                          BOUT_D_4(I),BIN_D_4(I), &
                          BOUT_D_5(I),BIN_D_5(I), &
                          BOUT_D_6(I),BIN_D_6(I), &
                          BOUT_D_7(I),BIN_D_7(I)
 END DO

 ENDFILE 250
 CLOSE (UNIT=250)

!output system optimum to net_opm.txt

 OPEN(UNIT=260,FILE="net_opm.txt",STATUS="OLD",IOSTAT=ios)

 DO I=1,N
   WRITE(UNIT=260,FMT='(I5,14F10.2)') I,OUT_D_1(I),IN_D_1(I), &
                          OUT_D_2(I),IN_D_2(I), &
                          OUT_D_3(I),IN_D_3(I), &
                          OUT_D_4(I),IN_D_4(I), &
                          OUT_D_5(I),IN_D_5(I), &
                          OUT_D_6(I),IN_D_6(I), &
                          OUT_D_7(I),IN_D_7(I)
 END DO

 ENDFILE 260
 CLOSE (UNIT=260)

PRINT *,"----------->>PROGRAMME APNETWORK IS DONE!!<<-----------"

END PROGRAM APNETWORK
```