ABSTRACT

Title of Document: REAL-TIME CONTROL MODEL IN AIRLINE DELAY MANAGEMENT

Han Dong, Master of Science, 2014

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Real-time control in airport management can reduce delay cost and alleviate delay propagation in an airline network. In this study, a model is developed for determining holding decisions and departure policies for flights which are ready to depart, except for their transfer passengers from late arrival flights. Optimization with downstream coordination (ODC) and without downstream coordination (ONDC) are presented in the model. The results show that ODC and ONDC could reduce system total cost when flights are delayed, and ODC performs better than ONDC. The sensitivity analysis of the total cost to various inputs is also discussed. The results show that the system total cost varies with holding time, slack time, number of transfer passengers and headway.

REAL-TIME CONTROL MODEL FOR AIRLINE DELAY MANAGEMENT

By

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Thesis submitted to the Faculty of the Graduate School of the
University of Maryland, College Park, in partial fulfillment
of the requirements for the degree of
Master of Science
2014

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Chapter 1: Introduction

1.1 Background

Air traffic volumes have increased rapidly in recent years. In order to satisfy the demands and efficiently utilize available resources, flights are tightly scheduled especially in hub airports. Unpredictable factors, such as air space congestion, severe weather, and mechanical problems may disrupt flight schedules and cause delay. Flight delays can create problems such as flights rescheduling, cancelation, or missed connection for passengers. Adding to this challenge is the fact that each flight's delay can propagate to disrupt subsequent downstream flights that await the delayed flight.

In airline networks, passengers use hub airports to transfer into flights to their intended destination. When delays of inbound flights occur, passengers on delayed flights may miss their connecting flights and have to reschedule their trips. Therefore, it is important to make real-time decisions to alleviate the occurrences and effects of missed connections and reduce the delay cost when delay occurs.

1.2 Research Objectives

The objective of this research is to develop an optimization model for reducing the number of missed connection passengers and the delay cost in an airline network.

This real-time control model focuses on decisions regarding flights' holding time and departure sequences at a hub airport and at airports downstream from it. When flights are delayed, the control model determines holding decision for outbound flights through an optimization process. The above real-time control model can adjust the pre-planned schedule in response to the arrival delay and the consecutive departure time of connecting flights.

This is done primarily by:

(1) Providing information on downstream demands, late flight arrival time, and scheduled departure time

(2) Formulating cost functions for evaluating system improvements obtained through recovery from routine disruptions.

(3) Developing a model structure for optimizing the holding and dispatching time based on given information.

(4) Introducing a numeric example with a simple network configuration that test the developed model.

(5) Analyzing the effects of different input data to determine how the optimized results vary with the uncertainties.

1.3 System Definitions

A real-time control model is introduced and performance of the above control model is also analyzed in this study.

The real-time control model focuses on decisions regarding each ready departure flight which is waiting for late arrival flights. When route disruptions occur, passengers on delayed incoming flights may miss their connection when transfer time is insufficient. The control model determines the holding time and departure sequence of waiting flights through an optimization process. Comprehensive probabilistic evaluation functions are used to minimize the various costs of held flights. The flights' travel time may be partially controllable in real world. In this study, the travel time distribution is based on historical data.

Considering the side effects of the holding decision that delays may propagate and affect airline schedules at downstream airport, integrated holding decisions and optimization process of departure sequences are applied at all airports in the study.

1.4 Organization of Thesis

In this thesis, Chapter 1 introduces the research background and motivation, the problem definition, research objectives, and research approach. Chapter 2 presents a literature review of descriptive studies of timed transfer systems, existing methodologies for decreasing flights delay propagation, and relevant works in schedule coordination of transit systems. Several previous studies of real-time control methods for dealing with delays through airline and cargo transfer networks are also discussed in this chapter.

In Chapter 3, a model for a real-time control problem is presented. An analysis of delay propagation, an integrated holding model for reducing delays and attenuating propagation are presented. According to the pre-planned flight schedule and real-time information, different strategies for holding decisions with different slack times are introduced. In Chapter 4, a sorting algorithm is used to solve the problem of flights' departure sequence and holding time.

In Chapter 5, this model is analyzed with an example of an airline network with multiple airports and multiple flights. Sensitivities of system total costs to various headways, slack times and number of transfer passengers are also analyzed. Finally, a summary of major findings, contributions and suggestions for future research directions are presented in Chapter 6.

Chapter 2. Literature Review

A robust plan can reduce the occurrence and impact of delays. Moreover, an effective delay reaction plan could also reduce the impact of delays and costs after delays occur. The methods of reducing airline delays and delay costs have been studied extensively and numerous models and algorithmic approaches have been developed. The literature reviewed in this section is divided into the following categories: Airline hub operation; airport gate assignments for stochastic flight delays; and scheduled slack time re-allocation for flight delays.

2.1 Airline Hub Operation

In previous research, Gordon and de Neufville (1973) analyzed the structure of passenger airline networks and compared with the objective of minimizing schedule delay. The authors pointed out that hub and spoke networks could minimize overall schedule delay for a given cost in the entire system.

Hall and Chong (1993) analyzed delays for passengers connecting between aircraft at a hub terminal. They found the arrival lateness distribution followed a shifted gamma distribution under normal conditions (delay less than 30 minutes) and a shifted exponential distribution under abnormal conditions, such as equipment failures or bad weather (delays greater than 30 minutes). In their study, the schedule was optimized based on a simulation model. It was concluded that about 50% of the time is required by the runway to serve the entire bank at normal condition. This yielded the minimum queuing delay and schedule delay at the hub terminal. However, their study did not consider the optimization plan of the airline schedule.

Trietsch (1993) developed two models for minimizing the total time cost plus the total unscheduled delay penalties, with and without waiting for late arrivals, for ready departure flights at hub airports. The study considered airline overtime expenses, time value of passengers and missed connection penalties in the total expected time and penalty. The research also developed a heuristic method for the waiting case without involving numerical integrals. However, he did not consider en-route slack time in the study which could overestimate the delay penalties.

Shen (1994) analyzed the optimal holding time of connecting flights at a hub airport when some flights are behind schedule. The objective was to minimize the sum of the connection cost, holding departure cost and fuel consumption cost to achieve connections at the next airport and the possible transfer cost at downstream airports. However, this model only considered an airline network with two hub airports.

2.2 Robust Airline Operations

Robust operation could improve an operating system's ability to perform effectively under ordinary conditions and unusual conditions. It has been studied by many researchers and applied in various fields. The methodologies used in this area include stochastic programming, uncertainty model and scenario planning. Stochastic and robust optimization concepts have been employed to deal with planning problems under uncertain disturbances in several fields. Mulvey et al (1995) used solution robustness and model robustness concepts to develop robust optimization models.

The airline schedule planning problem has been studied extensively. Many models and algorithmic approaches have been developed. Cohn and Barnhart (2003) presented structural overviews of this planning process and detailed literature review. The solution to the fleet assignment problem was the assignment of a specific aircraft type to each flight leg in the schedule, matching as closely as possible the seat capacity of aircraft to the demand. Lan et al. (2006) proposed a new approach to reduce delay propagation by intelligently routing aircraft and formulating the problem as a mixed integer programming problem with stochastically generated inputs. Their study considered miss connecting passengers and developed a new approach to minimize the number of passenger misconnections by retiming the departure times of flights within small time windows. However, they did not consider the cost of aircraft and passengers when retiming the schedule. Desaulniers et al. (1997) presented an application to solve a pairing problem with nonlinearities occur in the objective function and in a large set of constraints. They used a branch-and-bound algorithm to solve their model.

A number of analytical gate assignment models have been developed. In Bihr(1990), a conceptual solution to the gate assignment problem was introduced. The author discussed derivation of problem parameters and then solved several representative problems using linear programming. Cheng (1997) proposed a knowledge-based airport gate assignment system. The system was integrated with mathematical programming techniques and provided a solution which satisfies both static and dynamic situations within a reasonable computing time. A partial parallel assignment was introduced and a multi-objective function was applied to optimize the gate assignments. Yan and Chang (1998) developed a network model to solve gate assignment problem. An algorithm based on Lagrangian relaxation, with sub-gradient methods accompanied by a shortest path algorithm was developed to solve the problem.

Haghani and Chen (1998) presented a new integer programming formulation of the gate assignment problem and minimize passenger walking distance inside the terminal. In the study, the total walking distance was based on the passenger transfer volume between every pair of aircraft and the distance between every pair of gates. An efficient heuristic solution procedure was used for solving the problem and the performance showed the model could solve large scale gate assignment problem.

Bolat (2000) used a mixed-binary mathematical model with a quadratic function for minimizing the variance of idle time in the gate assignment problem. Gu and Chung (1999) resolved a gate assignment problem with real-time operations when there were stochastic flight delays. Yan et al. (2002) proposed a simulation framework evaluating the interrelation between the planned and the real-time gate assignment to reduce the stochastic flight delays that occurred in real operation. In the studies mentioned above, the objective functions included the minimization of the total passenger waiting time, the total passenger walking distance, the number of off-gate events, the range of unutilized periods for gates, the variance of idle times at gates. However, the proposed flight schedules in the models were fixed, and the common stochastic flight delays that occur in actual daily operations were neglected.

Kang (2004) introduced the concept of degradable airline scheduling and applied degradable schedule partitioning model (D-SPM), a degradable fleet assignment model (D-FAM) and degradable aircraft routing model (D-ARM). He used tabu search to locally optimize the schedule based on each flight's revenue. In order to minimize the lost, the model protected flights with higher revenue and sacrificed flights with lower revenue when delays occur. However, the study did not consider delay cost and missed connection cost of passengers at downstream airports when delays propagate.

Anderson and Carr, et al. (2000) developed a model of ground operations at hub airports. In the research, data from the Airline Service Quality Performance (ASQP) database was used and three models of aircraft arrival, turn-around and departure operation were built in order to capture the dynamics of busy hub airport operations. They pointed out that the models can be concatenated to build an airport congestion prediction capability and can be used to evaluate improvements in airport operations.

In Ting and Schonfeld (2007), a dispatching model for multi-route and multi-hub transit networks was developed for optimizing holding time for each ready vehicle based on arrival delays of late incoming vehicles. A heuristic algorithm was used to optimize the holding time based on real-time information. The results showed that ready vehicles should be dispatched immediately when uncertainty about late vehicle arrival is relatively large. They also showed how the dispatching time of ready vehicles should increase with the increases in expected connecting passengers.

Chen and Schonfeld (2010) developed an analytical model for coordinating vehicle schedules and cargo transfer at terminals. The model optimized the coordinated services frequencies for minimizing the total cost. Their study also considered two conditions of cargo delivery: (1) constant time function of cargos shipped through a single hub and (2) nonlinear time function of cargos shipped between multiple hubs. However, the study only considered cargo delivery through a hub or between multiple hubs and did not consider cargo deliveries between non-hub terminals and hubs.

2.3 Summary

After reviewing the above studies, it appears that the optimization of airline fleet assignment and gate assignment has already been well developed for both single and multiple hub airports. The study in the thesis focuses on a real-time control model considering optimizations of flight dispatching and sequencing decisions at multiple airports.

Chapter 3. Real-Time Control Model for Hub Airport

Over the last decade, automated systems and information systems have advanced greatly. Systems can accurately provide real-time information, which could be updated every one or two seconds to support operation controls. Based on such information, airlines can predict flights delays prior aircraft arrival and more accurately estimate late arrival time.

When delays occur in an airline network, efficiently rescheduling the departure time of outbound flights can largely reduce the cost caused by delayed incoming flights. When delay time exceeds the transfer slack time set between two flights, passengers on late arrival flight who need transfer may miss their connection.

In this chapter, a real-time control model is developed to minimize the total cost of an airline system by optimizing the holding time and departure sequence of held flights when delay occurs.

3.1 System Definition

The real-time control model presented here can reduce missed connection cost and alleviate delay propagation by holding ready departure flights and efficiently rescheduling held flights' departure sequences. Considering the propagation of delay at downstream airport when flights are held, the holding decision and departure sequence of outbound flights at downstream airports are also optimized in the model.

The purpose of the model is to obtain a minimum total system cost by determining the best holding time of each outbound flight after delays occur. When departure times of held flights conflict, the decision about departure sequence should be made to minimize the extra cost of waiting for departure. A sorting algorithm is used to solve the sequencing problem in which departure time of each flight should satisfy the time constraints.

In the network, two types of airports are defined: hub airport and non-hub airport. Airlines use hub airports to transfer passengers among flights. A hub airport is part of a hub and spoke model, where travelers moving between airports not served by direct flights, need to change planes en-route to their destinations. Non-hub airports are airports with no direct passenger transfers among flights. Multiple airplanes with different capacities and loading are also considered in the model. When disruptions occur, real-time holding decisions are considered for all flights which are coordinated at the hub airports. The flow chart in Figure 3.1 shows the optimization process of the model. Two stages of optimization are considered in the model. The first stage optimizes the holding time of held flights. The second stage optimizes the departure sequence of held flights when time slots between departure times of flights do not meet constraints.

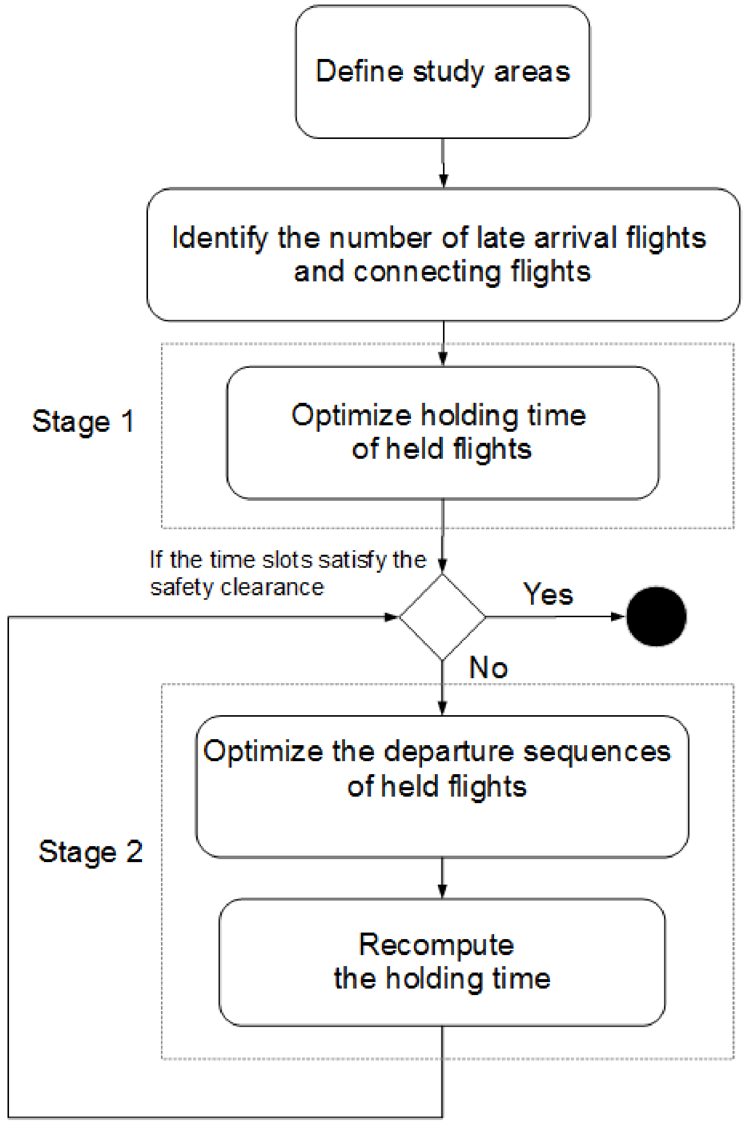

Figure 3.1 Flow Chart for Real-Time Holding Control

The model formulated below assumes that delay times of late arrival flights are obtained from a real time information system, while other flights arrive according to one of three possible probability distributions, namely Log-normal, Gamma or Weibull. The most suitable probability distribution is determined based on historical data and assumed to be known when the optimization process begins.

In airline operations, multiple flights may depart simultaneously when airports have enough capacity. However, it is assumed in the model that held flights in the model use the same runways to depart and thus interact when the departure time slot between two flights is less than departure clearance.

When there are no return flights from downstream airports, the holding decisions of waiting flights at origin airport can be made independently. In this study, it is assumed that held flights are operated independently from other flights in the same airports.

3.2 Definition of Time in Model

Definitions and components of time in the model are introduced in this section. Figure 3.2 shows a diagram of time used in airline operations. In the figure, SAT is the scheduled arrival time and ACT is the actual arrival time. SDT is the scheduled departure time and ADT is the actual departure time.

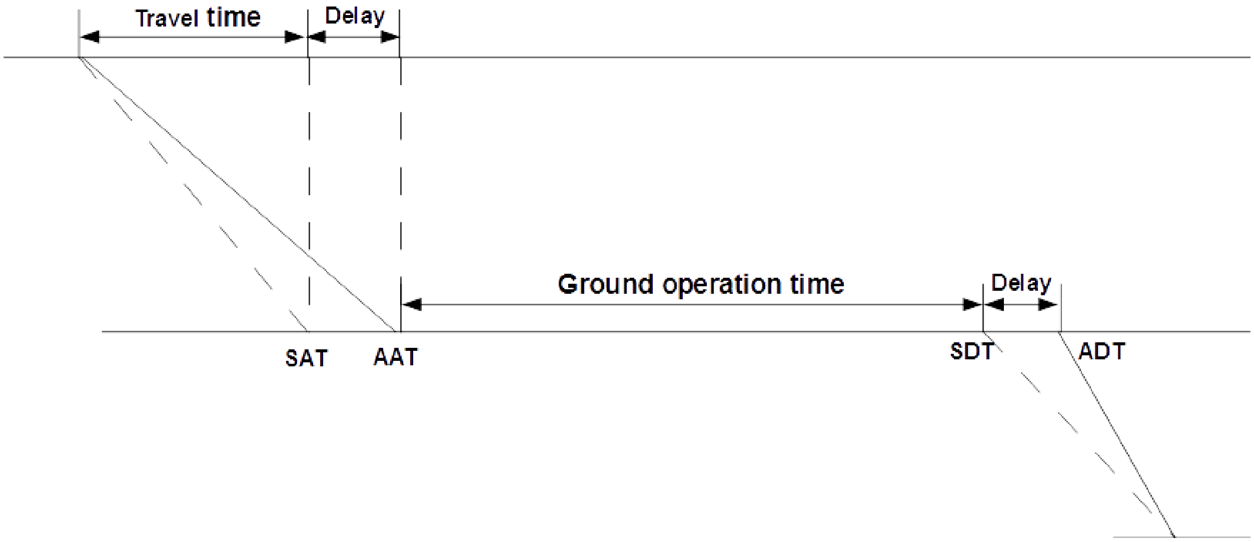

Figure 3.2 Time Components in Airline Operation

3.2.1 Ground Operation Time

Ground operation time includes ground handling time, taxi in time and taxi out time.

(1) Ground Handling Time

Ground handling includes cabin service, catering, ramp service, passenger service, and field operation service. When flights are delayed, an airport may speed-up its ground operation and save time by adding service equipment and labor. However, in our model, the ground handling times are assumed to be pre-determined.

(2) Taxi in Time and Taxi out Time

Taxi in time is the period between the time when aircraft's wheels touch the ground and the time that the aircraft arrives at a gate. Taxi out time is the duration from the time when an aircraft leaves the gate to the time when its wheels leave the ground. In order to obtain the distribution of taxi in time and taxi out time, we use the data on taxi in time and taxi out time in the TranStats database of the Bureau of Transportation Statistics. Since taxi in time and taxi out time are assumed to be fixed in the model, the average time in the database is chosen. Taxi in time is 5 minutes and taxi out time is 14 minutes.

3.2.2 Flight Time

The definition of flight time is a period of time an airplane spends traveling between two airports. In the study, the flight times are set due to travel distance between two airports and type of aircraft. We assume that when the departure delay exceeds en-route slack time, arrival delay occurs at the downstream airport.

3.2.3 En-Route Delay and Ground Delay

En-route delay occurs when a flight spends extra time en-route which exceeds the scheduled slack time. The distribution of flight en-route delay time can be obtained from historical data and can be described as a type of continuous distribution. Ground delay is also another factor when we consider the in on time performance of a flight. The distribution of ground delay time can also be obtained from historical data.

In this section, we determine the distribution of delays using the Airline Service Quality Performance (ASQP) database. The ASQP database provides flight information for each flight of major airlines in the United States. This database also provides the arrival and departure information for each flight. In the database, delays are usually strongly asymmetric, with some flights arrive and leave early, but most flights are on time or late. Therefore, the natural candidates for the delay distribution are the gamma, log-normal, and Weibull distributions.

SAS is employed to estimate the parameters and calculate the test statistics. The χ^2 test and the Kolmogorov test are used to determine if the delay follows a specific distribution. With a significance level of 0.01, the null hypothesis is accepted that 92% of all flights follow a log-normal distribution. Figures 4.3 and 4.4 show the distributions and summary statistics of en-route delay and ground delay.

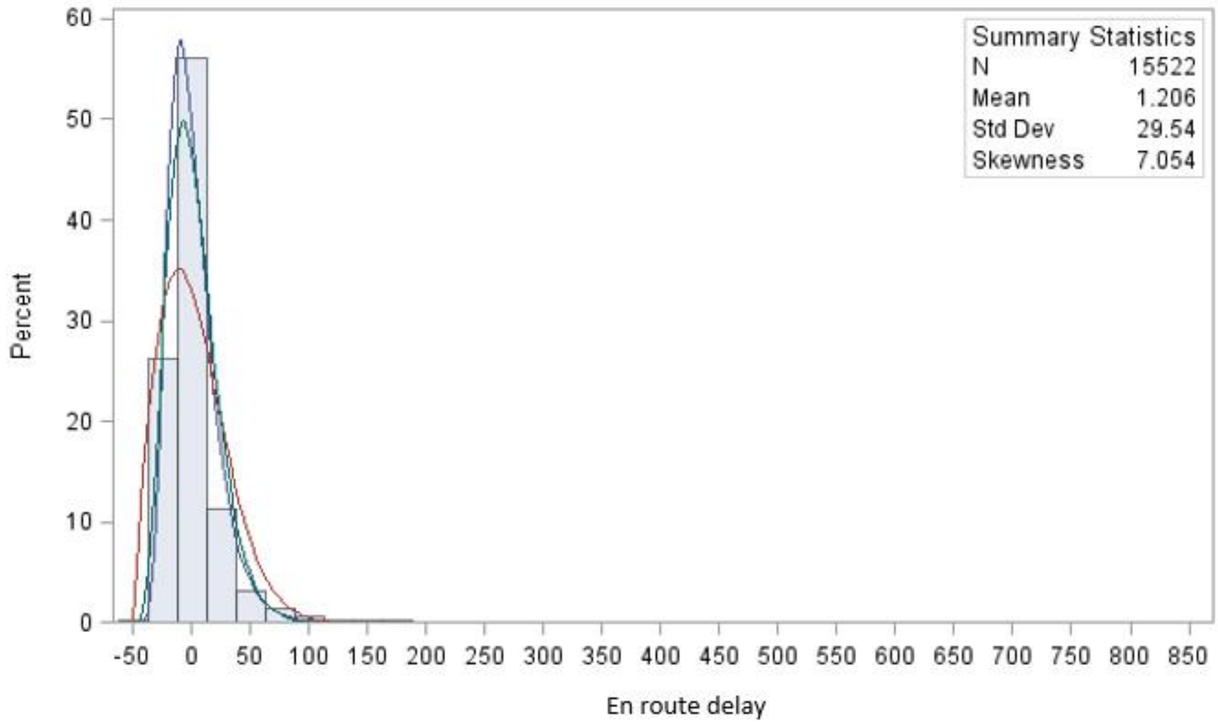

Figure 3.3 Distribution of en-route delay time

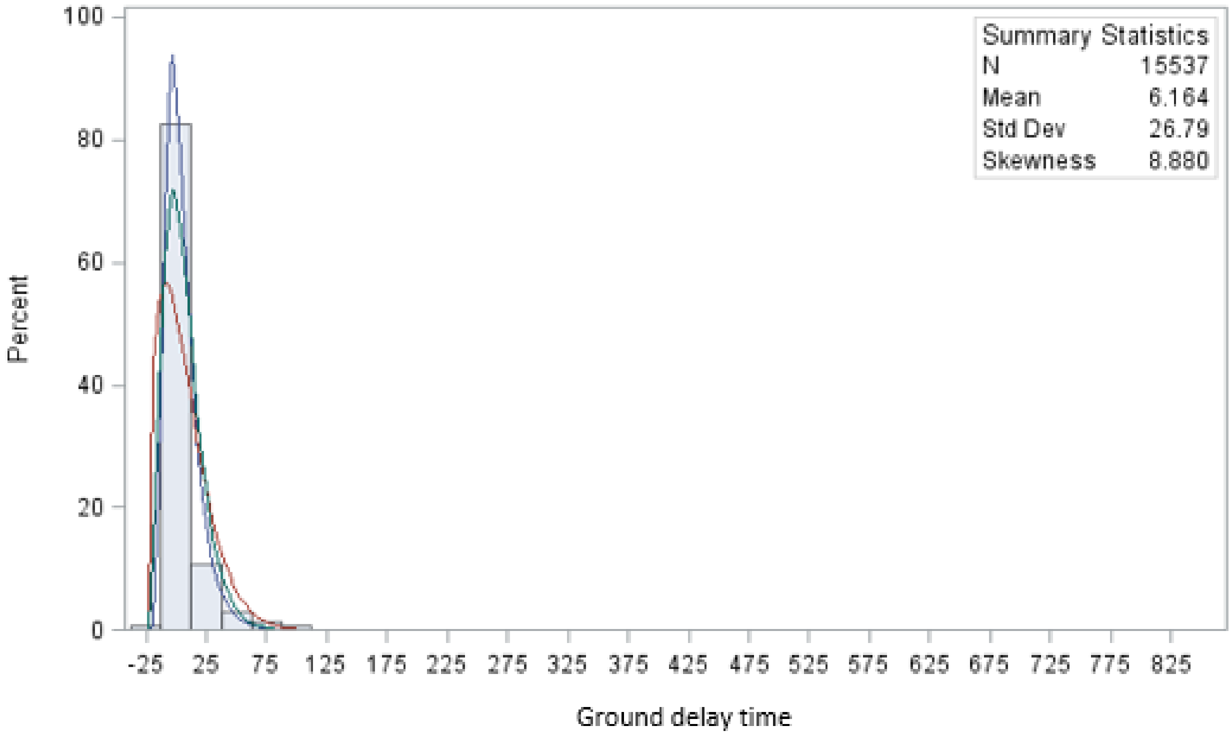

Figure 3.4 Distribution of ground delay time

It should be noted that delay can be negative when flights spend less time than scheduled and some arrival time distribution have infinite left tails which cannot strictly represent reality. However, even when such distributions are used to approximate the true arrival distributions, their negative tails are quite small.

3.2.4 Slack Time

Slack time is a safe margin set in flight's schedule to increase schedule's robustness. The holding decision may lead to delay of held flights. Delay propagates to downstream airports when slack time is insufficient to absorb it. Slack time can be set both en-route and at airports: (1) slack time set in the ground operation, S_g; (2) slack time set en-route, S_r; (3) slack time set in the transfer time of passenger from an incoming flight to an outbound flight, S_t. When delay time exceeds S_t, transfer passengers miss their connection and missed connection costs are incurred.

3.2.5 Holding Time

Holding time of flights is considered in the model. Adding holding time allows more transfer time for passengers from the late arrival flight to held flights, which could reduce the number of transfer passengers who miss connection. In the model, holding time consists of two parts: (1) basic holding time needed for passenger transferring from late arrival flight to outbound flights, Δ_b; (2) time spent waiting for departure after boarding is finished, Δ_s.

$$\Delta = \Delta_b + \Delta_s \tag{3.1}$$

Basic holding time can be estimated from incoming flights' arrival delay time and minimum ground operation time. Δ_s is determined from the time of waiting for departure. In order to determine Δ_s, the departure sequence of held flights should be determined.

Holding time can be formulated in objective functions that consider the operating cost of holding an aircraft, the waiting cost for passengers already on board, the missed connection cost for transferring passengers both on late arrival flights and held flights and the consequences of delay at downstream airports in the network.

3.3 Cost Function

In order to find the minimum total cost of flights in the system, a system-wide cost function is formulated in this section. Late arrival flights and outbound flights are considered in the model. A holding decision is made when time between a delayed flight's actual arrival time and connecting flight's departure time is insufficient for passengers' transfer. In order to minimize the total cost in the system, holding decisions can be made to reduce missed connection cost of transfer passengers. Four components in the objective function for the holding decision can be identified in the model: (1) flight's operating cost, (2) waiting cost for on board passengers, (3) missed connection cost for transfer passengers on incoming flights, (4) waiting cost for passengers waiting at downstream airports.

The total cost of holding ready flights at a hub airport is:

$$C = C_o + C_b + C_w + \mathrm{C}_m \tag{3.2}$$

where C: Total cost of holding ready aircraft f and letting late aircraft land first

C_o: Aircraft operating cost

C_b: Waiting cost for on board passengers

C_w: Waiting cost for passengers at downstream transfer airport

C_m: Missed connection cost for passengers on delayed flight

3.3.1 Operating Cost

The operating cost of flights includes the cost of aircraft and crews. The cost increases with the increase of operating time of an aircraft. Therefore, the aircraft's extra operating cost includes the cost of the holding time at upstream airports Δ_j and delay time d_j, for both aircraft and crew. B in the function is the unit operating cost of a flight.

$$C_o = B(\Delta_j + d_j + S_{rj} + S_{gj}) \tag{3.3}$$

where d_j: Delay time of outbound flight j before being held;

Δ_j: Holding time of flight j;

S_{rj}: En-route slack time of flight j;

S_{gj}: Ground slack time of flight j;

3.3.2 Delay Cost

In the model, there are two types of delay costs: (1) delay cost of boarding passengers who are waiting for an incoming flight, C_w; (2) delay cost for on-board passengers on held flight, C_b. In the delay cost function, d_{rj} are en-route delay time and d_{gj} are ground delay time of flight i at downstream airport. Equations 4.4 and 4.5 show the two types of delay cost.

$$C_w = \begin{cases} \mu \sum_j [(d_j + \Delta_j + d_{rj} + d_{gj} - S_{rj} - S_{gj})(q_{wj} + 0.5 q_{wlj})], \\ \qquad d_j + \Delta_j + d_{rj} + d_{gj} > S_{rj} + S_{gj} \\ 0, \\ \qquad d_j + \Delta_j + d_{rj} + d_{gj} \le S_{rj} + S_{gj} \end{cases} \tag{3.4}$$

$$C_b = \begin{cases} \mu \sum_j [(d_j + \Delta_j + d_{rj} - S_{rj}) q_{bj}], & d_j + \Delta_j + d_{rj} > S_{rj} \\ 0, & d_j + \Delta_j + d_{rj} \le S_{rj} \end{cases} \tag{3.5}$$

where C_w: Waiting cost for passengers who are waiting for held flights at downstream airport;

C_b: Waiting cost for on board passengers on held flights;

d_{rj}: En-route delay of flight j;

d_j: Ground delay of flight j;

Δ_j: Holding time of flight j;

q_{wj}: Number of passengers waiting for held flight j at downstream airport;

q_{wlj}: Number of passengers waiting for held flight j at downstream airport and arrive during flight late departure time;

$q_b j$: Number of passengers on board when flight j is held.

The probabilistic model for delay cost function consists of a probability distribution of delay time for held flights. Since the number of passengers that arrive during flights' holding time is quite small, the probability distribution of late arrival passengers' is not considered in the cost function. We should note that the probabilistic model of flights is applied at downstream airports.

$$C_w = \mu \sum_j [\left(\int_0^\infty (d_j + \Delta_j + f(d_{rj}) + f(d_{gj}) - S_{rj} - S_{gj}) d(t) \right) (q_{wj} + 0.5 q_{wlj})] \quad (3.6)$$

$$C_b = \mu \sum_j [\left(\int_0^\infty (d_j + \Delta_j + f(d_{rj}) - S_{rj}) d(t)\right) q_{bj}] \quad (3.7)$$

where $f(d_{rj})$: Density function of en-route delay time of flight j;

$f(d_{gj})$: Density function of ground delay time of flight j;

3.3.3 Missed Connection Cost

Missed connection of passengers occurs when a delayed flight arrives later than the departure of connecting flight or the time left for passenger transfer from late arrival flights to connecting flights is not enough. We assume the transfer distance and transfer time between two flights are neglected. Thus, we can only consider the situation that outbound flights are scheduled to depart during delay of late arrival flights. In the model, we also consider departure delay d_j of outbound flights. Delay time of late arrival flight d_i, is determined at first airport. Headway of outbound flights h_j is pre-determined in the schedule.

In the model, information of incoming flights' arrival delay time and outbound flights' departure delay time is updated when making holding decisions, while other input information is pre-scheduled in the system. When incoming flight's delay d_i exceeds transfer slack time $d_j + \Delta_j + {S^{ij}}_t$, missed connection cost occurs. We assume that the arrival delay of incoming flights and departure delay of outbound flights are independent of each other before being held. Equation 3.8 shows the missed connection cost.

$$\mathrm{C}_m = \begin{cases} \mu \sum_i \sum_j (h_j - d_i + S^{ij}{}_t) q_m^{ij}, & d_i - d_j - \Delta_j > S^{ij}{}_t \\ 0, & d_i - d_j - \Delta_j \leq S^{ij}{}_t \end{cases} \tag{3.8}$$

where C_m: Missed connection cost of passengers on flight i;

μ: Passenger's time cost ($/min-person);

h_j: Headway of connecting flight j or flights to the same destination;

q_m^{ij}: Number of passengers will transfer from delayed flight i to connecting flight j

d_i: Delay time of incoming flight i;

d_j: Delay departure time of outbound flight j before holding decision;

$S^{ij}{}_t$: Pre-planned transfer slack time between flights i and j .

Δ_j: Holding time of flight j

3.4 Total Cost of Holding Decision

Costs of three types of flights are considered in the model: (1) late arrival flights, (2) outbound flights which are waiting for late arrival flights and (3) outbound flights which are waiting at airports downstream from held flights. Delay cost, operating cost and missed connection cost are included in the cost function of real-time control model.

The total system cost is shown in Equation 3.9

$$C = C_i + C_j + C_c \tag{3.9}$$

where C_i: Cost for late arrival flights

C_j: Cost for holding outbound flight

C_c: Cost for holding outbound flight of held flights

3.4.1 Cost for Late Arrival Flights

When an incoming flight is delayed and scheduled transfer time between two flights is insufficient for transferring, transfer passengers incur a missed connection cost. Missed connection cost increases with the increase of delay time of an incoming flight. Holding decision on outbound flights allows more transfer time for passengers and can reduce delay cost and missed connection. In the model, only missed connection cost will be considered in the cost function of late arrival flights at first airport. The objective function is the total cost associated with the holding time of an outbound connecting flight. Equation 4.10 is the cost function of late arrival flight.

$$C_i = C_m \tag{3.10}$$

3.4.2 Cost for Holding Outbound Flights

Operating cost, waiting cost of on-board passengers, waiting cost of boarding passengers, missed connection cost of transfer passengers on held flights at downstream airports are included in the total cost of holding outbound flights at first airport.

The total cost function can be separated into two types according to locations: (1) Cost at upstream airport, where holding decision is made; (2) Cost at downstream airports when delay propagate. In the first type of cost, operating cost C_o and on-board passengers' delay cost C_b are included. The passenger waiting cost C_w of held flights and missed connection cost C_m are included in the second type of cost. Equation 3.11 shows the cost function of held flights

$$C_j = \sum_{c}(C_o + C_b + C_w + \sum_{k} C_m) \tag{3.11}$$

where c: Index of waiting flights at current airports;

k: Index of waiting flights at downstream airports;

3.4.3 Cost for Holding Outbound Flights of Held Flight

When a flight is held at an upstream airport, delays may occur and propagate to its downstream airports. In the model, the holding decisions of flights at downstream airport are determined based on the holding time and arrival delay time of incoming flights which are held at upstream airports. Equation 3.12 shows the delay time of incoming flights.

$$d_i = d_j + \Delta_i + d_r - S_r \tag{3.12}$$

where Δ_i: Holding time of incoming flights at upstream airport;

The operating cost C_o, delay cost for on-board passengers C_b and missed connection cost C_m are considered in the cost function. In order to simply the problem, only missed connection is considered at further downstream airport. Equation 3.13 shows the cost function of holding flights.

$$C_c = \sum_c (C_o + \mathrm{C}_b + \sum_k \mathrm{C}_m) \tag{3.13}$$

where c: Index of waiting flights at current airports;

k: Index of waiting flights at airports further downstream.

3.5 Summary

In this chapter, a real-time control model is introduced in two sections.

The first section introduces the system definition and the definition of time in airline operations. Three types of distributions are used to fit the historical data of en-route delay time and ground delay time. SAS is employed to test the distributions and find log-normal distribution has the best fitness.

In the second section, basic cost functions and cost functions for real-time control model are formulated.

Chapter 4. Solution Approach

Sorting algorithms are being well developed and are used to optimize the results when departure sequences are considered in the model. In this chapter, solution approaches of sequencing problem are introduced. Sections 4.1 and 4.2 briefly introduce the fundamental and the methodology of sorting algorithm. Some basic concepts of sorting algorithms are introduced below. The application of a sorting algorithm in the model is also introduced in Section 4.3.

4.1 Fundamentals of Sorting Algorithms

Demuth (1985) introduced the sorting algorithm which could be applied in computation. A sorting algorithm is an algorithm that puts elements of a list in a certain order. The most used orders are numerical order and lexicographical order. Efficient sorting is important for optimizing before using other algorithms which require input data to be in sorted lists. It is also often useful for normalization data and for producing human readable output. The output should satisfy two conditions:

1. The output is in non-decreasing order (each element is no smaller than the previous element according to the desired total order);

2. The output is a permutation of the input.

The data in the algorithm is often taken to be in an array, which allows random access, rather than a list, which only allows sequential access. Compared with a heuristic algorithm, a sorting algorithm can usually find a global optimum quickly.

4.2 Methodology

Merge sort is a comparison-based sorting algorithm. Most implementations produce a stable sort, which means that the implantation preserves the input order of equal elements in the sorted output. Merge sort is a divide and conquer algorithm that was invented by John von Neumann (1945). A detailed description and analysis of bottom-up merge sort is introduced by Goldstine and Neumann (1948).

A merge sort works as follow and Figure 4.1 shows an example of the algorithm:

1. Data is divided into n sub-lists and each contains one element.
2. Repeatedly merge sub-lists to produce new sorted sub-lists until there is only one sub-list remaining, which is the sorted list.

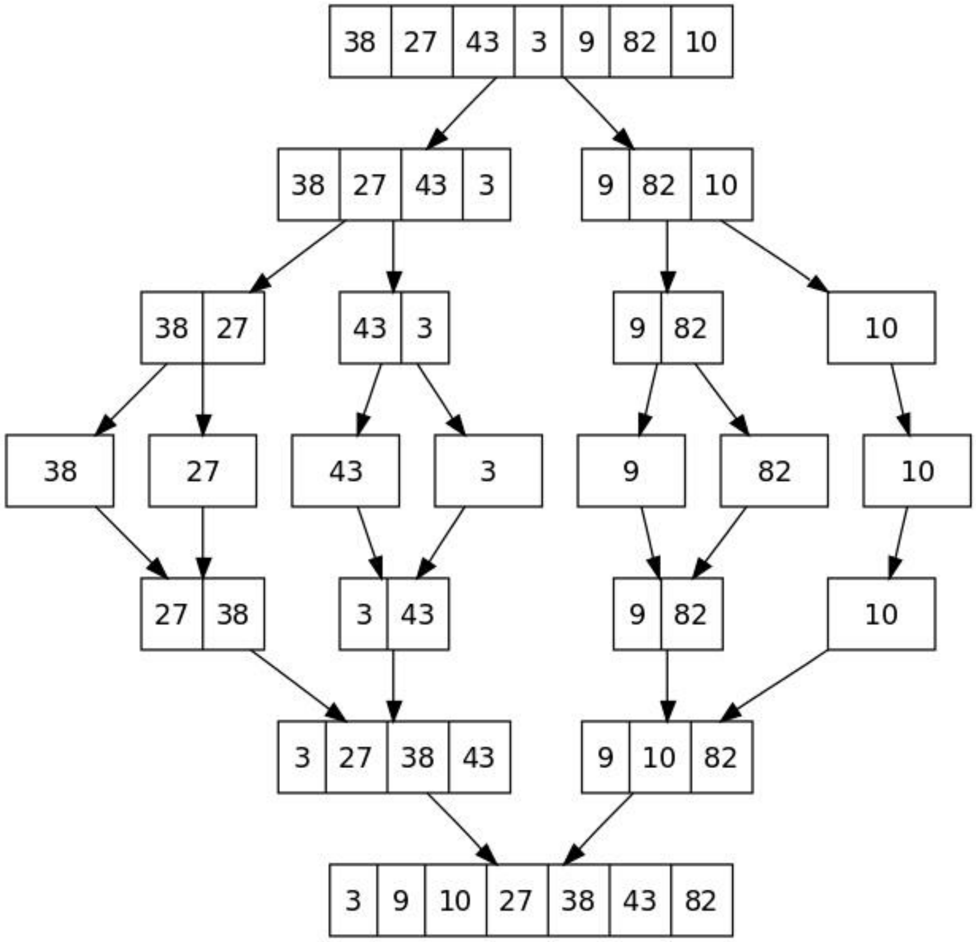

Figure 4.1 Example of merge sort algorithm

4.3 Solution Procedure

The merge algorithm is used in the model under the premise that held flights' departure time may conflict with others, which means the departure time slot between two ready flights is less than the minimum departure clearance. The model proceeds through the following steps:

1. Compute cost of each held flight with holding time increasing from 0 minute to 100 minutes in increments of 1 minutes;
2. List all the combinations of flights' holding time which satisfy constraints;
3. Use merge algorithm to find the best combination of holding time with minimum cost.

In the model, the cost of each held flight is calculated separately and the minimum total cost of all the held flights is determined based on the cost of each flight. The final result is an element with minimum total cost. Figure 3.2 shows the basic procedure of the algorithm in the model. $x_m$and y_m are the holding time of two held flights with conflict departure time. m means flight is held for m-1 minutes. In order to increase the sorting speed, the list of $x_m$and y_m are sorted based on the cost in an ascending order before merge sorting. Elements in the lists are also filtered with time constraints. As shown in the figure, the final result is a list of flights' holding time in ascending order of the total cost. The first column is the combination of holding time with minimum cost.

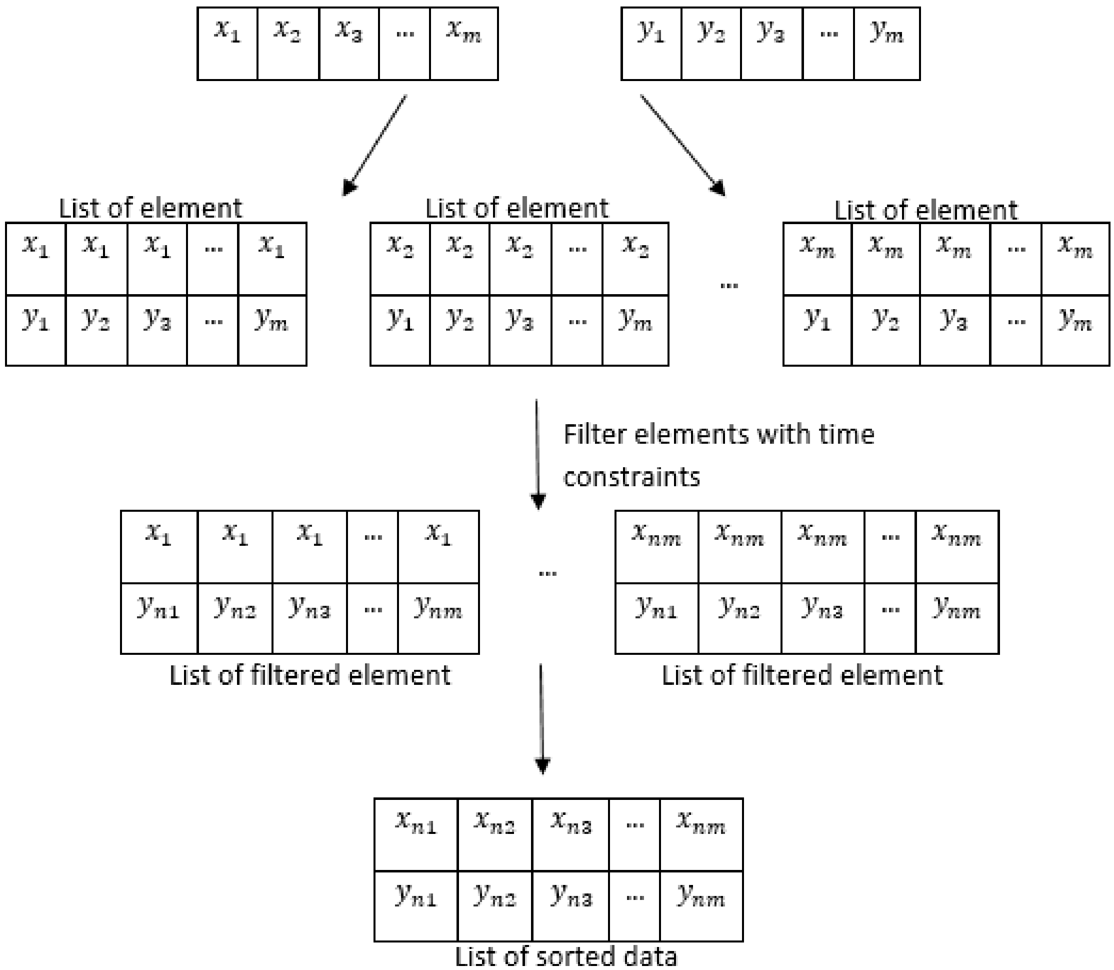

Figure 4.1 Sorting Procedure in the Model

4.4 Summary

In this chapter, fundamentals of sorting algorithm and details on the merge sorting algorithm are introduced. In the solution procedures, merge sorting algorithm is employed to solve the sequencing problem in the model.

Chapter 5. Performance assessment of a real-time control model

In this chapter, a numeric example is used to analyze the model introduced in previous chapters. Based on the proposed model, a sorting algorithm is employed to optimize the departure sequences of multiple held flights. Multiple airports and multiple flights are considered in the numeric example.

5.1 Model Applications and Analytical Results

This study seeks to optimize the holding times and departure sequences of outbound connecting flights at airports in the network. Some parameters in the applications are built with assumptions. Different types of airports, aircraft and routes are considered.

In the example, two types of airports are defined: hub-airport with passenger transfer and non-hub airport with no occurrence of passenger transfer. As introduced in the previous chapter, three types of aircraft are considered in the example: Large with more than 250 passengers; Medium with 100 to 250 passengers; Small with less than 100 passengers. In the system, small airplane is set to conduct daily commute between two airports, large and medium size airplanes are set to serve several airports in the network.

When service disruptions or delays occur, the proposed control model may affect further airports within the studied network due to the propagation of delays. Considering the propagation of delays, the model can also be applied at downstream airport. To compare the effects with and without using control model at downstream airports, we consider several airports in the network.

Delay caused by uncertain weather and mechanical problems is somewhat unpredictable. Thus, a probabilistic model is preferable to a deterministic model when considering en-route delay and ground delay in an airline network. It is illustrated in Chapter 4 that the log-normal distribution is the best fitting among three compared distributions. Therefore, the Log-normal distribution of en-route delay and ground delay will be applied in the example.

5.2 Numeric Example and Model Application

Flights may be delayed due to uncertain weather, mechanical problems or airport capacity limits, which lead to missed connection cost of transfer passengers on the delayed flights. In this numeric example, we consider a network with multiple delayed inbound flights, single outbound flight waiting at first airport and multiple outbound flights waiting for held flight at downstream airports. As shown in Figure 5.1, hub and non-hub airports are considered in the network.

Nine routes and six airports are included in the network of this example. O_1,O_2, D_3 and $D_4$are hub airports and D_1, D_2 are non-hub airports. I_1,I_2,I_3, I_4 are delayed flights. C_1 is the outbound flight of I_1,I_2,I_3 and I_4. C_2, C_3, C_4, $C_5$are outbound flights at O_1. OD demand of transfer passenger is shown in Table 5.1. Transfer slack time set between each pair of flights is shown in Table 5.2. Table 5.3 contains the information of En-route slack time and ground operation slack time.

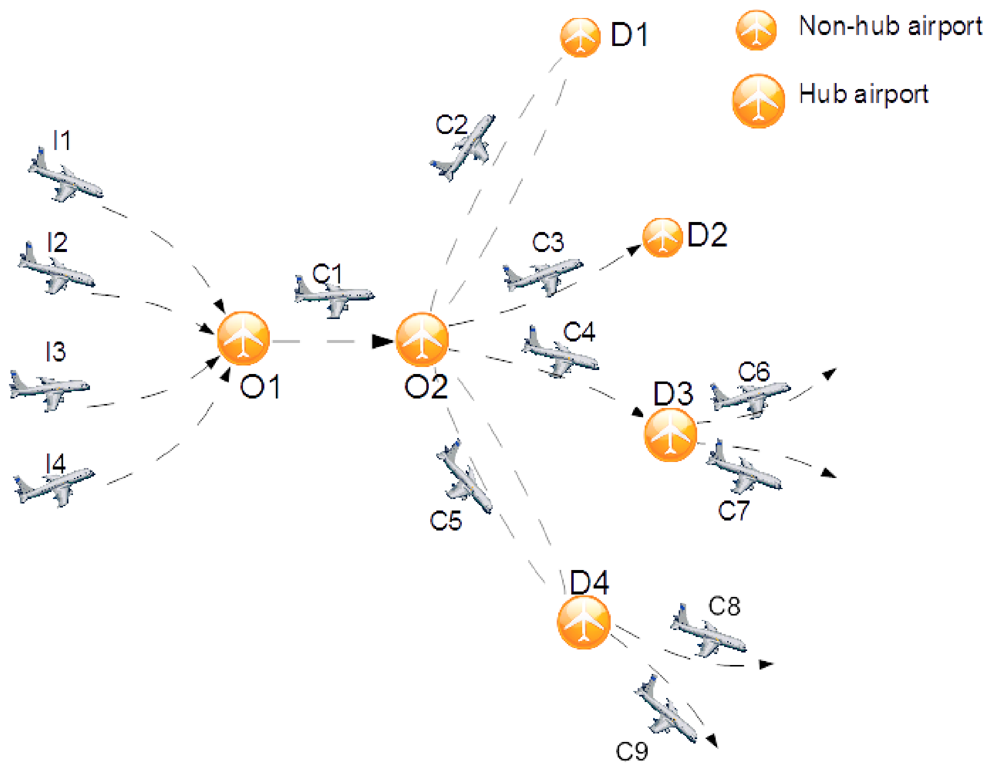

Figure 5. 1 Network Configuration for Numeric Example

Table 5.1 Passenger Transfer (OD) Information in Example (Units: persons)

O\D	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9
I_1	10	0	0	0	0	0	0	0	0
I_2	15	0	0	0	0	0	0	0	0
I_3	20	0	0	0	0	0	0	0	0
I_4	25	0	0	0	0	0	0	0	0
C_1	0	20	18	14	20	0	0	0	0

C_4	0	0	0	0	0	5	20	0	0
C_5	0	0	0	0	0	0	0	10	15

Table 5.2 Slack time for Passenger Transfer (Units: minutes)

O\D	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9
I_1	10	0	0	0	0	0	0	0	0
I_2	20	0	0	0	0	0	0	0	0
I_3	35	0	0	0	0	0	0	0	0
I_4	40	0	0	0	0	0	0	0	0
C_1	0	15	20	25	30	0	0	0	0
C_4	0	0	0	0	0	32	40	0	0
C_5	0	0	0	0	0	0	0	32	36

Table 5.3 Slack Time En-route and Ground Operation (Units: minutes)

	En-route slack time	Ground slack time
C_1	20	10
C_2	10	20
C_3	15	18
C_4	10	25
C_5	10	15

As introduced in Chapter 4, the delay times of incoming flights I_i are pre-determined when making holding decisions. Table 5.4 shows the delay information for incoming flights. In this example, en-route delay and ground delay of outbound flights C_i are set to be log-normally distributed. Table 5.5 shows the mean and standard deviation of en-route delay and of ground delay for each outbound flights.

Table 5.4 Delay Information of Incoming Flights

	I_1	I_2	I_3	I_4
Arrival Delay (min)	20	30	40	50

Table 5.5 Delay Information of Outbound Flights

		C_1	C_2	C_3	C_4	C_5
En-route Delay	Mean	1.2	2	10	4.6	8.4
	Std. Dev.	29.6	20.4	16.8	24.6	29.2
Ground Delay	Mean	6.2	8.2	4.6	6.2	2.8
	Std. Dev.	26.8	24.2	18.6	14.6	19.2

Some parameters of flights are also defined in this example and are shown in Table 5.6. Unit operating cost B of the small airplane is 10 $/aircraft minute, the cost of the medium airplane is 35 $/aircraft minute and operating cost of the large airplane is 50 $/aircraft minute. Unit time cost of passengers is 0.5 $/minute.

Table 5.6 Other Input Parameters of Flights

Flights	Capacity	Arrival Delay (min)	Headway (min)	Number of Passengers on Board	Number of Passengers Waiting for Boarding at Downstream Airport
I_1	250	20	NA	NA	NA
I_2	250	30	NA	NA	NA
I_3	250	40	NA	NA	NA
I_4	250	50	NA	NA	NA
C_1	250	NA	150	130	230
C_2	70	NA	60	50	56
C_3	70	NA	300	42	220
C_4	250	NA	240	224	0
C_5	170	NA	600	160	0

C_6	70	NA	120	45	NA
C_7	250	NA	330	215	NA
C_8	70	NA	150	43	NA
C_9	250	NA	480	200	NA

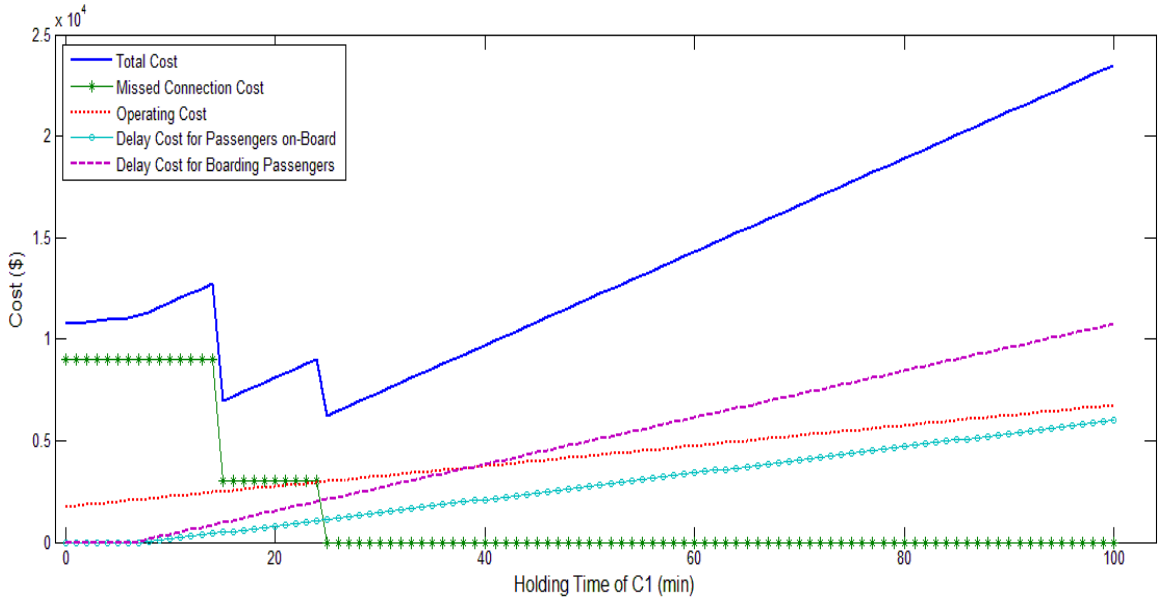

Figure 5.2 Costs of Flight c_1 at Airport o_1 with Increasing Holding Time

Costs of holding flight C_1 are shown in the Figure 5.2. The operating cost, waiting cost for both on-board passengers and boarding passengers increase with the increasing holding time. However, the missed connection cost drops sharply when holding time reaches some specific points. It is caused by the successful connection between late arrival flights and held flights. The total cost is also shown in the figure.

In this example, a holding decision is considered in two stages. 1) Holding decisions made to flight C_1; 2) Holding decisions made to outbound flights connecting with C_1 at downstream airport. Figure 5.3 shows the costs for different holding time under three different control methods. The "original" curve shows the cost when optimization and downstream coordination are not applied in the network. The optimization without downstream coordination (ONDC) means holding decisions of outbound flights at downstream airports are not applied based on the delay time of flight C_1. The optimization with downstream coordination (ODC) means holding decisions of outbound flights waiting for delayed flights are applied. In the figure, when $C_1$is not held, flight $C_1$and flights at downstream airports of O1will not be affected by the delay of incoming flights. Missed connection cost of transfer passengers on late arrival flights I_i is the only cost in the network, which makes the “Original” curve keep the same value. The cost of ONDC increases significantly after 21 minutes. It is caused by the propagated delay from upstream. The cost of ODC is lower than the one of ONDC after $C_1$is held for 25 minutes. The model finds the best holding time and sequence of flights at downstream airport. Figure 5.3 shows the minimum total cost of the network both without and with coordination. The minimum cost with downstream coordination is $9883.9 when holding time is 15 minutes and the one without downstream coordination is $11146 when holding time is 15 minutes.

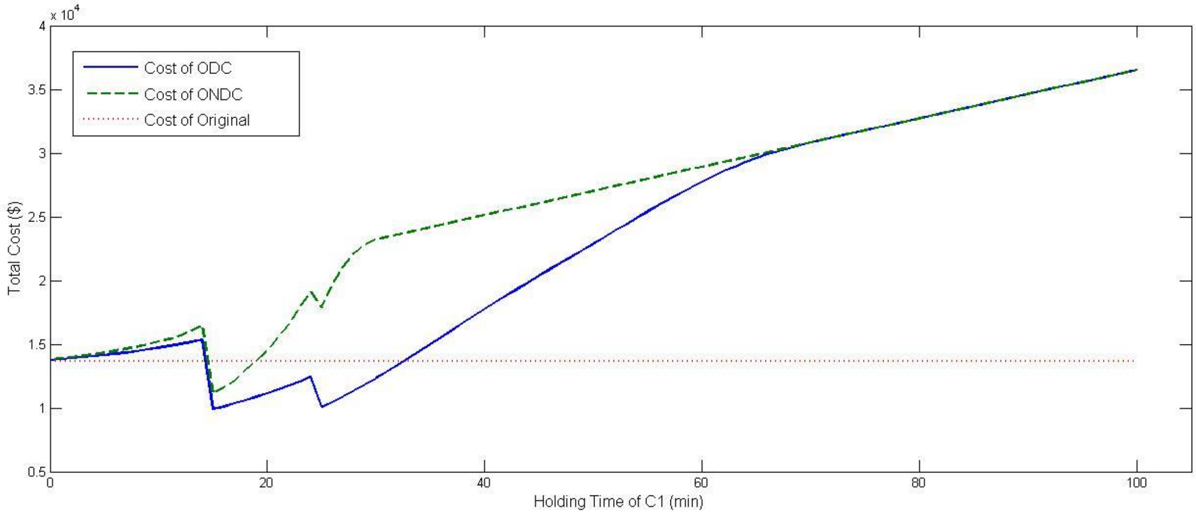

Figure 5.3 Minimum Total Cost of Different Policies with Increasing Delay Time

5.3 Sensitivity Analysis of Delay Time of Incoming Flights

Delay time of incoming flights I_i is the major factor affecting holding decision in the network. Holding decisions of flights C_j are modified based on the delay time of flights I_i to obtain the minimum total cost. Sensitivity of minimum total cost to the delay time of I_i is analyzed in this section.

We assume that delay times of late arrival flights increase from $0.1d_i$ to $3d_i$ with $0.1d_i$ increments. The minimum cost of each optimization at different delay times is shown in Figure 5.4. Curve "Original" shows the total cost without optimization. Both optimization methods, ODC and ONDC, can considerably reduce system total cost when delay time increases. ODC has a lower delay cost when delay time is between $0.2d_i$ and $2.3d_i$. It shows that ODC performs better in reducing delay cost.

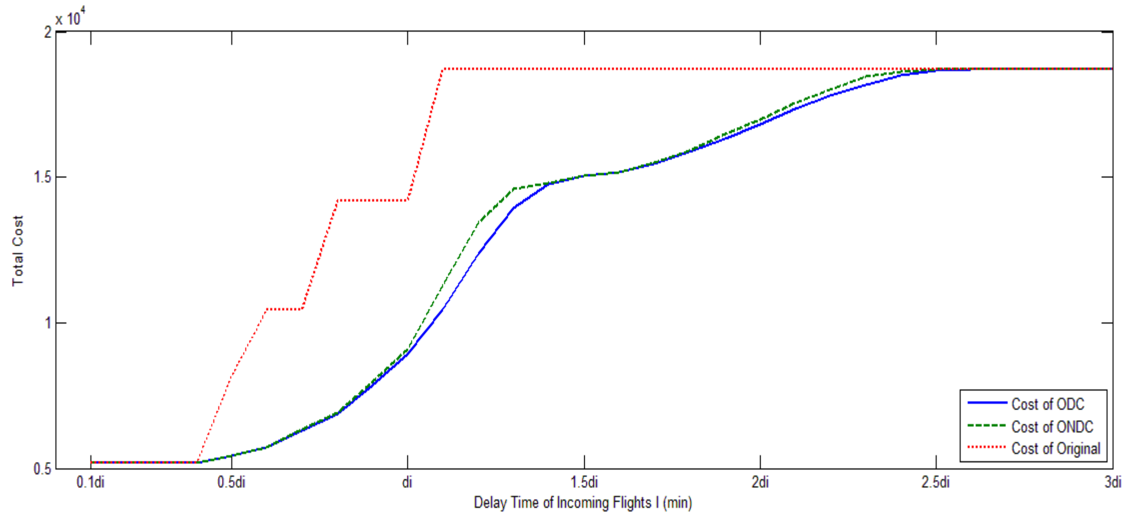

Figure 5.4 Minimum Cost of Different Optimizations with Increasing of Delay Time

5.4 Sensitivity Analysis of Slack Time Settings

A series of sensitivity analyses of system total costs to various holding times and slack times are introduced in this section. The total cost are obtained using ODC. Slack time is a safety margin of how much a schedule can be disrupted without changing the original plan. When service disruptions occur, the initial delays may cause delays downstream in the network. Additional slack time built into the schedule would increase the response and recovery abilities during the disruptions. However, operating cost and extra waiting cost may also increase with more slack time added into the system.

Slack time in the airline network includes transfer slack time, ground slack time and en-route slack time. To simplify the sensitivity analysis, we assume that all downstream airports will have the same incremental percentage of slack time, from 0.25*S to 2*S.

In this section, a sensitivity analysis of slack time is performed in order to observe the relation between slack time and delay costs. The slack time changes from 25% to 200% in 25% increments. Other input information is unchanged.

Figure 5.5 shows the total cost with different holding durations and different transfer slack times between each pair of connecting flights. The pre-scheduled transfer slack time is shown in Table 5.2. Longer holding time for outbound flights and longer transfer slack time lead to higher cost. The minimum cost occurs when holding time is 16 minutes and transfer slack time is 0.25S. More slack time could increase the total cost but reduce the miss connection cost.

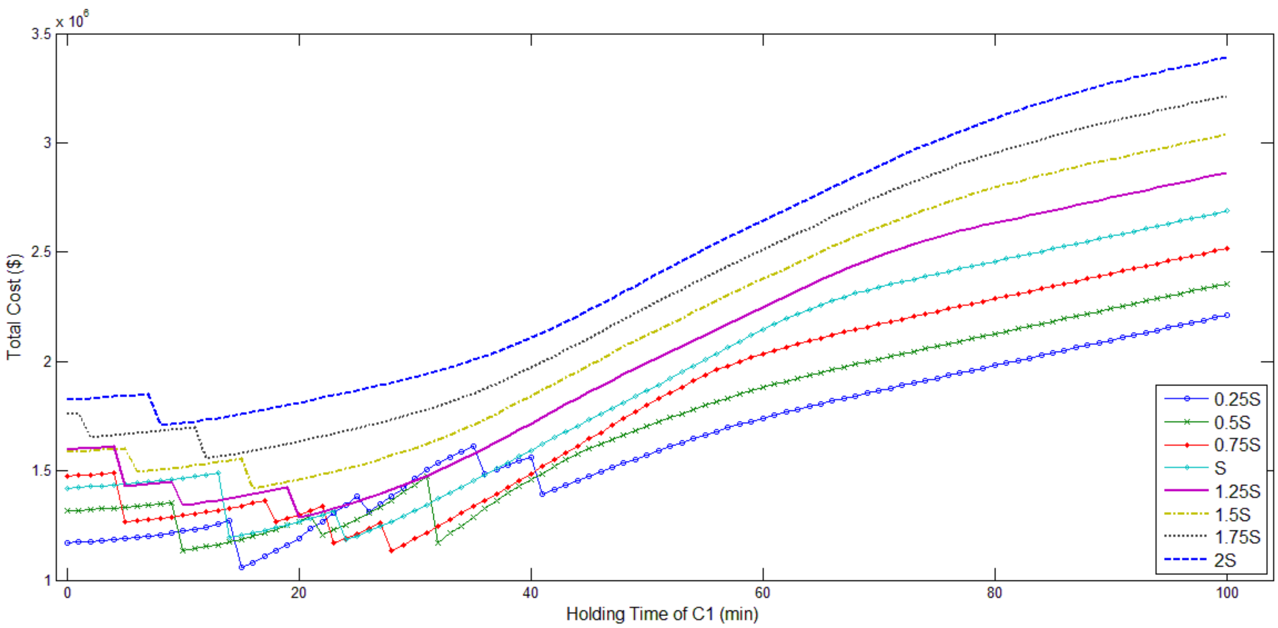

Figure 5.5 Total Cost vs. Transfer Slack Time

Figure 5.6 shows the total delay cost under different holding time durations and en-route slack times of each flight in the network. En-route slack time set in flight's schedule could increase the robustness of the schedule. The figure shows that the cost of 0.25S is lower than the cost of 2S when holding time is less than 6 minutes. However, more slack time could also increase operating cost in system. The cost of 0.25S increase significantly and is greater than the cost of 2S after 6 minutes. The minimum cost occurs when holding time is 25 minutes and en-route slack time is 2S. From the figure, we can know that more en-route slack time set in the system could more efficiently reduce propagate delays from upstream airport.

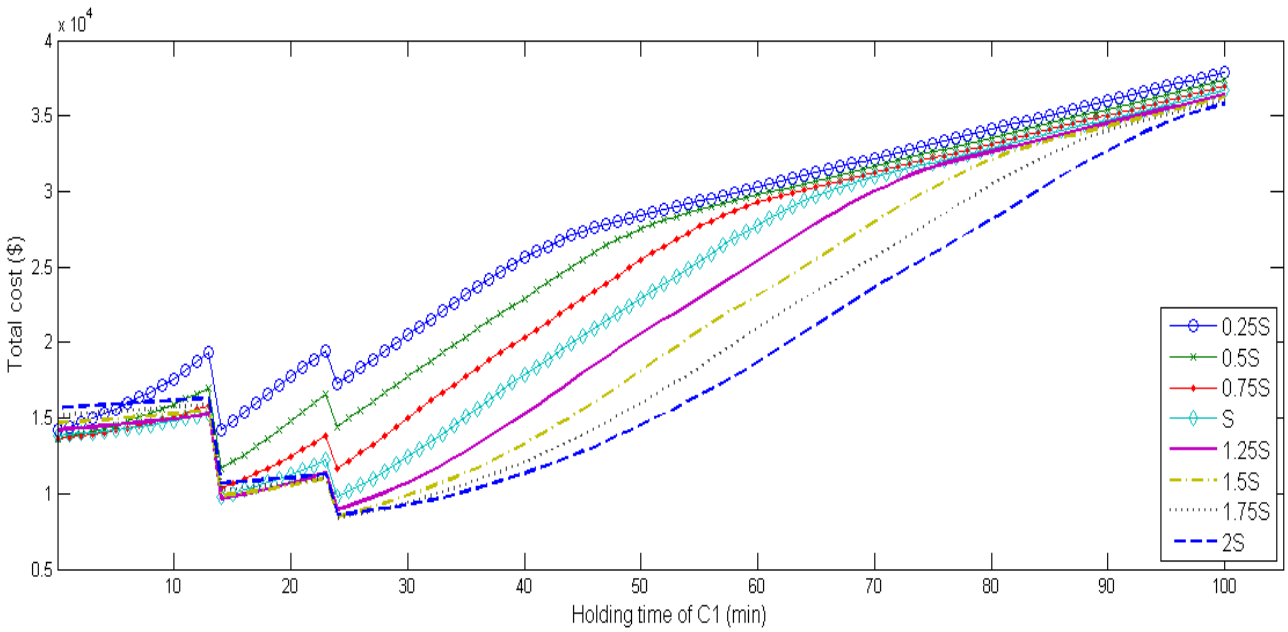

Figure 5.6 Total Cost vs. En-route Slack Time

The figure 5.7 clearly shows that the tradeoff between en-route slack times and minimum total cost. Comparing the minimum total cost under different en-route slack times, total cost reaches the minimum point when en-route slack time is 2S. After the minimum point, the total cost increases with increasing en-route slack time.

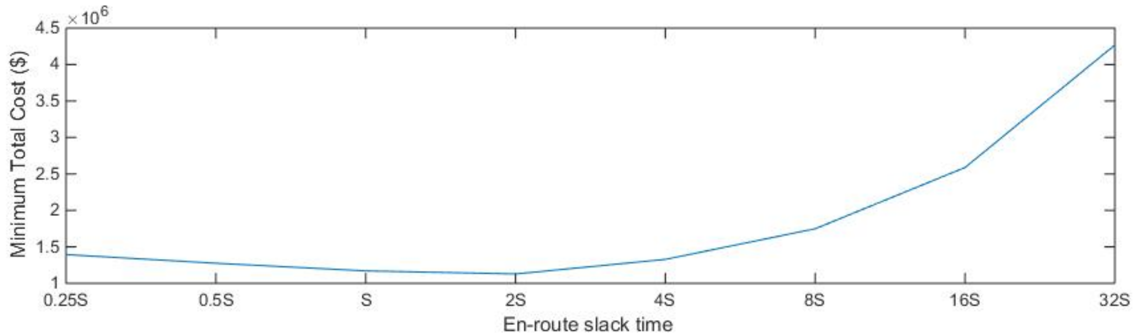

Figure 5.7 Minimum Total Cost vs. En-route Slack Time

Figure 5.8 shows the changes of the total cost under different holding times of C_1 and ground slack times of C_2, C_3, C_4 and C_5. Delay propagates from upstream airport which is caused by holding decision of C_1 can be absorbed by the ground slack time of C_2, C_3, C_4 and C_5. The minimum total cost occurs when ground slack time is 0.25S and holding time is 15 minutes. The figure shows that total cost increase with the increasing of ground slack time.

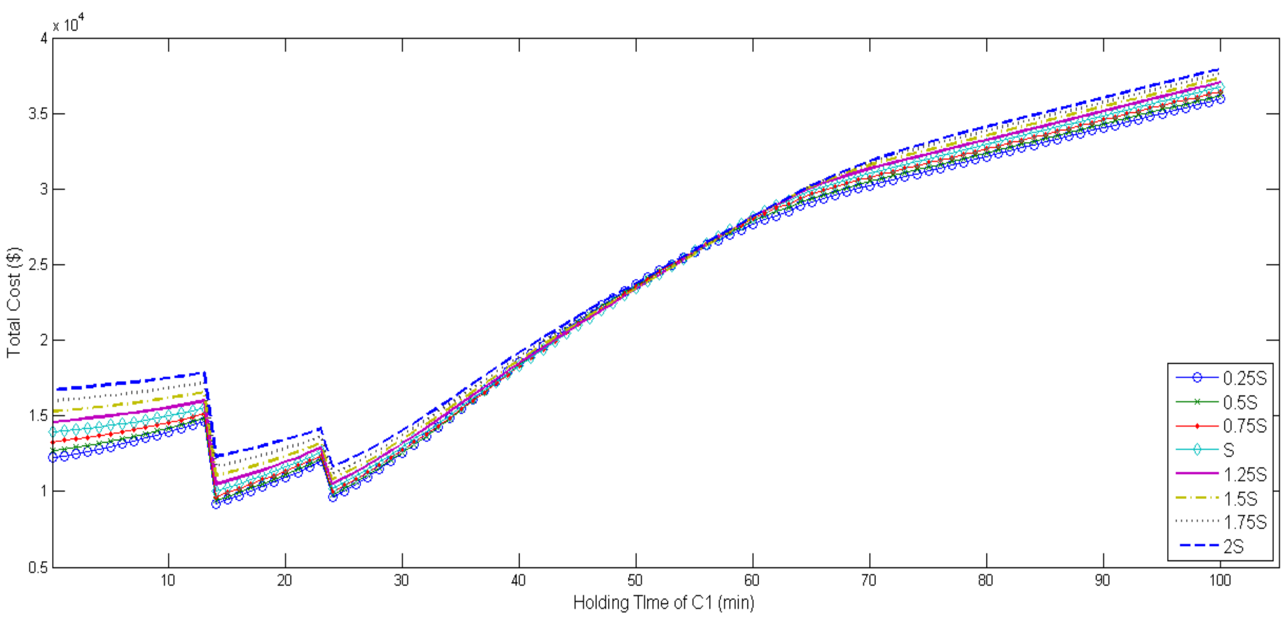

Figure 5.8 Total Cost vs. Ground Slack Time

5.5 Sensitivity Analysis of Number of Transfer Passengers

In this study, the missed connection cost is one factor contributing to the delay cost in the network. When transfer slack time between flights is set to be constant, less transfer passengers on delayed flights cause less missed connection cost. This section compares delay cost with increase of transfer passenger and holding time.

Figures 5.9 and 5.10 illustrate the relation between resulting delay costs and the increase of holding time and number of transfer passengers. As expected, fewer transfer passengers on late arrival flights have less missed connection cost when holding time and slack time stay the same. To simplify the sensitivity analysis, we assume that all downstream airports have the same incremental percentage of transfer passengers on incoming flights, from 0.25*q to 2*q.

Figure 5.9 shows the total cost for different numbers of passengers transferring from I_i to C_1. It shows that the total costs in the system increase with the increasing transfer passengers before the critical point when holding time is 25 minutes. After the critical point, when passengers successfully transfer to held flights, total cost only increase with the increasing holding time.

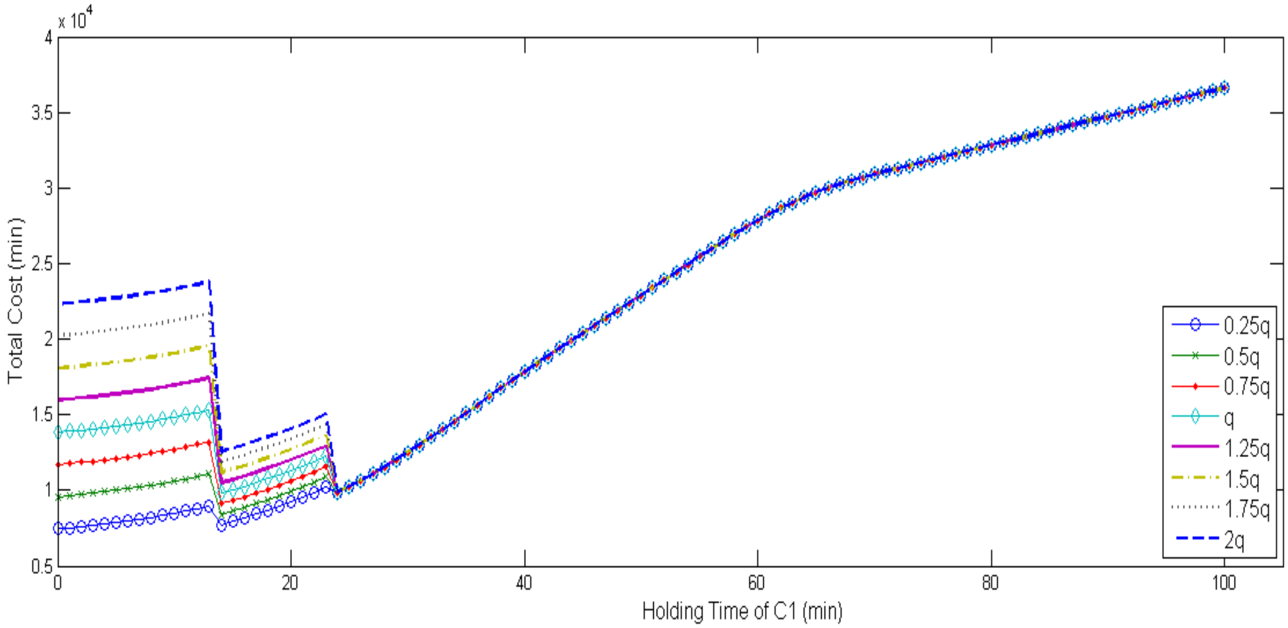

Figure 5.9 Total Cost vs. Number of Transfer Passengers from I_i to C_1

Figure 5.10 shows the total cost with different transfer passengers from C_1 to C_2, C_3, C_4, C_5. The critical point in the figure happens when holding time is 34 minutes. After the critical point, the cost increases with the increasing holding time of C_1 and the increasing transfer passengers. Longer holding time leads to greater arrival delay time of C_1at airport O_2. Optimization of holding decision and departure sequences of outbound flights at downstream airport could only reduce the effects of delay propagated from upstream airport. When the slack time cannot absorb the delay, the cost continues to increase when holding time increases.

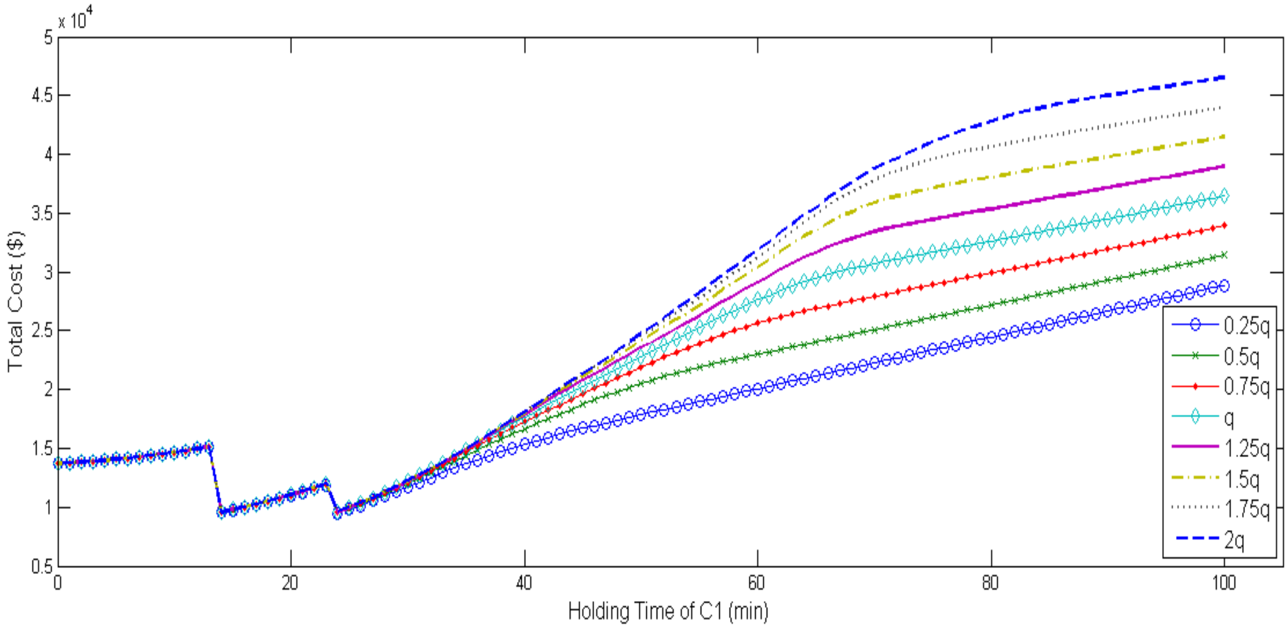

Figure 5.10 Total Cost vs. Number of Transfer Passengers from C_1 *to* C_2, C_3, C_4, C_5

5.6 Sensitivity Analysis of Headway

Headway of flights could influence missed connection cost when transfer passengers miss their flights and have to wait for the next available flights. Figure 5.11 shows the relation between total cost and flights' headway in the network. Longer holding times are needed to minimize the total cost when headways increase.

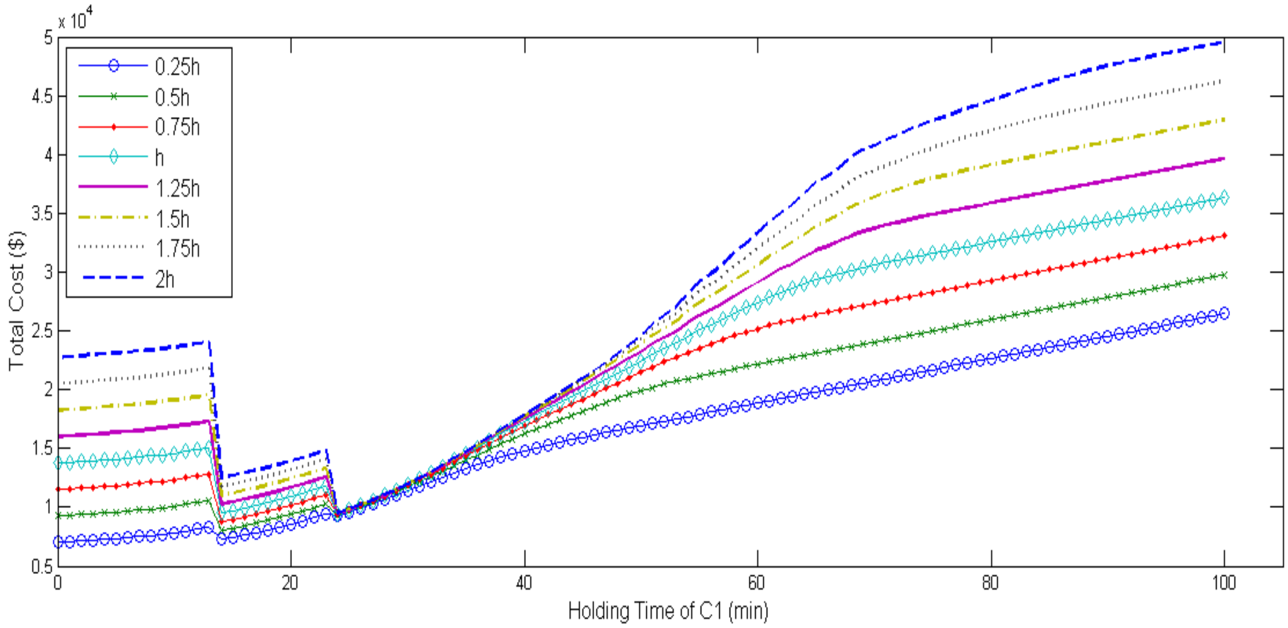

Figure 5.11 Total Cost vs. Headway

5.7 Summary

In this chapter, we examine the holding model introduced in Chapter 3 by considering the delay propagation. Delay may propagate through the entire networks and affect operational schedules. An analysis of the delay propagations and a sensitivity analysis with different slack time settings and with different number of transfer passengers are presented in this chapter.

Both ONDC and ODC could reduce delay costs by optimizing the holding time of each waiting flight. It should be noted that the optimization with downstream coordination (ODC) performs better. It has a lower delay cost and allows more delay time in a flight schedule without changing the pre-scheduled slack time.

Chapter 6. Conclusions and Future Research

The study mainly investigates the potential cost savings of holding decision for outbound flights which are waiting for delayed flights and coordinated operations at downstream airports compared to the ones without holding and uncoordinated operations in a multi-hub and multi-flights network. In Chapter 3, the general concepts of modeling the airport flights operating cost are discussed in detail and the mathematical model for optimizing the real-time control model are formulated. To capture the operational characteristics, a numeric example with a multi-hub and multi-flights network is introduced and analyzed in Chapter 5. Sensitivity analyses of total cost under different slack times, number of transfer passengers and headways are also shown in this chapter.

6.1 Contributions

This section summarized the primary contributions of this study as follows:

Routine service disruptions, such as airport capacity constraints, hazardous weather conditions or mechanical problem may cause delays of inbound flights and increase passenger waiting cost and missed connection cost. Thus, a real-time control model is developed to optimize the holding time for outbound flights. The model determines the best time to dispatch held flights based on minimum system-wide costs. Departure sequences of held flights are also optimized when considering time constraints.

Distributions of flights' en-route delay time and ground operation delay time are tested with historical flight data and a log-normal distribution is specified for a delay time in Chapter 3. The probabilistic model of delay time is considered in the real-time control model when dealing with flights' holding decision and departure sequence at downstream airports. In Chapter 5, the model is tested for a network under various assumptions. Sorting algorithms are applied in the optimization of held flights' departure sequences.

Optimization with downstream coordination (ODC) and optimization without downstream coordination (ONDC) are developed in the real-time control model and compared in the numeric example. The results show that both methods could reduce delay cost and ODC performs better.

6.2 Conclusions

The real-time control model developed in the study is used to generate analytic and numerical results. Some sensitivity analyses also verify the relation established in the model formulations. Two optimization polices, ONDC and ODC, are developed in the real-time control model. The results in the numeric examole show that both ONDC and ODC can significantly reduce delay cost by optimizing the holding time of outbound flights and ODC performs better than ONDC. The control model significantly increases the robustness of airline network and could reduce missed connection cost caused by flights' delay.

The sensitivity analyses show that slack time could increase the network's recovery abilities during service disruption. More transfer passengers and less transfer time in the network increase the missed connection cost. When comparing the total costs with different holding time periods, the results show that longer holding time would yield higher operating cost and higher passenger waiting cost, but lower missed connection cost. When ODC applied in the system, increasing numbers of transfer passengers at downstream airports do not affect the holding decisions at their upstream airport.

6.3 Future Research

Although this study provides several contributions in the area of airline delay management, especially in the fields of real-time control, several additional elements should be considered in future studies.

The developed model could be enhanced by considering detailed transfers inside terminals and gate assignment based on airport's limited capacity and passenger transfer procedures.

The sensitivity analyses introduced shows that the en-route and transfer slack times set in the system could also be optimized before applying the model.

Analyzing holding decision within large scale and complex network. The interrelations among arrival, departure, and travel delays should be considered in developing a real-time control model to alleviate delay propagation within the system. Return flights from downstream airports could also be considered.

Travel time or demand can vary during peak and off-peak seasons. Different statistical models of travel time and demand in peak and off-peak seasons should be identified and included in the developed model. More probabilistic models could be considered for the arrival of passengers and late arrival passengers at downstream airports.

References

Anderson, Kari, et al. "Analysis and modeling of ground operations at hub airports." (2000).

Barnhart, Cynthia, et al. "Airline crew scheduling." *Handbook of transportation science* (2003): 517-560.

Barnhart, Cynthia, and K. Talluri. "Airline operations research." *Design and Operations of Civil and Environmental Engineering Systems* (1997): 435-469.

Bihr, Richard A. "A conceptual solution to the aircraft gate assignment problem using 0, 1 linear programming." *Computers & Industrial Engineering* 19.1 (1990): 280-284.

Bolat, Ahmet. "Procedures for providing robust gate assignments for arriving aircrafts." *European Journal of Operational Research* 120.1 (2000): 63-80.

Chen, Cheng-Chieh (Frank), and Paul Schonfeld. "Modeling and performance assessment of intermodal transfers at cargo terminals." *Transportation Research Record: Journal of the Transportation Research Board* 2162.1 (2010): 53-62.

Chen, Cheng-Chieh (Frank), and Paul Schonfeld. "Alleviating schedule disruptions at intermodal freight transfer terminals." *Transportation Research Record: Journal of the Transportation Research Board* 2238.1 (2011): 32-43.

Cheng, Yu. "A knowledge-based airport gate assignment system integrated with mathematical programming." *Computers & Industrial Engineering* 32.4 (1997): 837-852.

Cohn, Amy Mainville, and Cynthia Barnhart. "Improving crew scheduling by incorporating key maintenance routing decisions." *Operations Research* 51.3 (2003): 387-396.

Desaulniers, Guy, et al. "Crew pairing at air France." *European Journal of Operational Research* 97.2 (1997): 245-259.

Demuth, Howard B. "Electronic data sorting." *Computers, IEEE Transactions on* 100.4 (1985): 296-310.

Gordon, Steven, and Richard De Neufville. "Design of air transportation networks." *Transportation Research* 7.3 (1973): 207-222.

Goldstine, Herman Heine, and John Von Neumann. "Planning and coding of problems for an electronic computing instrument." (1948).

Gu, Yu, and Christopher A. Chung. "Genetic algorithm approach to aircraft gate reassignment problem." *Journal of Transportation Engineering* 125.5 (1999): 384-389.

Hall, Randolph W., and C. Chong. "Scheduling timed transfers at hub terminals." *Transportation and Traffic Theory* (1993).

Haghani, Ali, and Min-Ching Chen. "Optimizing gate assignments at airport terminals." *Transportation Research Part A: Policy and Practice* 32.6 (1998): 437-454.

Kang, Laura Sumi. "Degradable airline scheduling: an approach to improve operational robustness and differentiate service quality." (2004).

Kanafani, Adib, and Atef A. Ghobrial. "Airline hubbing—some implications for airport economics." *Transportation Research Part A: General* 19.1 (1985): 15-27.

Lan, Shan, John-Paul Clarke, and Cynthia Barnhart. "Planning for robust airline operations: Optimizing aircraft routings and flight departure times to minimize passenger disruptions." *Transportation Science* 40.1 (2006): 15-28.

Lee, Kurt KT, and Paul Schonfeld. "Optimal slack time for timed transfers at a transit terminal." *Journal of Advanced Transportation* 25.3 (1991): 281-308.

Levin, Amos. "Scheduling and fleet routing models for transportation systems.*"* *Transportation Science* 5.3 (1971): 232-255.

Mulvey, John M., Robert J. Vanderbei, and Stavros A. Zenios. "Robust optimization of large-scale systems." *Operations research* 43.2 (1995): 264-281.

Rexing, Brian, et al. "Airline fleet assignment with time windows. *"Transportation Science* 34.1 (2000): 1-20.

Ting, Ching-Jung, and Paul Schonfeld. "Schedule coordination in a multiple hub transit network." *Journal of urban planning and development* 131.2 (2005): 112-124.

Ting, Ching-Jung, and Paul Schonfeld. "Dispatching control at transfer stations in multi-hub transit networks." *Journal of Advanced Transportation* 41.3 (2007): 217-243.

Trietsch, Dan. "Scheduling flights at hub airports." *Transportation Research Part B: Methodological* 27.2 (1993): 133-150.

Yan, Shangyao, Chi-Yuan Shieh, and Miawjane Chen. "A simulation framework for evaluating airport gate assignments." *Transportation Research Part A: Policy and Practice* 36.10 (2002): 885-898.

Yan, Shangyao, and Cheun-Ming Huo. "Optimization of multiple objective gate assignments." *Transportation Research Part A: Policy and Practice* 35.5 (2001): 413-432.

Yan, Shangyao, and Chia-Ming Chang. "A network model for gate assignment."*Journal of Advanced Transportation* 32.2 (1998): 176-189.

Yan, Shangyao, and Chung-Gee Lin. "Airline scheduling for the temporary closure of airports." *Transportation Science* 31.1 (1997): 72-82.

Yan, Shangyao, and Chung-Gee Lin. "Airline scheduling for the temporary closure of airports." *Transportation Science* 31.1 (1997): 72-82.