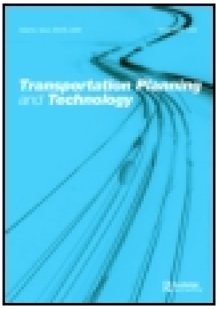

Transportation Planning and Technology
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/gtpt20

An Optimization Model for Assessing Flight Technical Delay

Jinn-Tsai Wong [a] , Sui-Ling Li [a] & David Gillingwater [b]
[a] Institute of Traffic and Transportation , National Chiao Tung University , 4F, 114, Sec. 1, Chung Hsiao W. Rd., Taipei, 10012, Taiwan, R.O.C.
[b] Transport Studies Group/CBE , Loughborough University , Loughborough, UK
Published online: 29 Oct 2010.

Transportation Planning and Technol., 2002, Vol. 25, pp. 121–153

AN OPTIMIZATION MODEL FOR ASSESSING FLIGHT TECHNICAL DELAY

JINN-TSAI WONG[a,*], SUI-LING LI[a,†] and DAVID GILLINGWATER[b]

[a]*Institute of Traffic and Transportation, National Chiao Tung University, 4F, 114, Sec. 1, Chung Hsiao W. Rd., Taipei, 10012, Taiwan, R.O.C.;* [b]*Transport Studies Group/CBE, Loughborough University, Loughborough, UK*

(Received 10 October 2000; Revised 18 January 2001; In final form 15 March 2001)

This paper identifies the causes as well as the practical measurement of aircraft flight delays. The performance of air traffic management is measured by examining technical delays and scheduled timetable delays, which are derived from a mathematical programming model. To validate the optimization model, flight delays are simulated under various service rules. The outcome of the simulation runs shows that the average delay for each aircraft estimated from the optimization model is marginally higher than that from the simulation run under the "first come first serve" rule. However, under the "arrival flight first" rule, the optimization model's results are either higher or lower than those of the simulation model. Nonetheless, both sets of simulated delays are strongly correlated with those of the optimization model. Results from regression analyses show that the optimization model has the capacity to predict flight technical delays.

Keywords: Flight delay; Technical delay; Scheduled timetable delay; Optimization model; Simulation; Regression

1. INTRODUCTION

Many congested airports throughout the world encounter flight delay problems. Due to the increasing demand for air transportation, available take-off/landing slots at some congested airports are highly sought-after during peak hours of operation. As a consequence, bad

*Corresponding author. Fax: 886-2-23494953. E-mail: jtwong@cc.nctu.edu.tw
†suiling@ms15.hinet.net

ISSN 0308-1060 print: ISSN 1029-0354 online
DOI: 10.1080/03081060290033212

weather or traffic congestion can expose the inadequacy of airport facilities. Although air traffic control was designed to face such conditions, its function can have a serious impact on the scheduled take-off and landings of flights, causing unnecessary loss of time to passengers and an increased workload for air traffic controllers.

There has been much research (cf. Newell, 1979; Glockner, 1993; Venkatakrishnan *et al.*, 1993; Luo and Yu, 1997, Rutner *et al.*, 1997) which has identified limited runway capacity as the leading cause of flight delays. Related approaches such as constructing new runways, improving the geometry of runways, taxiways, and air traffic control facilities, changing air traffic control procedures, thus modifying the take-off/landing sequence, can each enhance airport capacity and decrease flight delays. However, these methods either incur huge expenditures or have an impact on the environment or both. Furthermore, these changes generally take a long time to implement. Therefore, in addition to such long term improvements, in the short term, understanding how to make better use of an airport's existing limited capacity for flight take-offs and landings in accordance with safe air traffic control is potentially the most effective means of enhancing air traffic management. In order to evaluate the performance of air traffic management and to determine whether current capacity is being utilized effectively, it is necessary to develop a practical model of delay analysis.

This paper first reviews the concept of air traffic management in order to determine the importance of the delay model for air traffic control and to measure the performance of air traffic management. This involves defining what is meant by a delay and investigating approaches to measuring delays. Second, the paper constructs a mathematical model to measure and analyse both technical delays and scheduled timetable delays. Given a specific flight timetable, the optimization model to be proposed here, considering the constraints of approach and runway capacities, can be used to analyse air/ground delays of flight arrivals and departures. Third, the optimization model is applied to air traffic management using aircraft peak hour separation times at Taipei Airport. The objective function of this optimization model is set to measure technical delays and scheduled timetable delays so as to analyse the loading of the associated arrival/departure approaches. In addition, various weights are given to air/ground delays as a trade-off tool to test the performance of air traffic management. As for constraints, connecting flight take-off/landing separation patterns, the assignment of aircraft to a runway, the capacities of inbound/outbound fixes, and the level of demand of aircraft passing through inbound/outbound fixes are all included. Finally, the paper attempts to verify the suitability of the optimization model in analysing the performance of air traffic management through simulation and regression analyses.

2. DEFINITION OF DELAYS AND MEASURING PERFORMANCE OF AIR TRAFFIC MANAGEMENT

Flight delays can be divided into five types (Shaw, 1987) and include: traffic handling delays, aircraft turnaround delays, aircraft technical delays, air traffic control and airport delays, and weather delays. The U.S. FAA classifies delays into two types (Cheslow, 1990). The first type is called a technical delay. This is experienced by aircraft while waiting for air traffic control resources or traffic management flow restrictions. The second type is effective arrival delay. In this paper, only air traffic control and airport delays are discussed. Generally, flight delays are defined as the gap between the time an aircraft actually takes-off/lands and the scheduled take-off/landing time. When the time gap is more than 15 min, it is considered to be a delay to the normal operation of take-off/landing of an aircraft. That is to say, a 15 min interval between scheduled and actual take-off/landing of an aircraft at an airport is regarded as punctual. This difference between scheduled and actual arrival time is considered regardless of cause, so using these data alone does not clarify the cause of delay. Furthermore, it is not possible to assess responsibility for the delay. Thus the performance of air traffic management alone cannot be measured properly. In fact, aircraft delays associated with air traffic management exist mainly as a constraint on airport capacity. Air traffic control (ATC) must control the take-off/landing aircraft according to some predefined rule to ensure flight safety. As a result, additional time may be needed for an aircraft to take-off or land. This type of delay is known as a "technical delay". Technical delays do not include aircraft delays or other service delays attributable to an airline's internal operating difficulties.

In this paper technical delay is adopted as the key measurable index of performance of air traffic management at airports. In this way, management has the means to gauge and effectively reduce technical air/ground delays.

This paper aims to assist air traffic management in deciding which strategy to adopt to reduce air/ground technical delays, i.e., which aircraft should be delayed, and what sequence should be arranged for flights to take-off/land (Cheslow, 1990; Dear and Sherif, 1991; Helme and Lindsay, 1992; Janic, 1997). Previous attempts at optimization modelling of air traffic management (cf. Booth, 1994; Evans, 1997; Luo and Yu, 1997) have had similar aims to ours, but they have only considered total flight delay. Those studies only analysed total delay cost in the context of the ATC service rule of "first come first served" (FCFS) or "arrival priority". They did not explicitly incorporate technical delay due to flow control into their optimization formulations. As a consequence, those formulations could not effectively measure the performance of air traffic control or air traffic management.

Other related research which discusses how to reduce airport delays in order to enhance the utilization of airport capacity is often found in operations research literature associated with queuing theory (Newell, 1979; Evans, 1997; Gilbo, 1997), which discusses the basic relationship between capacity and delay in order to understand sound air traffic management. A series of aircraft in queues waiting for take-off /landing are generated to meet expected flight schedules and random characteristics. If an airport does not have sufficient capacity to meet demand, the result is increased delays. The relationship between shortfall capacity and delay is non-linear, so when the ratio of demand to capacity approaches unity, time delays increase rapidly. Therefore, some researchers (cf. Marchi, 1996) object to trying to simulate delay levels in capacity studies, arguing that delay is non-linear and that slight errors in analysis parameters will probably cause exaggerated and inaccurate changes in calculating delays. They claim delays are a symptom of insufficient capacity, and so quantity of capacity is better measured by maximum throughput per unit of time.

Gilbo (1997) considered the interaction between aircraft arrivals and departures, speculating that the ratio of arrivals to departures would have a significant impact on delays. He considered that airport capacity was not fixed but variable, with its values depending on the arrival/departure ratio. His second consideration included the capacity of arrival/departure fixes. However, the capacity of arrival/departure fixes was simplified as 10 flights per 15 min. He neglected the mutual flow interaction among arrival/departure routes and the limitations of runway capacity. The number of flights passing through the associated arrival/departure fixes was also not well enumerated. All the above-mentioned factors have an influence on the time an aircraft spends on the runway and thus the number of arrival/departure aircraft that a runway can handle. In addition, Gilbo's model estimated the total flight delay as being equal to the cumulative queue multiplied by the associated time interval. However, all waiting flights do not arrive/depart at the same time in every time interval, and the waiting time for each aircraft is not the same. This enumeration method will therefore cause errors. Therefore, regarding the performance measurement of air traffic management, there are still other areas to be studied, such as accurately estimating flight delay, discovering a better approach to handling the variable capacities, and properly formulating the interacting behaviour of arrival/departure aircraft.

In this paper, to fully exploit airport runway capacity, a delay analysis model is constructed, which discusses how to evaluate the performance of air traffic management under the constraints of runway and fix capacities, and given flight timetables. In addition to referring to the related procedures in air traffic management, it incorporates the smallest aircraft separation during peak periods, the patterns of flight take-off/landing sequences (the composition of consecutive arrival, consecutive departure, arrival–departure, and departure–arrival flights), the feature of separations associated with the different patterns, the constraints associated with capacities, and the interactions between arrival/departure flows.

3. DELAY MEASUREMENT

Incoming flights have to pass through arrival fixes before landing, and outgoing flights have to pass through departure fixes after leaving the runway. Therefore, at congested and busy airports, capacity constraints are probably due to limited runways or fixes, which affect the maximum throughput of airport facilities. Meanwhile, the distribution of the flow of aircraft through the arrival fixes also influences the efficiency of runway utilization. So this paper expands the analysis domain to cover the capacity system of the airport runway and the arrival/departure fixes. Because taxiways and gates at airports only indirectly influence technical delays, these sub-systems associated with ground operations are not included in the analysis in this paper.

The efficiency of runway utilization depends on whether the actual take-off/landing of aircraft in a specified time interval is close to theoretical capacity. When the facility is overloaded and becomes unable to bear the burden, flight technical delays will result. In order to utilize effectively the runway, consideration has to be given to the features of different separation times of merging/diverging flights toward arrival/departure fixes in relation to the same or different routes so as to make the best arrangement of flight take-off/landing sequences according to the advantageous separation time, and thus effectively enhance the efficiency of runway utilization and decrease aircraft delays. In other words, considering the constraints of flights passing through arrival/departure fixes and the shortest separation of flights will not only minimize total technical delay, but will also effectively improve the efficiency of runway utilization. On the other hand, due to the limitation of runway capacity, a reasonable range of flight take-offs/landings during a specified time interval exists. If the planned timetable demands take-offs/landings above this range, it will lead to scheduled timetable delays spreading to the take-off/landing operation of after-flights. In order to avoid a scheduled timetable delay ripple, an appropriate approach is to use the shortest separation time in arranging the take-off/landing sequence of aircraft to achieve the best utilization of runways – that is, to set the objective to minimize accumulated technical delays (including ATC technical delay and scheduled timetable delay) of aircraft through predetermined traffic control points.

3.1. Notation and Description

The notation used in the following sections of the paper are defined as follows:

$AA_{p,j}^{i,k}$ Represents the binary variable of consecutive arrival pattern, the pre-flight arriving through route i followed by arriving flight j via route k at the p time point. If at the p time point the pre-flight of flight j arrives through route i and is followed by flight j arriving through route k, then $AA_{p,j}^{i,k} = 1$, otherwise, $AA_{p,j}^{i,k} = 0$.

$AD_{p,j}^{i,k}$	Represents the binary variable of the arrival–departure pattern, the pre-flight arriving through route i followed by departing flight j via route k at the p time point. If at the p time point the pre-flight of flight j arrives through route i and is followed by flight j departing via route k, then $AD_{p,j}^{i,k} = 1$, otherwise, $AD_{p,j}^{i,k} = 0$.
$DA_{p,j}^{i,k}$	Represents the binary variable of departure–arrival pattern, the pre-flight departing through route i followed by arriving flight j via route k at the p time point. If at the p time point the pre-flight of aircraft j departs through route i and is followed by flight j arriving via route k, then $DA_{p,j}^{i,k} = 1$, otherwise, $DA_{p,j}^{i,k} = 0$.
$DD_{p,j}^{i,k}$	Represents the binary variable of consecutive departure pattern, the pre-flight departing through route i followed by departing flight j via route k at the p time point. If at the p time point the pre-flight of flight j departs through route i and is followed by flight j departing through route k, then $DD_{p,j}^{i,k} = 1$, otherwise, $DD_{p,j}^{i,k} = 0$.
$S_{AA}^{i,k}, S_{AD}^{i,k}, S_{DA}^{i,k}, S_{DD}^{i,k}$	Represents the separation time between flights of consecutive arrival patterns, arrival–departure patterns, departure–arrival patterns, consecutive departure patterns, respectively, with pre-flight passes through route i, and behind-flight passes via route k.
n_a	Number of arrival routes.
n_d	Number of departure routes.
M	Number of time points in the scheduled flight timetable.
T_P	Duration of the p time point.
$F(p)$	Number of flights scheduled at p time point.
A_p^i, D_p^k	The scheduled arrivals via fix i, and the scheduled departures via fix k, respectively, at the p time point.
X_p^+	The scheduled timetable delay at the p time point.
$R(A), R(D)$	The set of arrival and departure routes.

3.2. Model Formulation and Assumptions

In order to analyse flight technical delays, it is first necessary to define the technical delay of individual flights as the time difference between the permitted take-off/landing time and the scheduled flight time. Under this definition, more than one flight scheduled at the same time must produce a technical delay. However, flight timetables suggest that flights are almost always scheduled at some convenient time points such as 5, 10 min, etc. Therefore, on the time axis these time points are not continuous. They discontinue at the points of the scheduled time of flights. Unless the flight can take off or arrive early, the schedule cannot help but produce a technical delay. If the assumption is that all flights cannot take-off or arrive earlier than scheduled and the first flight would be on time at each time point, then technical delays will occur only on other flights at the same time point. Figure 1 shows that with five flights using the runway at the same time point, assuming that the first aircraft flight is on time to take off or arrive on the runway, the delay of the second flight is the separation time between the first flight and the second flight, and the delay of the third flight is the accumulation of separation time including the second flight separation time, and the separation time between the second flight and the third flight. Similarly, we obtain the accumulated separation approach, which gives us every flight delay value.

The separation time of every flight is related to the take-off/landing pattern between pre-flight and behind-flight. There are four take-off/landing patterns: the consecutive arrival pattern (AA), the arrival–departure pattern (AD), the departure–arrival pattern (DA), and the consecutive departure pattern (DD). Only one exact pattern exists between pre-flight and behind-flight among these four patterns; the other three patterns disappear at the same time. Therefore, the flight separation time can be formulated as follows: $S_{AA} \cdot AA + S_{AD} \cdot AD + S_{DA} \cdot DA + S_{DD} \cdot DD$, where AA, AD, DA, and DD represent the take-off/landing separation patterns of flights, which are binary integer

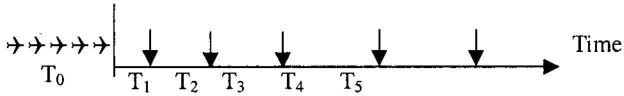

FIGURE 1 Relationship between flight delay and flight separation.

variables, and $AA + AD + DA + DD = 1$. S_{AA}, S_{AD}, S_{DA}, and S_{DD} represent the separation time of corresponding take-off/landing patterns, respectively. On this basis, the total delay of the above-mentioned example as a sum of the individual flight delay, except for the first flight at the time point, can be illustrated as follows:

$$\sum_{i=2}^{5}\left(S_{AA}\cdot\sum_{j=2}^{i}AA_j + S_{AD}\cdot\sum_{j=2}^{i}AD_j + S_{DA}\cdot\sum_{j=2}^{i}DA_j + S_{DD}\cdot\sum_{j=2}^{i}DD_j\right) \tag{1}$$

Consider that different arrival routes and departure routes possibly make the flight separation different from the above used separation time. If this is the case, the take-off/landing patterns at every time point become complicated. Taking the same example as the above, with five flights, but with n_a arrival routes and n_d departure routes, there will be $n_a \cdot n_a$ consecutive arrival patterns, $n_a \cdot n_d$ arrival–departure patterns, $n_d \cdot n_d$ consecutive departure patterns, and $n_d \cdot n_a$ departure–arrival patterns. In this example, the total delay similar to that shown in expression (1) can be written as follows:

$$\sum_{l=2}^{5}\sum_{j=2}^{l}\left(\sum_{i=1}^{n_a}\sum_{k=1}^{n_a}S_{AA}^{i,k}\cdot AA_j^{i,k} + \sum_{i=1}^{n_a}\sum_{k=1}^{n_d}S_{AD}^{i,k}\cdot AD_j^{i,k} + \sum_{i=1}^{n_d}\sum_{k=1}^{n_a}S_{DA}^{i,k}\cdot DA_j^{i,k} + \sum_{i=1}^{n_d}\sum_{k=1}^{n_d}S_{DD}^{i,k}\cdot DD_j^{i,k}\right) \tag{2}$$

The separation time of the flight j is:

$$\left(\sum_{i=1}^{n_a}\sum_{k=1}^{n_a}S_{AA}^{i,k}\cdot AA_j^{i,k} + \sum_{i=1}^{n_a}\sum_{k=1}^{n_d}S_{AD}^{i,k}\cdot AD_j^{i,k} + \sum_{i=1}^{n_d}\sum_{k=1}^{n_a}S_{DA}^{i,k}\cdot DA_j^{i,k} + \sum_{i=1}^{n_d}\sum_{k=1}^{n_d}S_{DD}^{i,k}\cdot DD_j^{i,k}\right)$$

and

$$\sum_{i=1}^{n_a}\sum_{k=1}^{n_a}AA_j^{i,k} + \sum_{i=1}^{n_a}\sum_{k=1}^{n_d}AD_j^{i,k} + \sum_{i=1}^{n_d}\sum_{k=1}^{n_a}DA_j^{i,k} + \sum_{i=1}^{n_d}\sum_{k=1}^{n_d}DD_j^{i,k} = 1$$

While analysing a time period including M time points and the flight number of time point p is $F(P)$, the total ATC technical delay for that time period is formulated as in expression (3).

$$\sum_{p=1}^{M}\sum_{l=2}^{F(p)}\sum_{j=2}^{l}\left(\sum_{i=1}^{n_a}\sum_{k=1}^{n_a} S_{AA}^{i,k}\cdot AA_{p,j}^{i,k}+\sum_{i=1}^{n_a}\sum_{k=1}^{n_d} S_{AD}^{i,k}\cdot AD_{p,j}^{i,k}+\sum_{i=1}^{n_d}\sum_{k=1}^{n_a} S_{DA}^{i,k}\cdot DA_{p,j}^{i,k}+\sum_{i=1}^{n_d}\sum_{k=1}^{n_d} S_{DD}^{i,k}\cdot DD_{p,j}^{i,k}\right) \quad (3)$$

Furthermore, although adopting the shortest separation time to arrange the flight take-off/landing sequence can avoid escalating flight delays, it is unable to remove flight delays completely. In fact, due to the limitation of runway capacity, even if carriers can make their flights conform to the scheduled plan of take-off or arrival at the runway, the take-off/landing slots associated with each time point will not always suffice for the scheduled operations. Flight delay, due to insufficient capacity at the previous time point, causes delays to the ensuing flights. Therefore, the first flight at every time point cannot always be on time as assumed in the above description. Delays caused by overloaded flight timetables may ripple over the peak periods and are defined in this paper as "scheduled timetable delays". These delays of course will result in an increase in the effective delay. Thus, to measure the effectiveness of an air traffic management scheme, both technical delays of individual flights at every time point and the scheduled timetable delays should be taken into account.

As for the measurement of scheduled timetable delays, it is assumed that the flights scheduled at p time point must wait for take-off/landing until all flights scheduled at the $p-1$ time point have completed their operations. Based on this assumption, the scheduled timetable delays can be calculated by using the information of the shortest completion time of the flight operations at every time point. The shortest completion time of the flight operations is derived from the flight sequence arranged with the least flight separation. If the completion times at some time points are earlier than the time allocated in the flight timetable, there will be no scheduled timetable delays at those time points. Otherwise, there will be scheduled timetable delays. The length of time of the scheduled timetable delay is equal to the difference between the expected completion time and the time allocated in the timetable.

For example, consider the five-flight case. The time interval between the first time point and the next time point is set to 5 min. That is to say, only 5 min are assigned in the timetable to operate these five flights. In addition, to avoid scheduled timetable delay, the first aircraft at the next time point also needs sufficient time to meet the separation requirement. By using the shortest separation time to arrange the five take-off/landing sequences, the total operation time is 4 min and 29 s. The remaining 31 s does not provide sufficient time to separate it from the next flight. The least separation time between the fifth flight and the first flight at the next time point is 88 s. Thus, the first flight at the next time point will not be on time. The scheduled timetable delay at the first time point is 57 s ($88 - 31 = 57$). Mathematically, it can be expressed as follows:

$$X_1^+ = \left[\sum_{j=2}^{6} \left(\sum_{i=1}^{n_a} \sum_{k=1}^{n_a} S_{AA}^{i,k} \cdot AA_j^{i,k} + \sum_{i=1}^{n_a} \sum_{k=1}^{n_d} S_{AD}^{i,k} \cdot AD_j^{i,k} + \sum_{i=1}^{n_d} \sum_{k=1}^{n_a} S_{DA}^{i,k} \cdot DA_j^{i,k} + \sum_{i=1}^{n_d} \sum_{k=1}^{n_d} S_{DD}^{i,k} \cdot DD_j^{i,k} \right) - 300 \right]^+$$

If the scheduled timetable delay of the subsequent time point still does not disappear, it will continuously influence the take-off/landing time of the ensuing flights. Therefore, the scheduled timetable delay at any time point p should be formulated as follows:

$$X_p^+ = \left\{ X_{p-1}^+ + \left[\sum_{j=2}^{F(P)} \left(\sum_{i=1}^{n_a} \sum_{k=1}^{n_a} S_{AA}^{i,k} \cdot AA_{p,j}^{i,k} + \sum_{i=1}^{n_a} \sum_{k=1}^{n_d} S_{AD}^{i,k} \cdot AD_{p,j}^{i,k} + \sum_{i=1}^{n_d} \sum_{k=1}^{n_a} S_{DA}^{i,k} \cdot DA_{p,j}^{i,k} + \sum_{i=1}^{n_d} \sum_{k=1}^{n_d} S_{DD}^{i,k} \cdot DD_{p,j}^{i,k} \right) \right] - T_p + \left(\sum_{i=1}^{n_a} \sum_{k=1}^{n_a} S_{AA}^{i,k} \cdot AA_{p+1,1}^{i,k} + \sum_{i=1}^{n_a} \sum_{k=1}^{n_d} S_{AD}^{i,k} \cdot AD_{p+1,1}^{i,k} + \sum_{i=1}^{n_d} \sum_{k=1}^{n_a} S_{DA}^{i,k} \cdot DA_{p+1,1}^{i,k} + \sum_{i=1}^{n_d} \sum_{k=1}^{n_d} S_{DD}^{i,k} \cdot DD_{p+1,1}^{i,k} \right) \right\}^+ \quad (4)$$

where

$$X_p^+ = \begin{cases} X_p & X_p \geq 0 \\ 0 & X_p < 0 \end{cases} \qquad \square$$

X_p^+ is determined from the least separation time of the take-off/landing sequence at time point p, which will not influence the best take-off/landing sequence at the time point $p+1$, and its value influences only the delays of flights scheduled at the ensuing time point.

The total scheduled timetable delay of flights at time point $p+1$ is $X_p^+ \cdot F(p+1)$. If the time period analysed includes M time points, the accumulated scheduled timetable delay of M time points is stated as follows:

$$\sum_{p=1}^{M-1} X_p^+ \cdot F(p+1) \tag{5}$$

The scheduled timetable delay causes the same time delay for each flight at the following time point. Therefore, it seems that the best flight sequence is not related to the flight sequence at the previous time point. Nevertheless, to be complete and to obtain the exact formulation, we must contemplate the interface between the consecutive time points. Thus, delays stated in Eqs. (3) and (5) are synthesized as shown in expression (6) so as to make total flight delay precise:

$$\sum_{p=1}^{M}\sum_{l=2}^{F(P)}\sum_{j=2}^{l}\left(\sum_{i=1}^{n_a}\sum_{k=1}^{n_a} S_{AA}^{i,k} \cdot AA_{p,j}^{i,k} + \sum_{i=1}^{n_a}\sum_{k=1}^{n_d} S_{AD}^{i,k} \cdot AD_{p,j}^{i,k} + \sum_{i=1}^{n_d}\sum_{k=1}^{n_a} S_{DA}^{i,k} \cdot DA_{p,j}^{i,k} + \sum_{i=1}^{n_d}\sum_{k=1}^{n_d} S_{DD}^{i,k} \cdot DD_{p,j}^{i,k}\right) + \sum_{p=1}^{M-1} X_p^+ \cdot F(p+1) \tag{6}$$

4. DELAY OPTIMIZATION MODEL

Since scheduled flights should follow a planned time and route to arrive or depart, to be realistic firstly the constraints representing the number of flights passing through a specified route and time should appear in the formulation. Equations (7) and (8) represent respectively the constraints of the number of arrivals and departures, which are scheduled to pass through route k at the time point p during the time period analysed. The expression within the parentheses of Eq. (7) represents whether flight j at the time point p is passing through route k to arrive at the airport or not. The sum of the flights at the time point p gives the number of arrivals passing through route k at time point p. Similarly, Eq. (8) represents the number of departures passing through route k at time point p.

$$\sum_{j=1}^{F(p)} \left(\sum_{i=1}^{n_a} AA_{p,j}^{i,k} + \sum_{i=1}^{n_d} DA_{p,j}^{i,k} \right) = A_p^k \quad \forall p, k \in R(A) \tag{7}$$

$$\sum_{j=1}^{F(p)} \left(\sum_{i=1}^{n_a} AD_{p,j}^{i,k} + \sum_{i=1}^{n_d} DD_{p,j}^{i,k} \right) = D_p^k \quad \forall p, k \in R(D) \tag{8}$$

Secondly, because every flight must conform to the flight plan and pass through its designated route, the relationship between flights should be established so that the flight sequence is consistent and realistic. That is to say, the separations between flights should be clearly, consistently, and accurately defined. For instance, if the former flight is an arrival and the latter flight is either an arrival or a departure, the type of flight separation should not be mistakenly handled as a consecutive take-off. Inequalities (9) and (10) are the constraints that establish this type of relationship.

$$\sum_{k=1}^{n_d} AD_{p,j}^{\alpha,k} + \sum_{k=1}^{n_a} AA_{p,j}^{\alpha,k} \leq 1 - \left[\sum_{i=1}^{n_d} \sum_{k=1}^{n_d} DD_{p,j-1}^{i,k} + \sum_{i=1}^{n_a} \sum_{k=1}^{n_d} AD_{p,j-1}^{i,k} + \sum_{i=1}^{n_d} \sum_{\beta \neq \alpha}^{n_a} DA_{p,j-1}^{i,\beta} + \sum_{i=1}^{n_a} \sum_{\beta \neq \alpha}^{n_a} AA_{p,j-1}^{i,\beta} \right] \quad \forall j, p, \alpha \tag{9}$$

$$\sum_{k=1}^{n_a} DA_{p,j}^{\alpha,k} + \sum_{k=1}^{n_d} DD_{p,j}^{\alpha,k} \leq 1 - \left[\sum_{i=1}^{n_a} \sum_{k=1}^{n_a} AA_{p,j-1}^{i,k} + \sum_{i=1}^{n_d} \sum_{k=1}^{n_a} DA_{p,j-1}^{i,k} + \sum_{i=1}^{n_a} \sum_{\beta \neq \alpha}^{n_d} AD_{p,j-1}^{i,\beta} + \sum_{i=1}^{n_d} \sum_{\beta \neq \alpha}^{n_d} DD_{p,j-1}^{i,\beta} \right] \quad \forall j, p, \alpha \tag{10}$$

Inequality (9) forms the relationship between flight j and its former flight, which is an arrival flight. The left side of the inequality represents whether the former flight is passing through route α to arrive or not. If the former flight passes through route α to arrive at the airport, then the value of $\sum_{k=1}^{n_d} AD_{p,j}^{\alpha,k} + \sum_{k=1}^{n_a} AA_{p,j}^{\alpha,k}$ is 1; otherwise, it is 0. In order to be sure that the connections of these flights are consistent, when a former flight is either a departure flight or passing through a route other than α to arrive, the value of the right hand side of the inequality must be 0. Inequality (9) can ensure the correct result. Similarly, Inequality (10) forms the relationship between flight j and its former flight, which is a departure flight.

In addition, considering a runway can allow only one flight to take-off/land, and every flight must be assigned once, this gives the following constraint:

$$\sum_{i=1}^{n_a}\sum_{k=1}^{n_a} AA_{p,j}^{i,k} + \sum_{i=1}^{n_a}\sum_{k=1}^{n_d} AD_{p,j}^{i,k} + \sum_{i=1}^{n_d}\sum_{k=1}^{n_a} DA_{p,j}^{i,k} + \sum_{i=1}^{n_d}\sum_{k=1}^{n_d} DD_{p,j}^{i,k} = 1, \quad \forall j,p \tag{11}$$

Finally, consider the capacity constraints at some check points. Every landing aircraft must pass through an arrival fix to the runway. If the demand to invoke the arrival fix is larger than the associated capacity, it will cause the arrival flights to be delayed in the air. Similarly, when the number of departure flights is larger than the available capacity, it will cause flights to be delayed on the ground. The total delay stated in expression (6) sums both air delays and ground delays, of which the air delay of the arrival flight is shown in (12) and the ground delay of the departure flight is stated in (13):

$$\begin{aligned}\sum_{p=1}^{M}\sum_{l=2}^{F(p)}\Bigg[\left(\sum_{i=1}^{n_a}\sum_{k=1}^{n_a} AA_{p,l}^{i,k} + \sum_{i=1}^{n_d}\sum_{k=1}^{n_a} DA_{p,l}^{i,k}\right)\cdot\sum_{j=2}^{l}\Bigg(\sum_{i=1}^{n_a}\sum_{k=1}^{n_a} S_{AA}^{i,k}\cdot AA_{p,j}^{i,k} \\ + \sum_{i=1}^{n_a}\sum_{k=1}^{n_d} S_{AD}^{i,k}\cdot AD_{p,j}^{i,k} + \sum_{i=1}^{n_d}\sum_{k=1}^{n_a} S_{DA}^{i,k}\cdot DA_{p,j}^{i,k} + \sum_{i=1}^{n_d}\sum_{k=1}^{n_d} S_{DD}^{i,k}\cdot DD_{p,j}^{i,k}\Bigg)\Bigg] \\ + \left[\sum_{p=1}^{M-1} X_p^{+}\cdot A_{p+1}^{k}\right]\end{aligned} \tag{12}$$

$$\sum_{p=1}^{M}\sum_{l=2}^{F(p)}\left[\left(\sum_{i=1}^{n_a}\sum_{k=1}^{n_d}AD_{p,l}^{i,k}+\sum_{i=1}^{n_d}\sum_{k=1}^{n_d}DD_{p,l}^{i,k}\right)\right.$$

$$\cdot\sum_{j=2}^{l}\left(\sum_{i=1}^{n_a}\sum_{k=1}^{n_a}S_{AA}^{i,k}\cdot AA_{p,j}^{i,k}+\sum_{i=1}^{n_a}\sum_{k=1}^{n_d}S_{AD}^{i,k}\cdot AD_{p,j}^{i,k}+\sum_{i=1}^{n_d}\sum_{k=1}^{n_a}S_{DA}^{i,k}\cdot DA_{p,j}^{i,k}\right.$$

$$\left.\left.+\sum_{i=1}^{n_d}\sum_{k=1}^{n_d}S_{DD}^{i,k}\cdot DD_{p,j}^{i,k}\right)\right]+\left[\sum_{p=1}^{M-1}X_p^+\cdot D_{p+1}^k\right] \tag{13}$$

We can now formulate our comprehensive optimization model as follows:

Min

$$w_1\left\{\sum_{p=1}^{M}\sum_{l=2}^{F(p)}\left[\left(\sum_{i=1}^{n_a}\sum_{k=1}^{n_a}AA_{p,l}^{i,k}+\sum_{i=1}^{n_d}\sum_{k=1}^{n_a}DA_{p,l}^{i,k}\right)\right.\right.$$

$$\cdot\sum_{j=2}^{l}\left(\sum_{i=1}^{n_a}\sum_{k=1}^{n_a}S_{AA}^{i,k}\cdot AA_{p,j}^{i,k}+\sum_{i=1}^{n_a}\sum_{k=1}^{n_d}S_{AD}^{i,k}\cdot AD_{p,j}^{i,k}\right.$$

$$\left.\left.+\sum_{i=1}^{n_d}\sum_{k=1}^{n_a}S_{DA}^{i,k}\cdot DA_{p,j}^{i,k}+\sum_{i=1}^{n_d}\sum_{k=1}^{n_d}S_{DD}^{i,k}\cdot DD_{p,j}^{i,k}\right)\right]$$

$$\left.+\left[\sum_{p=1}^{M-1}X_p^+\cdot A_{p+1}^k\right]\right\}$$

$$+w_2\left\{\sum_{p=1}^{M}\sum_{l=2}^{F(p)}\left[\left(\sum_{i=1}^{n_a}\sum_{k=1}^{n_d}AD_{p,l}^{i,k}+\sum_{i=1}^{n_d}\sum_{k=1}^{n_d}DD_{p,l}^{i,k}\right)\right.\right.$$

$$\cdot\sum_{j=2}^{l}\left(\sum_{i=1}^{n_a}\sum_{k=1}^{n_a}S_{AA}^{i,k}\cdot AA_{p,j}^{i,k}+\sum_{i=1}^{n_a}\sum_{k=1}^{n_d}S_{AD}^{i,k}\cdot AD_{p,j}^{i,k}\right.$$

$$\left.\left.+\sum_{i=1}^{n_d}\sum_{k=1}^{n_a}S_{DA}^{i,k}\cdot DA_{p,j}^{i,k}+\sum_{i=1}^{n_d}\sum_{k=1}^{n_d}S_{DD}^{i,k}\cdot DD_{p,j}^{i,k}\right)\right]$$

$$\left.+\left[\sum_{p=1}^{M-1}X_p^+\cdot D_{p+1}^k\right]\right\} \tag{14}$$

S.T.

$$X_p^+ \geq \Bigg\{ X_{p-1}^+ + \Bigg[\sum_{j=2}^{F(P)} \Bigg(\sum_{i=1}^{n_a} \sum_{k=1}^{n_a} S_{AA}^{i,k} \cdot AA_{p,j}^{i,k} + \sum_{i=1}^{n_a} \sum_{k=1}^{n_d} S_{AD}^{i,k} \cdot AD_{p,j}^{i,k} + \sum_{i=1}^{n_d} \sum_{k=1}^{n_a} S_{DA}^{i,k} \cdot DA_{p,j}^{i,k} + \sum_{i=1}^{n_d} \sum_{k=1}^{n_d} S_{DD}^{i,k} \cdot DD_{p,j}^{i,k} \Bigg) \Bigg] - T_p + \Bigg(\sum_{i=1}^{n_a} \sum_{k=1}^{n_a} S_{AA}^{i,k} \cdot AA_{p+1,1}^{i,k} + \sum_{i=1}^{n_a} \sum_{k=1}^{n_d} S_{AD}^{i,k} \cdot AD_{p+1,1}^{i,k} + \sum_{i=1}^{n_d} \sum_{k=1}^{n_a} S_{DA}^{i,k} \cdot DA_{p+1,1}^{i,k} + \sum_{i=1}^{n_d} \sum_{k=1}^{n_d} S_{DD}^{i,k} \cdot DD_{p+1,1}^{i,k} \Bigg) \Bigg\} \quad \forall p \tag{15}$$

$$\sum_{j=1}^{F(P)} \left(\sum_{i=1}^{n_a} AA_{p,j}^{i,k} + \sum_{i=1}^{n_d} DA_{p,j}^{i,k} \right) = A_p^k \quad k \in R(A), \ \forall p \tag{16}$$

$$\sum_{j=1}^{F(P)} \left(\sum_{i=1}^{n_a} AD_{p,j}^{i,k} + \sum_{i=1}^{n_d} DD_{p,j}^{i,k} \right) = D_p^k \quad k \in R(D), \ \forall p \tag{17}$$

$$\sum_{k=1}^{n_d} AD_{p,j}^{\alpha,k} + \sum_{k=1}^{n_a} AA_{p,j}^{\alpha,k} \leq 1 - \left[\sum_{i=1}^{n_d} \sum_{k=1}^{n_d} DD_{p,j-1}^{i,j} + \sum_{i=1}^{n_a} \sum_{k=1}^{n_d} AD_{p,j-1}^{i,k} + \sum_{i=1}^{n_d} \sum_{\beta \neq \alpha}^{n_a} DA_{p,j-1}^{i,\beta} + \sum_{i=1}^{n_a} \sum_{\beta \neq \alpha}^{n_a} AA_{p,j-1}^{i,\beta} \right] \quad \forall j, p, \alpha \tag{18}$$

$$\sum_{k=1}^{n_a} DA_{p,j}^{\alpha,k} + \sum_{k=1}^{n_d} DD_{p,j}^{\alpha,k} \leq 1 - \left[\sum_{i=1}^{n_a} \sum_{k=1}^{n_a} AA_{p,j-1}^{i,k} + \sum_{i=1}^{n_d} \sum_{k=1}^{n_a} DA_{p,j-1}^{i,k} + \sum_{i=1}^{n_a} \sum_{\beta \neq \alpha}^{n_d} AD_{p,j-1}^{i,\beta} + \sum_{i=1}^{n_d} \sum_{\beta \neq \alpha}^{n_d} DD_{p,j-1}^{i,\beta} \right] \quad \forall j, p, \alpha \tag{19}$$

$$\sum_{i=1}^{n_a} \sum_{k=1}^{n_a} AA_{p,j}^{i,k} + \sum_{i=1}^{n_a} \sum_{k=1}^{n_d} AD_{p,j}^{i,k} + \sum_{i=1}^{n_d} \sum_{k=1}^{n_a} DA_{p,j}^{i,k} + \sum_{i=1}^{n_d} \sum_{k=1}^{n_d} DD_{p,j}^{i,k} = 1, \quad \forall j, p \tag{20}$$

$$X_p^+ \geq 0 \tag{21}$$

$$AA_{p,j}^{i,k}, AD_{p,j}^{i,k}, DA_{p,j}^{i,k}, DD_{p,j}^{i,k} \text{ are binary integer variables} \tag{22}$$

The objective function (14) sums the weighted air and ground delays including both technical delay and scheduled timetable delay. Constraint (15) is the expression which calculates scheduled timetable delay, and its value must be non-negative. Constraints (16) and (17) represent respectively the number of flights scheduled to arrive and depart via a designated route and time point. Inequalities (18) and (19) represent the connections between any two flights. Equation (20) states the assignment of flights to take off/land from/to a runway. Inequality (21) shows that the scheduled timetable delay at each time period should be greater than or equal to 0.

If the weight in objective function (14) is equal, that is $w_1 = w_2$, then the objective function can be simplified to a linear function and the formulation becomes:

$$\text{Min} \sum_{p=1}^{M} \sum_{l=2}^{F(p)} \sum_{j=2}^{l} \left(\sum_{i=1}^{n_a} \sum_{k=1}^{n_a} S_{AA}^{i,k} \cdot AA_{p,j}^{i,k} + \sum_{i=1}^{n_a} \sum_{k=1}^{n_d} S_{AD}^{i,k} \cdot AD_{p,j}^{i,k} + \sum_{i=1}^{n_d} \sum_{k=1}^{n_a} S_{DA}^{i,k} \cdot DA_{p,j}^{i,k} + \sum_{i=1}^{n_d} \sum_{k=1}^{n_d} S_{DD}^{i,k} . DD_{p,j}^{i,k} \right) + \sum_{p=1}^{M-1} X_p^+ \cdot F(p+1) \tag{23}$$

S.T. (15)–(22).

5. MODEL APPLICATION: THE CASE OF TAIPEI AIRPORT

5.1. Case Description

This section of the paper analyzes the technical delay resulting from the capacity constraints identified at Taipei Airport. It is assumed that all aircraft take-off/land on time as scheduled in the timetable. This simplification does not cause serious problems for the practical

TABLE I Statistics of flight separations (unit: min)

After-flight	*Pre-flight*			
	A^E	A^W	D^E	D^W
A^E	(2.00, –, 1)	(1.67, 0.49, 12)	(1.22, 0.44, 9)	(1.55, 0.50, 42)
A^W	(1.72, 0.57, 18)	(1.46, 0.68, 102)	(1.29, 0.46, 65)	(1.52, 0.50, 301)
D^E	(0.82, 0.60, 11)	(1.23, 0.54, 57)	(3.00, 0, 3)	(1.19, 0.40, 26)
D^W	(1.00, 0.47, 37)	(1.08, 0.57, 312)	(1.24, 0.66, 17)	(1.23, 0.60, 109)

Note: The numbers in parentheses represent the average, standard deviation, and number of samples. A,D represent arrival and departure, respectively. E,W represent the east and the west route, respectively.

analysis since the time difference between flight arriving/departing to and from the runway and gate can be modified as necessary. If the time difference is a constant, the timetable of flight arrivals/departures to and from the runway can be adjusted accordingly. As to the flight separations, the key parameters in the optimization model were obtained from the Control Tower of Taipei Airport, and only data under good weather conditions and the associated peak periods lasting more than 1 h were selected and analyzed. The reason for choosing samples from those peak periods is that the data were more typical, better represented the air controller's capability and workload, and inconsistent data would be avoided (Wong *et al.*, 1997).

To analyze differences in flight separations under various conditions, data from March 1995 to March 1997 were collected. The statistics for flight separations are shown in Table I. These indicate that flights passing through the east route corridor are infrequent, resulting in separations being unreasonably long (about 2 and 3 min, respectively). When these separations are ignored, the statistics show that separation ranges from 0.82 to 1.72 min.

5.2. Scenario Analysis

Two analyses have been undertaken with the optimization model devised for Taipei Airport which show the performance of air traffic management under different weights accorded to air and ground delays.

5.2.1. Equal Weights for Air and Ground Delay

The outcomes of equal weight being given to air and ground delays are shown in Table II. Among the technical delays from the constraints associated with facility capacity, air delay is more serious than ground delay. On average flight delay is 4.69 min. As to the associated flight sequence (Table III), the arrangement follows the rule of minimum separation.

Furthermore, from Tables II and III we can also see the inadequacy of the timetable settings, which leads to the propagation of scheduled timetable delay. As nine flights were prepared for take-off/landing at 09:10:00 and the operating time allocated was only 10 min at this time point, it was inevitable that such a schedule would lead to a delay ripple and influence subsequent flights. (This information could be useful for revising the flight timetable so as to reduce the avoidable flight delay.) Also, the flight sequence shown in Table III suggests

TABLE II Outputs of flight delay during peak hour (unit: min)

Type of delay	*Air delay*	*Ground delay*	*Total*
ATC technical delay	82.90	45.95	128.85
Scheduled timetable delay	31.05	37.10	68.15
Total delay	113.95	83.05	197.00
Average delay	5.43	3.95	4.69

TABLE III Details of the model outputs (unit: min)

Time point	*Optimal flight sequence*	*ATC technical delay*	*Scheduled timetable delay*
09:00:00	$D^W A^E D^E D^W A^W$	11.100	0
09:05:00	A^W	0	0.950
09:10:00	$D^W A^W D^W A^W A^W A^W A^W A^W A^W$	47.783	0
09:20:00	$D^E D^W A^W D^W D^W D^E$	18.000	13.800
09:25:00	$A^E D^E D^W$	3.617	12.400
09:30:00	$A^E D^W A^E D^W A^W$	13.383	12.667
09:35:00	$A^W A^W$	1.467	8.367
09:40:00	$D^W D^W A^W D^W A^W D^W A^W$	26.250	15.167
09:50:00	$D^W D^W D^W A^W$	7.250	4.800
Total		128.85	68.150

TABLE IV Results of flight delays by routes (unit: min)

Type of delay	*Arrival from the east route*	*Arrival from the west route*	*Departure to the east route*	*Departure to the west route*
ATC technical delay	3.55(0.887)	79.35(4.667)	9.45(2.363)	36.50(2.147)
Scheduled timetable delay	9.20(2.300)	21.85(1.285)	8.73(2.182)	28.37(1.669)
Total delay	12.75(3.187)	101.20(5.952)	18.18(4.545)	64.87(3.816)

Note: The numbers in parentheses represent average delay per flight.

that in order to increase runway efficiency by keeping flight separation to a minimum, attention should be paid to timetable planning so that the ratio of arrivals to departures at each time point is well considered.

Currently, aircraft fly mainly on the western corridor. Consequently, flight delay on the west route is expected to be higher, as demonstrated in Table IV. Here the average technical delay to flights arriving from the west route is 4.667 min, those departing along the west route is 2.147 min, those arriving from the east route is 0.887 min, and those departing along the east route is 2.363 min. These outcomes show clearly that the load on the west route is heavier, and so flights arriving via that route have greater delays.

5.2.2. *Different Weights for Air and Ground Delays*

Due to the danger and cost associated with air delays, methods to reduce them are often exercised. However, these can cause a transfer from air delay to ground delay. Thus, to study the possible substitution between these two types of delay, we have experimented with different weightings for air and ground delays in our analyses.

Table V shows that when ground technical delay is minimized, air technical delay will be 85.433 min; on the contrary, when air technical delay is minimized, its value will be reduced to 44.367 min, a 41 min decrease. In comparison, ground technical delay increases from 46.383 to 100.668 min, about a 54 min increase. While the air/ground delay weight varies from 2/1 to 3/1, the decrease in the air technical delay is rather limited. By transferring air delay to ground delay, the air technical delay is indeed improved. However, because the arriving aircraft gets priority, the flight sequence will not be optimal and the

TABLE V ATC technical delay for different delay weights (unit: min)

Delay weight air: ground	*Eastern flight air delay* (1)	*Western flight air delay* (2)	*Total air delay* (3) = (1) + (2)	*Eastern flight ground delay* (4)	*Western flight ground delay* (5)	*Total ground delay* (6) = (4) + (5)	*Total ATC technical delay* (7) = (3) + (6)
0 : 1	8.167	77.266	85.433	7.567	38.816	46.383	131.817
	(2.042)	(4.545)	(4.068)	(1.892)	(2.283)	(2.209)	(3.138)
2 : 1	9.450	43.467	52.917	7.617	79.050	86.667	139.583
	(2.363)	(2.557)	(2.520)	(1.904)	(4.650)	(4.127)	(3.323)
3 : 1	9.450	42.333	51.783	7.617	80.817	88.433	140.217
	(2.363)	(2.490)	(2.466)	(1.904)	(4.754)	(4.211)	(3.338)
1 : 0	7.700	36.667	44.367	10.233	90.450	100.683	145.050
	(1.925)	(2.157)	(2.113)	(2.558)	(5.321)	(4.794)	(3.454)
1 : 1	3.550	79.350	82.900	9.450	36.500	45.950	128.850
	(0.887)	(4.667)	(3.948)	(2.363)	(2.147)	(2.188)	(3.068)

Note: The numbers in parentheses represents average delay per flight.

TABLE VI Scheduled timetable delay for different weights (unit: min)

Delay weight air: ground	*Eastern flight air delay* (1)	*Western flight air delay* (2)	*Total air delay* (3) = (1) + (2)	*Eastern flight ground delay* (4)	*Western flight ground delay* (5)	*Total ground delay* (6) = (4) + (5)	*Total Scheduled timetable delay* (7) = (3) + (6)
0 : 1	10.833	29.134	39.967	8.867	37.600	46.467	86.433
	(2.708)	(1.714)	(1.903)	(2.217)	(2.212)	(2.213)	(2.058)
2 : 1	10.983	29.050	40.033	9.017	37.600	46.617	86.650
	(2.746)	(1.709)	(1.906)	(2.254)	(2.212)	(2.220)	(2.063)
3 : 1	10.983	29.083	40.067	9.017	37.700	46.717	86.783
	(2.746)	(1.711)	(1.908)	(2.254)	(2.217)	(2.225)	(2.066)
1 : 0	12.283	33.133	45.417	10.017	43.083	53.100	98.517
	(3.071)	(1.949)	(2.163)	(2.504)	(2.534)	(2.529)	(2.346)
1 : 1	9.200	21.850	31.050	8.730	28.370	37.100	68.150
	(2.300)	(1.285)	(1.411)	(2.182)	(1.669)	(1.686)	(1.623)

separation time is thus enlarged. As a consequence, departing flights will be held on the ground to wait for available slots. This non-optimal sequence will also lengthen the associated scheduled timetable delay and cause the delay ripple to increase continuously. Therefore, given a known demand, if the scheduled timetable delay cannot be effectively handled, air delay is difficult to improve significantly. This phenomenon is illustrated in Table VI.

Table VII, which combines data from Tables V and VI, shows that the total delays for the cases with unequal air/ground delay weight

TABLE VII Total delay for different weights (unit: min)

Delay weight air: ground	*Eastern flight air delay* (1)	*Western flight air delay* (2)	*Total air delay* (3) = (1) + (2)	*Eastern flight ground delay* (4)	*Western flight ground delay* (5)	*Total ground delay* (6) = (4) + (5)	*Total delay* (7) = (3) + (6)
0 : 1	19.000 (4.75)	106.400 (6.259)	125.400 (5.971)	16.433 (4.108)	76.417 (4.495)	92.850 (4.421)	218.250 (5.196)
2 : 1	20.433 (5.108)	72.517 (4.266)	92.950 (4.426)	16.633 (4.158)	116.650 (6.862)	133.283 (6.347)	226.233 (5.387)
3 : 1	20.433 (5.108)	71.417 (4.201)	91.850 (4.374)	16.633 (4.158)	118.517 (6.971)	135.150 (6.436)	227.000 (5.405)
1 : 0	19.983 (4.996)	69.800 (4.106)	89.783 (4.275)	20.250 (5.063)	133.533 (7.855)	153.783 (7.323)	243.567 (5.799)
1 : 1	12.750 (3.187)	101.200 (5.952)	113.950 (5.43.)	18.180 (4.545)	64.870 (3.816)	83.050 (3.95)	197.000 (4.69)

Note: The numbers in parentheses represent average delay per flight.

are higher than for the case with the same weight. For safety reasons, air delay should be minimized. In this case, the total delay will increase from 197 to 243 min, about a 46 min increase. And the average delay to each flight is 5.799 min. The total air delay is reduced from 113.95 to 89.783 min, only a 24.167 min improvement. The total ground delay, however, increases from 83.05 to 153.783 min, a substantial 70.733 min increase. On average, the ground delay of each flight is 4.421 min. While the ground delay is minimized, it will also cause the total delay to increase by 21 min, from 197 to 218.25 min. In addition, if the air/ground delay weight is adjusted to 2/1 or 3/1, air delay can only be marginally improved, by about 15 – 16 min. This phenomenon reflects the point that if the ratio of take-offs/landings at each time point and the flight timetable are not well planned, the improvement through the weight adjustment will be not effective.

6. RESULTS AND DISCUSSION

The technical delay to a flight is measured in our optimization model by subtracting the scheduled flight time on the timetable from the time arranged for the flight to take-off/land. This sort of delay depends on the original scheduled time, but not on the time a flight is ready to take-off/land. Although flights aim to be on time, in reality they are unable to follow precisely the time scheduled on the timetable. Times for flights scheduled at a specific time ready to take-off/land are randomly distributed over some period of time. The assumption that all flights will follow precisely the scheduled time may result in overestimating flight technical delay. In order to clarify this inconsistency and the possible discrepancy between our optimization model and the real world, this paper goes a step further by conducting simulation and regression analyses.

6.1. Testing of the Optimization Model

Quite clearly, actual flight technical delays should be based on real flight operations. Thus we have simulated take-off/landing times of flights so as to sort their sequence in order for delay analysis. Flight times were randomly distributed over the allocated time interval. For instance, at 09:00, five flights are shown on the timetable and the allocated time interval for these flights to operate is 5 min. The simulated flight time can thus be randomly generated as follows: 09:03:16 (A^W), 09:01:03 (D^E), 09:04:28 (A^E), 09:04:05 (D^W), and 09:03:32 (D^W). The sequence of these flights to take-off/land depends, however, on the ordering rule used in the simulation study. Two rules were considered in this simulation study: the "first come first served" (FCFS) rule and the "arrival priority" rule (which means that when there is competition for the time slot between arrival and departure, the arrival flight always has priority). Under the FCFS rule, the sequence of these five flights will be 09:01:03 (D^E), 09:03:16 (A^W), 09:03:32 (D^W), 09:04:05 (D^W), and 09:04:28 (A^E). Under the "arrival priority" rule, the sequence becomes 09:01:03 (D^E), 09:03:16 (A^W), 09:03:32 (D^W), 09:04:28 (A^E), and 09:04:05 (D^W). By using these sorts of sequence data, the actual technical delay associated with each service rule can then be calculated and compared to those from the optimization model.

Four samples with 42 hourly operations were selected from the timetables during the period from March 1995 to March 1997. For each sample, we tested 30 simulation runs and the statistics were analysed. The results are shown in Table VIII.

TABLE VIII Results of the simulation study (unit: min)

Sample	*fcfs* (1)	*Arrival priority* (2)	*Optimization* (3)	(1)–(3)	(2)–(3)
1	137.97(34.28)	164.68(37.95)	168.25	−30.28	−3.57
2	150.97(42.05)	200.65(53.15)	197.00	−46.03	3.65
3	206.01(34.09)	231.39(42.61)	236.55	−30.54	−5.16
4	204.15(41.32)	256.34(48.89)	246.17	−42.02	10.17
Average	174.78	213.27	211.99	−37.21	1.28
SD	35.402	39.596	36.099	0.697	3.497

Note: The numbers in parentheses are the standard deviations of 30 simulation runs.

The total delay under the FCFS rule is smaller than that suggested by the optimization model. This is due to the assumption made in the theoretical delay optimization model, in which flights except those influenced by the scheduled timetable delay were assumed to be on time. If a flight is not on time, it will be assumed to be a technical delay resulting from ATC procedures. The difference in total delay between the optimization model and the FCFS rule is about 30 – 46 min for the 42 flights, and the difference in the average delay is about 0.71 – 1.1 min per flight.

The total delay under the "arrival priority" rule may be either smaller or larger than that of the optimization model, but the amount is marginal. The difference in the total delay between the optimization and the arrival priority rule is about −5–10 min, and the difference in the average delay is about –0.11–0.24 min per flight. Going one step further, we examine the delay distribution of the simulation results for the four samples. It suggests that while the arrival/departure flights fluctuate over the study period (with a larger standard deviation of flight operations per 5 min), no matter which rule is used, the total flight delay will generally increase. Among the four samples, the standard deviation of sample 1 is the smallest; its total delay appears to be the smallest too. Meanwhile, samples 3 and 4 have larger deviations, and their delays are also higher. All these results meet our expectations.

Meanwhile, from the simulation runs, we could observe clearly that under a given flight timetable, flight delay is not a constant. Instead, it is a random variable and is influenced by actual flight operations, which in essence is random. In the case of sample 2, details of the 30 simulation runs are listed in Tables IX and X. These data suggest that when the standard deviation of air delay or ground delay increases, the corresponding total delay also increases. When the total separation of flights and their standard deviations are small, the associated total delays tend to be small. Under the FCFS rule, because of the regulation on flight separation, following flights must wait for service until the completion of service of the previous flight. Therefore, when the

TABLE IX The 30 simulation runs of sample 2 under FCFS rule (unit: min)

Number	*Air delay*	*Ground delay*	*Total delay*	*Total separation time*
1	61.468(2.023)	74.389(2.315)	135.857(2.035)	54.900(0.284)
2	66.965(2.170)	77.023(2.343)	143.988(2.051)	54.500(0.297)
3	103.310(3.427)	118.324(3.581)	221.634(3.220)	57.100(0.387)
4	87.645(3.089)	108.478(3.457)	196.124(3.232)	55.983(0.393)
5	60.368(1.881)	85.376(2.512)	145.744(1.965)	54.883(0.173)
6	57.900(2.095)	74.240(2.515)	132.139(2.393)	53.583(0.281)
7	84.466(2.801)	89.767(2.787)	174.233(2.609)	54.883(0.300)
8	70.189(2.325)	88.814(2.663)	159.002(2.293)	54.433(0.276)
9	59.997(2.260)	68.026(2.444)	128.023(2.518)	53.450(0.297)
10	80.193(3.136)	88.212(2.885)	168.404(3.152)	56.767(0.396)
11	69.563(1.995)	74.424(2.220)	143.987(1.702)	54.550(0.316)
12	51.248(1.704)	53.694(1.610)	104.941(1.516)	54.483(0.298)
13	87.170(3.310)	106.285(3.343)	193.455(3.372)	56.250(0.396)
14	79.256(2.683)	93.731(2.572)	172.987(2.278)	54.950(0.294)
15	124.586(4.075)	150.648(4.280)	275.235(3.623)	57.050(0.399)
16	40.823(1.432)	45.578(1.428)	86.401(1.389)	53.867(0.291)
17	65.156(1.968)	50.841(1.677)	115.997(1.684)	54.850(0.301)
18	90.883(2.960)	118.249(3.336)	209.132(2.723)	56.483(0.405)
19	71.974(2.607)	84.486(2.419)	156.460(2.363)	54.850(0.291)
20	85.919(2.887)	100.494(2.958)	186.414(2.657)	54.683(0.289)
21	62.939(2.327)	91.195(2.716)	154.133(2.474)	56.333(0.390)
22	87.819(2.985)	94.955(2.855)	182.774(2.716)	57.483(0.470)
23	68.423(2.209)	76.861(2.229)	145.284(1.933)	53.800(0.300)
24	53.585(1.861)	67.978(2.022)	121.562(1.822)	53.900(0.293)
25	49.716(1.516)	62.608(1.870)	112.324(1.476)	53.717(0.294)
26	51.746(1.775)	44.505(1.570)	96.250(1.715)	54.067(0.292)
27	57.986(1.965)	68.013(2.089)	125.999(1.909)	54.533(0.286)
28	48.338(1.536)	41.586(1.518)	89.924(1.307)	54.033(0.279)
29	62.482(2.082)	70.986(2.124)	133.468(1.334)	55.233(0.314)
30	51.629(1.592)	65.616(1.959)	117.245(1.428)	54.467(0.285)
Average	69.791	81.179	150.971	55.002
SD	18.407	24.375	42.054	1.144

Note: The numbers in parentheses are the standard deviations of flight delay or separation.

TABLE X The 30 simulation runs of sample 2 under arrival priority rule (unit: min)

Number	*Air delay*	*Ground delay*	*Total delay*	*Total separation time*
1	24.835(0.820)	129.172(4.506)	154.007(4.153)	55.517(0.299)
2	22.120(0.913)	185.539(6.434)	207.659(6.121)	54.783(0.298)
3	21.455(0.917)	273.727(8.849)	295.182(8.505)	57.617(0.384)
4	17.852(0.868)	207.599(7.098)	225.451(6.844)	53.767(0.298)
5	23.340(0.924)	130.831(4.223)	154.171(3.892)	54.267(0.304)
6	17.059(0.728)	229.020(7.446)	246.079(7.172)	55.717(0.283)
7	24.184(0.954)	195.684(6.305)	219.868(5.931)	56.433(0.404)
8	19.913(0.951)	179.257(6.108)	199.170(5.837)	55.317(0.288)
9	18.585(0.881)	158.728(5.809)	177.313(5.576)	54.617(0.285)
10	13.281(0.645)	208.578(7.469)	221.859(7.279)	57.517(0.404)
11	18.274(0.797)	142.270(4.337)	160.544(4.062)	54.383(0.279)
12	7.460(0.369)	286.781(9.273)	294.241(9.146)	55.667(0.301)
13	14.928(0.675)	193.806(6.838)	208.733(6.622)	54.567(0.294)
14	18.893(1.002)	248.156(7.979)	267.049(7.696)	56.233(0.300)
15	31.108(1.297)	281.793(8.698)	312.9(8.195)	57.550(0.391)
16	14.354(0.527)	118.279(4.161)	132.633(3.952)	55.750(0.311)
17	25.599(1.113)	121.818(4.493)	147.417(4.219)	55.483(0.299)
18	22.999(1.041)	267.251(7.709)	290.250(7.306)	54.783(0.298)
19	20.718(0.889)	203.324(6.502)	224.042(6.178)	56.033(0.305)
20	20.526(0.924)	210.457(6.677)	230.983(6.358)	55.100(0.279)
21	18.449(0.797)	137.247(4.337)	155.696(4.062)	54.900(0.279)
22	15.400(0.669)	163.323(5.396)	178.723(5.162)	54.300(0.291)
23	18.460(0.757)	177.553(5.413)	196.013(5.106)	56.150(0.399)
24	9.401(0.482)	213.398(6.913)	222.803(6.760)	55.267(0.289)
25	20.127(0.727)	129.461(4.412)	149.587(4.120)	55.017(0.302)
26	21.63(0.911)	109.794(4.160)	131.425(3.921)	54.700(0.279)
27	13.855(0.561)	140.225(4.359)	154.080(4.130)	55.433(0.286)
28	15.992(0.596)	125.849(4.230)	141.841(3.989)	55.017(0.305)
29	17.134(0.681)	162.328(4.927)	179.461(4.637)	54.583(0.304)
30	25.864(0.940)	114.338(3.679)	140.202(3.314)	54.867(0.289)
Average	19.127	181.52	200.646	55.378
SD	4.973	53.362	53.145	0.972

distribution of flights tends to fluctuate and is concentrated on some time points, the flight inter-arrival/departure times will frequently be less than the required separation times. This will cause flight delays to spread and increase. In these situations, the flight delay under FCFS is possibly larger than that of the optimization model. In Table IX, numbers 3, 15, 18, 20 and 22 of the simulation runs show this phenomenon. The associated air and ground delays are not only larger, but their standard deviations are also higher. On the other hand, if the inter-operation times are more uniformly distributed, the flight delay and the associated standard deviation will be smaller.

The 16 and 26 simulation runs shown in Table IX reveal this delay pattern.

Under the "arrival priority" rule, total delay is influenced less by the inter-operation times, but is more influenced by the flight arrival/departure sequence. This is especially true when there is heavy competition for slots for take-off/landing between arrivals and departures. Because arrivals have priority over departures, when consecutive arrivals occur frequently with small gaps, it causes not only delays to the following consecutive arrivals, but also to the departure flights. For instance, although a departure is expected to be earlier than the arrival, when the separation time is not good for the operation, the oncoming arrival still gets priority to use the runway and the take-off flight has to wait. Therefore, total delay under the "arrival priority" rule is generally higher than that of the optimization model. In Table X, simulation runs 3, 12, 14 and 15 show high ground and total delays. The total delay and the standard deviations illustrated in Table X reveal that flight delay under "arrival priority" is more serious than that of the FCFS rule in Table IX.

TABLE XI Results of the optimization model (unit: min)

Sample	*Total separation time*	*Air delay*	*Ground delay*	*Total delay*	*Air scheduled timetable delay*	*Ground scheduled timetable delay*	*Total scheduled timetable delay*	*Air technical delay*	*Ground technical delay*	*ATC technical delay*
1	52.42	91.63	76.62	168.25	28.45	26.98	55.43	63.18	49.63	112.82
2	52.22	113.95	83.05	197.00	31.05	37.10	68.15	82.90	45.95	128.85
3	52.12	134.85	101.70	236.55	40.70	53.93	94.63	94.15	47.77	141.92
4	52.47	140.40	105.77	246.17	46.23	63.07	109.3	94.17	42.70	136.87
5	50.92	82.82	55.53	138.35	10.55	7.95	18.50	72.27	47.58	119.85
6	49.10	63.52	46.97	110.48	8.70	4.45	13.15	54.82	42.52	97.33
7	49.20	65.65	48.80	114.45	13.88	8.25	22.13	51.77	40.55	92.32
8	49.78	78.28	52.93	131.22	10.55	7.95	18.50	67.73	44.98	112.72
9	49.68	77.02	53.75	130.77	10.92	7.88	18.80	66.10	45.87	111.97
10	47.92	58.52	55.25	113.77	11.02	9.98	21.00	47.50	45.27	92.77
11	48.92	56.08	43.70	99.78	17.87	6.73	24.60	38.22	36.97	75.18
12	48.88	56.85	48.70	105.55	21.07	6.25	27.32	35.78	42.45	78.23
13	48.82	63.15	45.07	108.22	19.45	7.92	27.37	43.70	37.15	80.85
14	48.92	64.17	46.63	110.80	23.40	8.20	31.60	40.77	38.43	79.20
15	50.95	97.12	83.58	180.70	29.08	34.37	63.45	68.03	49.22	117.25
16	48.33	95.92	65.78	161.70	47.92	18.47	66.38	48.00	47.32	95.32
17	46.08	72.05	53.43	125.48	24.85	15.25	40.10	47.20	38.18	85.38
18	46.08	93.85	69.32	163.17	44.05	28.62	72.67	49.80	40.70	90.50
19	46.78	86.30	83.63	169.93	45.05	22.17	67.22	41.25	61.47	102.72
20	46.35	87.53	97.15	184.68	43.55	24.72	68.27	43.98	72.43	116.42

6.2. Correlation Analysis of Delays from Optimization and Simulation Models

A correlation between delays obtained from the optimization model and the simulation runs can be observed from the previous analyses. In order to make the optimization model more realistic, we tried a further 20 simulations and observations. The results from the optimization model and the simulations are shown in Tables XI–XIII, respectively. The estimated delays varied within some reasonable ranges. In Tables XII and XIII, the 95% confidence intervals clearly suggest that under a given flight timetable, the technical delay is not constant. The technical delay will vary with some uncontrollable factors; and the magnitude of the variation will increase with the number of hourly flights. This suggests that the more the delay grows, the more effective good air traffic management will be. On the other hand, it also implies that if the delay is large, forecasting flight delay exactly becomes more difficult.

The sample data and the associated results clearly show a high correlation between the estimated delays from the optimization model and the simulations. In addition, a high correlation is evident between total delay and the standard deviations of arrivals and departures per 5 min. Therefore, after a variety of correlation analyses, three variables – total delay from the optimization model, the standard deviation of arrivals, and the standard deviation of departures – were selected for the regression analysis in an attempt to predict actual flight delays.

However, among these selected variables, the correlation coefficient between the standard deviation of arrivals and the standard deviation of departures is found to be very low (−0.0153) and almost independent. But the correlation coefficient is high between the total delay of the optimization model and the standard deviation of arrivals/departures. In order to avoid the co-linearity occurring in the regression analyses, only the variable of delay from the optimization model is selected. The regression equation is estimated as follows:

(1) The regression of flight delays for the FCFS rule:

$$\widehat{\text{Delay}}_{\text{FCFS}} = -20.3231 + 0.920155\ \text{Delay}_{\text{Optimal}}$$
$$t = (-2.317)\ (16.328),\ R^2 = 0.937,\ F = 266.588,\ N = 20$$

TABLE XII The simulation results under FCFS rule (unit: min)

Sample	*Air delay*	*Ground delay*	*Total delay*	*Standard deviation of air delay*	*Standard deviation of ground delay*	*Standard deviation of total delay*	*Lower bound of 95% confidence interval*	*Upper bound of 95% confidence interval*
1	67.28	70.70	137.97	17.36	19.29	34.28	94.43	217.73
2	69.79	81.18	150.97	18.41	24.37	42.05	89.92	221.63
3	99.30	106.71	206.01	18.05	18.49	34.09	156.25	269.59
4	90.13	114.02	204.15	20.19	31.69	41.32	147.49	268.12
5	73.36	91.73	165.08	18.68	18.59	35.14	111.12	216.99
6	42.76	48.55	91.31	15.03	17.81	31.97	60.17	163.26
7	33.53	41.68	75.21	7.69	11.05	17.21	50.67	111.83
8	35.66	43.32	78.98	9.31	9.96	17.12	56.31	112.65
9	37.24	43.76	81.00	12.28	13.80	24.53	53.25	148.16
10	39.70	46.28	85.98	10.28	16.92	26.03	54.08	148.85
11	40.53	43.73	84.26	7.95	8.71	15.70	60.35	110.72
12	46.33	32.68	79.01	8.95	7.83	15.57	57.94	113.07
13	50.79	36.01	86.80	8.60	6.23	12.35	66.47	107.97
14	52.25	37.74	89.99	8.64	7.84	14.56	70.59	117.06
15	54.04	35.20	89.24	10.98	6.79	10.91	72.01	107.66
16	80.19	46.62	126.81	12.77	7.43	18.75	105.28	169.39
17	55.68	49.54	105.22	9.18	9.04	15.30	83.14	130.34
18	74.04	64.82	138.86	14.16	10.18	22.91	107.35	168.63
19	63.49	66.29	129.78	8.05	7.03	12.52	112.60	150.68
20	66.16	78.58	144.74	9.53	9.58	14.81	126.07	173.19

(2) The regression of flight delays for the "arrival priority" rule:

$$\hat{\text{Delay}}_{\text{PRIORITY}} = 0.972079\,\text{Delay}_{\text{Optimal}}$$
$$t = (35.513),\; R^2 = 0.867,\; F = 124.222,\; N = 20$$

The coefficients of both regressions clearly demonstrate that the total delays derived from the optimization model are larger than those of both the FCFS and "arrival priority" rules, as seems reasonable. In addition, the *U*-statistic values for estimations of the FCFS and the "arrival priority" rules (0.0066 and 0.0148), respectively are close to 0. This indicates that this estimator can reasonably be applied to estimate the flight delays under the rules of both FCFS and "arrival priority". Tables XIV and XV show that the 20 samples are all well predicted within 95% confidence intervals. The forecasting capability of the optimization model can therefore be regarded as rather good and reliable. Therefore, it could have potential as tool for measuring the performance of air traffic management; it could also be applied

TABLE XIII The simulation results under the "arrival priority" rule (unit: min)

Sample	*Air delay*	*Ground delay*	*Total delay*	*Standard deviation of air delay*	*Standard deviation of ground delay*	*Standard deviation of total delay*	*Lower bound of 95% confidence interval*	*Upper bound of 95% confidence interval*
1	21.63	143.05	164.68	6.25	38.65	37.95	121.55	245.23
2	19.13	181.52	200.65	4.97	53.36	53.15	132.63	295.18
3	27.45	203.94	231.39	8.19	41.06	42.61	164.25	318.26
4	25.36	230.98	256.34	6.08	47.32	48.89	172.77	329.76
5	17.53	184.55	202.08	6.46	42.00	41.64	136.72	276.55
6	15.65	94.32	109.98	5.56	30.44	31.93	67.06	169.32
7	13.96	72.43	86.39	3.39	16.07	17.16	59.46	124.09
8	12.55	81.80	94.34	3.66	19.15	20.23	65.81	131.53
9	13.32	77.70	91.02	4.14	26.28	25.27	61.75	144.75
10	17.15	80.65	97.80	4.54	29.99	29.30	60.68	167.28
11	15.57	83.39	98.96	4.64	16.32	17.92	75.53	129.65
12	24.94	71.81	96.75	6.87	30.20	29.96	69.41	174.95
13	22.14	85.54	107.69	4.57	22.18	20.93	80.03	150.28
14	23.62	83.80	107.43	6.21	20.55	18.46	80.11	143.01
15	27.06	79.66	106.71	6.41	17.00	16.11	85.78	139.98
16	21.00	133.25	154.25	4.61	22.31	19.95	123.9	190.89
17	16.21	117.92	134.14	5.48	21.93	20.18	98.02	159.24
18	15.20	186.75	201.95	6.49	35.30	35.14	154.26	264
19	12.97	146.56	159.54	3.78	18.03	17.76	136.47	192.08
20	13.62	157.72	171.33	4.84	16.77	16.85	144.23	199.31

to evaluate the appropriateness of a flight timetable by calculating the associated scheduled timetable delay.

7. CONCLUSIONS

Flight delays at an airport affect not only passengers and airlines but also the performance of the airport and its air traffic management. Thus, a convincing tool is needed to measure effectively technical delay. In this paper, a theoretical static delay optimization model with related constraints has been formulated, tested, and its performance analysed. In addition, simulation and regression analyses were introduced to help clarify the validity of the model. The major findings from this study can be briefly stated as follows:

First, the origin of technical delay may come from either insufficient facility capacity or poor schedule planning. Therefore, technical delay due to air traffic control should be distinguished from scheduled

TABLE XIV Delay forecasting for flights under the FCFS rule (unit: min)

Sample	*Lower bound of 95% confidence interval from the simulation*	*Average delay from the simulation*	*Upper bound of 95% confidence interval from the simulation*	*Forecast average delay*
1	94.43	137.97	217.73	134.49
2	89.92	150.97	221.63	160.95
3	156.25	206.01	269.59	197.34
4	147.49	204.15	268.12	206.19
5	111.12	165.08	216.99	145.95
6	60.17	91.31	163.26	106.98
7	50.67	75.21	111.83	81.34
8	56.31	78.98	112.65	84.99
9	53.25	81.00	148.16	100.42
10	54.08	85.98	148.85	100.01
11	60.35	84.26	110.72	84.36
12	57.94	79.01	113.07	71.49
13	66.47	86.80	107.97	76.80
14	70.59	89.99	117.06	79.26
15	72.01	89.24	107.66	81.63
16	105.28	126.81	169.39	128.47
17	83.14	105.22	130.34	95.14
18	107.35	138.86	168.63	129.82
19	112.60	129.67	150.68	136.04
20	126.07	144.74	173.19	149.61

timetable delay so as to capture the essence of delay and propose appropriate countermeasures.

Second, results from the data samples for Taipei Airport show that both simulated flight delays under FCFS and "arrival priority" service rules are highly correlated with delays obtained from the optimization model. The flight delays predicted by using the regression model are also satisfactory. This shows that the optimization model is not only an analytical tool which is capable of measuring the performance of air traffic management schemes, but also useful for evaluating the appropriateness of a flight timetable and in planning a sound timetable.

Third, the arrangement of take-offs/landings has significant influences on flight technical delay. When flights are more evenly distributed, delay is lower; otherwise, technical delay will be higher. In addition, under a specified flight timetable, the flight technical delay is not constant, but varies. The magnitude of the variation increases with the scheduled hourly operations. These phenomena indicate that the greater the flight delays, the more improvements air traffic

TABLE XV Delay forecasting for flights under the arrival priority rule (unit: min)

Sample	*Lower bound of 95% confidence interval from the simulation*	*Average delay from the simulation*	*Upper bound of 95% confidence interval from the simulation*	*Forecast average delay*
1	121.55	164.68	245.23	163.55
2	132.63	200.65	295.18	191.50
3	164.25	231.39	318.26	229.95
4	172.77	256.34	329.76	239.30
5	136.72	202.08	276.55	175.65
6	67.06	109.98	169.32	134.49
7	59.46	86.39	124.09	107.40
8	65.81	94.34	131.53	111.25
9	61.75	91.02	144.75	127.56
10	60.68	97.80	167.28	127.12
11	75.53	98.96	129.65	110.59
12	69.41	96.75	174.95	96.99
13	80.03	107.69	150.28	102.60
14	80.11	107.43	143.01	105.20
15	85.78	106.71	139.98	107.71
16	123.90	154.25	190.89	157.19
17	98.02	134.14	159.24	121.98
18	154.26	201.95	264.00	158.61
19	136.47	159.54	192.08	165.19
20	144.23	171.33	199.31	179.52

management could make. However, it also implies that forecasting flight delay precisely during busy periods is becoming more difficult.

Finally, the expected take-off/landing times of the scheduled flights in the simulation studies were randomly generated. Other possible distributions have not yet been analysed. Further work on the expected take-off/landing distributions are needed to make the optimization model more convincing. The basic assumption of the optimization model is that flights must follow exactly the original scheduled departure/arrival time. This does not agree with actual flight operations and causes the optimization model to over-estimate flight delays. In future, we suggest that research should relax this constraint so as to make the model more realistic and hence more reliable.

References

Booth, G.R. (1994) "Flow management in the United States", In: Winter, H. and Nußer, H.G. (Eds.), *Advanced Technologies for Air Traffic Flow Management* pp. 107–119. Springer-Verlag.

Cheslow, M. (1990) "Analysis of national delay and throughput impacts of a new Denver airport", *Transportation Research Record* **1296**, 1–12.

Dear, R.G. and Sherif, Y.S. (1991) "An algorithm for computer assisted sequencing and scheduling of terminal area operations", *Transportation Research* **25A**(2/3), 129–139.

Evans, J.E. (1997) "Safely reducing delays due to adverse terminal weather", In: Bianco, L., Dell'Olmo, P. and Odoni, A.R. (Eds.), *Modeling and Simulation in Air Traffic Management* pp. 185–202. Springer-Verlag.

Gilbo, E.P. (1997) "Optimizing airport capacity utilization in air traffic flow management subject to constraints at arrival and departure fixes", *IEEE Transactions on Control System Technology* **5**(5), 490–503.

Glockner, G.D. (1993) "Effects of air traffic congestion delays under several flow management policies", *Transportation Research Record* **1517**, 29–35.

Helme, M.P. and Lindsay, K. (1992) "Optimization of traffic flow to minimized delay in the national airspace system", *Proceedings of 1st IEEE Conference on Control Application* **1**, 435–437.

Luo, S. and Yu, G. (1997) "On the airline schedule perturbation problem caused by the ground delay program", *Transportation Science* **31**(4), 298–311.

Marchi, R. (1996) "New development in ATC technology and airport capacity", *Air Hub Development Seminar – Challenges and Strategies of Modern Airports* 89–100. National Chiao Tung University, Taiwan.

Janic, M. (1997) "The flow management problem in air traffic control: a model of assigning priorities for landings at a congested airport", *Transportation Planning and Technology* **20**(2), 131–162.

Newell, G.F. (1979) "Airport capacity and delays", *Transportation Science* **13**(3), 201–241.

Rutner, S.M., Mundy, R.A. and Whitaker, J. (1997) "Alternatives for reducing delays at the United States' busiest airport", *Transportation Journal* Spring, 18–25.

Shaw, S. (1987) *Airline Marketing and Management*. Pitman, London.

Venkatakrishnan, C.S., Barnett, A. and Odoni, A.R. (1993) "Landing at airport: describing and increasing airport capacity", *Transportation Science* **27**(3), 211–227.

Wong, J.T., Han, F.W. and Li, S.L. (1997) "Runway capacity estimation for Sung Shan domestic airport", *Journal of the Chinese Institute of Transportation*, Taiwan, **10**(4), 113–126.