



A survival model for flight delay propagation

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A B S T R A C T

Keywords:

Flight delay propagation
Survival analysis
Cox proportional hazards model

This paper examines flight delay propagation involving a Taiwanese domestic airline. The Cox proportional hazards model is used to develop departure and arrival delay models that show how flight delay propagation can be formulated through repeated chain effects in aircraft rotations. The hazard ratios obtained provide measures of the chances of recovering from flight delays under a variety of situations and the effects that individual contributing factors of flight delays have on airline schedule reliability.

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1. Introduction

Airline passenger complaints concerning delays, cancellations, and denied boarding have prompted the US Congress to consider stronger measures to ensure passenger protection (US Government Accountability Office, 2011). Of the delay costs analyzed by Austrian Airlines, only 22% can be attributed directly to the effect of delays; 24% stem from permanent loss of passenger loyalty and 54% stem from induced knock-on delays in aircraft rotation schedules (Airline Business, 1999). United Airlines estimates that it saves approximately \$1.6 million by using a flight delay projection model during the first quarter of 2004 (Abdelghany et al., 2004). Both of these cases suggest that the consequences of delays and their propagation in the air transport system, including decrease of productivity of aircraft as well as loss of time and loyalty of passengers, cannot be neglected.

Optimizing aircraft utilization requires airlines have tight turnaround times between flights, but this can increase the likelihood of delays in subsequent flights. The typical approach to dealing with disruptions is to re-optimize the schedule, but a more proactive approach can be to build robustness into the schedule at the planning stage (Lan et al., 2006; Wu and Caves, 2002). One prerequisite to the development of tools for building more robust airline schedules is an understanding of the relationship between planned schedules and delay propagation.

A range of methodologies has been adopted to deal with the issue of airline delay propagation. Abdelghany et al. (2004) used a deterministic model to predict the propagated delays along aircraft routes

based on the concept of resource networks and shortest paths, while Beatty et al. (1998) used a 'delay multiplier' metric to estimate the scale of delay propagation. Schaefer and Millner (2001) used the 'detailed policy assessment tool' to model delay propagation in a network of airports when facing inclement weather conditions. To limit flight delays, considerable efforts have also been made to develop proactive schedule recovery models. Delays in airline schedules may be the result of many different causes but most attention has been paid to the technical aspects of optimizing airline schedules and failed to consider the role played by airline ground operations and other delay causes in contributing and controlling delays in daily operations; Wu and Wong (2007) being an exception.

Although different methods have been used to investigate flight delay propagation, the stochastic effects of flight delay propagation resulting from various delay causes have not been thoroughly captured. Major shortcoming of using airline dependability statistics is that they are ex post measurements and only reveals the results of schedule delays without any investigating the determining factors such as schedule design and airline operations (Wu and Caves, 2002). In addition, different causes of flight delays may have different effects on airline schedule reliability, and the effects of flight delays resulting from the same delay cause may not be the same in all cases.

Here we develop a way to explore the problem of flight delay propagation in a dynamic operating environment by considering the stochastic characteristics of turnaround and block operations and clarifying the relationship between flight delays and the associated causes.

2. Flight delay mechanisms

The flights assigned to the same aircraft during one cycle (usually one day for domestic operations and one week for international

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operations) form the ‘routes’ on which the aircraft is operated. Buffer times play an important role in the implementation of recovering schemes associated with irregular operations. Turn-around buffer time, which is the extra time scheduled beyond the time required for ground handling, is usually built-in to accommodate potential delays from late inbound aircraft and aircraft turnaround operations. Scheduled block buffer time, on the other hand, is the extra time added to a flight’s scheduled arrival time to permit a degree of variability in flight operations between airports. Although a published airline schedule generally incorporates buffer time, flight delays can occur when accumulated delays exceed the buffer time.

2.1. Departure delay

Fig. 1 illustrates the relationships among flight delays in an airline schedule. The solid arrows represent the original schedule of departures and arrivals for flight legs $i-1$ and i . STD and STA refer to scheduled time of departure and scheduled time of arrival, respectively, and STA_{-1} refers to scheduled time of arrival of flight f_{i-1} . The dotted arrows represent the actual departures and arrivals of these flight legs. ATD and ATA refer to actual time of departure and actual time of arrival, respectively, and ATA_{-1} refers to actual time of arrival of flight f_{i-1} . Eq. (1) describes the relationship between the scheduled time of arrival of flight f_{i-1} (STA_{-1}), the on-chock time, and the scheduled time of departure of flight f_i (STD), the off-chock time. The scheduled turnaround time of flight f_i (T^S) is the interval between the arrival of flight f_{i-1} at the gate and the time at which this aircraft departs for flight f_i , comprising two parts: the scheduled required ground handling time (g^s) and scheduled turnaround buffer time (b^{sg}) (Eq. (2)).

$$STD = STA_{-1} + T^S \tag{1}$$

$$T^S = g^s + b^{sg} \tag{2}$$

If the delay in an aircraft’s arrival is shorter than the scheduled turnaround buffer time, the scheduled turnaround buffer time is

capable of absorbing it. A delay, however in arrival exceeding the scheduled turnaround buffer time might cause a delay in the departure of the next flight. Given the interactions between fixed flight schedules and stochastic disruptions associated with turnaround operations, there might also be a ground delay for flight f_i (G^d). If the scheduled turnaround buffer time is incapable of absorbing this ground delay, it could lead to a delay in subsequent departure. Thus, the departure delay of flight f_i (D^d) can be caused by the arrival delay of the previous flight (A_{-1}^d) and a ground delay at the current airport (G^d). Eq. (3) shows that the scheduled turnaround buffer time (b^{sg}) may be able to absorb these delays.

$$D^d = \max\{0, A_{-1}^d + G^d - b^{sg}\} \tag{3}$$

2.2. Arrival delay

The scheduled block time of flight f_i (F^S) includes the scheduled required block operation time (f^s), the minimum time required to complete the activities of taxi-out, airborne operation, and taxi-in, and the scheduled block buffer time (b^{sr}) (Fig. 1). This buffer is expected to absorb any potential delays at the origin airport and in the block operations. Inbound flight f_i might also have a block delay (R^d) resulting from problems such as severe weather or air traffic control restrictions en-route or at destination airport. This would result in an arrival delay if the scheduled block buffer time (b^{sr}) cannot absorb this block delay. Therefore, the arrival delay of flight f_i (A^d) can be influenced by a departure delay at the origin airport (D^d) and a block delay between airports (R^d), which might be absorbed by the scheduled block buffer time (b^{sr}). Eq. (4) describes this relationship.

$$A^d = \max\{0, D^d + R^d - b^{sr}\} \tag{4}$$

By combining the mechanisms of departure and arrival delays, flight delay propagation in an airline network can be formulated through repeated chain effects. The challenge is to model the departure and arrival delays with their associated causes.

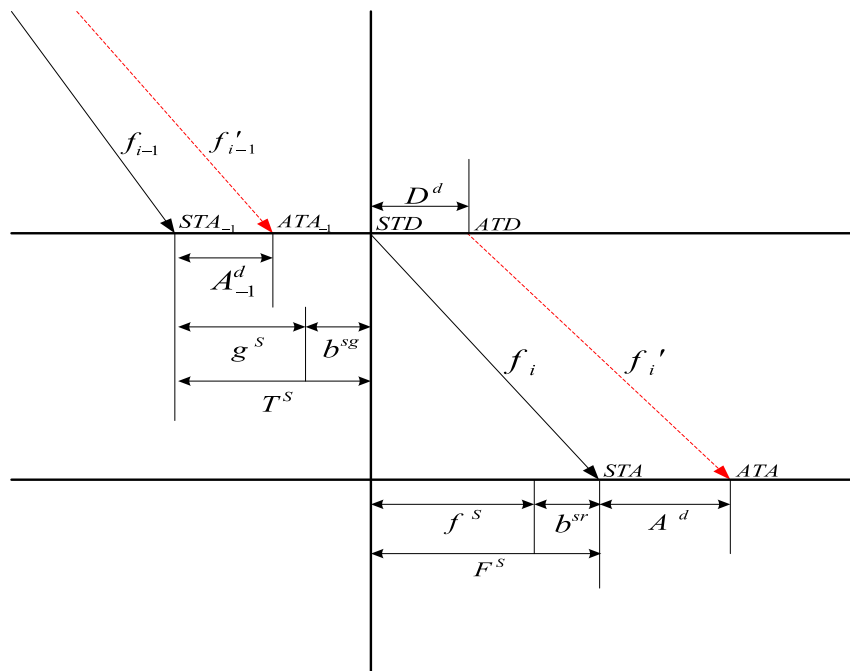


Fig. 1. Relationships among flight delays in an airline schedule.

3. Data

We collected flight data from a Taiwanese domestic airline ('Airline A') to explore the effects of flight delay propagation that requires an extensive flight network with a very high frequency of flights. After the launch of high-speed rail services along the west coast of Taiwan in January 2007, many passengers switched from traveling by airlines to high-speed rail, forcing airlines to reduce flight frequency and terminate some services. Our flight data was collected over twelve months in 2005, prior to the commencement of the high-speed rail service. It lists the state of the departing and arriving aircraft as they rotated through the airport system and indicates the causes for delays in the operations.

Because flight delays may have a wide range of causes and the associated disturbances may result in various durations of flight delays, it is worthwhile investigating the relationship between delays and their causes. Table 1 shows the delay causes of Airline A in nine categories.

Although the cause of a delay is recorded when an aircraft departs from an airport gate, an inbound flight can also be delayed during taxi-out, airborne operation, or taxi-in prior to arrival at an airport gate. The delay in arrival can be due to weather en-route or weather at the destination or at an alternative airport, which can also be the cause of departure delay if ground-holding policies are implemented (Vranas et al., 1994). Similarly, air traffic control restrictions en-route or at the destination airport can be the cause of arrival delay, or the cause of departure delay when ground-holding policies are imposed. Hence, of the delay causes of Airline A, 'weather' and 'air traffic control restrictions' are the causes of arrival delay. On the other hand, departing flights can be disrupted by any of the causes listed in Table 1, which are therefore considered as the causes of departure delay (Fricke and Schultz, 2009).

Table 1
Categories of delay causes.

Category	Description of Category	Delay Cause
1	Airport facilities or governmental authorities	Mandatory security, immigration, customs, health, airport facilities (e.g., air bridge, gate, parking space), etc.
2	Flight operations and crewing	Crew late in position, crew change, crew legality, etc.
3	Cargo and mail handling	Late positioning of cargo/mail, readjustment of cargo/bag position or change of load plan, documentation, errors, etc.
4	Technical and aircraft equipment	Unable to release aircraft for maintenance reason, awaiting engineers/AOG spares, non-scheduled maintenance, etc.
5	Passenger and baggage handling	Late check-in, check-in error, oversales, missing checked-in passenger, baggage processing, etc.
6	Reactionary	Late arrival of aircraft.
7	Weather	Ground handling impaired by adverse weather conditions, weather at departure airport, weather en-route, weather at destination or alternative airport.
8	Air traffic control restrictions	ATC restriction en-route or capacity, ATC restriction due to staff shortage or equipment failure en-route, ATC restriction at destination airport, ATC restriction due to weather at destination airport.
9	Miscellaneous	Industrial action within own airline, industrial action outside own airline, not covered by any of other defined codes, etc.

Because Airline A operates short-haul routes with many of its aircraft flying up to 10 consecutive segments in a day, delays in one segment could easily propagate to following flights. Fig. 2 shows that the distribution of delay time is "right-skewed," indicating that the airline has more short delays and fewer long delays. Meanwhile, departure delays are closely related to arrival delays (Fig. 3).

Although airline companies normally schedule buffer times within turnaround operations at airports in addition to the ground handling time required, the information related to actual turnaround buffer time was unavailable in the dataset of Airline A. To obtain this information, the actual turnaround times of flights in each route were ordered from the smallest to the largest. The 25th percentile (1st quartile) of the ordered actual turnaround times was selected as the required ground handling time, the minimum time required to complete all turnaround activities. Therefore, for every outbound aircraft,

$$\begin{aligned} \text{actual turnaround buffer time} &= \text{scheduled time of departure} \\ &\quad - \text{actual time of arrival} \\ &\quad - \text{required ground handling time.} \end{aligned} \tag{5}$$

This means that after an inbound aircraft arrives at the gate, the difference between the actual time of arrival and the scheduled time of departure for the next flight is the time available for the turnaround of the aircraft. The actual turnaround buffer time can be derived by subtracting the required ground handling time from the available turnaround time. Thus, the actual turnaround buffer time is positive if the available turnaround time exceeds the required ground handling time, and negative (generally resulting from a late flight arrival) if the available turnaround time is shorter than the required ground handling time.

Conversely, the block time includes block buffer time and required block operation time, which is the minimum time required to complete the activities of taxi-out, airborne operation, and taxi-in. However, the obtained dataset did not contain the information related to actual block buffer time. To derive this information, the actual block times of flights in each route were ordered from the smallest to the largest. The 25th percentile of the ordered actual block times was then selected as the required block operation time. Therefore, for every inbound aircraft,

$$\begin{aligned} \text{actual block buffer time} &= \text{scheduled time of arrival} \\ &\quad - \text{actual time of departure} \\ &\quad - \text{required block operation time.} \end{aligned} \tag{6}$$

In other words, after an outbound aircraft departs from the airport gate, the difference between the actual time of departure and the scheduled time of arrival represents the time available for the block operation of the aircraft. The actual block buffer time can be derived by deducting the required block operation time from the available block time. Thus, the actual block buffer time is positive if the available block time exceeds the required block operation time, and negative (generally resulting from a late flight departure) if the available block time is shorter than the required block operation time.

4. Delay modeling

4.1. Methodology

Survival analysis (Kleinbaum and Klein, 2005) is a method of analyzing survival data or failure time data. The outcome variable of

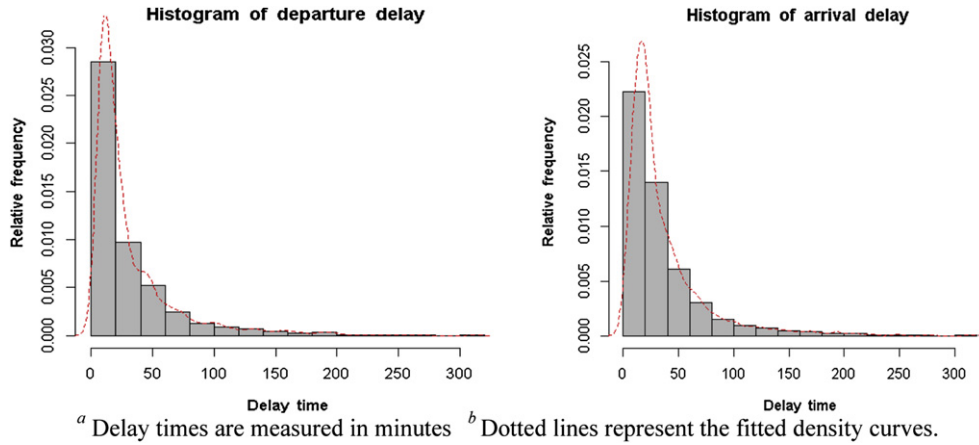


Fig. 2. Histograms of departure delays and arrival delays.

interest is ‘time to event,’ usually referred to as survival time or failure time. In aircraft rotation, the duration of a delay represents the period of time that the delay has survived before coming to an end. Therefore, ‘survival time’ refers to the number of minutes from the beginning of an individual flight delay until an event occurs, while an ‘event’ means that the delay of an individual flight has come to an end. For inbound aircraft, the survival time of arrival delay ends when the aircraft arrives at an airport gate; for outbound aircraft, the survival time of departure delay ends when the aircraft departs from an airport gate. Because of the survival characteristics of flight delays, survival analysis is therefore an appropriate approach to explore the problem of flight delays and their associated causes and to analyze the distributions of delays propagated throughout an airline network.

In survival analysis, the object of primary interest is the survival function, which is defined as

$$S(t) = \Pr(T > t) \tag{7}$$

The survival function indicates the probability that a flight delay survives longer than specified time t . The survival distribution is plotted as a function that starts with the survival probability of 1 and descends down to the survival probabilities approaching zero for very long delays. Another key concept is the hazard function, which gives the instantaneous probability for an event to occur conditional on survival to time t and specifies the related survival function as well.

Our focus is to investigate the impact of delay contributing factors on flight delays. To examine the relationship between the survival distributions of flight delays and associated covariates, we

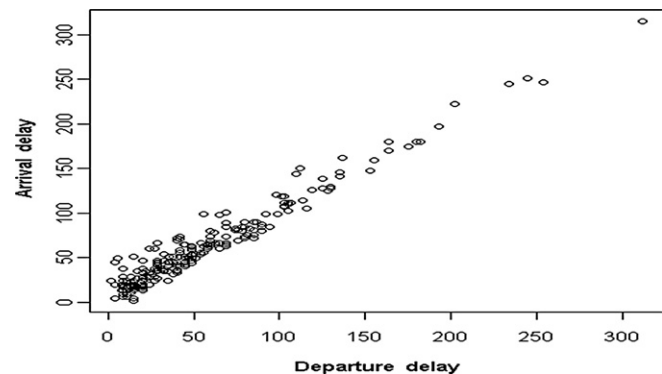


Fig. 3. Correlation of departure delays and arrival delays in minutes.

employ the Cox proportional hazards (PH) model (Eq. (8)), a method widely applied in survival analysis, to model flight delays in a multiple-airport environment.

$$h(t|X) = h_0(t, \alpha) \exp(\beta'X) \tag{8}$$

This model provides a hazard expression for a flight at delayed time t with a given specification of explanatory variables that is being modeled to predict the hazard of a flight delay. Meanwhile, as shown in Eq. (9), one can easily evaluate the percentage change (increase or decrease) in the hazard of flight delay with a one-unit increase in x_k , while other covariates remain unchanged.

$$\frac{\hat{h}(t|x_k + 1) - \hat{h}(t|x_k)}{\hat{h}(t|x_k)} = e^{\hat{\beta}_k} - 1 \tag{9}$$

Because airlines often assign different types of aircraft to various routes in aircraft daily operations, the distributions of flight delays may be influenced by aircraft type, route, peak/off-peak hour, and season, in addition to delay cause (Allan et al., 2001). Therefore, the survival curves of flight delay using the Kaplan–Meier estimator are used to examine the possible impact of factors on delays in departure and arrival. Taking the survival curves for aircraft types as an example, it reveals that FK 50 aircraft tend to have delays with longer survival times than FK 100 aircraft for both departure and arrival delays (Fig. 4). Using the log-rank tests, the results in Table 2 indicate significant differences in the survival distributions of flight delays for the selected variables. Therefore, in addition to the variables influencing turnaround and block operations, aircraft type, route, delay cause, peak/off-peak hour, and season are also considered as the covariates for developing the departure delay and arrival delay models.

Due to the strong causal relationship between departure and arrival delays via aircraft routing, flight delay propagation can be investigated by recursively combining the departure delay and arrival delay models. Here, ‘recursively’ means that the output of the departure delay model serves as the input of the arrival delay model, and the output of the arrival delay model serves as the input of the departure delay model. Accordingly, the development of models for departure and arrival delay is a prerequisite to exploring flight delay propagation.

4.2. Model specification

To formulate a departure delay model, the relationship between variables must be further clarified. First of all, there will be a longer

buffer time in turnaround operations if ground handling activities are completed rapidly; conversely, there will be a shorter turnaround buffer time if more time is required to complete ground handling activities. In addition, the late arrival of flights also results in a reduction in turnaround buffer time. Therefore, to avoid any bias resulting from the highly correlated relationship with ‘turnaround buffer time’, ‘arrival delay’ and ‘ground handling time’ should be deleted from the model. Similarly, the routes of Airline A are operated using different types of aircraft, and flight delays are subject to the routes to which the aircraft are assigned. Accordingly, ‘route’ should also be removed from the model because the delays associated with a ‘route’ are already reflected in the delays of the ‘aircraft type’, and a bias would be generated if both ‘route’ and ‘aircraft type’ are used as covariates. Furthermore, a delay caused by ‘late arrival of an aircraft’, recorded as ‘reactionary’ by airlines, is already counted as an ‘arrival delay’ and reflected in ‘turnaround buffer time’ in the model. Consequently, ‘reactionary’ should also be deleted from the delay causes considered. Thus, the departure delay model is formulated as Eq. (10).

$$h(\text{departure delay}|\text{covariates}) = h_0(\text{departure delay}) \exp \left(\beta_1 \times \text{turnaround buffer time} + \beta_2 \times \text{aircraft type} + \sum_{i=1}^8 \beta_{i+2} \times \text{category of delay cause}_i + \beta_{11} \times \text{peak/off - peak hour} + \sum_{j=1}^3 \beta_{j+11} \times \text{season}_j \right) \quad (10)$$

In aircraft rotations, a shortened taxi-out time, airborne time, and taxi-in time will result in a longer buffer time in block operations. By contrast, the block buffer time is shortened when taxi-out time, airborne time, and taxi-in time are longer. In addition, the late departure of flights also results in a reduction in block buffer time. Because the lengths of taxi-out time, airborne time, and taxi-in time depend on whether aircraft are operating in peak or off-peak hours, the delay information associated with these factors can also be obtained from ‘peak/off-peak hour’ in the model. Therefore, ‘departure delay’, ‘taxi-out time’, ‘airborne time’, and ‘taxi-in time’ should be removed from the model to avoid an interdependent relationship between these covariates and the ‘block buffer time’. Similarly, ‘route’ should also be deleted to avoid simultaneously including both ‘route’ and ‘aircraft type’, as discussed in the establishment of the departure delay model. The resulting arrival delay model is formulated as Eq. (11).

$$h(\text{arrival delay}|\text{covariates}) = h_0(\text{arrival delay}) \exp \left(\beta_1 \times \text{block buffer time} + \beta_2 \times \text{aircraft type} + \beta_3 \times \text{category of delay cause} + \beta_4 \times \text{peak/off - peak hour} + \sum_{j=1}^3 \beta_{j+4} \times \text{season}_j \right) \quad (11)$$

The variables used in the departure delay and arrival delay models for capturing the chain effects of flight delay propagation are listed in Table 3.

5. Results

5.1. Departure delay model

The results of the departure delay model are shown in Table 4; because ‘season’ and ‘peak/off-peak hour’ were not statistically significant, they were deleted. The higher the hazard is for an event to occur, the more likely the flight delay will end. Thus, for each 1-min increase in turnaround buffer time, which varies depending on arrival time or ground handling time, the chance of ending departure delays increases by only 0.4%. This reveals that departure delays may not be greatly improved though turnaround operations include built-in buffer time. Therefore, airlines may investigate other reasons behind the flight delays before taking the measure of increasing buffer time. With respect to aircraft type, Fokker 50 aircraft have a 35.9% lower chance of ending departure delays than Fokker 100 aircraft.

Compared to the delays caused by ‘airport facilities or governmental authorities’, departure delays resulting from ‘flight opera-

tions and crewing’, including crew arriving late for their position, crew change, crew legality, etc., have a 41.7% lower chance of recovery. As it is understood, an aircraft will be grounded unless problems associated with crew assignment are fixed. Departure delays caused by ‘cargo and mail handling’ and ‘passenger and baggage handling’, on the other hand, have 52.7% and 40.0% lower chances of recovery, respectively. In addition, departure delays resulting from ‘technical and aircraft equipment’ have lower chance of recovery by 46.3%. Each of these significant contributing factors is related to airline operations, suggesting that potential improvements could be achieved through a suitable delay management program. Departure delays caused by ‘weather’ are with 43.7% lower chance of recovery and are beyond the control of airlines. Nevertheless, a well-designed contingency plan and useful management techniques could be helpful for airlines to alleviate the consequences of delays caused by weather. Air traffic control restrictions en-route or at the destination airport can be the cause

of departure delay when ground-holding policies are imposed. It reveals that departure delays caused by ‘air traffic control restrictions’ have a 25.4% lower chance of recovery.

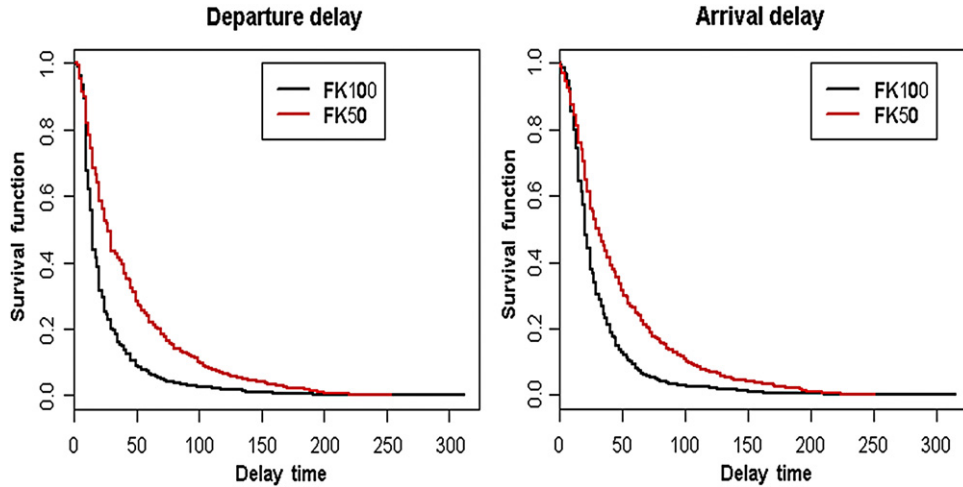


Fig. 4. Survival curves of various types of aircraft.

Table 2
Difference test of survival curves.

Factor	Departure/Arrival delay	Chi-square
Aircraft type	Departure delay	158.2***
	Arrival delay	107.4***
Route	Departure delay	305.3***
	Arrival delay	271.1***
Delay cause	Departure delay	373.8***
	Arrival delay	10.1***
Peak/off-peak hour	Departure delay	11.8**
	Arrival delay	12.3**
Season	Departure delay	7.6***
	Arrival delay	10.7***

Significance levels 0%***, 0.1%** , 1%*.

Table 4
Results of departure delay model.

Factor	β	$(e^\beta - 1) \times 100\%$
Turnaround buffer time	0.004 ^a	0.4%
Aircraft type	-0.445 ^a	-35.9%
Category of delay cause		
Flight operations and crewing	-0.539	-41.7%
Cargo and mail handling	-0.749 ^a	-52.7%
Technical and aircraft equipment	-0.622 ^a	-46.3%
Passenger and baggage handling	-0.511 ^a	-40.0%
Weather	-0.575 ^a	-43.7%
Air traffic control restrictions	-0.294	-25.4%
Miscellaneous	-0.316	-27.1%

^a Statistically significant at 5% level.

Table 3
Variables used in departure and arrival delay models.

Variable	Departure Delay Model	Arrival Delay Model	Dummy Code	Description
Turnaround buffer time	✓		-	-
Block buffer time		✓	-	-
Aircraft type	✓	✓	0	Fokker 100
			1	Fokker 50
Category of delay cause	✓		0	Airport facilities or governmental authorities
			1	Flight operations and crewing, cargo and mail handling, technical and aircraft equipment, passenger and baggage handling, weather [#] , air traffic control restrictions, miscellaneous
		✓	0	Air traffic control restrictions
			1	Weather [#]
Peak/off-peak hour	✓	✓	0	Peak hour
			1	Off-peak hour
Season	✓	✓	0	Spring
			1	Summer, fall, winter

Notes: [#]Including ground handling impaired by adverse weather conditions, weather at departure airport, weather en-route, and weather at destination or alternative airport. [#]Including "only" weather en-route and weather at destination or alternative airport. Dummy code 0: Base type.

5.2. Arrival delay model

Table 5 shows the results of the arrival delay model. Note that 'aircraft type', 'season', and 'peak/off-peak hour' were not statistically significant and were therefore deleted from the model. The results indicate that the key contributing factors of arrival delays include 'block buffer time' and 'weather'. For each 1-min increase in block buffer time, which varies depending on departure time or block operation time, the chance for arrival delays to end increases by 6.8%. Most arrival delays are beyond the control of airlines except for delays that develop at departure airports. This implies that developing the means to prevent departure delays could be the key to reducing arrival delays from the origin.

Whilst outbound flights are subject to a wider range of difficulties leading to delays, inbound flights can be delayed by 'weather' or 'air traffic control restrictions' en-route or at destination airport. Compared to the delays caused by 'air traffic control restrictions', arrival delays resulting from 'weather' have a 61.6% lower chance of recovery. As found in both the departure delay and

Table 5
Results of arrival delay model.

Factor	β	$(e^\beta - 1) \times 100\%$
Block buffer time	0.066 (0.000) ^a	6.8%
Category of delay cause		
Weather	-0.957 (0.000) ^a	-61.6%

LR = 294.3, p-value = 0.000.

^a Statistically significant at significance level $\alpha = 0.05$.

arrival delay models, 'weather' is the cause of delays that tends to result in longer departure and arrival delays.

6. Conclusions

When irregularities occur, airlines might need to provide additional resources to resume normal operations, resulting in extra operating expenses. Planning a schedule control program that allows greater schedule flexibility and reliability against disruptions is a factor in reducing the problem of flight delays. Due to the stochastic characteristics of aircraft rotations, there has been a great deal of discussion on how to reduce flight delays while maximizing the utilization of aircraft with very tight connections between flights. If a flight schedule is, however, only designed to absorb stochastic delays without addressing the root problem of flight delays, the schedule might not be adequately robust for future operations. Here we investigated the factors behind the mechanisms of departure and arrival delays to clarify the phases and activities involved in flight delays through an airline schedule.

The models for departure and arrival delay developed are able to capture the dynamic characteristics of flight delays and differ from the methods used in previous studies such as simulation models or statistical analyses. Cox regression analysis reveals that the key contributing factors of departure delays include 'turnaround buffer time', 'aircraft type', 'cargo and mail handling', 'technical and aircraft equipment', 'passenger and baggage handling', and 'weather', whilst the key contributing factors of arrival delays include 'block buffer time' and 'weather'. The hazard ratios

obtained enable airlines to examine the chances of recovering from flight delays. This provides airlines the direction of how to allocate resources to maintain a well-designed schedule.

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