Simulation analysis of the effect of initial delay on flight delay diffusion

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Abstract. The initial delay of the flight is an important factor affecting the spread of flight delays, so clarifying their relationship conduces to control flight delays in the aeronautical network. Through establishing a model of the chain aviation network and making simulation analysis of the effects of initial delay on the delay longitudinal diffusion, it's found that the number of delayed airports in the air network, the total delay time and the average delay time of the delayed airport are generally positively correlated with the initial delay. This indicates that the occurrence of the initial delay should be avoided or reduced as much as possible to improve the punctuality of the flight.

1. Introduction

China's flight punctuality rate is only about 70% at present [1], and flight delays have become a major obstacle to the development of China's air transport industry. In the aviation network, a small number of flight delays can spread to other flights at the downstream airport through the coupling between the network nodes, which resulting in a chain reaction and leading to the multiple effect of the number of flight delays and delay time [2]. Therefore, it is necessary to contemplate and analyze the phenomenon of delay spread in order to decrease the flight delay.

The study of flight delay has become a hotspot in the field of aviation research in recent years. Cao Weidong, etc. [3] established Bayesian models of a single airport and multi-airport station time to analyze the impact of aircraft type and preflight delay time on adjusting the transit time of the flight. They considered the adjustment of flight station time when preflight delays could effectively reduce the diffusion of time delay to the downstream airport. The results of the study of Zhu Xinghui and his partners [4] showed that station slack time optimization based on flight delay risk classification could effectively reduce the diffusion of flight delays, lest the total delay was reduced, and the flight punctuality and passenger satisfaction was improved. For the sake of predicting flight delays, a Web service system was designed by Feng Yao et al [5] through utilizing the linear regression method. When passengers input flight number, departure airport, arrival airport and departure time, the system could forecast the arrival time of flights according to the flight history and weather information. Wan-ming Liu [6] proposed a dual-objective multi-commodity network flow model based on flight delay diffusion for minimizing the total delay and operating costs of airlines with his teammates. The results showed that the method could significantly reduce the delay spread and bring better real-time performance and robustness of aircraft scheduling. Shervin Ahmad Beygi, etc. [7] considered the
effect of aircraft and crew on the flight delay, and proposed the use of adjusting the relaxation time to reduce the propagation of flight delay.

Through modeling and simulating analysis of the impact of initial delay on the flight delay spread to find out their relationship, it’s helpful to reduce the flight delay, improve the service level of the airlines and promote the development of China's air transport industry.

2. Analysis on the principle of longitudinal diffusion of flight delay in aviation network

2.1. Factors for evaluating the flight delay diffusion

For the degree of flight delays caused by flight delay diffusion, we need some factors to evaluate or measure. In this paper, we use three factors: the number of delayed airports, the total delay time of all delayed flights and the average delay time of each delayed flight in the whole aviation network. Just rely on individual evaluation factors and cannot fully show the degree of diffusion through the flight delay for the aviation network, and the combination of these three elements of assessment can reflect the flight delay caused by flight delays spread better.

2.2. Establishment of delayed longitudinal diffusion model in aviation network

The longitudinal diffusion of flight delays vertical diffusion refers to the delays spread in the flight chain. A flight ring is a chain-like structure consisting of a sequence of flights sharing some resources for flights. The resources shared in the flight string include: aircraft, pilots, flight attendants and so on. There is a connective relationship among the flights due to one airplane implementing a few flights, thus one delayed flight might propagate the downstream flights, and causes flights delay chain reaction [8].

Fig. 1 is a flight ring composed of four airports and in the assumption that the the same aircraft is used to implement four flights. And then the subsequent flight will show the phenomenon of delay diffusion when a flight is delayed beyond the critical conditions.

![Figure 1: A schematic model of flight ring consisting of 4 airports.](image)

The meanings of the symbols in Fig.1 are given in Table 1. The operation process of flights in the entire chain is: the plane will first perform the flight F1 and depart from the departure airport A1 at Tsdep(A1). The flying time is T1 and it is expected to arrive at the airport A2 at Tsarr(A2). The aircraft stays in the A2 for Tp(A2) to complete all the preparatory work, and then performs flight F2. It reaches the airport A3 at Tsarr(A3) after flying for T2. Then it performs flight F3 after a stop for Tp(A3) at Tsdep(A3), and arrives at airport A4 at Tsarr(A4) after T3 minutes. Upon completion of all preparations, the plane performs flight F4 at Tsdep(A4) and returns to airport A1 at Tsarr(A1) after T4 minutes. At this point the aircraft has completed a closed chain flight task.
2.3. **Analysis on the principle of delay diffusion in the flight ring**

(1) Parameter description of delay diffusion in the flight ring

In order to facilitate the description of the delay diffusion in the flight chain, the relevant parameters are illustrated in Table 1.

| Parameter | Meaning |
|-----------|---------|
| Tt        | Turnaround time, the interval between two contiguous flights, usually indicates the time required to clean the nacelle, supplement the fuel, load and unload the cargo, and so on. The minimum value is 55 minutes in China's "Civil Aviation Flight Normal Statistical Measures". |
| Tp        | Stop time, the time between the previous flight and the next flight. |
| Ts        | Relaxation time, i.e., stop time in addition to turnaround time. |
| fi        | Flight number (i = 1, 2 ..), where i = 1 represents the first flight. |
| Adep      | Departure airport |
| Tsdep     | Estimated time of departure |
| Tadep     | Actual departure time |
| Aarr      | Destination airport |
| Tid       | Initial delay time |
| Tsarr     | Estimated time of arrival |
| Taarr     | Actual time of arrival |
| Tppd      | Estimated time of spread |
| Tapd      | Actual spread time |
| Δt        | Δt = 15 minutes: If the delay time is not more than 15 minutes, the flight is not classified as a delayed flight. |
| Judge(Ai) | Judge the flight delay or not at the airport Ai. |

(2) Algorithm description

In the aeronautical network as shown in Figure 1, if the delay spread occurs, the following algorithm can be used to calculate the number of delayed flights, the total delay time and the average delay time in the entire network and analyze the flight delay diffusion law:

Step 1: determine whether the initial flight is delayed.

Step 2: if there is no delay, the flight status of the next airport in the aviation network will be estimated. If the time of flight delay is no more than the relaxation time, the delay time of the first airport in the downstream will be canceled by the relaxation time, and the next flight is a normal flight. If the delay time exceeds the relaxation time, the next flight will be delayed, and its "actual wave delay time" is equal to "expected wave delay time" minus "relaxation time".

Step 3: determine whether the next flight is delayed in airline network, then repeat the step 2 until all the flights are finished, and output the relevant data.

The above-mentioned algorithm and its steps are as shown in Fig. 2.
In Figure 2, the basic meaning of each step is as follows:

Judge $(Ai) = 0$ when $(Tppd(Ai) - Ts(Ai)) < \Delta t$, i.e., there is no flight delays at airport $Ai$. There are two cases at this time:

The following calculation relationship exists when $(Tppd(Ai) - Ts(Ai)) \leq 0$:
- $Tadep(Ai) = Tsdep(Ai)$;
- $Taarr(Ai+1) = Tsarr(Ai+1)$;
- $Tadep(Ai+1) = Tsdep(Ai+1)$;

That is: the flight is normal at this time (delay time $\leq 15$ minutes).

When $0 < (Tppd(Ai) - Ts(Ai)) < 15$ minutes, there is the following relationship:
- $Tadep(Ai) = Tsdep(Ai) + (Tppd(Ai) - Ts(Ai))$;
- $Taarr(Ai+1) = Tsarr(Ai+1) + (Tppd(Ai) - Ts(Ai))$;
- $Tadep(Ai+1) = Tsdep(Ai+1)$;

Namely: the delay time of the first airport downstream is less than 15 minutes, so the flight is still regarded as a normal flight.

In the case of the above two types of delay diffusion, there is no delay in any airports after the airport $Ai+1$, i.e., there is no change in the flight schedule.

$j = i + 2; j \leq n; j++;$ indicates that the airport downstream of airport $(Ai+1)$ has the following computational relation:
- $Taarr(Aj) = Tsarr(Aj)$;
- $Tadep(Aj) = Tsdep(Aj)$;
- $Tapd(Aj) = Tppd(Aj) = 0$;
Namely: the subsequent flights are all normal, and the expected time and the actual time of delay diffusion are 0.

Judge \((A_i) = 1\) when \((T_{ppd} (A_i) - T_s (A_i)) < \Delta t\), ie airport is delayed.

At this point, the following calculation relationship can be used to calculate the delay time:

\[
T_{adep} (A_i) = T_{aarr} (A_i) + T_t;
\]
\[
T_{aarr} (A_i+1) = T_{adep} (A_i) + t_i;
\]
\[
T_{ppd} (A_i) = (T_{ppd} (A_i) - T_s (A_i));
\]
\[
T_{ppd} (A_i+1) = T_{ppd} (A_i);
\]

Namely: calculating the impact of delay diffusion in the subsequent flights.

3. Simulation analysis of the impact of relaxation time on flight delay diffusion

3.1. Analysis on the principle of delay diffusion in the flight ring

In order to study the influence of initial delay on the longitudinal dispersion of flight delays, a chain air network model consisted of 4 airports is established and shown in Fig. 3

![Network model of longitudinal dispersion of flight delays.](image)

Assuming \(A_1\) is the originating airport. The stop time of flights at \(A_2, A_3\) and \(A_4\) are all 85 minutes, ie \(T_p (A_2) = T_p (A_3) = T_p (A_4) = 85\) minutes. At this point, \(A_{dep} (F001) = A_1, A_{aarr} (F001) = A_2; A_{dep} (F002) = A_2, A_{aarr} (F002) = A_3; A_{dep} (F003) = A_3, A_{aarr} (F003) = A_4; A_{dep} (F004) = A_4, A_{aarr} (F004) = A_1\). Flight times of \(F001, F002, F003\) and \(F004\) are 180 minutes, 120 minutes, 180 minutes and 120 minutes respectively. Taking the initial delay as independent variable and other factors unchanged, the influence of the initial delay on the longitudinal dispersion of flight delay is studied according to the algorithm mentioned above.

3.2. Calculation of simulation results

The system model has four airports, the minimum turnover time of flights at four airports is

\(T_t = 55\) minutes, and \(\Delta t = 15\) minutes. Supposing flight \(F001\) takes off at 06:00, namely \(T_{sdep} (A1) = 06:00\). Then under normal conditions, \(T_{sarr} (A2) = 09:00, T_{sdep} (A2) = 10:25; T_{sarr} (A3) = 12:25, T_{sdep} (A3) = 13:50; T_{sarr} (A4) = 16:50, T_{sdep} (A4) = 18:15, T_{sarr} (A1) = 20:15\).

Assuming \(T_{id} = 60\) minutes, using the above algorithm to calculate the longitudinal dispersion of flight delays as follows:

1. Calculate the delay spread of flight \(F001\)
   The actual departure time of \(F001\) at airport \(A1\) is \(T_{adep} (A1) = T_{sdep} (A1) + T_{id} = 07:00\).
   The estimated delay time of airport \(A2\) is \(T_{ppd} (A2) = T_{id} = 60\) minutes.
   The actual time that the flight arrives at \(A2\) should be \(T_{aarr} (A2) = T_{sarr} (A2) + T_{id} = 10:00\).
2. Determine whether flight \(F002\) is delayed
The relaxation time of Airpo
rt A2 is \( T_s(A2) = T_p(A2) - T_t = 30 \) minutes. At this point,
\( T_{ppd}(A2) - T_s(A2) = 30 \) minutes > \( \Delta t \), thus Judge(A2) = 1, ie the airport A2 is delayed for 30 minutes.

(3) Calculate the delay spread of flight F002

Due to the flight delays at airport A2, the actual flight departure time of flight F002 is:

\[ T_{adep}(A2) = T_{sdep}(A2) + (T_{ppd}(A2) - T_s(A2)) = 10:55. \]

The actual time of flight F002 arrives at Airport A3 is:

\[ T_{aarr}(A3) = T_{sarr}(A3) + (T_{ppd}(A2) - T_s(A2)) = 12:55. \]

(4) Determine whether flight F003 is delayed

The relaxation time of Airport A3 is \( T_s(A3) = T_p(A3) - T_t = 30 \) minutes. At this point,
\( T_{ppd}(A3) - T_s(A3) = 0 \) min < \( \Delta t \). Thus Judge(A3) = 1, ie there is no delay at A3.

(5) Calculating the subsequent diffusion of the delay

Due to the absence of delays at Airport A3, the actual takeoff time of flight F003 is \( T_{adep}(A3) = T_{sdep}(A3) = 13:50. \)

The time that flight F003 actually arrives at airport A4 is \( T_{aarr}(A4) = T_{sarr}(A4) = 16:50. \)

The actual departure time of flight F004 from the airport A4 is \( T_{adep}(A4) = T_{sdep}(A4) = 18:15. \),
and the actual arrival time at airport A1 is \( T_{aarr}(A1) = T_{sarr}(A1) = 20:15. \)

(6) Summary

In accordance with the above steps, calculate the number of delayed airports, total delay time and average delay time of delayed airports when \( T_{id} \) is equal to 60,70,80,90,100,110,120,130,150 and 180 minutes respectively. Summarize the results as shown in Table 2 below.

Table 2. Simulation results of longitudinal dispersion of flight delays (time unit: minutes).

| Initial delay | Tapd of A1 | Tapd of A2 | Tapd of A3 | Tapd of A4 | Number of delayed airports | Total delay time | Average delay time of delayed airports |
|---------------|------------|------------|------------|------------|---------------------------|------------------|----------------------------------------|
| 60            | 60         | 30         | 0          | 0          | 2                         | 90               | 45                                      |
| 70            | 70         | 40         | 10         | 0          | 2                         | 120              | 60                                      |
| 80            | 80         | 50         | 20         | 0          | 3                         | 150              | 50                                      |
| 90            | 90         | 60         | 30         | 0          | 3                         | 180              | 60                                      |
| 100           | 100        | 70         | 40         | 10         | 3                         | 220              | 73.3                                    |
| 110           | 110        | 80         | 50         | 20         | 4                         | 260              | 65                                      |
| 120           | 120        | 90         | 60         | 30         | 4                         | 300              | 75                                      |
| 130           | 130        | 100        | 70         | 40         | 4                         | 340              | 85                                      |
| 150           | 150        | 120        | 90         | 60         | 4                         | 420              | 105                                     |
| 180           | 180        | 150        | 120        | 90         | 4                         | 540              | 135                                     |

3.3. Analysis of simulation results

(1) Effect of initial delay on the number of delayed airports

From Table 2, we can grope for the relationship between the initial delay and the number of delayed airport caused by the longitudinal dispersion of flight delays, as shown in Fig. 4.
As can be seen from the figure that the number of airports affected by delays are roughly positively correlated with the initial delay. As the initial delay time increases, the number of delayed airports increases step by step. Due to the relaxation time of the airport, the number of delayed airports will remain constant over a certain period of initial delay. When the initial delay exceeds a certain value, all airports in the flight chain will be delayed. (2) Effect of initial delay on the total delay time

From Table 2, we can explore the relationship between the initial delay and the total delay time of the entire aviation network, as shown in Fig. 5.

From the above picture, the total delay time is positively related to the initial delay. The straight dashed line is the fitted curve, which shows that the relation between them is close to linear relationship. The total delay time raises rapidly as the initial delay time of the flight raises.

(3) Effect of initial delay on the average delay time of delayed airports

From Table 2, we can get the relationship between the average delay time of delayed airports and the initial delay, as shown in Fig. 6.
As shown in Figure 6, the average delay time of the delayed airports is also basically positively related to the initial delay of the flight, that is, the average delay time of the delayed airports goes up with the initial delay time. In some cases, the average delay time of the airport is reduced when the initial delay time increases by a certain value. The reason for the fluctuation is the artificial setting that the airports delayed for no more than 15 minutes are not counted as delayed airports.

4. Conclusion
In this paper, the number of delayed airports, the total delay time and the average delay time of the delayed airports are used as the evaluation elements of the longitudinal diffusion of flight delays in the chain aviation network. Through modeling and simulation analysis, it is found that all the three elements have a positive correlation with the initial delay of the flight. This indicates that the longer the initial delay, the more severe the flight delay in the aeronautical network.

According to the simulation results, in order to reduce the flight delay in the chain aviation network, what should be done is to try to avoid the initial delay, or take various effective measures to reduce the initial delay to improve the flight punctuality rate, so as to improve the airline's operational efficiency.

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