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FLIGHT DELAY CHARACTERISTICS ON PERTURBED AIRCRAFT ROUTINGS

KHUSNUL NOVIANINGSIH[1,*], RIESKE HADIANTI[2]

[1]Department of Mathematics Education, Faculty of Mathematics and Science Education, Universitas Pendidikan Indonesia, Jl. Dr. Setiabudi No 229, Bandung 40194, Indonesia
[2]Department of Mathematics, Faculty of Mathematics and Natural Sciences, Institut Teknologi Bandung, Jl. Ganesha No 10, Bandung 40132, Indonesia
*Corresponding Author: k_novianingsih@upi.edu

Abstract

We investigate a problem on robust aircraft routings in order to improve their performance in operations. We perturb flight schedules by retiming departure or arrival times of flights, then, we characterize some schedule perturbations analytically. The robustness of aircraft routings can be increased by adding longer slack or flight times, and especially, if departure time of flights in aircraft routings is moved no longer than the change of departure time of prior flights. Based on the characteristics, we propose a new optimization model for retiming departure time of flights. The model is constructed to avoid dependence of the optimal solution on historical delay data. The computational results show that the model produces schedules that significantly improve overall schedule performance.

Keywords: Aircraft routing, Flight delay, Propagated delay, Schedule perturbation, Slack.

1. Introduction

Airline schedules are often disrupted by some uncertain conditions. These might induce flight delays or cancellations. Any flight delays or flight cancelations are not only bad for passenger's satisfaction, but also will increase the airline operational costs. During delayed flights, airlines might pay extra for fuel, crews, or delay compensation to passengers. Hence, a proactive strategies are needed by airlines to reduce operational cost. Planning robust schedules is one way to deal with schedule disruptions.

Recently, some authors have proposed some approaches on improving the robustness of airline schedules. They perturb flight schedules to re-allocate slack in schedule connections or to revise flight time. They built optimization models to obtain the optimal perturbation. Using flight delay simulation, they showed that the perturbed schedules can improve the robustness of the schedules. Chiraphadanakul and Bernhard [1] and AhmadBeygi et al. [2] observed that the reallocating slack in schedule connections can improve the robustness of flight schedules in aircraft routings and passenger itineraries. Sohoni et al. [3] provided an optimization model to determine the flight time of robust flight schedules. Schaefer and Nemhauser [4] characterized perturbed schedules that can improve on-time performance while they did not increase the planned crew cost. Novianingsih and Hadianti [5] proposed optimization model for minimizing total propagated delay in crew schedules and aircraft schedules by retiming departure time of flights. Other research in this area can be found in [6-8].

In this research, we characterize the perturbations that increase the performance of aircraft routings. Unlike Schaefer et al. [9] who characterize perturbed schedules for given crew schedules, this paper investigate perturbation in aircraft schedules. We believe this research is the first study that shows how to obtain the optimal perturbation analytically. Research in perturbed aircraft routing find the optimal perturbation via optimization model for given historical delay data [1, 2, 5]. As a result, the optimal solution obtained from given delay data is often invalid for other data sets. Therefore, we need to find optimal perturbations that are applicable for any situations.

We analyze the types of perturbations that improve the performance of aircraft routings by adding more slack or more flight time according to the mathematical expression of departure delay and arrival delay. We modify the planned flight schedules by moving departure times earlier or moving arrival times later. This perturbation will result aircraft routings with shorter slack and longer flight time. We show that if the departure time of each flight in an aircraft routing is moved no longer than the departure-time changes of the previous flights, we will obtain a better performance of the aircraft routing. Based on our findings, we propose an optimization model for retiming departure times of flights in the given aircraft routings. We test our model using real schedules of an airline. We obtain that the model produces schedules that significantly improve overall schedule performance.

2. Materials and Methods

Analytical methods will be used to find the characteristics of perturbations that can improve the performance of aircraft routing in operations. The performances are measured according to the comparison between departure or arrival delay before and after retiming flights. For this purpose, we derive the equations of departure delay and arrival delay according to decomposition of flight delay in Lan et al. [10]. Then, we investigate how slack, flight time, and departure change will affect to schedule performances. Finally, we propose an optimization model to retiming departure time such that the optimal slack can be allocated. To test our model, we present a computational study in real airline schedules.

2.1. Aircraft routing problem

An aircraft routing problem is a problem for assigning aircrafts to flights such that each flight in airline schedules is covered by exactly one aircraft and the total assignment cost is minimum. Typically, the total cost represents the cost of total delays. To solve the problem, first, we should find all feasible routings in the schedules.

Let F be a set of flights. We use the symbol dep_i and $dept_i$ to denote the departure airport and the departure time of flight f_i, respectively. We also write arr_i and $arrt_i$ for the arrival airport and the planned arrival time of flight f_i, respectively. The planned flight time ft_i of flight f_i is defined by $ft_i = arrt_i - dept_i$. We called $f_1,...,f_n$ as a feasible routing if it satisfies the following properties.

1. $dep_{i+1} = arr_i$, for $i = 1,...,n-1$.
2. $t_{i,i+1} = dept_{i+1} - arrt_i \geq m_{i,i+1}$, for $i = 1,...,n-1$. Here $t_{i,i+1}$ denotes the planned turn time between f_i and f_{i+1}, and $m_{i,i+1}$ denotes the minimum turn time required for turning f_{i+1} after f_i.
3. dep_1 and arr_n are at specific airports called as maintenance bases.

Let R be a set of feasible routings. . Let $A = (a_{ij})$ be a $|F| \times |R|$ binary matrix which represents all feasible routings. Define $a_{ij} = 1$ if and only if flight f_i belongs to routing j. x_j is a binary decision variable where $x_j = 1$ if and only if routing j includes in the optimal solution. The aircraft routing problem can be formulated as follows:

Minimize:

$$\sum_{j\in R} c_j x_j, \tag{1}$$

Subject to:

$$\sum_{j\in R} a_{ij} x_j = 1, \forall i \in F, \tag{2}$$

$$\sum_{j\in R} x_j \leq N, \tag{3}$$

$$x_j \in \{0,1\}, \forall j \in R, \tag{4}$$

where c_j is the estimated cost of delays along routing j, and N is the number of available aircrafts. The optimization model (1) – (4) is used to construct aircraft routings that minimize flight delays when they are operated.

In the next section, we will discuss how to calculate total delay in an aircraft routing. Then, it will be used to measure the performance of flight schedules. We also observe the effects of perturbed flights to its performance. We define the perturbed flights as flights which their departure times or arrival times is moved earlier or later.

2.2. Flight delays under push-back recovery

Recovery is a process to react disruptions in schedule operations. One of the methods in recovery is push-back recovery. Using this method, flights are delayed until all of the resources are available [11].

Consider a push-back recovery. We categorize the sources of a delay into a block-time delay and a ground delay. A flight experiences a block-time delay if its actual flight time is longer than its planned flight time. We call a delay before an aircraft take-off as a ground delay. Note that the delay does not include propagated delay caused by the previous flights. Let $f_1,...,f_n$ be a sequence of flights in routing $r\in$. We will denote by θ_i and ϑ_i the random departure and arrival delay of flight f_i in R, respectively. Both θ_i and υ_i are nonnegative. Using these notations, we obtain the departure and arrival time of flight f_i as $\gamma_i = dept_i + \alpha_i$ and $\delta_i = arrt_i + \beta_i$, respectively. We will use the symbol ζ_i and η_i for flight f_i in r to denote the ground delay and block-time delay, respectively. The random variables ζ_i and η_i are nonnegative. For simplicity, we ignore the dependence of the distribution of ground-time and block-time delay on the time. We can now formulate the departure delay equation in the following proposition.

Proposition 2.1. *Let* $\rho_{i-1,i} = t_{i-1,i} - m_{i-1,i}$ *be the planned connection slack of flight* f_{i-1} *and* f_i. *Then*

$$\theta_i = \begin{cases} \zeta_i, i = 1, \\ \zeta_i + \max\{\theta_{i-1} + \eta_{i-1} - \rho_{i-1,i}, 0\}, i = 2, \dots, n. \end{cases}$$

Proof: We first compute the relation between propagated delay and departure delay according to Lan et al. [10]. Let us denote by $p_{i-1,i}$ the propagated delay in flight connection (f_i , f_{i-1}). Then

$$\theta_i = \zeta_i + p_{i-1,i}, \tag{5}$$

for $i = 1,\dots,n$. Since there is no propagated delay for f_1, we obtain $\theta_i = \zeta_i$. For $i = 2,\dots,n$, if arrival delay of flight f_{i-1} larger than $\rho_{i-1,i}$, the slack cannot absorb the delay. Hence the delay will propagate f_i by

$$p_{i-1,i} = \max\{\vartheta_{i-1} - \rho_{i-1,i}, 0\}. \tag{6}$$

By substituting Eq. (6) to Eq. (5), we thus get

$$\theta_i = \zeta_i + \max\{\vartheta_{i-1} - \rho_{i-1,i}, 0\}, \tag{7}$$

for $i = 2,...,n$. Since the arrival delay of flight f_{i-1} is as the contribution of its departure delay and its block-time delay, it follows that

$$\vartheta_{i-1} = \theta_{i-1} + \eta_{i-1}. \tag{8}$$

We complete the proof by substituting Eq. (8) to Eq. (7).

The following results being a consequence of Proposition 2.1. As

$$\max\{\theta_{i-1} + \eta_{i-1} - \rho_{i-1,i}, 0\} \leq |\theta_{i-1} + \eta_{i-1} - \rho_{i-1,i}|, \tag{9}$$

and

$$|\theta_{i-1} + \eta_{i-1} - \rho_{i-1,i}| \leq \theta_{i-1} + |\eta_{i-1} - \rho_{i-1,i}| \tag{10}$$

we have

$$\theta_i \le \zeta_i + \theta_{i-1} + |\eta_{i-1} - \rho_{i-1,i}| \quad (11)$$

Substituting Eq. (5) into Eq. (11) recursively gives

$$\begin{aligned}\theta_i &\le \zeta_i + (\zeta_{i-1} + \theta_{i-2} + |\eta_{i-2} - \rho_{i-2,i-1}|) + |\eta_{i-1} - \rho_{i-1,i}| \\ &\le \zeta_i + \zeta_{i-1} + \zeta_{i-2} + \theta_{i-3} + |\eta_{i-3} - \rho_{i-3,i-2}| + |\eta_{i-2} - \rho_{i-2,i-1}| \\ &\quad + |\eta_{i-1} - \rho_{i-1,i}| \\ &\le \sum_{k=1}^{i} \zeta_k + \sum_{k=2}^{i} |\eta_{k-1} - \rho_{k-1,k}|. \quad (12)\end{aligned}$$

We can now rephrase Corollary 2.2 as follows.

Corollary 2.2. *The departure and arrival delay of flight f_i satisfy*

$$\theta_i \le \sum_{k=1}^{i} \zeta_k + \sum_{k=2}^{i} |\eta_{k-1} - \rho_{k-1,k}|, \quad (13)$$

and

$$\vartheta_i \le \eta_i + \sum_{k=1}^{i} \zeta_k + \sum_{k=2}^{i} |\eta_{k-1} - \rho_{k-1,k}|. \quad (14)$$

In the next section, we will formulate our main results on perturbed aircraft routings. The preliminary study about this topic can be found in Novianingsih [12].

3. Results and Discussion

Here are the main results of our research.

3.1. Perturbed aircraft routing

We begin this section by defining perturbed aircraft routing. We assume that all aircraft connection is preserved. Let **a** and **b** be a nonnegative vector in $\mathbf{R}^{|F|}$.

Definition 3.1. *A perturbed aircraft routing r + (**a**,**b**) is defined as the new aircraft routing which obtained from r by moving the departure time and the arrival time of flight f_i on* ($dept_i - a_i$) and ($arrt_i + b_i$)*, respectively.*

Definition 3.2. *A Perturbed aircraft r + (**a**,**b**) is a feasible perturbed aircraft routing if the planned aircraft routing r remains feasible under perturbed aircraft routing r +* (**a**,**b**).

According to Definition 3.1, we obtain the new flight time and slack of flight f_i in r + (**a**,**b**) as $ft_i' = ft_i + a_i + b_i$ and $\rho_{i-1,i}' = \rho_{i-1,i} + a_i + b_i$, respectively. Given a feasible perturbed routing $r' := r +$ (**a**,**b**) which consists n flights. For flight f_i in r', let us denote by θ_i' and ϑ_i' the random departure delay and arrival delay, respectively. We also write ζ_i' and η_i' for the random ground delay and block-time delay of f_i, respectively.

Proposition 3.3. *If* $\rho_{i-1,i} \le \rho_{i-1,i}'$, $i = 2,\ldots,n$ and $ft_i = ft_i'$, *then* $\theta_i' \le \theta_i$, $i = 1,\ldots,n$.

Proof: According to Proposition 2.1, it is clear that $\theta_1' \le \theta_1$. Let we assume that $\theta_{i-1}' \le \theta_{i-1}$. We know that

$$p_{i-1,i} = \max\{\theta_{i-1} + \eta_{i-1,i} - \rho_{i-1,i}, 0\}, \quad (15)$$

and

$$p'_{i-1,i} = \max\{\theta'_{i-1} + \eta_{i-1,i} - \rho'_{i-1,i}, 0\}. \tag{16}$$

Since $\rho_{i-1,i} \le \rho'_{i-1,i}$ and $\theta'_{i-1} \le \theta_{i-1}$, according to our assumption, we have $p'_{i-1,i} \le p_{i-1,i}$. Applying Eq. (5), we conclude that

$$\theta'_i = \zeta_i + p'_{i-1,i} \le \zeta_i + p_{i-1,i} = \theta_i, \tag{17}$$

and the proof is complete.

Proposition 3.4. *If* $ft_i \le ft'_i$, *i* = 1,...,*n* and $\rho_{i-1,i} = \rho'_{i-1,i}$, *i* = 2,...,*n, then* $\theta'_i \le \theta_i$, *i*= 1,...,*n*.

Proof: As the proof in Proposition 3.3, by assuming $\theta'_{i-1} \le \theta_{i-1}$, we obtain the block-time delay of f_{i-1} in *r*' relative to *r* in the form

$$\max\{\eta_{i-1} + ft_{i-1} - ft'_{i-1}, 0\}. \tag{18}$$

This gives

$$\vartheta_{i-1} = \theta_{i-1} + \max\{\eta_{i-1} + ft_{i-1} - ft'_{i-1}, 0\}. \tag{19}$$

Since $\vartheta_{i-1} = \theta_{i-1} + \eta_{i-1}$ and $ft_i - ft'_i \le 0$, we thus get $\vartheta'_{i-1} \le \vartheta_{i-1}$. We conclude from Eq. (15) and Eq. (16) that $p'_{i-1,i} \le p_{i-1,i}$. After the plane experiences a ground delay ζ_i, we see that $\theta_i = \zeta_i + p_{i-1,i}$ and $\theta'_i = \zeta_i + p'_{i-1,i}$. Now $\theta'_i \le \theta_i$, which is do the fact that $p'_{i-1,i} \le p_{i-1,i}$.

Proposition 3.3 and 3.4 show that more slack or more flight time will reduce departure delays of flights in aircraft routings. The other type of perturbation that will improve the aircraft routing performance is formulated by the following theorem.

Theorem 3.5. *If* $a_{i-1} \ge a_i$, *i* = 2,...,*n, then* $\theta'_i \le \theta_i$, *i* = 1,...,*n*.

Proof: We will proof that $\theta'_i \le \theta_i$ for all flight f_i by induction. According to Proposition 2.1, we have $\theta_i = \zeta_i$ and $\theta'_i = \zeta_i$. So, $\theta'_1 \le \theta_1$. We will assume that $\theta'_{i-1} \le \theta_{i-1}$. The flight time change of f_{i-1} is $ft_{i-1} + a_{i-1} + b_{i-1}$ in perturbed schedules. This gives

$$\eta'_{i-1} = \eta_{i-1} - a_{i-1} - b_{i-1}. \tag{20}$$

Consequently, flight f_{i-1} arrive

$$\vartheta'_{i-1} = \max\{\theta'_{i-1} + \eta_{i-1}, -a_{i-1} - b_{i-1} 0\} \tag{21}$$

late in perturbed schedules. In original schedule, the arrival delay of f_{i-1} is $\vartheta_{i-1} = \theta_{i-1} + \eta_{i-1}$. While $\theta'_i \le \theta_i$ and $a_{i-1}, b_{i-1} \ge 0$, it is clear that $\vartheta'_{i-1} \le \vartheta_{i-1}$. If $\vartheta_{i-1} = 0$, then $\vartheta'_{i-1} = 0$. It follows that $p_{i-1,i} = 0$ and $p'_{i-1,i} = 0$. Therefore, we have $\theta_i = \theta'_i = \zeta_i$. Otherwise, suppose $\vartheta_{i-1} > 0$. Since $\vartheta'_{i-1} \le \vartheta_{i-1}$, we will consider two cases, that are $\vartheta'_{i-1} = 0$ or $\vartheta'_{i-1} > 0$. If $\vartheta'_{i-1} = 0$, we have the same argument as the previous explanation.

Let $\vartheta'_{i-1} > 0$. Then we now have

$$p'_{i-1,i} = \vartheta'_{i-1} - \rho'_{i-1,i}$$

$$= \max\{\theta'_{i-1} + \eta_{i-1} - a_{i-1} - b_{i-1}, 0\} - (\rho_{i-1,i} - b_{i-1} - a_i). \quad (22)$$

If $pd'_{i-1}, i > 0$, then

$$p'_{i-1,i} = (\theta'_{i-1} + \eta_{i-1} - a_{i-1} - b_{i-1}) - (\rho_{i-1,i} - b_{i-1} - a_i)$$

$$= \theta'_{i-1} + \eta_{i-1} - a_{i-1} + a_i. \quad (23)$$

Since $a_{i-1} \geq a_i$, then $p'_{i-1,i} \leq \theta'_{i-1} + \eta_{i-1} - \rho_{i-1,i}$. According to the induction hypothesis, we obtain $p'_{i-1,i} \leq \theta_{i-1} + \eta_{i-1} - \rho_{i-1,i}$. We conclude from Eq. (15) for $p_{i-1,i} > 0$ that $p_{i-1,i} = \theta'_{i-1} + \eta_{i-1} - \rho_{i-1,i}$, hence $p'_{i-1}, i \leq p_{i-1,i}$, and finally $\theta'_i \leq \theta_i$ is proved.

The following corollary is the consequence of $\vartheta_i = \theta_i + \eta_i$.

Corollary 3.6. *If* $a_{i-1} \geq a_i$, $i = 2,...,n$, *then* $\vartheta'_i \leq \vartheta_i$, $i = 1,...,n$.

Let us consider the following equation:

$$\theta'_i = \vartheta_i + \max\{\theta'_{i-1} + \eta'_{i-1} - \rho'_{i-1,i}, 0\}. \quad (24)$$

Since

$$\rho'_{i-1,i} = \rho_{i-1,i} - a_i - b_{i-1} \quad (25)$$

and

$$\eta'_{i-1} = \eta_{i-1} - a_{i-1} - b_{i-1}, \quad (26)$$

then

$$\theta'_i = \vartheta_i + \max\{\theta'_{i-1} + \eta_{i-1} - \rho_{i-1,i} + a_i - a_i, 0\}. \quad (27)$$

Equation (27) shows that perturbed arrival time of flights will not affect to their departure delays. On the other hand, adding the planned flight time will increase crew costs [9]. However, the lower bound of the planned crew costs is given by the planned flight time. These Facts show that we can reduce departure delays and maintain the original flight time by perturbing flight f_i in r such that

1. $a_{i-1} \geq a_i$, $i = 2,...,n$.
2. $b_i = -a_i$, $i = 1,...,n$.

By adapting the retiming model in Novianingsih and Hadianti [5], we propose an optimization model for retiming departure time of flights in aircraft routings. Since an unnecessary slack might reduce aircraft utility and crew productivity, we derive the model to obtain the optimal perturbations for departure-time of flights and to allocate optimal slack in flight connections. The optimal slack are slack with the minimum lengths while can keep a certain level of schedule robustness. Unlike research in perturbed aircraft routing which find the optimal perturbation via optimization model for given historical delay data [1, 2, 5], we avoid dependence of the optimal solution on historical delay data by including the property of departure delay on Theorem 3.5 as constraint of the model. As a result, the optimal solution obtained from given delay data is often invalid for other data sets.

We assume that: We move departure times of flights earlier in small time windows, as long as the minimum required connecting time can be fulfilled; We maintain the planned flight times of flights by moving arrival time of each flight earlier in the same length of time with its departure time change; The fleet assignments and aircraft routings are fixed; We maintain the feasibility of connecting aircraft assignments.

Let A and A_1 be a set of aircraft connections and a set of the first flights in aircraft routings, respectively. We define x_i as the variable of the model that determines the change of departure time of $f_i \in F$, and we limit the change of the departure time by u_i. The retiming model is formulated as follows.

Minimize:

$$\mathrm{E}\left(\sum_{f_i \in F} \theta_i\right). \tag{28}$$

Subject to:

$$\rho'_{i,j} = \rho_{i,j} + x_i - x_j, \forall(f_i, f_j) \in A, \tag{29}$$

$$p_{i,j} \geq \vartheta_i - \rho'_{i,j}, \forall(f_i, f_j) \in A, \tag{30}$$

$$p_{i,j} = 0, \forall(f_i, f_j) \in A_1, \tag{31}$$

$$\theta_j \geq \zeta_j + p_{i,j}, \forall f_j \in F, \tag{32}$$

$$\vartheta_j \geq \theta_j + \eta_j, \forall f_j \in F, \tag{33}$$

$$x_i - x_j \geq 0, \forall(f_i, f_j) \in A, \tag{34}$$

$$0 \leq x_j \leq u_j, \forall f_j \in F, \tag{35}$$

$$x_j \in Z, \forall f_j \in F, \tag{36}$$

$$\rho'_{i,j} \geq 0, \forall(f_i, f_j) \in A, \tag{37}$$

$$p_{i,j} \geq 0, \forall(f_i, f_j) \in A, \tag{38}$$

$$\theta_j, \vartheta_j, \zeta_j, \eta_j \geq 0, \forall f_j \in F, \tag{39}$$

Total expected departure delay is minimized by the objective function in Eq. (28). Constraints in Eq. (29) calculate the new slack between two flights after moving the departure times, and non-negative constraints in Eq. (37) ensure that every aircraft connection remains feasible. Constraints in Eq. (30), (31), and (38) calculate the propagated delay in each flight connection. Constraints in Eq (32) determine total departure delay for each flight. Constraints in Eq. (33) are used to calculate the arrival delay of each flight. Constraints in Eq. (34) restrict the departure change of two consecutive flights, and the amount of the change is limited by Eq. (35). Constraints in Eq. (36) state that the change of the departure time in integer value. Constraints in Eq. (39) ensure that all parameters and variables are non-negative values.

3.2. Numerical results

We applied our retiming model to the flight schedules of a major Indonesia airline in our computational experiments. We used 92 aircraft routings which consisted of 287 flights. Since the retiming model included uncertain parameters (θ_j and η_j), we can classify the model as stochastic discrete optimization models. We solved the model by implementing the technique proposed by Novianingsih and Hadianti [5]. We generated a finite number of scenarios firstly. For each scenario, we generated a number of delayed flights randomly, including their ground delays and block-time delays. Then, we considered the retiming model as a deterministic model to minimize total departure delay. We chose the median of the solution from all scenarios as the optimal solution of the retiming model.

We collected one-year historical delay data of the airline, then we used it for generating ground delays in each airport. We found that the ground delay data followed log-normal distributions:

$$f(x;\mu,\sigma)=\frac{1}{x\sigma\sqrt{2\pi}}\exp\left(-\frac{(\ln x-\mu)^2}{2\sigma^2}\right), x>0, \tag{40}$$

where $\mu\in[2.8, 3.4]$ and $\sigma\in[0.4, 0.6]$. We assumed that the distribution of block-time delays followed uniform distributions in [0, 30] minutes.

Using 1000 scenarios, the departure time of flights is moved earlier in [0, 15] minutes. In each scenario, the re-timing model was solved using Matlab 2015b. The optimal solution of the model was shown at Table 1. According to Table 1, we obtain that the retiming model produces new schedules with larger slack. The average of slack in schedule connections increase more than 4 minutes.

Table 1. The retiming results.

	Original schedules	Perturbed schedules
Total slack	3220	3952
Average of slack	15	19.4
Average of departure changes	-	11.2

To compare the robustness of the perturbed schedules and the original schedules, we used a flight delay simulation in Novianingsih and Hadianti [5]. For both perturbed schedules and original schedules, we executed the simulation in 100000 iterations. We take the average value of total departure delays, arrival delays, and propagated delays as the robustness measures. The performance of both schedules is summarized in Table 2. According to Table 2, total propagated delay is reduced in the perturbed schedules, and hence the total departure delay is also decreased in the perturbed schedules. This fact is being a consequence of larger slack in the perturbed schedules. Because we have the same flight times in the original and the perturbed schedules, we obtain the same proportion in reducing the arrival delay for the new schedules. We discover that the performance gap of the propagated delay is declined about 10% in the perturbed schedules, and 16% in the total departure delay. Like the previous studies [1, 2, 4,5 , 12], these results also provided that the retiming flights could improve the robustness of airline schedules. Moreover, we proposed a method for improving the robustness aircraft routing by retiming flights in aircraft routings as we show in Theorem 3.5.

Table 2. The robustness comparison between the original schedules and the perturbed schedules.

Robustness measures (mins)	Original schedules	Perturbed schedules
Total propagated delay	4703.6	4231.7
Total departure delay	5040.1	4225.2
Total arrival delay	5438.3	4623.4

4. Conclusions

By analytical way, we show that improving the aircraft routing performance can be done by increasing slack or flight times. We also suggest that by reducing slack in aircraft connections, flight times can be enlarged. Moreover, the better performance of aircraft routings will be obtained if the departure time of flights is moved no longer than the departure time changes of the prior flights. Based on this, we propose an optimization model to revise departure time of flights. such that we obtain the aircraft schedules with slightly increased slack. Computational results show that our approach can produce aircraft routings with better performance.

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