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Flight Re-timing Models to Improve the Robustness of Airline Schedules

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Abstract : We study a problem on improving the robustness of airline schedules. A schedule is robust if the schedule can minimize the effect of flight delays in day-to-day operations. We improve the robustness of flight schedules by re-timing departure time of flights. We derive stochastic optimization models to change departure times of flights in which the feasibility of both aircraft and crew connections are maintained. We solve the models using flight delay simulation. The computational results show that the re-timing flights can improve the robustness of aircraft routings significantly.

Keywords : re-timing flight; flight delays, robust schedule; simulation

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1 Introduction

Airline schedules are operated under some uncertain conditions. Some factors such as bad weather conditions or high aircraft traffic often disrupt the schedule operations, and these may cause flight delays or cancellations. Any flight delay or flight cancelation is not only bad for passenger satisfaction, but also it will increase the airline operational costs. For example, the airlines might pay extra money for fuel or extra salary for their crews; the passengers should be gave delay compensation during long waiting for their flights.

To reduce operational cost, airlines need to have proactive strategies by planning robust schedules. Robust schedules are the schedules that are insensitive to yield delay propagations, or easy (or cheap) to recover. Hence, a robust schedules can minimize operational costs while increasing on-time performance of the airline.

In airline schedules, each aircraft or crew must serve a sequences of flight. In these sequences, we find slacks between two consecutive flights. Slack is defined as the additional time beyond the time required for each aircraft connection, crew connection, or passenger connection in the schedule [8]. An insufficient slack will increase the probability of propagated delay, while an unnecessary slack might reduce aircraft utility and crew productivity. Thus, we can have a robust schedule if we can allocate optimal slacks into the schedule. We mean by the optimal slacks as the slacks with the minimum lengths while can keep a certain level of schedule of robustness.

Recently, some authors have shown that slacks in schedule connections can be distributed by re-timing departure time of flights or arrival time of flights. Lan et al. [7] constructed a re-timing model to obtain robust aircraft routes which minimized the expectation of total propagated delays, where the model might construct new aircraft routing due to re-timing. The other model was also developed in [7] to select departure time of flights that minimized the expected number of disrupted passengers, while maintained the current fleeting, aircraft routes, and passenger itineraries. The re-timing models have been considered to improve the robustness of the integrated schedules. Lee [4] introduced a multi-objective model to revise departure time of flights without change the fleet assignment, aircraft routings, and crew pairings. The same approach is used by [2] for simultaneous re-timing flights and aircraft re-routing, subject to fixed fleet assignment. Other research in this area can be found in [5, 6].

In [1], they derived deterministic mix-integer programming models to re-time departure time of flights. The models are constructed to reduce delay propagations due to aircrafts and cockpit crews. To capture delay propagation from multiple resources, they use propagation tree. But the propagation tree still can not accurately take into account simultaneous delay from different propagation trees, [8]. In [8], slacks were re-allocated by re-timing both departure time and arrival time of flights. The re-timing model was build to minimize total arrival delay of flights in aircraft routings according some delay scenarios. A delay scenario was represented by one-day operation in historical data. Then, the re-timing model is solved under a number of delay scenarios. But this approach will work well if each delay scenario is equally like. In this paper, we derive stochastic programming models for re-timing departure times of flights in which we preserve the connecting flights in aircraft routings and crew pairings, since the aircraft routings and crew pairings in the original schedule are one which minimize the total planned cost. But unlike the models in [1] and [8] which just consider propagated delays along aircraft routings, our re-timing model consider propagated delay along aircraft routings and crew pairings[2] as well. By considering more factors that can cause propagated delays, it is hopped that we have more realistic models.

We propose a solution technique by assuming that we have a finite set of scenarios. In each scenario, we generate primary delays randomly according primary delay distributions in departure airports, which inferred from the historical delay data. This delay generation yields a deterministic optimization model which can be solved with any deterministic solution method. We perform a large number of the delay generations so that we can obtain a large number solutions. From these solutions, we choose the median of the solutions as the optimal solution.

This paper is written as follows. We discuss flight departure model in Section 2. A model to re-time departure times of flight is presented in Section 3. A re-timing model with combined propagated delay is discussed in Section 4. The solution technique for solving our models is discussed in Section 5. We present the data, and the computational result in Section 6. We conclude and focus on our future work in the last section.

2 Flight Delay Model

In this section we derive mathematical expressions of departure delay and propagated delay. A model we derive here is based on a flight delay decomposition defined by Lan et al. (2006) [7]. Lan et al. (2006) stated that a flight delay can be decomposed into two components, that are

1. Propagated delay
   Flight delay caused by waiting for incoming aircraft.
2. Primary delay
   Flight delay caused by other reasons.

Let dep_i and $\overline{dep}_i$ be the planned departure time of flight f_i and the actual departure time of flight f_i, respectively.

Definition 2.1. *The departure delay of flight f_i is defined as*

$$dd_i = \overline{dep}_i - dep_i.$$

If d_i and pm_i are the propagated delay of flight f_i and the primary departure delay of flight f_i, respectively, the departure delay of flight f_i is expressed as

$$dd_i = d_i + pm_i. \tag{2.1}$$

[2] A crew pairing is a sequence of flights starting and ending ending at the cockpit crew base

Let F be a set of flights. Let $\mathcal{R}$ be a set of aircraft routings, where each $r \in \mathcal{R}$ is defined by $r = (f_1, ..., f_i, f_j, ..., f_n)$, $f_i \in F$, $i = 1, ..., n$. A set of aircraft connections, denoted by $\mathcal{A}$, is a set all $(f_i, f_j) \in r$, $r \in \mathcal{R}$, where $f_i, f_j \in F$.

Definition 2.2. *Slack between two consecutive flights f_i and f_j in $\mathcal{A}$, denoted by s_{ij}, is defined by*

$$s_{i,j} = c_{i,j} - m_{i,j},$$

where $c_{i,j}$ is the connecting time between flights f_i and f_j, and $m_{i,j}$ is the minimum required connecting time between flights f_i and f_j.

Assume that there is no delay in the air. The following proposition shows the relationship between departure delay and propagated delay in an aircraft routing r.

Proposition 2.1. *The departure delay of flight f_i in routing r is given by*

$$dd_1 = pm_1, dd_i = pm_i + \max\{d_i + pm_i - s_{i-1,i}, 0\}, \tag{2.2}$$

for $i = 2, ..., n$.

Proof. It is clear that we do not have propagated delay for the first flight in r. So, we have $dd_1 = pm_1$. For flight f_i, i = 2,...,n, we have

$$d_i = max\{ad_{i-1} - s_{i-1,i}, 0\},$$

where ad_i is arrival delay of flight f_{i-1}. Since we assume that there is no delay in the air, we have $ad_i = dd_i$. Hence, we get

$$d_j = \max\{d_i + pm_i - s_{ij}, 0\}, \tag{2.3}$$

for $i = 2, ..., n$. Use Equation (2.1) to complete the proof. □

3 The Model

In day-to-day operation, each aircraft or crew serves a sequence of flights. If there is not enough slack between two consecutive flights in that sequence, one flight delay often results in delay propagations for downstream flights. But the large size of slack can decrease aircraft utility or crew productivity. It means that slack should be allocated optimally.

Our modeling approach is to reduce propagated delay by re-allocating slack in aircraft connections. We re-distribute slack by re-timing departure times of flights. To protect passenger prediction in flight schedule generation, we limit the departure changes in small time windows. Figure 1 illustrates an example of re-timing flights and their effect on propagated delay. Assume that flight a, flight b, and flight c in the same routing. Suppose, based on historical data, flight a is often delayed for 25 minutes. If $m_{a,b} = m_{b,c} = 25, s_{a,b} = 5$ and $s_{b,c} = 10$ minutes, then flight b will be delayed for 20 minutes, and causing flight c to be delayed. But, if flight a is moved 15 minutes earlier and flight b is moved 5 minutes later, we have new slack for connecting flight a and flight b, $s'_{a,b} = 25$, and new slack for connecting flight b and flight c, $s'_{a,b} = 5$. This new slack for connecting flight a and flight b will omit propagated delay to flight b and flight c.

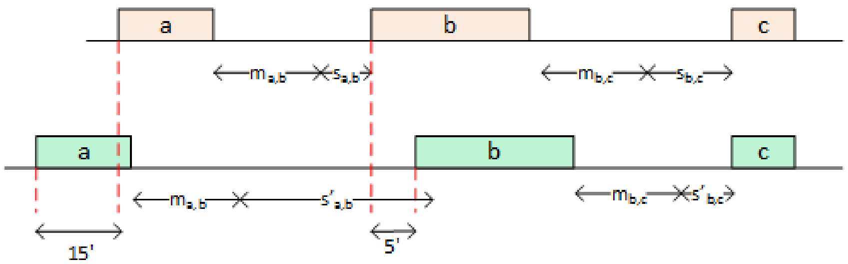

Figure 1: An example of re-timing flights.

Since delays propagate along the aircraft routes, we propose flight re-timing models for moving departure times of flights in aircraft routing. The model is derived to allocated slack in important connections that are needed, so that the expectation of total propagated delay is minimum. We assume that: We re-time departure times of flights in small time windows, as long as the required minimum connecting time can be fulfilled; The flight times of flights before and after re-timing are not changed. So, the change of arrival time of each flight is the same with the change of the departure time; The fleet assignments and aircraft routings are fixed; We maintain the feasibility of connecting aircraft assignments.

We define sets, parameters, and variables of re-timing models as follow:

Sets:

F : a set of flights

$\mathcal{A}$: a set of aircraft connections

$\mathcal{A}_0$: a set of the first flights in each aircraft connection

$\mathcal{W}$: a set of delay scenarios

Parameters:

s_{ij} : slack between flight f_i and flight f_j in the original schedule, $(f_i, f_j) \in \mathcal{A}$

$pd^{\omega}_{f_j}$: primary delay of flight $f_j \in F$ for given delay scenario $\omega \in \mathcal{W}$

l_j : the limit of departure time of flight $f_j \in F$ to be changed earlier

u_j : the limit of departure time of flight $f_j \in F$ to be changed later

Variables:

x_j : the change of departure time of $f_j \in F$

$s'_{i,j}$: the new slack of between flight f_i and f_j, $(f_i, f_j) \in \mathcal{A}$

d^{ω}_j : propagated delay to flight $f_j \in F$ for given delay scenario $\omega \in \mathcal{W}$

dd^{ω}_j : departure delay of flight $f_j \in F$ for given delay scenario $\omega \in \mathcal{W}$

We set the variable x_j by a negative value if the departure time of flight f_j is moved earlier, and we takes a positive value for x_j if the departure time of flight f_j is moved later. The re-timing model for flights in aircraft routing is formulated as the following model.

Minimize:

$$\mathbb{E}\left(\sum_{f\in F} d_f\right) \tag{3.1}$$

Subject to:

$$\begin{aligned}
s'_{i,j} &= s_{i,j} - x_i + x_j & \forall (f_i, f_j) \in \mathcal{A}, && (3.2)\\
d_j^{\omega} &\geq dd_i^{\omega} - s'_{i,j} & \forall (f_i, f_j) \in \mathcal{A}, \forall \omega \in \mathcal{W}, && (3.3)\\
d_j^{\omega} &= 0 & \forall f_j \in \mathcal{A}_0, \forall \omega \in \mathcal{W}, && (3.4)\\
dd_j^{\omega} &= d_j^{\omega} + pm_j^{\omega} & \forall f_j \in F, \forall \omega \in \mathcal{W}, && (3.5)\\
l_j \leq x_j &\leq u_j & \forall f_j \in F, && (3.6)\\
x_j &\in \mathbb{Z}, & \forall f_j \in F, && (3.7)\\
s'_{i,j} &\geq 0 & \forall (f_i, f_j) \in \mathcal{A}, && (3.8)\\
dd_j^{\omega}, d_j^{\omega} &\geq 0 & \forall f_j \in F, \forall \omega \in \mathcal{W}. && (3.9)
\end{aligned}$$

The objective function (3.1) is to minimize the total expected propagated delay over all flights. Constrain (3.2) calculates the new slack between two flights after moving the departure times. Constrain (3.3) and (3.4) calculate the propagated delay for each flight connection. Constrain (3.5) determines total departure delay for each flight. We limit the change of departure time of each flight in constrain (3.6). Constrain (3.7) states that the change of the departure time in integer value. Constrain (3.8) and (3.9) ensure that all variables are non negative values.

The optimization model above almost similar with flight re-timing model proposed by Chiraphadhanakul and Bernhart (2013) [8]. The main difference are that our model consider total departure delay and only re-time departure times of flights. But, Chiraphadhanakul and Bernhart's model consider total arrival delay and re-time both departure times and arrival times of flights. Chiraphadhanakul and Bernhart'model did not yet consider propagated delay caused by crew late. In reality, delayed flights are often caused by waiting for crews. In the next section, we will extend the above model by consedering combined propagated delays along aircraft routes and crew pairings.

4 The Re-timing Model with Combined Propagated Delays

Let $\mathcal{C}$ be a set of crew connections. Let S and T be a set of first flights in $\mathcal{A}$ and $\mathcal{C}$, respectively. If $(f_i, f_j) \in \mathcal{A}$ and $(f_k, f_j) \in \mathcal{C}$, by Proposition 2.1, the propagated delay of flight f_j caused by flight f_i along a path in aircraft connection is calculated as

$$d_j^A = \max\{d_i^A + pm_i - s_{i,j}, 0\}, f_j \in F, f_j \notin S; \text{ and } d_{f_j}^A = 0, f_j \in S.$$

By using the same formula, we also can calculate propagated delay of flight f_j caused by flight f_k along a path in crew connection as

$$d_j^C = \max\{d_k^C + pm_k - s_{k,j}, 0\}, f_j \in F, f_j \notin T; \text{ and } d_j^R = 0, j \in T.$$

Now, We determine combined propagated delay of flight j as

$$d_j = \max\{d_i^A + pm_i - s_{i,j}, d_k^C + pm_k - s_{k,j}, 0\}.$$

Flight re-timing model with combined propagated delay is modeled as follow.

Minimize:

$$\mathbb{E}\left(\sum_{f \in F} d_f\right) \tag{4.1}$$

Subject to:

$$s'_{i,j} = s_{i,j} - x_i + x_j \qquad \forall (f_i, f_j) \in \mathcal{A}, \tag{4.2}$$
$$d_j^{A,\omega} \geq dd_i^\omega - s'_{i,j} \qquad \forall f_j \in F, \forall f_j \notin \mathcal{A}_0, \forall (f_i, f_j) \in \mathcal{A}, \forall \omega \in \mathcal{W}, \tag{4.3}$$
$$d_j^{A,\omega} = 0 \qquad \forall f_j \in \mathcal{A}_0, \forall \omega \in \mathcal{W}, \tag{4.4}$$
$$d_j^{C,\omega} \geq dd_k^\omega - s'_{k,j} \qquad \forall f_j \in F, \forall f_j \notin \mathcal{C}_0, \forall (f_k, f_j) \in \mathcal{C}, \forall \omega \in \mathcal{W}, \tag{4.5}$$
$$d_j^{C,\omega} = 0 \qquad \forall f_j \in \mathcal{C}_0, \forall \omega \in \mathcal{W}, \tag{4.6}$$
$$d_j^\omega = \max\{d_j^{A,\omega}, d_j^{C,\omega}\} \qquad \forall f_j \in F, \forall \omega \in \mathcal{W}, \tag{4.7}$$
$$dd_j^\omega \geq d_j^\omega + pm_j^\omega \qquad \forall f_j \in F, \forall \omega \in \mathcal{W}, \tag{4.8}$$
$$x_j = 0 \qquad \forall f_j \in F_0, \tag{4.9}$$
$$x_j \in \mathbb{Z} \qquad \forall f_j \in F, \tag{4.10}$$
$$l_j \leq x_j \leq u_j \qquad \forall f_j \in F, \tag{4.11}$$
$$s'_{i,j} \geq 0 \qquad \forall (f_i, f_j) \in C, \mathcal{A} \tag{4.12}$$
$$dd_j^\omega, d_j^\omega, d_j^{A,\omega}, d_j^{C,\omega} \geq 0 \qquad \forall f_j \in F, \forall \omega \in \mathcal{W}. \tag{4.13}$$

The objective function (4.1) is to minimize the total expected propagated delay over all flights. Constrain (4.2) calculates the new slack between two flights after moving the departure times. Constrain (4.3) and (4.4) calculate the propagated delay for each flight connection in each aircraft routing. Constrain (4.5) and (4.6) calculate the propagated delay for each flight connection in each crew pairing. The combined propagated delay is given by Constrain (4.7). Constrain (4.8) determines total departure delay for each flight. Constrain (4.9) ensures that the duty period of each crew before and after re-timing are not changed. Constrain (4.10) states that the change of the departure times in integer values. We limit the change of departure times of each flight in constrain (4.11). Constrain (4.12) and (4.13) restrict all variables in non negative values.

5 Solution Technique

Our re-timing models are stochastic discrete optimization models. We solve the re-timing models by performing flight delay simulations. Given primary delay distributions of flight depart from airports and a finite number of scenarios. In each scenario, we perform the following steps.

1. Generate primary delays of each flight randomly according primary delay distributions in departure airports.
2. Consider the re-timing models as the deterministic models, and then solve the models.

To obtain optimal solutions of the re-timing models, we choose the median of the solution from all scenarios. The objective function we choose is

$$\mathbb{E}\left(\sum_{f\in F} d_f\right) = \sum_{f\in F}\sum_{\omega\in\mathcal{W}} p_f \mathbb{E}(d_j^\omega),$$

where p_f is probability of flight f to be delayed.

Let $B = (b_{ij})$ be a coefficient matrix corresponding to constrains (3.2)-(3.5).

Proposition 5.1. *The solution of* (3.1)-(3.9) *are integer, given all integer constrain parameters.*

Proof. Consider an aircraft routing $r = (f_1, ..., f_n)$ where $f_k \in F$ for $k = 1, ..., n$ and $(f_{(k-1)}, f_k) \in \mathcal{A}$ for $k = 2, ..., n$. The departure delay of flight $f_k \in r$ is given by:

$$\begin{aligned}
dd_k^\omega &= d_k^\omega + pm_k^\omega \\
&\geq dd_{(k-1)}^\omega - s'_{(k-1),k} + pm_k^\omega \\
&= dd_{(k-1)}^\omega - (s_{(k-1),k} - x_{(k-1)} + x_k) + pm_k^\omega \\
&= d_{(k-1)}^\omega + pm_{(k-1)}^\omega - s_{(k-1),k} + x_{(k-1)} - x_k + pm_k^\omega \\
&\geq dd_{(k-2)}^\omega - s'_{(k-2),(k-1)} + pm_{(k-1)}^\omega - s_{(k-1),k} + x_{(k-1)} - x_k + pm_k^\omega \\
&\geq dd_{(k-2)}^\omega - (s_{(k-2),(k-1)} - x_{(k-2)} + x_{(k-1)}) + pm_{(k-1)}^\omega - s_{(k-1),k} \\
&\quad + x_{(k-1)} - x_k) + pm_k^\omega \\
&= dd_{(k-2)}^\omega + x_{(k-2)} - x_k - \textstyle\sum_{j=k-1}^k s_{(j-1),j} + \sum_{j=k-1}^k pm_j^\omega \\
&\vdots \\
&\geq dd_1^\omega + x_1 - x_k - \textstyle\sum_{j=2}^k s_{(j-1),j} + \sum_{j=2}^k pm_j^\omega \\
&= pm_1^\omega + x_1 - x_k - \textstyle\sum_{j=2}^k s_{(j-1),j} + \sum_{j=2}^k pm_j^\omega \\
&= x_1 - x_k - \textstyle\sum_{j=2}^k s_{(j-1),j} + \sum_{j=1}^k pm_j^\omega
\end{aligned}$$

Then, for each $f_k \in r$

$$dd_k^\omega - x_1 + x_k \geq \sum_{j=1}^{k} pm_j^\omega - \sum_{j=2}^{k} s_{(j-1),j}. \tag{5.1}$$

Equation 5.1 shows that Constrain (3.1)-(3.9) can be reduced by Equation (5.1). From Equation (5.1), we know that all entries B are -1,0, or +1.

For any collection of column $B = (b_{ij})$, let C_1 be a set of columns associated with the decision variable dd_i^ω, and C_2 be a set of columns associated with the decision variable x_i. For each row j of C_1 and C_2,

$$\sum_{j \in C_1} a_{ij} = 1 \text{ and } \sum_{j \in C_2} a_{ij} = 0.$$

Therefore

$$|\sum_{j \in C_1} a_{ij} - \sum_{j \in C_2} a_{ij}| = 1, \forall i.$$

According Ghouila-Houri, B is totally unimodular matrix. Hoffman and Kruskal' Theorem stated that if B be a totally unimodular matrix and let b, l, and u be integral vectors, then polyhedron $\{x | Ax \leq b, l \leq x \leq u\}$ is integral. The Theorem complete our proof. □

Property 5.1 shows the technique to solve our model efficiently. Since the coefficient matrix corresponding to constrains (5.1) is totally unimodular, and constrains (3.6) - (3.9) are bound constrains, to solve the optimization model (3.1) - (3.9), we do not need consider the model as the integer programming. But we only need to solve the linear programming relaxation of the model, and give all integer parameters of the model.

The linear programming relaxation technique can not be applied to solve model (4.1) - (4.13). The model is a non linear integer programming that is NP-hard problem. We use heuristic genetic algorithm to solve the model efficiently.

6 Computational Study

We use one-day schedules of an airline in Indonesia for computational study, where the data characteristics are shown in Table 6. By using the technique in [3], we model the probability distribution of primary delay for each airport based on the one-year historical delay data of the airline. We found that for all airports, the probability distributions of primary delays can be modeled as log-normal distributions. The probability density function of a log-normal distribution is given by

$$f(x; \mu, \sigma) = \frac{1}{x\sigma\sqrt{2\pi}} \exp(-\frac{(\ln x - \mu)^2}{2\sigma^2}), x > 0, \tag{6.1}$$

where μ and σ are mean and standard deviation, respectively. We found that the logarithm of parameters in the log-normal distributions for our historical data are $\mu \in [2.8 - 3.4]$ and $\sigma \in [0.4 - 0.6]$.

Table 1: The planned schedule characteristics

Number of flights	287
Number of aircraft routings	92
Number of crew pairings	89
Number of aircraft connections	195
Number of crew connections	185

We use 1500 scenarios, where in each scenario we generate primary delay of each flight randomly. To solve the re-timing models, we use the technique in Section 5. Table 2 shows the re-timing results of model in Section 3 (Model 1) and Section 4 (Model 2). From Table 2, we know that the departure changes cause the increasing of the average slack in connections. Since model 1 only consider propagated delays along aircraft routings, the average slacks of Model 1 is higher than the average slacks of Model 2.

Table 2: The re-timing results.

Minutes	**Original**	**Model 1**	**Model 2**
Total slacks	3220	4792	4269
Average of slacks	15	20	18
Average of departure changes	-	12	8

In order to compare the robustness of the revised schedules and the original schedules, we construct a robustness simulation in which in each iteration consists of the following steps:

1. Generate a number of flight delays and their primary delays.
2. Check all connecting times due to the flight delay generated. We perform reactionary delays using push-back recovery strategy, so that a minimum connecting time is fulfill in all connecting times. Mathematically, for $(f_i, f_j) \in \mathcal{T}$, let f_i is delayed by η minutes. Then, flight f_j will be delayed for $\max\{\eta - s'_{i,j}, 0\}$.
3. Calculate total propagated delays and total departure delays.

We perform the simulation to both the revised schedules and the original schedules, each for 100000 iterations. In each iteration, we compute the average value of the robustness measures for comparison. Table 3 shows that both new schedules can decrease total propagated delay significantly. Hence, it causes the reduction of total departure delay. We obtain the same pattern for the number of flight delays. If we use 15-OTP as the on-time performance metric (see Table 4), the new schedules of Model 1 reduce 8% of flight delays and the new schedules of Model 2 reduce 17% of flight delays. An 15-OTP measures the percentage of flights that depart at the gate no later than 15 minutes after the schedule departure time. This results indicate that the new schedules are more robust than the old schedules. The schedules of Model 2 is the most robust schedules since the schedules consider propagated delay along both aircraft routings and crew pairings.

Table 3: The robustness measures.

Robustness measure	**Original**	**Model 1**	**Model 2**
Total propagated delay (mins)	4403.2	2358.1	1040
Total departure delay (mins)	5870.3	3725.2	2707.7
delayed flights (%)	28	22	15

Table 4: The distribution of total departure delays.

	(0,15]	**(15,20]**	**(20,30]**	$>$ **30**
Original schedules (%)	77	8	10	5
Model 1 (%)	85	9	4	2
Model 2 (%)	94	2	3	1

7 Conclusion

In this paper we develop two stochastic optimization models to improve the robustness of flight schedules by distributing slacks between two consecutive flights. We developed a model to re-time departure times of flights in the schedules such that the estimation of total propagated delay along aircraft routings can be minimize. Then, the model is extended to integrate propagated delay caused by late crew. We test our models by implementing them to real schedules of an airline in Indonesia. Our simulation for measuring the robustness of the original and the revised schedules show that our models can improve the robustness of airline schedules.

Our models revise only departure time of flights and does not change any aircraft routings, any fleet assignments, and any crew pairings. It means that our method can improve the schedule robustness without increasing the planned cost significantly. Hence, our technique can be implemented at a post-traditional optimization step to generate robust schedules. In reality, passenger late also gave the significant contribution to the delayed flights. It is means that to get more realistic models we should include passenger connection to our models. This is the subject of our further research.

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