IMPROVEMENT OF PUSHBACK TIME ASSIGNMENT UNDER UNCERTAINTIES

Ryota Mori*
***Electronic Navigation Research Institute**

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Abstract

TSAT (Target Start-up Approved Time) operation is a promising method to reduce fuel burn during airport ground taxiing operation. Under TSAT operation, the aircraft with assigned TSAT has to wait at the gate until the assigned TSAT time so that the aircraft can wait at the gate with engines off instead of burning unnecessary fuel in a long queue at the runway. However, if the aircraft arrives at the runway too late, it cannot take off at the expected time. This take-off delay is caused by the uncertainty in airport operation, and the uncertainty effect should be considered to apply TSAT operation in the real world. Therefore, this paper proposes a new TSAT assignment algorithm considering such an uncertainty. Useful information on the ground is identified, and TSAT time is calculated based on the obtained information. The problem is formulated as a combinatorial optimization. The proposed algorithm is evaluated in terms of the take-off delay as well as the fuel burn reduction.

1 Introduction

Airport congestions have recently become a critical problem at many major airports in the world. Both departure and arrival aircraft often form a queue at the runway because a certain separation is required between take-off/landing aircraft. Arrival flow is usually a target of research, because additional flight time obviously requires extra flight time and fuel. However, departure aircraft also consume sufficient amount of fuel during taxiing. One solution is electric taxiing, which uses electric motors for pushback and taxiing with engines off[1]. However, it requires additional onboard or ground systems, and will not appear soon. On the other hand, TSAT (Target Start-up Approved Time) operation can be easily applied in the real world, because no additional hardware system is required. In TSAT operation concept, an air traffic controller (ATC) assigns TSAT to a certain departure aircraft when a long departure queue at the runway is expected. This aircraft must wait at the gate until the assigned TSAT time. The aircraft can smoothly go taxiing to the runway after leaving the gate, and finally take off at the expected take-off time, and therefore reduce fuel burn by waiting at the gate with engines off.

In the research community, TSAT operation is one of the hot topics for airport operation and several approaches have been proposed[2][3][4][5][6]. The key of the TSAT operation is that the departure queue length is minimized, i.e., TSAT time is assigned as late as possible to maximize fuel burn reduction. In an ideal environment, TSAT should be set so that all aircraft arrive at the runway without waiting in a departure queue at the runway. However, airport operation includes considerable uncertainties, which can delay the arrival at the runway, which causes take-off delays. The take-off delay is unwanted in terms of passenger service and airport capacity, so TSAT operation should be done as long as take-off delay is sufficiently small. However, the existing researches mentioned above evaluate the uncertainty effect in a simple way only. If the sufficiently large uncertainty is assumed in advance, the take-off delay is not caused, but the fuel burn reduction is also limited. By considering the uncertainty effect directly, the fuel burn reduction will be maximized while keeping the take-off delay at an acceptable level. This paper proposes a new TSAT assignment algorithm to improve the TSAT operation performance by considering uncertainties in the environment directly.

TSAT operation has already been implemented at some airports in the world, and Tokyo Haneda International Airport (below Haneda Airport) started TSAT operation trial in April 2013. Therefore, this research also focuses on Haneda Airport and assumes the ongoing air traffic control operation.

2 Overview of Airport Operation and Its Simulation Model

2.1 Airport Operation at Haneda Airport

Haneda Airport is the busiest airport in Japan with about 425,000 movements (1,164 movements per day) in 2014. There are four runways at this airport as shown in Fig. 1. This time, north wind operation is considered because departure aircraft is more congested under north wind operation. Due to the layout of the runways, they cannot be used simultaneously. When arrival aircraft approaches C runway, departure aircraft from both C and D runway cannot take off.

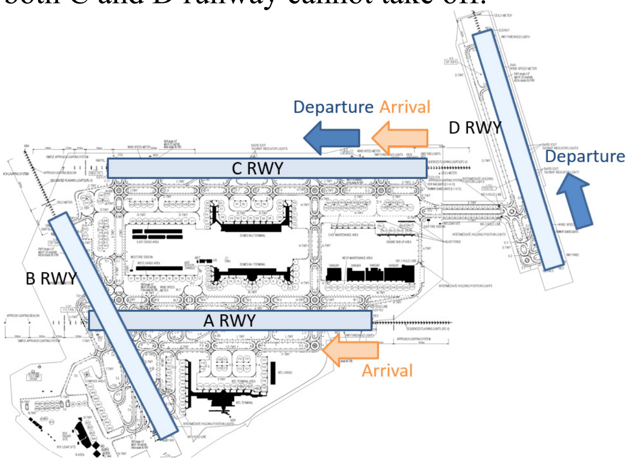

Fig. 1 Airport operation under north wind.

2.2 TSAT Operation at Haneda Airport

The traffic volume is relatively stable throughout a day, because this airport mainly handles domestic flights. However, both departure and arrival traffic are concentrated in the evening time (6 – 8 pm) when the airport is the most congested, so a trial of TSAT operation is conducted at this evening time only.

TSAT operation at this airport proceeds as follows. First, airlines provide TOBT (Target Off-Block Time) to ATC at least 35 minutes EOBT, and TOBT should be updated as required. Based on TOBT, ETOT is calculated considering the estimated taxi-out time. As for landing aircraft, ELDT (Estimated Landing Time) is calculated by the system installed at this airport. In each runway, the runway sequencing system calculates the aircraft sequence by the order of ETOT and ELDT. ETOT and ELDT are updated as required, so the runway sequence is also updated every minute. The assigned take-off and landing time are denoted by CTOT (Controlled Take-Off Time) and CLDT (Controlled Landing Time). Based on CTOT, TSAT assignment system calculates TSAT of each aircraft. Here, due to airlines requests, TSAT must be notified to airlines no later than 25 minutes before TOBT, and the assigned TSAT cannot be changed. When the pilot requests pushback, ATC provides the assigned TSAT to the pilot, and the pilot must wait at the gate until the assigned TSAT. The TSAT operation flow is shown in Fig. 2. This paper focuses on TSAT assignment system, and the performance will be improved by introducing a better TSAT assignment algorithm.

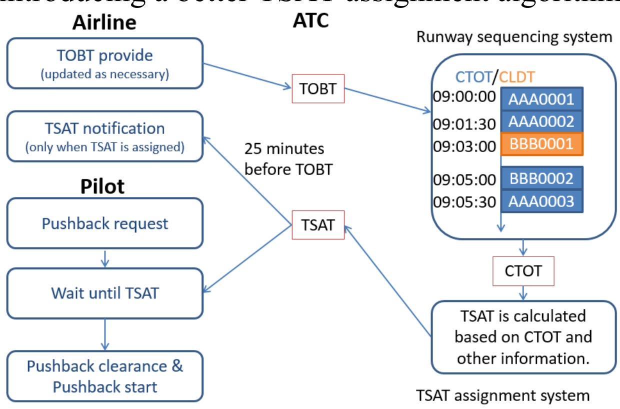

Fig. 2 TSAT operation flow.

2.3 Stochastic Airport Simulation Model

To consider and evaluate the uncertainty effect, a stochastic airport simulation model is used. Although the development of a simulation model was a focus of our previous work[7], it is briefly explained here to aid the reader's understanding of this paper.

The simulation model consists of two components; runway component and taxi component. The runway component serves take-offs and landings based on the take-off and landing separations. The take-off and landing separations are set based on the actual traffic at Haneda airport. Since these separations are randomly distributed, the separation distribution is modeled by a probabilistic density function (e.g. normal distribution) and the random separation is used in the simulation. The mutual interaction between runways and wake turbulence category (e.g. heavy, medium, and light) are also considered.

The taxi component calculates the time between the pushback start and runway arrival. This time is called "taxi time", which is different from "taxi-out time". (Taxi-out time includes the waiting time in a departure runway queue.) Taxi time is linearly related to the taxiing distance (spot to the runway) according to the data analysis, so taxi time is modeled by the taxiing distance and the uncertainty. The uncertainty is modeled by the probability density function. In addition, the taxi time considers the spot conflict too. Since a single aircraft can occupy a single spot and a single pushback route, this condition is also simulated in the model. When TSAT is used, the departure aircraft wait at the gate, so the arrival aircraft sometimes cannot enter the gate due to the departure aircraft. In such a case, the spot-in time of arrival aircraft is delayed, which can be evaluated in the simulation.

3. TSAT Assignment Algorithm

3.1 Basic Idea of TSAT Assignment

In this section, the fundamental approach of TSAT assignment is explained. TSAT assignment flow is shown in Fig. 3. The calculation starts with TOBT, which is provided by airlines. Once the spot and the runway is decided, the taxiing distance is calculated, so the expected taxi time can also be calculated. Here, "expected taxi time" refers to the taxi time without uncertainty, which is different from the actual taxi time. Using TOBT and expected taxi time, ETOT can be calculated, which is the expected earliest take-off time. Once ETOT of each aircraft is calculated, the aircraft is sequenced by the runway sequencing system. The calculated sequenced time is CTOT, which is the expected take-off time considering the runway queue.

When TSAT is calculated, the calculation starts with CTOT. To reach the runway at CTOT exactly, the aircraft should leave the spot at CTOT – "expected taxi time". If uncertainty did not exist, all aircraft would leave at this time, and reach the runway at CTOT. This time is called ideal TSAT. However, due to the uncertainty, a buffer is usually set to absorb uncertainty. Finally, the assigned TSAT is calculated by Ideal TSAT – buffer. If this buffer is small, the aircraft is less likely to reach the runway at CTOT, so the take-off delay will happen more often. However, the taxi-out time reduction is also large. If the buffer is set large, the result is the opposite. Therefore, TSAT assignment problem is equivalent to setting a buffer to each aircraft.

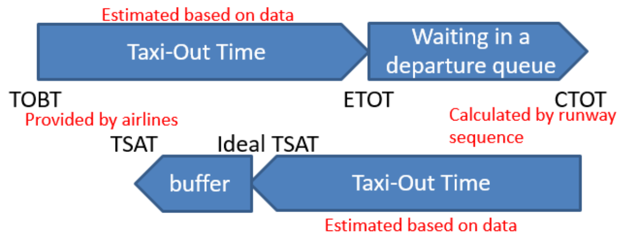

Fig. 3 TSAT assignment flow.

The most straightforward strategy is to set the same buffer to all aircraft. This strategy is referred to a a constant buffer strategy. However, the constant buffer is not an optimal strategy considering stochastic environment, here a better buffer assignment strategy is proposed.

3.2 Runway Sequencing System

To conduct TSAT operation, both a runway sequencing system and a TSAT assignment system are required. This research focuses on the latter system (TSAT assignment system), but the runway sequencing system is also briefly explained here.

It is assumed that each runway has a virtual runway slot for take-off or landing at the constant interval. This time, the interval is set to 90 s. A single aircraft can contain a single aircraft only. In sequencing, first, the arrival aircraft are ordered by ELDT, and they get the earliest available runway slot after ELDT. After all arrival aircraft occupy the slot, the departure aircraft are ordered by ETOT, and they get the earliest available runway slot after ETOT. Since ELDT and ETOT are updated as required, the runway sequencing is also updated every minute. The assigned take-off and landing time are denoted by CTOT and CLDT, which are set later than ETOT and ELDT.

3.3 Informative Parameters

As mentioned before, the performance can be improved by changing the buffer depending on the situation, but we need to identify the "situation" to change the buffer. In this research, three parameters are identified, and each parameter is explained in the following three subsections.

3.3.1 x_1: actual buffer ahead of the aircraft

The first parameter is x_1. One of the reasons why the constant buffer is not optimal is that the actual buffer is changed due to the uncertainty. As shown in Fig. 3, when TSAT is assigned, a certain buffer is used. However, even after the TSAT assignment, CTOT can be changed due to the uncertainty, but the assigned TSAT is not changed. This means that "actual buffer" is changed after the TSAT is assigned. If the actual buffer gets smaller than the assigned buffer, the aircraft is more likely not to reach the runway at CTOT. In such a case, another aircraft which is still at the gate should leave the gate as early as possible to reach the runway instead of that aircraft. The first parameter is set to account for the actual buffer as shown in the following expression.

$$
\begin{aligned}
&x_1 = E(CTOT_i - ETOT_i) \\
&i \in \{departure\ aircraft \mid \qquad (1) \\
&\quad ETOT_{TSAT} \le CTOT_i \le CTOT_{TSAT}\}
\end{aligned}
$$

where i denotes the i th aircraft in a virtual queue, and "TSAT" denotes the aircraft where TSAT is being assigned. *E(s)* indicates the average value for s. x_1 shows the actual buffer of aircraft ahead in a virtual runway queue. Even if TSAT is not assigned, the aircraft can arrive at the runway at the earliest at $ETOT_{TSAT}$, so the actual buffer of aircraft whose CTOT is later than $ETOT_{TSAT}$ is calculated.

3.3.2 x_2: number of following aircraft

The second parameter is x_2, which focuses on the number of aircraft after the aircraft where TSAT is being assigned. The take-off delay often propagates to the following aircraft in a queue. For example, if a single aircraft delays take-off by 1 minute, the take-off delay is 1 minute. However, if 10 aircraft are in a queue and the first aircraft delays take-off by 1 minute, all aircraft will delay take-off by 1 minute, and a total of 10 minutes take-off delay will be caused. Therefore, the impact of delay depends on the number of following aircraft where TSAT is being assigned. The second parameter x_2 is defined as follows:

x_2: Number of consecutive aircraft in a virtual runway queue after aircraft TSAT.

3.3.3 x_3: number of aircraft ahead

The third parameter is x_3. If there are many aircraft before the aircraft where TSAT is being assigned, there are already some aircraft compensating for other aircrafts' delay. Therefore, the third parameter x_3 is defined as follows:

x_3: Number of consecutive aircraft in a virtual runway queue before aircraft TSAT.

3.4 Problem Formulation

Using the three parameters mentioned above, the buffer (b) is set based on the following expression.

$$
b = b_0 + f(x_1) + g(x_2) + h(x_3) \qquad (2)
$$

$$
\begin{aligned}
&f(x_1), g(x_2), h(x_3) \in \{-2,-1,0,1,2,99\}\ [\text{min}] \\
&x_1 \in \{>1,2,3,\ldots,8,9,10<\} \\
&x_2 \in \{0,1,2,3,\ldots,17,18,19<\} \\
&x_3 \in \{0,1,2,3,\ldots,17,18,19<\}
\end{aligned}
$$

b_0 is the nominal buffer. The assigned buffer is the sum of b_0, $f(x_1)$, $g(x_2)$, and $h(x_3)$. "$>a$" indicates that a or smaller, and "$a<$" indicates that a or greater. Each $f(x_1)$, $g(x_2)$, and $h(x_3)$ has 6 possible variables, and the range of each parameter is limited. Here, the optimal strategy

$$F(\mathbf{x}) = \{f(>1), f(2), ..., f(10<), \\ g(0), g(1), ..., g(18), g(19<), \\ h(0), h(1), ..., h(18), h(19<)\}^T$$

should be found. This becomes a combinatorial optimization problem with 6^{50} possible solutions.

3.5 Solve the Problem

To find the best strategy, i.e. $F(\mathbf{x})$, tabu search is used. Tabu search is a metaheuristic search method, and applicable to combinatorial optimization. The objective function consists of taxi-out time reduction and take-off delay. The objective function to be maximized is defined in the following form consisting of two variables, the saved taxi-out time Δt_{save} and the take-off delay Δt_{delay} with the weight parameter of β.

$$r = \Delta t_{save} - \beta \Delta t_{delay} \tag{3}$$

The optimization process is the same as the previous work and details are described in Ref. [8].

4 Simulation Results

4.1 Simulation Environment

First of all, the simulation environment is explained. To conduct a simulation, scenario data is required, which includes the traffic pattern on the day. In actual operation, the traffic congestion level differs from day to day, because the traffic patterns vary. Here, the traffic patterns include the departure pushback time and the arrival aircraft landing time. Although the flight schedule remains the same, the actual traffic pattern slightly differs among days which causes a big difference in the traffic situation. The proposed TSAT assignment algorithm should work on all days, so several traffic patterns are assumed in the simulation. In this paper, 6 days scenario data are used in 2012 and 2013 (called Day1, Day2,…, Day6). The simulation is conducted between 6 pm and 9 pm so that the busiest time is included. Although the airport is most congested between 6 pm and 8 pm, it proves that the proposed algorithm work both in congested time and non-congested time. Table 1 summarizes the total waiting time of departure aircraft via simulation on each day. In simulation, the calculation result is changed stochastically, so the average total waiting time of 10,000 times simulation is shown here. In addition, the actual total waiting time via data is also shown. As expected, the total waiting time varies greatly with each days. Also, the total waiting time in simulation and actual data agrees well on each day, though they should not be exactly the same because the actual data can be considered as a single example of stochastic process. Day2 is the most congested day, while Day3 is potentially the least congested day. It is interesting that the waiting time difference is more than double while the traffic volume is almost the same. In the strategy optimization, all 6 days are used, and the average of the objective function of 6 days is used.

Table 1 Average total waiting time via simulation on each day.

Day	Average total waiting time [min]	Actual total waiting time [min]
1	193.22	199.25
2	423.90	478.00
3	275.02	214.42
4	193.75	256.00
5	219.32	254.42
6	216.05	180.75

4.2 Result by The Constant Buffer Method

First of all, the simulation result by the constant buffer method is shown. The buffer is changed between 4 and 8, and the relationship between the taxi-out time reduction and take-off delay is shown in Fig. 4. As expected, large taxi-out time saving as well as the large take-off delay are observed when the buffer is small, and vice versa. For further analysis, Fig. 5 shows the relationship on each day. The overall trend of each line is from upper-right to lower-left, which is the same as the average result. However, there is a difference among the daily results. On Day2, the take-off delay is almost zero regardless of the margin used. On this day, the total waiting time is also the largest according to Table 1, so the traffic pattern on that day is likely to cause a runway congestion. On the other hand, the take-off delay is the largest on Day6, when the simulated total waiting time is also smallest. However, the taxi-out time saving is the smallest on Day4, but the simulated total waiting time is not the smallest. Although there should be a relationship between the total waiting time and the potential taxi-out time saving, the traffic pattern seems to have a big impact on both potential taxi-out time saving and potential take-off delay.

If the relationship between the traffic pattern and potential taxi-out time saving/take-off delay is revealed, more efficient TSAT can be assignment. (e.g. a small margin is applied under the traffic pattern like Day2) The investigation is still ongoing.

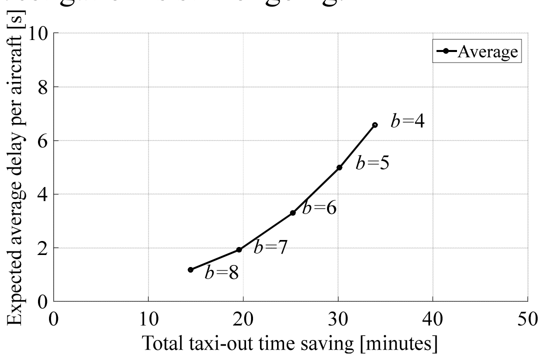

Fig. 4 Relationship between taxi-out time saving and take-off delay using constant buffer method for 6 days average.

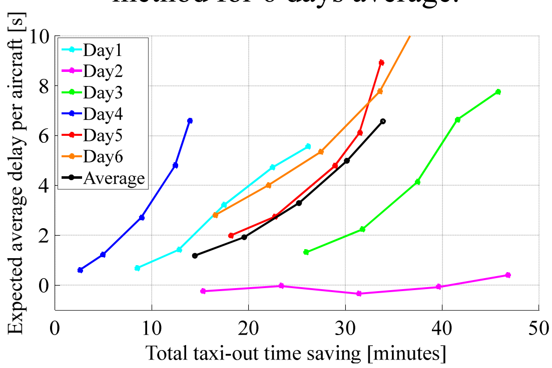

Fig. 5 Relationship between taxi-out time saving and take-off delay using constant buffer method on each day.

4.3 Result by the Proposed Method

Next, the result of proposed buffer assignment strategy is shown in this subsection. In this research, three parameters are chosen to assign the best buffer as explained in Sec. 3.3. First, to evaluate the importance of each parameter, the best strategy using a single parameter is calculated, and the result is shown in Fig. 6. Six days average is shown and three weight parameters are chosen; $\beta = 5$, 10, and 20.

The figure shows that all strategies show a better performance than the constant buffer method, but each strategy leads to a different result. When β is 5 (the right upper result), the strategy using x_3 (number of aircraft ahead) shows the best performance, but the strategy using x_2 (number of following aircraft) shows the best performance for β being 20 (left lower result). This means that the parameter x_3 is useful when a certain delay is acceptable, but the parameter x_2 is more useful when little delay is acceptable. In this way, these parameters have different characteristics, so the better strategy will be obtained if all parameters are used for strategy optimization.

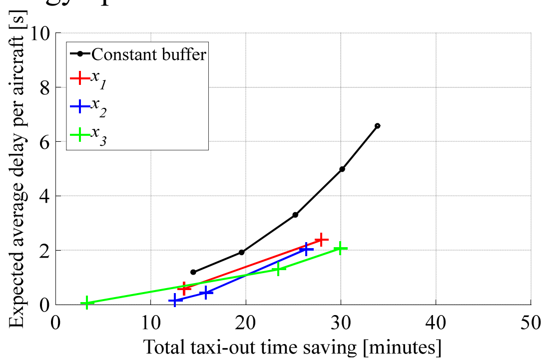

Fig. 6 Relationship between taxi-out time saving and take-off delay using a single parameter strategy optimization. (6 days average)

Fig. 7 shows the result of the best strategy using all parameters. As expected, the best strategy using all parameters shows a better performance compared to the one using a single parameter only. However, the performance improvement by using all parameters is not so big. Since the airport operation includes considerable uncertainty, further improvement might be possible by reducing uncertainty only.

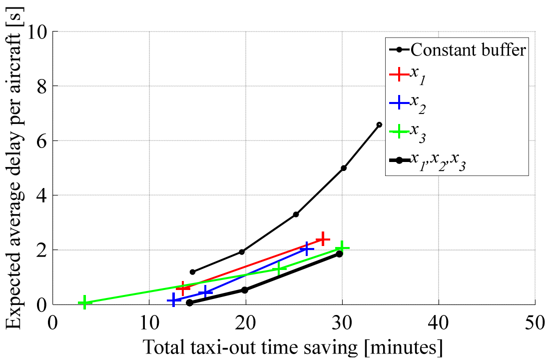

Fig. 7 Relationship between taxi-out time saving and take-off delay using all parameters strategy optimization. (6 days average)

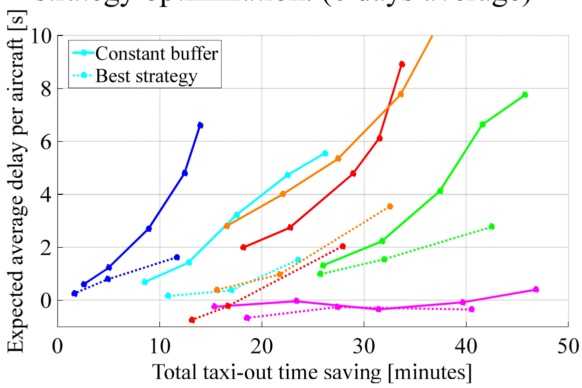

Fig. 8 Relationship between taxi-out time saving and take-off delay using all parameters strategy optimization on each day.

Fig. 8 shows the simulation result by constant buffer method and best strategy on each day. According to this figure, the performance has been improved on all days by the best strategy. On Day2, the take-off delay is little even with constant buffer method, so the improvement is also little. While the performance is improved very much on Day1, Day5, and Day6, the performance improvement is not big on Day3 and Day4 especially when the take-off delay is small. Even if the same strategy is used, the performance improvement varies due to each day's traffic pattern.

5. Conclusions

To reduce the fuel burn of departure aircraft, this paper focused on TSAT operation. Since TSAT operation can be improved by assigning TSAT more appropriately, a better TSAT assignment strategy was developed by using informative parameters. The strategy optimization was done via Tabu search heuristics. The simulation results showed that the proposed TSAT assignment strategy performed better than a simple algorithm. On the other hand, the TSAT operation performance highly depended on the traffic pattern on each day. Further investigation about the traffic pattern and TSAT operation will be a subject of future work.

6 Contact Author Email Address

r-mori@mpat.go.jp

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