Improvement of Pushback Time Assignment Algorithm via Stochastic Optimization

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***Abstract*— Pushback time assignment is a promising method to reduce the fuel burn of departure aircraft on the ground. Departure aircraft can wait at the gate with engines off instead of waiting in a long queue before the runway. However, airport operation includes considerable uncertainties which often result in unexpected situations such as take-off time delays. This paper proposes a new algorithm to assign the optimal pushback time under uncertainty via stochastic optimization. Useful information sources on the ground are identified, and the pushback time is controlled based on the obtained information. The problem is formulated as a combinatorial optimization, and tabu search technique is applied to solve it. The simulation result shows that the proposed algorithm reduces negative effect by uncertainty while maintaining fuel burn savings.**

Keywords- TSAT, uncertainty, tabu search, combinatorial optimization, stochastic optimization

I. INTRODUCTION

Airport operation research has recently been highlighted as an important contributor to efficient air traffic management. The runway is the most critical resource, so several air traffic controller (ATC) support tools, such as departure and arrival manager (DMAN/AMAN), have been developed to improve efficiency. Such tools have already been implemented at some airports, which has allowed for the introduction of Target Start-up Approved Time (TSAT) operations. Also in Japan, Tokyo International (Haneda) Airport started a trial of TSAT operation. TSAT operation is the pushback time control operation of departure aircraft. A departure aircraft usually starts pushback soon after it is ready for pushback. However, due to the required minimum take-off/landing separation at the runway, departure aircraft often make a queue before the runway (called a departure queue here) if many aircraft arrive at the runway in a short time interval. Once the aircraft leaves the gate, the aircraft cannot shut down its engines so it consumes additional fuel in a departure queue. TSAT operation is proposed to avoid the additional fuel consumption on the ground. In this operation, TSAT is assigned to some aircraft so that these aircraft cannot start pushback until TSAT. This means that they leave the gate later and therefore arrive at the departure queue later. If they arrive at the departure queue later, they can shorten their waiting time, and save fuel without any influence on the take-off time.

The TSAT operation system consists of two subsystems: runway sequencing subsystem and TSAT assignment subsystem. The runway sequencing subsystem calculates the sequence of runway use of each aircraft based on Estimated Take-Off Time (ETOT) of each aircraft. The obtained runway sequence is called a virtual runway queue. The TSAT assignment subsystem calculates the TSAT of each aircraft based on a virtual runway queue. The calculated TSAT is communicated to ATC who tells the pilot the assigned TSAT.

This paper focuses on the second subsystem, TSAT assignment subsystem. The main concern of the TSAT operation is that the aircraft cannot reach the runway at the assigned take-off time (TTOT: Target Take-Off Time) because of the TSAT assignment, which leads to a take-off delay. Here, "take-off delay" is defined as the time difference of take-off time between the pushback time controlled case and nominal case (pushback time non-controlled case). The take-off delay is mainly caused by the uncertainty of ETOT. If a departure queue is long enough, the take-off delay will be negligible because many other aircraft compensate the delay of a single aircraft and take off instead of the delayed aircraft. However, to obtain further reduction of fuel burn, uncertainty should also be accounted for, otherwise large take-off delay would be observed.

There are several researches regarding TSAT assignment, but few discuss uncertainty. To the best of our knowledge, no research evaluates the uncertainty effect quantitatively. The author has been working on TSAT assignment improvement under existing uncertainties. In the previous work, various uncertainties in the airport operation were identified, and stochastic airport simulation model was developed[1]. This paper goes a step further, and elaborates on the following two parts. First, the uncertainty effect is evaluated quantitatively, and the relationship between the reduction of taxiing time and take-off delay is revealed. Second, the TSAT assignment algorithm is improved via stochastic optimization by using various useful information sources to minimize the uncertainty effects.

Section II starts with a literature reviews of related works, and provides a brief summary of TSAT operation at Tokyo International Airport. The developed stochastic simulation model is also introduced. In Section III, the details of TSAT assignment algorithm are explained. The simple overview of

TSAT assignment is firstly shown, and the improved assignment algorithm is explained. The parameter optimization for the improved algorithm is also described here. Section IV reveals the relationship between the reduction of taxi-out time and take-off delay by using a simple method. Next, the performance of the simple method and the improved method is compared. The existing problems for TSAT operation are also described. Section V summarizes this paper.

II. Related works and TSAT operation at Tokyo International Airport

A. *Literature Review and Optimization Method*

As stated before, two subsystems are required to implement TSAT operation, i.e. a runway sequencing subsystem and a TSAT assignment subsystem. As for a runway sequencing subsystem, there are many works proposed which handle departure only, arrival only or both. Optimizing the sequence can result in capacity increase, waiting time reduction, and smooth traffic both on the ground and in the air. Although the optimization approach varies with each objective, the following approaches are often observed: constrained position shifting[2][3][4], mixed-integer linear programming[5][6], genetic algorithms[7]. As for TSAT assignment subsystem, which is the main target of this research, there are less works because most authors seem to think that a simple TSAT assignment algorithm is sufficient. The uncertainty effect is especially important in TSAT assignment, because too long pushback delay causes take-off delay. However, most works related to TSAT assignment algorithm ignore uncertainty or assume that uncertainty is absorbed by a certain phase[8][9][10][11][12]. Recently, there are a few works to consider uncertainty for runway sequencing[13][14], but none of them is for TSAT assignment algorithm.

There are usually two mathematical approaches to optimize stochastic environment: robust optimization and stochastic optimization. The robust optimization first defines the possible uncertainty, and considers the worst case scenario. Under TSAT assignment, the longest taxi-out time is assumed, and TSAT is assigned so that all aircraft should reach the runway no later than the assigned take-off time. In such an approach, the stochastic optimization is formulated as a normal deterministic optimization. However, the obtained optimal solution is valid only for the defined uncertainty. In the real world, however, uncertainty width is usually unlimited and cannot be expressed accurately, so the uncertainty is usually defined with time windows of e.g. 95 % probability. Under TSAT assignment, if the rest of 5 % results in very long take-off delay, the obtained result might not be optimal any more. On the other hand, the stochastic optimization handles the stochastic environment directly, and the stochastic effect can be considered. In this paper, "stochastic optimization" is defined as the optimization procedure handling stochastic processes. However, the deterministic optimization cannot be applied directly, and the computational cost also increases. The entire stochastic process must be known or assumed in advance.

Several researches considering the uncertainty mentioned before apply robust optimization[13][14]. This research uses a stochastic optimization approach, because further improvement is expected in the area and besides a stochastic simulation model has already been developed.

B. *TSAT Operation at Tokyo International Airport*

Tokyo International Airport (Haneda Airport) is the busiest airport in Japan with more than 1000 take-offs and landings every day. This airport handles domestic flights mainly, so the traffic volume is relatively stable throughout a day. However, both departure and arrival traffic are concentrated in the evening (6 pm-8 pm) when the airport is most congested, so a trial of TSAT operation starts at this evening time only. Figure 1 shows an airport map and runway operation under north wind. There are four runways. A runway is used for arrivals only, and D runway is used for departures only. C runway is shared by departures and arrivals. B runway is not used under north wind operation. Due to the departure route structure, the runway a departure aircraft uses is determined in advance by the destination airport. According to the actual airport data observation, the apron area is congested and aircraft conflict sometimes happens. On the other hand, the normal taxi route is set between each gate position and each runway, so it is rare to observe the conflict along the taxiway. Besides, due to the limited space of the airport, it is difficult to change the take-off sequence just before the runway, so the take-off is operated on the first-come-first-served basis.

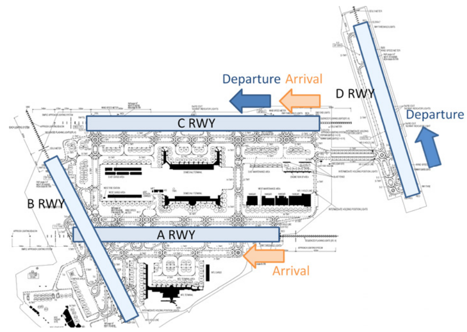

Figure 1. Airport map at Tokyo International Airport.

TSAT operation at this airport proceeds in the following way. First, airlines provide TOBT (Target Off-Block Time) to ATC at least 35 minutes before TOBT, and TOBT is updated as required. Based on TOBT, ETOT is calculated considering the estimated taxi-out time. As for the landing aircraft, ELDT (Estimated Landing Time) is calculated by a system called "terminal ATM". In each runway, the runway sequencing subsystem calculates the aircraft sequence by the order of ETOT and ELDT. Note that the landing aircraft is always given priority in the sequence. ETOT and ELDT are updated continuously, so this runway sequence is also updated every minute. The assigned take-off time and landing time are denoted by TTOT and TLDT (Target LanDing Time). Based on TTOT, TSAT assignment subsystem calculates the TSAT of each aircraft. Here, due to airlines requests, TSAT is notified to airlines no later than 25 minutes before TOBT, so TSAT is

Identify applicable sponsor/s here. *(sponsors)* calculated just 25 minutes before TOBT. Once TSAT is assigned, TSAT is not updated anymore. When the pilot requests pushback, ATC can choose whether the assigned TSAT is used or cancelled. If used, the pilot has to wait to get pushback clearance until assigned TSAT time. If cancelled, the pilot gets pushback clearance immediately. The TSAT assignment flow is summarized in Fig. 2.

Compared to the standard TSAT operation, this operation has two distinctive characteristics. First, airlines are notified of the TSAT 25 minutes before TOBT. TSAT is usually assigned when the pushback is requested, but earlier notification allows the airlines to estimate the future situation in advance. However, the early assignment of TSAT means that TSAT is assigned under larger uncertainty, so its performance will get worse. Second, ATC can choose whether the assigned TSAT is used or cancelled. This is due to the early assignment of TSAT. ETOT and ELDT are continuously updated, so the runway situation might drastically change in 25 minutes. If ATC thinks that the assigned TSAT is inappropriate, ATC can cancel TSAT. This decision is made by a human controller without any advisories. This is the current TSAT operation at this airport, so the proposed TSAT assignment also follows this flow.

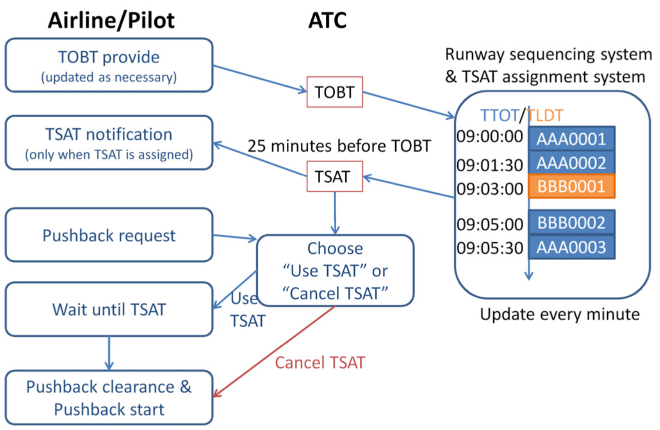

Figure 2. TSAT Assignment Flow.

C. *Stochastic Airport Simulation Model*

Although the development of a simulation model was a focus of our previous work[1], it is briefly explained here to aid the reader's understanding of this paper. Airport operation has many stochastic components, and the actual airport operation can be considered as a single result of stochastic simulations. The stochastic components can be split into two groups, i.e. runway components and taxi components. First, the runway components are described. The runway serves take-offs and landings, but the minimum separation is required between them. The minimum separation depends on the pair of aircraft type (wake turbulence category, i.e. heavy, medium, and small), but the actual separation is not exactly the same as the minimum separation. Therefore, based on the actual data, the distribution of the separation is obtained in each combination of wake turbulence category, and it is modeled by a distribution function. According to the previous work, the visibility also affects the separation, so its effect is also included in the model. In addition, as shown in Fig. 1, departure of D runway is affected by arrival of C runway, so its mutual interaction is also considered in the model.

Second, the taxi components are described. The taxi-out time (as well as taxi-in time) varies with taxiing distance, pilot taxiing speed, ATC instruction, and conflict of aircraft on the ground. The taxi-out time is further split into two parts, before and after the taxiing start. As for the taxi-out time after taxiing start (and also taxi-in time), according to the data analysis, the taxiing distance is obviously the major element to determine the taxiing time. At Tokyo International Airport, the nominal taxiing route is defined by the combination of gate position and runway, so the taxiing distance is automatically fixed once the gate position and the used runway are fixed. Therefore, the taxi-out time is calculated as a function of taxiing distance only, and the rest is considered as uncertainty. The uncertainty tends to increase with the taxiing distance, so this effect is also modeled. As for the taxi-out time before taxiing start, the aircraft is pulled by pushback truck first, then the aircraft prepares for taxiing. This process is almost the same for all aircraft, so the same distribution is assumed. All the distribution functions used are either normal distribution or Erlang distribution, or a combination of those.

In addition to these two factors, the conflict at apron area is also considered. When considering TSAT assignment, the conflict at apron area sometime becomes a serious problem. Therefore in this model, the conflict effect at apron area is simply modeled. The "gate" node and "apron" node are defined, and the aircraft is in gate node before pushback, and the aircraft is in apron node after pushback. When start taxiing, the aircraft leaves apron node. The apron node is shared by several gates depending on the airport structure, and a single node can contain a single aircraft only. This model can represent the conflict of aircraft at gate area simply.

Although a more complicated model might improve the simulation accuracy, it will lead to a longer calculation time as well. This research considers a stochastic optimization, so a single simulation should be fast. Actually, it takes about 1 second to complete 5000 simulations, which is applicable for stochastic optimization. The accuracy of the developed airport simulation model is also shown in our previous work.

When conducting a simulation, scenario data is required. The scenario data contains the pushback start time, the gate position, and the used runway of each departure aircraft, as well as the landing time, the gate position, and the used runway of each arrival aircraft. The scenario data is constructed based on actual data, and all 6 variables are set the same as the actual data. Although these 6 variables are the same as the actual data, the take-off time and the spot-in time are different in each simulation due to the uncertainty. In addition, before pushback or landing, the pushback time or landing time is just the estimation, so they are different from the actual time. This difference affects runway sequencing and TSAT assignment.

III. Development of An Improved TSAT Assignment Algorithm

A. Basic Idea of TSAT Calculation

In this subsection, the fundamental approach of TSAT assignment is explained. The basic idea of TSAT assignment is summarized in Fig. 3. The calculation starts with TOBT. TOBT also includes uncertainty before pushback. Based on TOBT, ETOT is calculated by TOBT + VTT. VTT indicates Variable Taxi Time, which is the nominal taxi-out time when the gate position and the used runway are determined. VTT can be obtained by the developed stochastic simulation model. Once ETOT of each aircraft is calculated, the aircraft is sequenced by the runway sequencing subsystem. The runway sequencing subsystem calculates TTOT of each aircraft, and its details are explained in the next subsection. The difference of TTOT and ETOT is the estimated waiting time in a departure queue.

The next calculation starts with TTOT. To reach the runway at TTOT exactly, the aircraft has to leave the spot at TTOT – VTT. If uncertainty does not exist, all aircraft leave at this time, then all aircraft can reach the runway at TTOT. This time is called ideal TSAT. However, due to the uncertainty, a buffer is usually set, and the assigned TSAT is calculated by subtracting the buffer time from the ideal TSAT. If this buffer is small, the probability that the aircraft reaches the runway gets smaller, and the take-off delay is likely to happen, but the taxi-out time reduction is also large. If the buffer is set large, the result is opposite. Therefore, TSAT assignment problem is equal to setting a buffer for each aircraft.

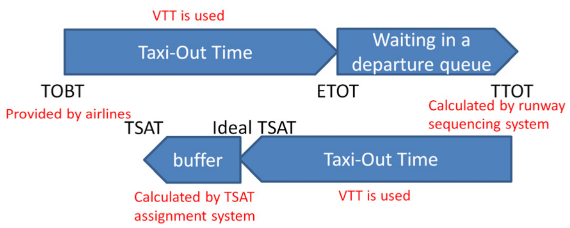

Figure 3. TSAT calculation flow.

The most straightforward strategy is to set the same buffer for all aircraft, and such a constant buffer is used by most researches[9][10]. This strategy is referred to a constant buffer strategy. In this strategy, the buffer is set to absorb the maximum uncertainty, so the strategy can be considered as a robust optimization. This research, however, uses stochastic optimization method by assigning a different buffer to each aircraft.

B. Runway Sequencing Subsystem Used in This Simulation

Although the runway sequencing subsystem is not the target of this research, it is required for TSAT assignment and is therefore briefly explained here. In its simplest version, the aircraft are sequenced based on their ETOT/ELDT, and a nominal separation is applied for every aircraft pair. This is the method used at present at Tokyo International Airport. However, since it is difficult to change the landing time due to the arrival route structure at this airport, the landing aircraft are sequenced first, and the departure aircraft are sequenced in the remaining vacant runway slots. This research also uses the same strategy.

Although a sophisticated runway sequencing subsystem can provide a better sequence by considering the wake turbulence category of aircraft, it is difficult to change the take-off sequence as well as the landing sequence at the runway at this airport as explained before. Therefore, even if optimal sequence is made in a virtual runway queue, it is expected to be changed very often. Therefore this research focuses on a simple runway sequencing algorithm.

For the runway sequencing subsystem, ETOT or ELDT is required, but their uncertainty affects the result. Here, the following rules are applied in the simulation.

- TOBT of each departure aircraft is obtained 60 minutes before TOBT, with the error of standard deviation (SD) of 5 minutes. ETOT is calculated by this TOBT. Once ETOT is obtained, the aircraft is sequenced.
- TOBT of each departure aircraft is updated 35 minutes before TOBT, with the error of SD of 2.5 minutes. ETOT is updated by the updated TOBT.
- TSAT assignment subsystem calculates TSAT 25 minutes before TOBT.
- Once the aircraft starts pushback, the actual off-block time (AOBT) is obtained. ETOT is updated by AOBT.
- TLDT of each arrival aircraft is obtained 60 minutes before TLDT with the error of SD of 2 minutes.

In addition to the above rules, the runway sequence is updated every minute by the order of ETOT and ELDT. As mentioned before, landing aircraft are given priority in the sequencing. All uncertainties involved in TOBT and TLDT are assumed to follow normal distribution.

C. Improvement of TSAT Assignment Algorithm and Problem Formulation

To improve the performance of the TSAT assignment algorithm, we need to find information sources to minimize the uncertainty effects. This paper considers two factors for that, though there are possible other factors too. The first factor is the “actual buffer”. Since the runway sequence is continuously updated even after TSAT assignment, TTOT is also updated continuously while TSAT is not updated once assigned. This means that the “actual buffer” (= TTOT – TSAT – VTT) varies after TSAT assignment. If the actual buffer gets smaller than the assigned buffer, this aircraft is more likely not to reach the runway at TTOT. 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 second factor is the delay propagation. The take-off delay usually 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 delay take-off by 1 minute, and a total of 10 minutes take-off delay is caused. The impact of a single aircraft delay differs by the departure queue length. If the above two factors are considered, the TSAT assignment performance can be improved. Assigning TSAT can be influenced by various factors which need to be quantitatively described as parameters (variables) in the simulation. For example, to account for the actual buffer, there are many possible variables, such as the average value of the actual buffer ahead of the aircraft, and the minimum value of the actual buffer ahead of the aircraft. This time, the following two variables (x_1 and x_2) are chosen by trial-and-error. The choice of the variables can potentially improve the TSAT assignment performance even further, but this will be a subject of the future work. Also, even if the variables are changed, the optimization flow proposed below can be used in the same way.

$$x_1 = E(TTOT_i - ETOT_i)$$
$$i \in \{departure\ aircraft \mid ETOT_{TSAT} \le TTOT_i \le TTOT_{TSAT}\}$$

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

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 earliest at $ETOT_{TSAT}$, so the average actual buffer is calculated only when $ETOT_{TSAT} \le TTOT_i \le TTOT_{TSAT}$. x_2 shows the number of aircraft affected by the take-off delay of aircraft *TSAT*. If the estimated separation of two aircraft is large enough, the delay will not be propagated, so "consecutive aircraft" is defined as aircraft separated by less than 3 minutes. TLDT is used for arrival aircraft instead of TTOT.

The buffer is set based on these two variables (x_1 and x_2). Since the buffer is usually set in minutes, the following buffer (b) is applied.

$$b = b_0 + f(x_1) + g(x_2) \quad (1)$$

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

b_0 is the nominal buffer [minute], and the assigned buffer is the sum of b_0, $f(x_1)$, and $g(x_2)$. ">*a*" indicates that *a* or smaller, and "*a*<" indicates that *a* or larger. Each $f(x_1)$ and $g(x_2)$ have 6 options as indicated below (1), and the range of x_1 and x_2 is limited. Here, the optimal strategy

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

should be found. This becomes combinatorial optimization problem, and the possible number of solutions is 6^{30}.

In the calculation, at the assignment of TSAT (25 minutes before TOBT), x_1 and x_2 are obtained from a virtual runway queue. Once x_1 and x_2 are determined, b is calculated based on the optimal strategy. TSAT can be finally calculated by b and the ideal TSAT. If the calculated TSAT is less than TOBT, TSAT is not assigned. The constant buffer strategy is the same when all values in $F(\mathbf{x})$ are 0.

D. Strategy Optimization

To find the best strategy, i.e. $F(\mathbf{x})$, tabu search[15] is applied to solve the combinatorial optimization. The tabu search is a metaheuristic search method. The solution starts at one point, and searches its neighbors. After the search, the solution goes to the best neighbor, and searches its neighbors again. It is important to go to a worse solution than the current one if no better neighbors are available than the current solution, as this prevents convergence to a local minimum. In addition, each solution is put into the tabu list, and solutions cannot be duplicated, which also helps the algorithm avoid local minima. The current best solution is also updated in a best solution list, so that the best solution is contained in the solution list after sufficient number of searches.

The application of the tabu search method to this study is explained below. First of all, the objective function is set by the following form consisting of two variables, the saved taxiing time (Δt_{save}) and the take-off delay (Δt_{delay}) with the weight parameter of β.

$$r = \Delta t_{save} - \beta \Delta t_{delay} \quad (2)$$

The initial solution starts with all $f(x_1)$ and $g(x_2)$ being 0. b_0 is set to 5 minutes. The neighbor is chosen as follows: the current solution is copied to the neighbor solution. One state is randomly chosen out of 30 states, and the value of this state is changed to the next one randomly. (If the current value is 0, the next one is either –1 or 1.) 8 neighbors are created in the same way. If a neighbor is the same as the one written in the tabu list, this neighbor is deleted. Next, the objective function is calculated in each neighbor and the best solution among all 8 neighbors is found. Finally, the current solution moves to the best solution. The current solution is written in the tabu list, and is also written in the best solution list if it is better than the existing best one. The number of tabu list is usually limited, and it is set to 30.

Since the simulation is stochastic, it is not easy to find the best solution among all neighbors. One method often used is the sample average approximation (SAA) method[16]. SAA uses the limited number of samples, and its average is treated as the actual output. However, if the number of samples is small, the difference of the obtained average and the actual average will be large, which results in choosing a non-optimal solution as optimum. On the other hand, if the number of samples is too large, the computational cost will be too large, so the optimal solution cannot be obtained. Therefore, this research proposes an interval estimation technique. Here, the actual objective function based on the strategy $F(\mathbf{x})$ is defined as $r_{act}(F(\mathbf{x}))$, and the obtained objective function with limited number of samples is defined as $r_n(F(\mathbf{x}))$ and its SD is defined as $\sigma_n(F(\mathbf{x}))$, and the objective function by a single calculation with stochastic component of ξ is defined as $r(\xi, F(\mathbf{x}))$. The following equations are obtained.

$$r_n(F(\mathbf{x})) = \sum_{i=1}^{n} \frac{r(\xi_i, F(\mathbf{x}))}{n} \tag{3}$$

$$r_{act}(F(\mathbf{x})) = \lim_{n\to\infty} r_n(F(\mathbf{x})) \tag{4}$$

If $r(\xi, F(\mathbf{x}))$ is assumed to follow the normal distribution, the following equation is satisfied with 95 % probability using the standard error.

$$r_n(F(\mathbf{x})) - \frac{2\sigma_n(F(\mathbf{x}))}{\sqrt{n}} \le r_{act}(F(\mathbf{x})) \le r_n(F(\mathbf{x})) + \frac{2\sigma_n(F(\mathbf{x}))}{\sqrt{n}} \tag{5}$$

This means that the range of the actual objective function (the confidence interval) can be estimated in a limited number of simulations, and the confidence interval shrinks with more simulations. Using this notion, the best neighborhood can be found with a certain probability while minimizing the number of simulations necessary. In particular, the following steps are used to find the optimal neighbors. There are 8 initial neighbors ($F_1(\mathbf{x}),...,F_8(\mathbf{x})$).

1) In each neighbor, 1000 times of simulations are conducted with uncertainty components being randomly distributed, and the average ($r_n(F_i(\mathbf{x}))$) and SD ($\sigma_n(F_i(\mathbf{x}))$) of objective function are obtained.

2) Among the existing neighbors, the best neighbor ($F_{best}(\mathbf{x})$) is chosen based on $r_n(F_i(\mathbf{x}))$.

3) In each neighbor, if (6) is not satisfied, this neighbor is deleted. When (6) is satisfied, $r_{act}(F_{best}(\mathbf{x}))$ is greater than $r_{act}(F_i(\mathbf{x}))$ with about 95 % probability.

$$r_{n_i}(F_i(\mathbf{x})) + \frac{5\sigma_{n_i}(F_i(\mathbf{x}))}{4\sqrt{n_i}} < r_{n_{best}}(F_{best}(\mathbf{x})) - \frac{5\sigma_{n_{best}}(F_{best}(\mathbf{x}))}{4\sqrt{n_{best}}} \tag{6}$$

4) If there are more than one neighbors, return to the step 1). If there is only one neighbor left, this is the best solution. If the number of simulations reaches the maximum number of simulations (this time 50,000 simulation), $F_{best}(\mathbf{x})$ is treated as the best solution.

This process can reduce the number of simulations. The tabu search iteration is run 1000 times. It takes about one day to complete the calculation by using multi-threading (12 threads) programming with Core i7-4930K (3.4GHz).

E. *Choice of TSAT Use or Cancel*

In the TSAT assignment flow shown in Fig. 2, the ATC can choose whether TSAT is used or cancelled. Although this procedure is now in the hands of a human controller it needs to be implemented in the simulation, so a rule is required. One possibility is to cancel TSAT when this cancel action can compensate other take-off with high probability. This often happens when there are few aircraft in a virtual queue. Therefore, the number of consecutive aircraft ahead of the aircraft is counted, and TSAT is cancelled if its number is less than 6. Although this strategy is simple, the take-off delay is reduced by up to 50 % according to the simulation analysis. Here, we will not get into the detail of the TSAT Use/Cancel algorithm, but it also has a potential to improve the TSAT performance. This will be a subject of future work.

IV. Simulation Results

A. *Simulation Environment*

First of all, the simulation environment is explained. As explained in Sec. II C, the simulation requires scenario data. The scenario data includes the traffic pattern on that day. Even if the same TSAT assignment algorithm is applied, the taxiing time reduction is little if the traffic is little and the runway is not congested on that day. Even if the traffic is busy, the concentration of the traffic also affects the congestion level of the runway. Therefore, this time, 5 days scenario data are chosen (called Day1, Day2, …, Day 5), and the simulation is conducted between 6 pm and 9 pm, so that the busiest time is included. As mentioned before, the airport is most congested between 6 pm and 8 pm, but less congested time is also included in the simulation, because it proves that the TSAT assignment algorithm works in both congested and non-congested time. Fig. 4 shows the waiting time in a departure queue on Day3 without assigning TSAT. The aircraft are ordered by the take-off time. The blue bar indicates the actual waiting time of each aircraft in a departure queue, while the red bar indicates the average waiting time of each aircraft in simulations. The actual data can be seen as a single result of the stochastic simulation, so a certain difference between the average value obtained in the simulation and the actual data is expected. However, the overall trend is similar, e.g. the maximum waiting time is observed at 64th aircraft. Table 1 summarizes the total waiting time of actual data and the total average waiting time in simulations on all days. Day3 shows the smallest waiting time, while Day4 shows the largest waiting time. The difference is more than double while the traffic volume is almost the same. The traffic pattern on each day seems to affect the runway congestion very much. The average of total waiting time on 5 days is about 300 minutes, and this is the maximum possible reduction of taxiing time. However, due to the uncertainty, the reduction of waiting time is much smaller than 300 minutes. In addition, the waiting time of actual data and simulation average have similar values, which infers that the simulation model works well. For the rest of this section, unless otherwise noted, the simulation result show the average of all 5 days. The optimization process also uses the objective function of the average of all 5 days.

TABLE I. SUMMARY OF WAITING TIME IN A DEPARTURE QUEUE ON EACH DAY.

	Actual total waiting time [minutes]	Average total waiting time in simulations [minutes]
Day1	257.7	230.4
Day2	257.3	237.4
Day3	199.9	214.8
Day4	479.0	453.0
Day5	214.6	282.8

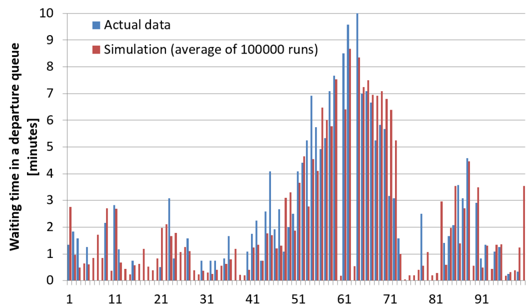

Figure 4. Waiting time of each aircraft in a departure queue on Day3.

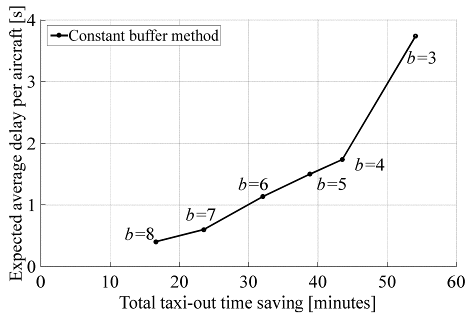

Figure 5. Relationship between the total taxi-out time saving and the average delay per aircraft for various buffers via constant buffer strategy.

B. Trade-Off between Taxi-out Time Reduction and Take-Off Delay

The simulation result is shown under the constant buffer TSAT assignment algorithm as explained in Sec. III A. Under this algorithm, the buffer between ideal TSAT and assigned TSAT is constant. This buffer is denoted by b. A small buffer indicates the larger taxiing time reduction and larger take-off delay and vice versa. The simulation is conducted for 100,000 times per case. Fig. 5 shows the relationship between the taxiing time reduction and take-off delay in each buffer. As expected, large buffer shows the large total taxi-out time saving and large take-off delay. Considering the case where the buffer is 4 minutes, about 45 minutes of taxiing is achieved, which corresponds to about 15 % of total waiting time in a departure queue. Since it is difficult to reduce the small waiting time such as 1 minute or 2 minutes, it would be almost impossible to reduce e.g. 50 % of total waiting time. As for the take-off delay, about 1.8 s take-off delay per aircraft is caused by TSAT assignment, which corresponds to about 3 minutes take-off delay in total. Although it is questionable whether 3 minutes delay out of 100 aircraft is acceptable or not, the author thinks that such a 3 minutes delay is not negligible.

C. Performance of the Improved TSAT Assignment Algorithm

Figure 5 shows the relationship between the taxiing time reduction and take-off delay with a constant buffer TSAT assignment algorithm, but the performance can be improved by using the proposed method described in Sec. III C. The optimal strategy is changed by the weight parameter β in the objective function, so three cases of β (5, 10, and 20) are used and the optimization is conducted for each β. The obtained optimal strategy with β = 20 is shown in the following equation.

$$F(\mathbf{x}) = \{99,1,99,1,99,99,-2,-2,-1,-1,\\ 1,1,1,0,0,-1,2,2,99,1,-1,-2,99,99,99,99,1,99,1,99\} \quad (7)$$

First 10 values show the strategy based on x_1 (average actual buffer), and the last 20 values show the strategy based on x_2 (number of consecutive aircraft in a virtual queue). According to this result, a small buffer should be set for large x_1, and TSAT should not be assigned for large x_2. This result is intuitively well understandable, so the result seems appropriate. Further analysis of the obtained result is of interest and will be subject of our future work.

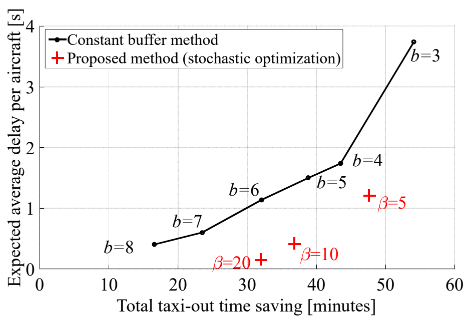

Figure 6. Relationship between taxi-out time saving and take-off delay by improved method and constant buffer method.

Figure 6 shows the relationship between the taxiing time reduction and take-off delay with the improved method. The figure clearly shows that the take-off delay is reduced very much while keeping the same taxiing time reduction. As for the case with β = 20 , the total 32 minutes waiting time is reduced while only 0.15 s of the average take-off delay is caused which seems to be almost negligible. Compared to the constant buffer algorithm, about 85 % reduction of the average take-off delay is achieved under almost the same reduction of taxiing time. On the other hand, as for the case with β = 10, compared to the case β = 20, the taxi-out time reduction is increased by 15% only while the take-off delay is increased by more than double. The proposed method does not provide the same reduction ratio of the take-off delay compared to the simple method, and there might be a limit of the reduction considering uncertainty.

To investigate the performance of the proposed algorithm further, the waiting time of individual aircraft is observed. Figure 7 shows the waiting time of each aircraft in a departure queue without TSAT, with TSAT via the constant buffer strategy (*b*=6), and with TSAT via stochastic optimization (β=5) on Day3. Note that the two TSAT assignment strategies show similar delays according to Fig. 6 (about 1.2 s per aircraft). As for the constant buffer method, the maximum waiting time in a departure queue reduces from about 9 minutes to about 6 minutes, because the buffer is set to 6 minutes. By using the stochastic optimization result, the maximum waiting time in a departure queue decreases to about 4.5 minutes while keeping the same delay level. The other aircraft with less than 4.5 minutes waiting time hardly reduces its waiting time, which means that the TSAT assignment algorithm works only when the large waiting time is expected. This also means that TSAT operation works only for the aircraft with long waiting time in a departure queue (this case, e.g. 4.5 minutes). It seems difficult to reduce the waiting time of a departure queue at non-congested time.

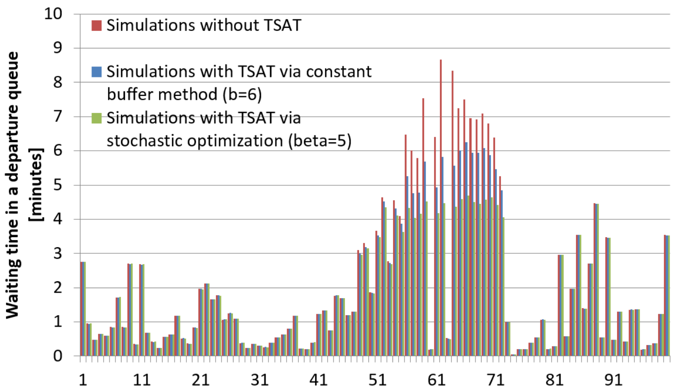

Figure 7. The waiting time of aircraft without TSAT, with TSAT via a constant buffer method, and with TSAT via stochastic optimization on Day3.

V. Conclusions

TSAT operation is a powerful tool to reduce the fuel burn of the departure aircraft on the ground. However, even if the fuel burn is reduced, TSAT operation will not be accepted by airlines if it induces take-off delays. The delay is usually caused by uncertainty, so this paper revealed the impact of TSAT assignment to the taxiing time reduction and the take-off delay quantitatively. This result will be useful for the understanding of TSAT operation for many stakeholders, which can choose the optimal operation considering both taxiing time reduction and take-off delay. In addition, this paper proposed a new TSAT assignment algorithm via stochastic optimization, while the existing researches used robust optimization. The simulation result showed that the proposed method successfully reduced the take-off delay by up to 85 % compared to the existing method. By improving the TSAT assignment algorithm, the probability of the take-off delay could be minimized while keeping the same reduction of fuel burn. The proposed TSAT assignment flow was based on the existing TSAT operation flow at Tokyo International Airport, so the new algorithm will be easily implemented. Further improvement will be a future work.

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