A STUDY ON FINDING A SUBSTITUTE TO THE FIRST COME- FIRST SERVED RULE APPLIED TO AIRCRAFT SEQUENCING

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Abstract

At present the conventional way to sequence aircraft in the terminal area is to follow the first-come, first-served rule. Even though such sequencing is considered fair to all airlines and is associated with no increase in the workload of air traffic controllers, it is not always the optimal solution in terms of fuel burn and runway capacity. In this research a substitute to the first-come, first-served rule which would reduce the total fuel burn during the descent is considered. The approach taken is to provide air traffic controllers with a simple guideline which can help them determine the sequence without increasing their workload too much and whenever possible add up to runway capacity. Sequencing is based on fuel burn simulations of single aircraft entering the terminal area of a sample airport. First, optimal aircraft sequences and their associated flight times are determined by Sequential Quadratic Programming. Next, the results are analyzed considering several attributes and three sequencing rules are proposed. Their effect is verified through Monte-Carlo simulations and it is concluded that through two simple swaps significant fuel savings can be achieved while shortening the arrival time of the last aircraft in the sequence thus increasing runway capacity.

1 Introduction

1.1 Research Background

Currently, at most airports around the world priorities for landing are given on first-come, first-served (FCFS) basis. According to FCFS rules, aircraft land according to their order of arrival, i.e. the earlier the estimated time of arrival (ETA) is, the earlier the aircraft is going to get landing clearance. This rule has become so popular because of its simplicity and easy application which is a key factor for the workload of air traffic controllers. Another advantage of FCFS is that it is fair to all airlines since no preferences are executes. However, with the recent increase in air traffic, more importance has been placed on fuel burn and airport capacity and these factors need to be considered when determining the arrival sequence. Numerous systems aiding air traffic scheduling have been developed [1], [2], [3], but they all include hardware or/and software installation and staff training associated with the new tool. Furthermore, despite the notable advances in technology, air traffic control is likely to remain a human-centered operation for the foreseeable future. Therefore, the goal of this research is to propose a sequencing guideline for air traffic controllers which is simple enough to be comprehended and applied in real time, excels the first-come, first-served rule and results in less combined fuel burn by all aircraft involved. An important characteristic of this research is that it makes use of the difference in aircraft type and its influence on the required minimum separation between two aircraft.

2.2 Paper Organization

This paper is organized as follows: the simulation assumptions are presented in Section

2. They include description of the terminal area, traffic conditions, fuel burn modeling, operational constraints, such as minimum separation, precedence constraints and position shift constraints, and finally fuel burn evaluation, i.e. the parameter defined to evaluate each sequence presented later in the paper.

Section 3 deals with optimal aircraft sequencing. First, under the assumptions described in Section 2, the fuel burn for a conventional sequencing is estimated and these results are shown in Section 3.1. These results are used as a reference for all other sequences proposed later in the paper. Next, optimal sequences are determined using Sequential Quadratic Programming and the results are presented in Section 3.2. Based on analysis of the optimal sequence, a search for rules is done (see Section 4). The extracted rules are verified in Section 5. This paper is summarized in Section 7.

2 Simulation Assumptions

2.1 Terminal Area

In this research the aircraft re-sequencing is performed in the terminal area. The model of the terminal area considered is based on the former operations of the airport with the most passengers in Japan, Tokyo International Airport (Fig.1).

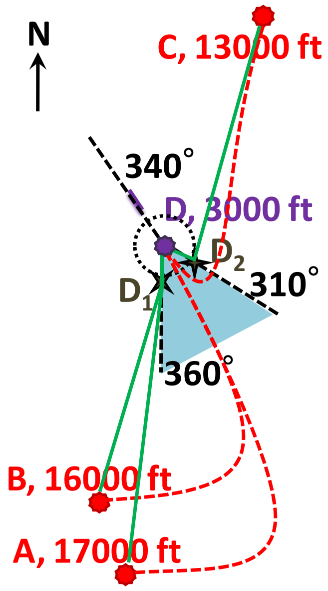

Fig. 1. Waypoints in the terminal area considered

Recently, air traffic operations have been changed, but for the purposes of this research the previous scheme is sufficient. After the aircraft enter the terminal area at one of the three waypoints A, B or C, they are sequenced and exit at the final approach waypoint D. The incoming traffic should be merged before it is handed to the approach control, so all sequencing and spacing occurs in this area. Aircraft are usually directed following the red dotted lines. Since the combined traffic from the south accounts for 70% of the total traffic, usually aircraft coming from the south are given priority and aircraft coming from the north are placed when there is an available slot in the waiting sequence.

2.2 Traffic Conditions

Traffic was simulated considering actual flow at Tokyo International Airport. Here, scenarios with 10 aircraft entering the terminal area in an interval of 13 minutes are generated. The ratio of heavy to medium aircraft is 1:1. Furthermore, 2 aircraft enter the terminal area at point A, 5 at waypoint B and 3 at waypoint C, which is proportional to the traffic volume at these three entry waypoints. These assumptions can adequately model the traffic at this airport in congested times.

2.3 Fuel Penalty for Delays

Every aircraft has an ideal descent time which minimizes the fuel burn. However, congestions in the terminal area often require changes in the descent time. The extra fuel burn incurred by positive or negative delays is often modeled as a combination of linear functions [4]. This research, however, uses a refined fuel burn model based on the optimization of single aircraft descent trajectories. The point mass aircraft model is used and constraints such as maximum allowed flight path angle (glide angle) of 3 deg are enforced. Simulations results confirmed that for each entry waypoint and aircraft type there is an ideal, optimal descent time which minimizes the fuel burn. However, since aircraft cannot always follow its optimal profile, constraints on the descent time are applied and the flight path for minimum fuel burn is determined. The graph showing the minimum fuel burn for various descent times can be seen in Fig.2.

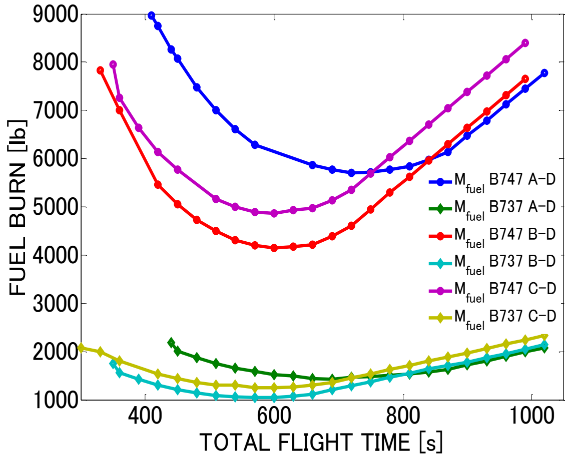

Fig. 2. Relations between the fuel burn and descent time

Simulations are performed for two types of aircraft, representatives of the heavy and medium category according to ICAO standards (to be discussed later in Section 2.3). It is also verified that around the optimal descent time, fuel burn can be modeled by a quadratic function with an error of less than 3.4 lb.

$$f=a(t-t_{opt})^2 \qquad (1)$$

Here, f is the fuel burn increase, a is a parameter related to the aircraft type and entry waypoint altitude and distance from the final approach way point, t_{opt} is the absolute optimal flight time, i.e. the descent time that minimizes the fuel burn, and t is the actual flight time. The heavy aircraft have bigger values of *a* and the entry waypoints that are further from the final approach waypoint are associated with larger a. Details on the optimization of single aircraft descents can be found in our previous work [5]. Therefore, instead of the commonly-used combination of linear functions, we model the fuel burn increment by a quadratic function.

2.4 Operational Constraints

2.4.1 Minimum Aircraft Separation

International Civil Aviation Organization (ICAO) has established minimum separation requirements to guarantee that aircraft do not suffer from the wake vortices induced by leading aircraft [6]. These separation requirements depend on the size of the aircraft pair, as shown in Table 1.

Table 1ICAO separation standards

Lead \ Follower	Heavy	Medium	Light
Heavy	4 nm	5 nm	6 nm
Medium	3 nm	3 nm	5 nm
Light	3 nm	3 nm	3 nm

When performing the descent optimization of single aircraft trajectories, an assumption about the speed at the terminal area exit waypoint (the final approach waypoint) is done, i.e. all aircraft pass at waypoint D at speed of 240 kt. Therefore, the distance required minimum separation can be interpreted in seconds, instead of nautical miles.

Table 2 Minimum time separation at speed of 240 kt at the terminal area exit waypoint

Lead \ Follower	Heavy	Medium	Light
Heavy	60 s	75 s	90 s
Medium	45 s	45 s	75 s
Light	45 s	45 s	45 s

Besides, at Tokyo International Airport, whose terminal area is considered in this research, no light aircraft are to be seen. Since we are looking for simple sequencing rules, the minimum time separation has been further simplified to just two values- 90 s and 60 s respectively, as shown in Fig.3. Even these separation standards are changed for some reason, as long as there is a separation difference among the aircraft classes, significant fuel gains are to going to be observed.

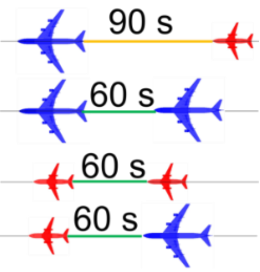

Fig. 3. Simplified required separation minimum

It is assumed that as long as the separation minimum between any two successive aircraft in a sequence is met, the minimum separation for all pairs of aircraft is also met.

Also, obviously at each of the entry points the separation requirements are met.

2.4.2 Precedence Constraints

Furthermore, certain precedence constraints are forced. Successive aircraft entering the terminal are at the same entry waypoint are not allowed to overtake each other, i.e. aircraft flying within the same jet route cannot swap positions in the final sequence. Similar assumptions were made by other researchers, so these are to be followed here, too [4], [7].

2.4.3 Position Shift Constraints

At present, the most commonly-used sequencing strategy is the first-come, first-served rule. However, it is not always the optimal one in terms of fuel burn and airport runway capacity. If a batch of aircraft consists of heavy and medium aircraft which are alternating in the sequence, the required minimum separation will be bigger than that for several heavy aircraft in a row, followed by several medium aircraft in a row, for example. Intuitively, this will result in delayed landing of the aircraft later in the sequence and thus overall reduced runway capacity. However, it is also unlikely to believe that in a batch of say 10 aircraft the last aircraft will come first in the adjusted sequence. Such a major change of the sequence will increase the workload of the air traffic controllers and most probably result in increased combined fuel burn of all aircraft. The terminal area of a busy airport is often congested so any suggested re-sequencing strategy should take into account the possible workload problems. In this research, the issue is tackled by introducing constrained position shifting [7]. We assume that an aircraft may be moved by no more than one position in the final sequence, i.e. the i^{th} aircraft can land either on position $i-1$, i or $i+1$.

Constrained position shifting has several advantages. First, since it does not change the sequencing too much, it is performed relatively easy. Second, it is still fair to all airlines because no aircraft will be delayed by more than one position. Third, by putting constraints on the position shifts allowed, the number of possible sequences reduces greatly. This characteristic is of key importance for determining the optimal sequence.

In this research we consider batches of 10 aircraft, but to illustrate the possible sequences with constrained position shifting, an example for a batch of 5 aircraft is shown in Fig.4. Obviously, the same rules which govern the choice of possible positions in the final sequence for a batch of 5 aircraft apply to a batch of 10 aircraft, too

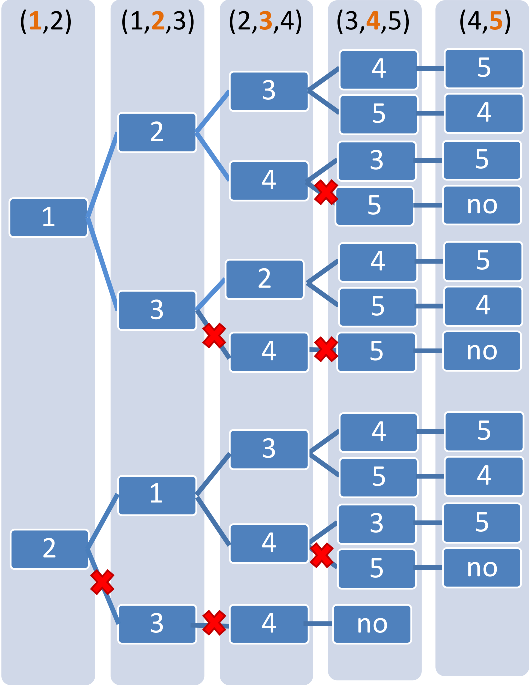

Fig 4. For illustration purposes, the possible sequences for just five aircraft with constrained position shifting of 1 position are shown. The columns show the position in the final sequence, while the numbers in the boxes show the position of the aircraft in the FCFS sequence.

At the first position in the final sequence can be placed only the first or the second aircraft from the FCFS sequence. At position 2 in the final sequence there might come aircraft 1, 2 or 3 from the FCFS sequence. Consider the following sequence of the first three aircraft in the final sequence 1-2-4. The next aircraft can be either 3 or 5. For aircraft 3, the follower will be aircraft 5, so the final sequence will be 1-2-4-3-5. If the sequence is 1-2-4-5, though, no aircraft is left for the last position in the final sequence. Therefore, in this case, the branching

1-2-4-5 is impossible, so we are left with the only option 1-2-4-3-5. Following the same logic the number of possible sequences for *n* aircraft with constrained position shifting of 1 position can be determined by

$$Seq(n)=Seq(n-1)+Seq(n-2) \qquad (2)$$

where

$$Seq(1)=1 \qquad (3)$$

$$Seq(2)=2$$

On the other hand, if no constrained position shifting is considered and all permutations are taken into account, the number of possible sequences is *n!*. In our research we consider a batch of 10 aircraft, so with the constrained position shifting the number of possible sequences to be investigated is 89. If there were no position shift constraints, that number would be 3628800.

2.5 Fuel Burn Evaluation

In this research the objective function used to evaluate each sequence is related to the combined fuel burn by all ten aircraft. First, the first come, first served sequence is considered. If all aircraft could land at its estimated time of arrival, then the total fuel burn increase would be zero. We are interested only in the fuel burn increase inferred by any delays, being positive or negative, because only this fuel burn increase above the nominal one, i.e. the fuel burn penalty for delays, can be influence by any sequencing decisions. If FCFS sequence required some aircraft to be delayed, then this delays cause some fuel burn increase, which sum is defined as $fuel_{FCFS}$.

To evaluate any other sequencing, a new parameter f_{par} is introduced. Suppose the total fuel burn increase for all ten aircraft for a certain sequencing is $fuel_{seq}$. In such a case, f_{par} is defined as:

$$f_{par} = \frac{fuel_{sec} - fuel_{FCFS}}{fuel_{FCFS}} \qquad (4)$$

In other words, *fpar* shows how much fuel is necessary for the adjustments in a particular sequence compared to the fuel necessary when FCFS rule is applied. Positive values of *fpar* indicate sequences which are worse than FCFS in terms of fuel burn and negative values indicate sequences which result in fuel saving compared to FCFS.

3 Optimal Sequencing

3.1 First Come, First Served Sequence

Here, only the static case is considered, i.e. ion each simulation we have full knowledge of all 10 aircraft, i.e. their expected arrival time (ETA) and their type is known. For systems aiming at real-time optimization such an assumption is a constraint, but since we are going to use the optimization results just to extract rules, the static case is completely sufficient.

First, the FCFS arrival sequence is considered and the necessary flight time adjustments are made to meet the separation requirements discussed in Section 2.4.1. At this point, aircraft are not required to land earlier than their estimated time of arrival even if such a change would not infringe the separation minimum with the leading aircraft. This assumption reflects the common FCFS execution at most airports. Once the necessary time adjustments are determined, the fuel burn increase $fuel_{FCFS}$ is calculated based on the results obtained by single aircraft descent optimization shown in Section 2.3. $fuel_{FCFS}$ varies in each scenario, but on average it is about 12% of the total fuel burnt during the descent in the terminal area.

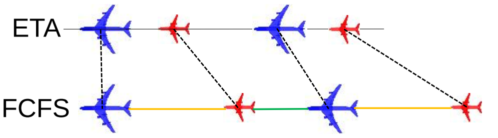

Fig. 5. Aircraft sequencing according to FCFS, i.e. aircraft are scheduled according to their ETA by simply applying the required minimum separation between them

3.2 Optimal Sequence

Next, the optimal sequence for each scenario and the associated flight time adjustments are found. This is done as follows. The 89 possible sequences generated for a batch of 10 aircraft with a maximum allowed position shift 1 are considered (see Section 2.4.3). For each sequence, optimization of the flight times of all ten aircraft is performed using Sequential Quadratic Programming (SQP). Because of the nature of the optimization, if no precedence constraints are imposed, i.e. if the possible sequences are not generated beforehand and a general solution is sought, in most cases the program gets trapped into a local minimum and there is no guarantee that the obtained sequence is the best one. To deal with this problem we look into all 89 possible sequences and vary just the flight times looking for the combination which will minimize the total fuel burn for all aircraft. Once the minimum fuel burn for each sequence is determined, these 89 values are compared and the minimum one is chosen as the best sequencing candidate. The fuel burn increase associated with this sequencing is written as $fuel_{opt}$.Finally, $fuel_{opt}$ is compared to $fuel_{FCFS}$. A histogram of the results for Monte-Carlo simulations for 100 scenarios is shown in Fig.6.

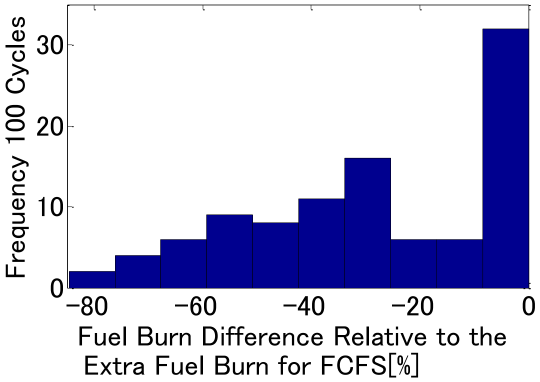

Fig. 6. Fuel savings by optimal sequencing of 10 aircraft. The horizontal axis shows the fuel parameter $f_{par}=(fuel_{opt} - fuel_{FCFS})/fuel_{FCFS}$ in percentage, i.e. how much fuel is necessary for the optimal adjustments compared to the fuel necessary when FCFS rule is applied.

As seen from Fig.6, even though in 32% of the cases almost no fuel savings were observed, in the remaining 68% improvements of up to 80% of the extra fuel needed to compensate for the congestion when FCFS is applied.

Next, the number of swaps in each scenario is investigated. For example, when the optimal sequence is 1-2-4-3-5-6-7-8-9-10, there is only one swap between the positions of aircraft 3 and aircraft 4, when the optimal sequence is 2-1-4-3-5-6-7-8-9-10 there are two swaps, one between 2 and 1 and another one between 3 and 4. For 10 aircraft the maximum number of swaps is 10 and happens if the optimal sequence is 2-1-4-3-6-5-8-7-10-9. The number of swaps per scenario is shown in Table 3.

Table 3 Number of swaps in the optimal sequencing for 100 scenarios

100 scenarios	0 swaps	1 swap	2 swaps	3 swaps
Scenarios	36	40	18	6

In one third of the cases the optimal sequence if the one decided by the FCFS rule, but in 40% of all cases one swap minimizes the total fuel burn.

4 Sequencing Rules Extraction

If we want to suggest some intuitive re-sequencing rules, though, knowing the number of swaps will not be enough. Next, we tried to determine what kind of FCFS configurations were subject to swaps. Here, the swaps are divided in 8 types based on the size of aircraft included in the swap and the two aircraft preceding the pair and following the pair. The number of aircraft in each configuration is chosen to be 4 because when a pair of aircraft is swapped, it affects the separation time required to the preceding and the following aircraft. For example, if the 4th and the 5th aircraft in the sequence are swapped, we look at the size of aircraft 3, 4, 5 and 6. The 8 types of swaps are shown in Fig.7.

We are not interested in swaps of aircraft of the same size since it is expected that such swaps will lead to just minor improvements in the total fuel burn because the coefficients characterizing the fuel burn increase a (discussed in Section 2.1) for same-sized aircraft are very similar. Several observations on the required separation can be made. Consider the minimum time required to land all four aircraft t_{four}. t_{four} decreases by 30 sec for swaps type 2 and type 8 , increases by 30 sec for swaps type 4 and type 6 and does not change for other swaps. In other words, swaps 2 and 8 improve both fuel burn and runway capacity, while swaps 4 and 6 might improve the fuel burn, but would result in decreased runway capacity.

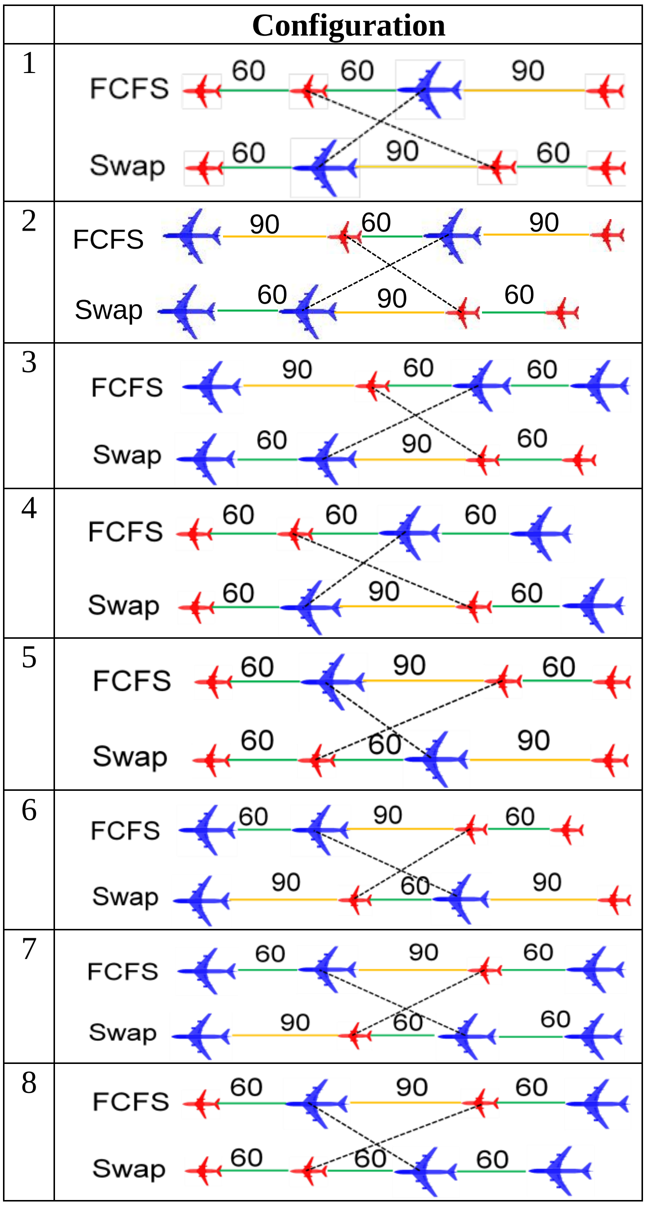

Fig. 7. Swap types depending on the size of the swapped aircraft pair, the preceding aircraft and the following aircraft. The changes in the required minimum separation are also shown.

To investigate the type of swaps in more detail a new series of Monte-Carlo simulation for 1000 random scenarios is conducted. The analysis approach taken is slightly changed. All configurations shown in Fig.7 are investigated. Sample sequencing is shown in Fig.8.

In this case, the optimal configuration is 1-3-2-4-5-6-7-8-9-10, a one swap scenario. It should be noted that most optimal sequencing scenarios included just a single swap. As you go through the FCFS sequence, you first isolate the swapped pair and two aircraft around it, in this case 1-3-2-4. This is a swap type 3 according to Fig.7. The next group of 4 aircraft is of type 1, but there is no swap here. Next comes a group of type 5, followed by a group of type heavy-medium-medium-heavy. Since for the groups at the beginning and the end of the sequence there are no four aircraft to form the group, all possibilities are considered, so we count a group of type 1 and 6. As a result, the analysis of this sequencing is one "swap" type 1, two "no swap" type 1, one "no swap" type 5, one "no swap" type 6.

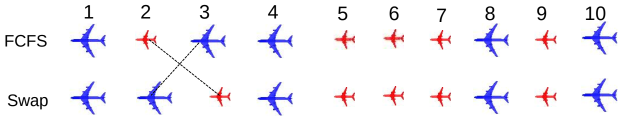

Fig. 8. A sample configuration used to analyze the type of swaps performed to obtain the best sequence which minimizes the total fuel burn

A similar analysis was done for 1000 scenarios randomly generated. The results are summarized in Table 4.

Table 4 Number of swapped and non-swapped 4-aircraft groups for 1000 scenarios

Type	1	2	3	4	5	6	7	8
Swap	132	294	61	30	60	6	0	155
No swap	460	180	113	479	492	541	196	308

Swaps of type 2 and 8 are of the greatest interest not only because they are dominant among the swapped pairs, but also because such swaps would result in a longer sequence of aircraft of the same size uninterrupted by aircraft of other size.

The next step is to determine under what conditions aircraft in configuration type 2 and type 8 are swapped. To do so, several attributes of the configuration are investigated. They are shown in Fig.9. ETA is the estimated time of arrival, i.e. the flight time which would minimize the fuel burn had there been no other interfering aircraft. Available time of arrival is the time which would be required in the FCFS sequence considering the earliest time at which the first aircraft in the configuration can land, i.e. the earliest available arrival time. This accounts for possible delays carried over from the previous configurations.

The authors are aware that interaction between the attributes is very likely, but the conditions for swapping need to be simple and straightforward so an approach such as neural network is not appropriate. The proposed attributes are considered in different combination pairs and the optimization results are analyzed. However, satisfying results are obtained only for swaps type 2 with attributes at_1 and at_2. Swaps type 8 cannot be analyzed well using a simple combination of the above attributes.

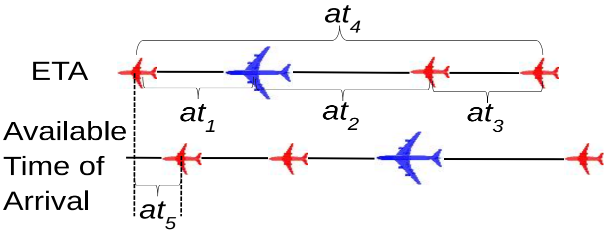

Fig. 9. Attributes of the aircraft configuration which might influence swapping

The results of type 2 swap analysis are shown in Fig. 10. The green dots represent swapped aircraft pairs and the blue crosses represent the non-swapped aircraft pairs. It can be seen that more swaps occurred when the first three aircraft in the sequence were relatively close to each other.

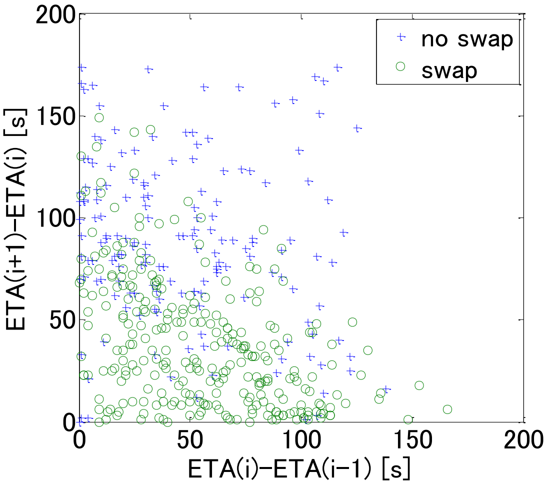

Fig. 10. Swapped and non-swapped pairs of type 2 configurations

5 Sequencing Rules

Based on the results discussed in Section 4, the following three rules were formulated and their effect on fuel burn was investigated through Monte-Carlo simulations.

Rule 1

Swap the ith and the i+1th aircraft if :

1.1)they are part of configuration type 2

1.2)(ETA(i+1)-ETA(i))+(ETA(i)-ETA(i-1))<120 [s]

Rule 2

Swap the ith and the i+1th aircraft if :

2.1)they are part of configuration type 2

2.2)(ETA(i+1)-ETA(i))+(ETA(i)-ETA(i-1))<120 [s] AND ETA(i)-ETA(i-1)<60 [s]

Rule 3

Always swap the ith and the i+1th aircraft if they are part of configuration type 8.

5.1 Rule 1

In the Monte-Carlo simulations the aircraft are required to land as early as possible in order to maximize the runway capacity. The results for 1000 cycles are shown in Fig.11. 138 swaps are performed with average fuel parameter f_{par} (as defined in Section 2.5) of -11.1%.

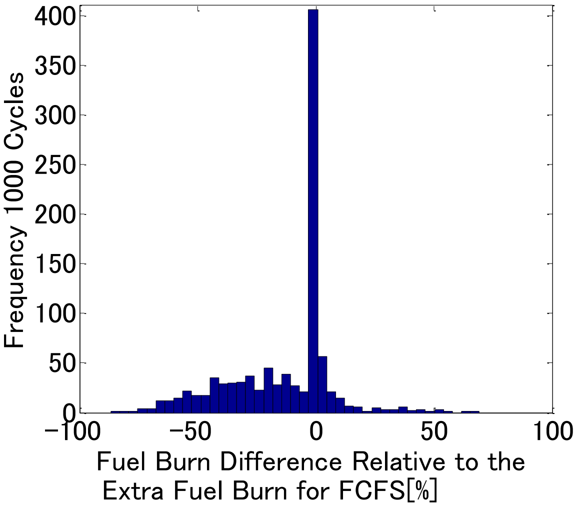

Fig. 11. Fuel improvements by the introduction of Rule 1

5.2 Rule 2

In a manner similar to Section 5.1, the effects of Rule 2 are verified in Monte-Carlo simulations and the results are shown in Fig.12. Here, compared to the 138 swaps performed with Rule 1, there are only 96 swaps. The average fuel parameter f_{par} is -11.8%, or just slightly better than that of Rule 1. Rule 2 results in fewer swaps with more fuel savings, but the rule itself is more complicated than Rule 1, so taking this into account we conclude that the simpler Rule 1 excels overall.

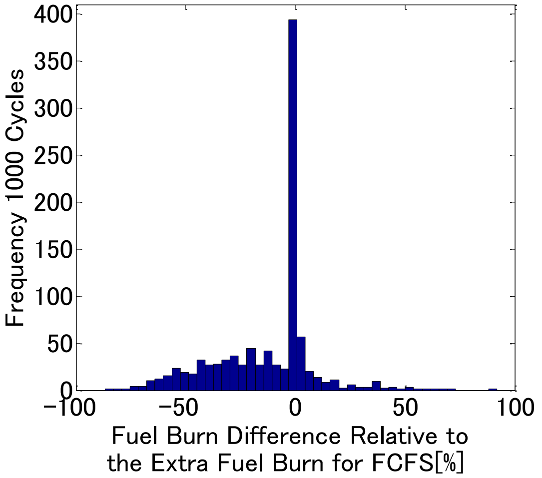

Fig. 12. Fuel improvements by the introduction of Rule 2

5.3 Rule 3

The effects of Rule 3 were analyzed not only in terms of fuel burn improvements, but also in regard of the runway capacity by considering the arrival time of the last aircraft in the group. The results from Monte-Carlo simulations are shown in Fig.13 and Fig.14. This rule could not be extracted very accurately from the optimal results, i.e. swaps are made even at places where they shouldn't be made. Even so, the fuel gains from the appropriately swapped aircraft exceed the fuel losses by the inappropriate swaps and the average f_{par} is -12.3%, higher than expected. Besides, the arrival time of the last aircraft in the group was on average 35 s earlier than that in the case of FCFS, which means that Rule 3 not only decreases the total fuel burn, but increases runway capacity, too.

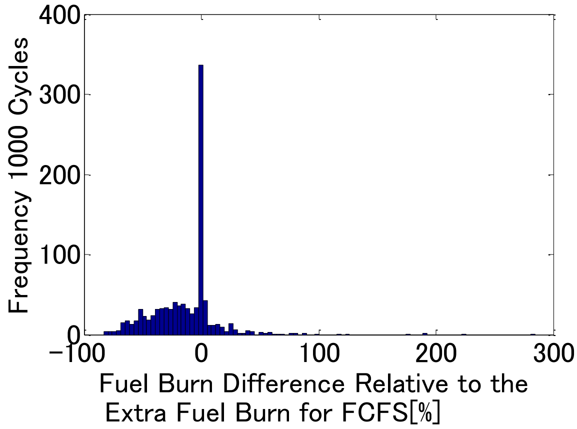

Fig. 13. Fuel improvements by the introduction of Rule 3

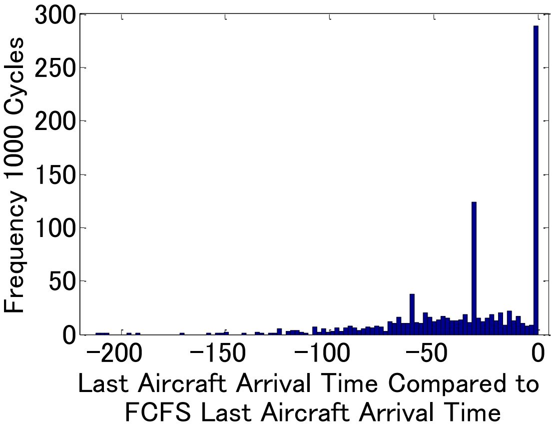

Fig. 14. Capacity improvements by the introduction of Rule 3

When Rule 1 and Rule 3 are combined and applied simultaneously, on average, the last aircraft lands 34.6 s earlier than in the FCFS sequence and the fuel parameter is -17%.The histograms of these results are shown in Fig.15 and Fig.16.

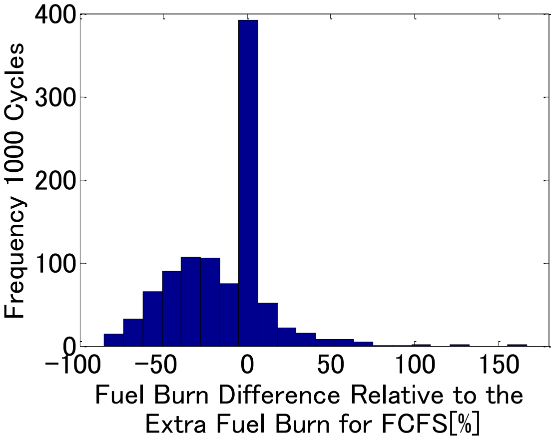

Fig. 15. Fuel improvements by the introduction of Rule 1 and Rule3

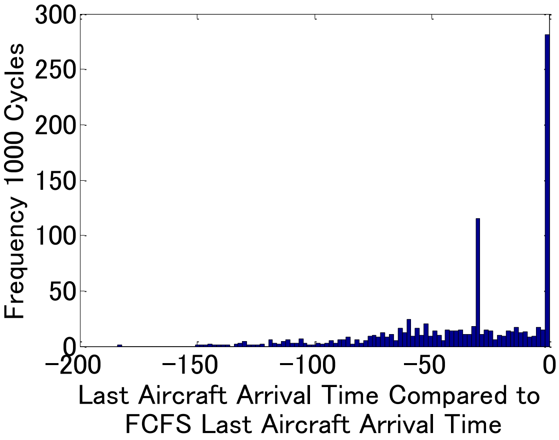

Fig. 16. Capacity improvements by the introduction of Rule 1 and Rule 3

Fuel savings by the simultaneous application of Rule 1 and Rule 3 are measured by a fuel parameter of -17%, which is twice less than that by the optimal sequencing discussed in Section 4 and is less than the sum of fuel savings of Rule 1 and Rule 3 applied independently. Several possible reasons might be behind these numbers. First, in the optimal solution the flight time can be adjusted very precisely to minimize the fuel burn and no aircraft arrives uselessly early. The flight time adjustments might play just an important role in the fuel burn as the sequencing itself. Next, there are aircraft configurations which might be subject to both Rule 1 and Rule 3 re-sequencing, but because the possible re-sequencing groups overlap, only one of the rules is applied. However, even though the obtained results are not optimal, they are better than the conventional sequencing.

6 Summary

This research suggests guidelines for aircraft sequencing in order to minimize the fuel burn by aircraft in the terminal area and whenever possible increase the runway capacity. It makes use of the information of aircraft size available to air traffic controllers on their radar. First, optimal sequencing based on descent trajectories minimizing aircraft fuel burn are computed. These sequences are analyzed and knowledge about the kind of swaps made is extracted. Three rules are proposed and their efficiency is verified by Monte-Carlo simulations of groups of 10 aircraft. It is concluded that if the rules summarized in Fig.17 are applied, the fuel burn increase caused by terminal area congestions can be decreased by 17% and the time necessary to land all 10 aircraft can be shortened by 34 s.

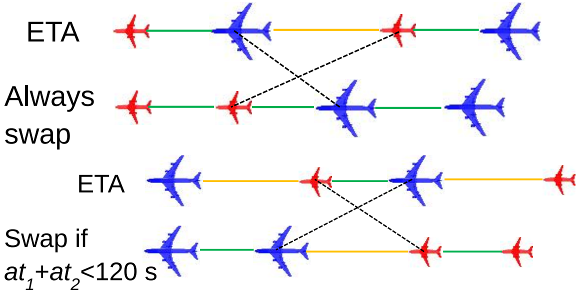

Fig. 17. Rules defining the most efficient swaps

The suggested guidelines are considered simple enough to be applied and their performance is going to be verified by simulations with an air traffic controller in the loop in the near future.

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