Aircraft Resequencing with Available Arrival Time Window Constraints

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***Abstract*—Limited airport capacity and environmental issues are expected to pose major problems for hub airports. New technology can contribute to the solution, but it always requires enormous financial and time investments. Improvements in air traffic management operations, though, are relatively easily implemented and far less expensive. This research investigated the possible fuel savings obtained only by resequencing of arrival aircraft in the terminal area. The simulations were based on results of previous studies done by the author. A major role in the decision was played by the aircraft size. It was found that a simple rule can lead to an average fuel savings of 2.8% and maximum savings of 34%.**

***Index Terms*— aircraft sequencing, aircraft size, minimum fuel burn, guideline**

I. Introduction

Aviation accounts for 2.5% of the global carbon dioxide emissions[1]. In recent years, the growth of this sector, however, has placed an importance on this figure as it is expected to grow steadily for the foreseeable future. To conquer this issue, numerous measures have already been taken. Advanced materials used in new airplanes have made aircraft lighter so that less fuel is burnt per passenger per kilometer. New engines have made it possible to make the most of the propulsion technology improvements. These two examples require that the airline purchase new aircraft, though, so their implementation and introduction into service requires both time and financial resources. As promising as the new technologies might be, we believe that there is enough room for improvement by optimizing operations only, both ground and air traffic. Such a strategy requires less investment on the airline side and even though the expected fuel savings cannot be as high as those associated with material and propulsion technology improvements, all parties involved can only benefit from them.

In this research, we focused on air traffic management operations, and on aircraft descent sequencing in particular. Every flight can be divided into several stages: taxing, take-off, climb, cruise, descent, final approach, landing and taxing. In general, climb is performed at close to maximum thrust so that the aircraft leaves the vicinity of the airport as soon as possible. This is done because the constantly increasing air traffic poses pressure to the airports. Cruising is performed at a flight speed close to the optimal (to be discussed later). Descent, on the other hand, is thought to be the stage which still requires a lot of optimization as it allows for changes without jeopardizing the safety of the flight within the scope of the technologies available at present. Therefore, we focused on the descent stage, whose control is in the hands of air traffic controllers at the terminal area. Furthermore, modern navigation enables the execution of optimal flight paths. A major role in the trajectory optimization is played by the introduction of RNAV (aRea NAVigation) [2]. RNAV is a method of navigation that allows aircraft operation on any desired course within the coverage of station-referenced navigation signals or within the limits of a self-contained system capability, or a combination of these. RNAV was developed to provide more lateral freedom and thus more complete use of available airspace. This method of navigation does not require a track directly to or from any specific radio navigation aid, and has three principal applications. First of all, a route structure can be organized between any given departure and arrival point to reduce flight distance and traffic separation. Second, aircraft can be flown into terminal areas on varied pre-programmed arrival and departure paths to expedite traffic flow. Third, instrument approaches can be developed and certified at certain airports, without local instrument landing aids at that airport. In our research we take advantage of such "free" descents and consider *the most efficient plausible arrival sequence in terms of combined fuel burnt by all aircraft involved*. This sequence is subject to operational constraints such as minimum separation and available arrival time window.

This paper is organized as follows: the background and previous work is briefly explained in Section II. In Section III an overview of the sequencing problem and the way we have approached it are presented. Section IV is about simulations without available time window constraints, with these being introduced in the next Section V. Here, various sequencing rules and their effect on fuel burn re also examined. The research is summarized in Section VI with some discussions and conclusions.

II. Terminal Area and Single Aircraft Trajectory Optimizations

In our past studies [3],[4], optimal descent trajectories with time constraints were investigated through numerical simulations. The considered terminal area is a model of Tokyo International Airport with the air traffic management operations which used to be executed until recently (Fig.1). Actually, operations were changed but for the purposes of this research the past model is considered sufficient. The assumed coordinates and waypoint altitudes are shown in

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Table 1. After the aircraft enter the terminal area at one of the three waypoints A, B or C, air traffic controllers have to merge the traffic coming from south and north in the terminal area while keeping the separation minima, which will be explained in detail later in Section III. The landing sequence is also decided at this point, as usually no reordering occurs once the aircraft is directed to the final approach waypoint D where it is transferred to the tower air traffic control and considered out of the scope of the terminal control.

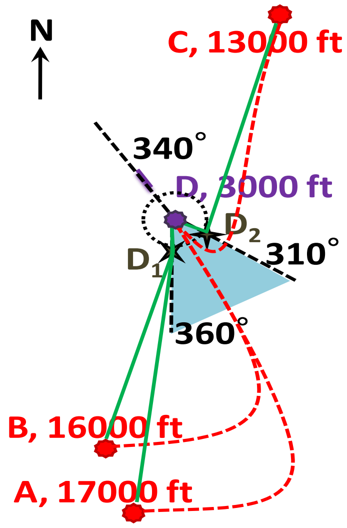

Fig. 1. Terminal area assumptions. Aircraft are usually navigated along the dotted lines, but RNAV would allow more efficient descents like the ones shown in solid lines.

TABLE I
WAYPOINTS COORDINATES

Waypoint	Distance East	Distance North	Altitude
A	-5.96 nm	-52.50 nm	17000 ft
B	-11.68 nm	-40.10 nm	16000 ft
C	15.99 nm	36.81nm	13000 ft
D	0 nm	0 nm	3000 ft

Optimizations were performed with the sequential quadratic programming method (SQP) and included representatives of heavy and medium aircraft. Based on the maximum take-off weight aircraft are divided into three main categories- light (less than 15 400 lb), medium (less than 300 000 lb but more than 15400 lb) and heavy (more than 300 000 lb)[5]. In our numerical calculations we consider a heavy and a medium civil aircraft. The medium aircraft is chosen to be the Boeing 737, as this is one of the most-widely used aircraft in its category in the civil aviation. Boeing 737 is a short-to-medium range airplane with a maximum take-off weight of 180 000 lb and a standard seating capacity of 137. From the heavy aircraft group we have chosen the Boeing 747 (Jumbo Jet), a long-range airplane, which has come to symbolize its class. Its maximum take-off weight is 875 000 lb and the standard seating capacity is 366.

Suppose the optimal flight time for minimum fuel burn is the expected time of arrival (ETA) which would have been the arrival time had the aircraft followed their optimal descent profile in the best time without taking into account the other aircraft. However, not all aircraft can follow their optimal descent profile all the time due to other traffic, weather conditions or after-landing issues. The minimum fuel burn under certain descent time constraints is shown in Fig. 2. The aircraft was required to be either early (negative time shift) of late (positive time shift). It was proven that close to the optimal descent time the fuel burn changes can be described by a quadratic function with a maximum deviation of 3.4 lb.

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

where f is the fuel burn increase, a is a parameter related to the entry waypoint and aircraft type and t_{opt} is the optimal flight time and t -the actual flight time. More on the simulated terminal area and flight procedures for single aircraft descent trajectories can be found in our previous work [3],[4].

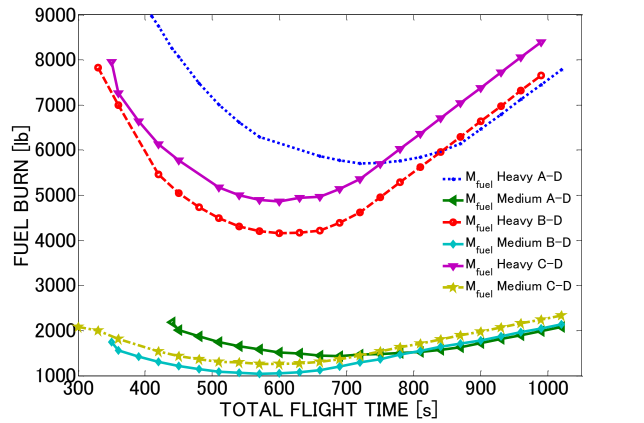

Fig. 2. Fuel burn vs. descent time. Around the optimal descent time the fuel burn can be adequately modeled with a quadratic function.

III. Sequencing Problem Definition

A. *Minimum Aircraft Separation*

All aircraft should be separated by a certain distance according to International Civil Aviation Organization (ICAO) separation standards [6] to avoid wake turbulence areas generated by the preceding aircraft. We have assumed a certain velocity at the terminal area exit waypoint for all aircraft, which allowed us to convert the distance separation requirement into a time separation requirement. In our simulations the separation standard is simplified, i.e. when a medium aircraft follows a heavy one, the required separation was considered to be 90 s, and in all other case- 60s. When the difference between ETA is not enough, the aircraft should be shifted forward or backward.

TABLE II
ICAO SEPARATION STANDARDS

Lead Follower	Heavy	Medium	Light
Heavy $W > 136t$	4 nm	5 nm	6 nm
Medium $7\,t < W \leq 136$	3 nm	3 nm	5 nm
Light $W \geq 7\,t$	3 nm	3 nm	3 nm

B. *Available arrival time*

Because only one aircraft can land or depart from a runway at the same time, and because aircraft must be separated by a certain time interval to avoid collisions, every airport has a finite capacity; it can only safely handle so many aircraft per hour. This capacity depends on many factors, such as the number of runways available, layout of taxi tracks, availability of air traffic control, but also on current or anticipated weather. Especially the weather can cause large variations in capacity because strong winds may limit the number of runways available, and poor visibility may

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necessitate increases in separation between aircraft. Air traffic control can also be limiting, there are only so many aircraft an air traffic control unit can safely handle. Staff shortages, radar maintenance or equipment faults can lower the capacity of a unit. This can affect both airport air traffic control as well as en-route air traffic control centers.

These issues reflect the aircraft sequence greatly. To describe them mathematically, we consider an available arrival time window defined by the earliest and latest arrival time at which aircraft is allowed to cross the terminal area exit waypoint. The latest arrival time is determined by the fuel available onboard and possibly by any subjective constraints induced by the airlines. In this research, however, the latest available time constraint is always weaker than the earliest available time constraint, because we are trying to not only achieve minimum fuel burn, but also have as short arrival time of the last aircraft as possible, thus maximizing the airport's capacity. Therefore, in the rest of the paper by available arrival time (AAT) we will mean the earliest available arrival time.

C. *Problem formulation*

The nature of the sequencing problem imposes a lot of constraints. As air traffic control is human-centered, we aim at developing an easy-to-implement procedure which will reduce the total fuel consumed even if it will not make it minimum. In other words, a trade-off between simplicity and fuel savings is acceptable to a certain extent.

Throughout this research, two questions should be answered:

1) What is the optimal sequencing? How is it different from the FCFS sequence?

2) How are the ETAs changed to achieve this optimal sequence?

IV. Scenario Simulations Without Available Arrival Time Constraints

A. *Batches of Two and Three Aircraft*

First, simulations without available arrival time constraints were considered, i.e. the first aircraft was allowed to arrive as early or as late as suited and the rest of the aircraft in the batch were to keep the separation minimum.

Consider two aircraft entering the terminal area shown in Fig.1. Since the fuel burn was approximated to a quadratic function, the minimum total fuel can be found both analytically and numerically. Furthermore, using SQP we extended the simulations to three aircraft to account for all waypoints and thus the most critical scenarios. Consider three aircraft entering the terminal area. The first series of our calculations confirmed our expectations that if all aircraft are of the same type, they should be shifted equally to provide sufficient separation. Without loss of generality, we considered the ETA of one aircraft to be zero and allowed for negative as well as positive ETA of the other two aircraft. The rest of the simulations were divided in two groups- A) two heavy (indices 1 and 2) and a medium aircraft (index 3, ETA3=0) and B) two medium (indices 1 and 2) and a heavy aircraft (index 3, ETA3=0). For three aircraft there are six possible sequences. If no changes in the sequence occur, the arrival sequence should depend only on ETAs as shown in Fig.3. We call this sequence "intuitional" sequence, or the FCFS sequence.

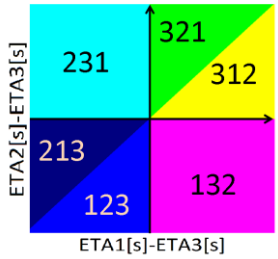
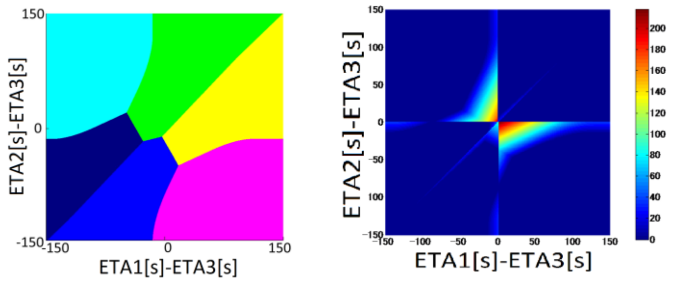


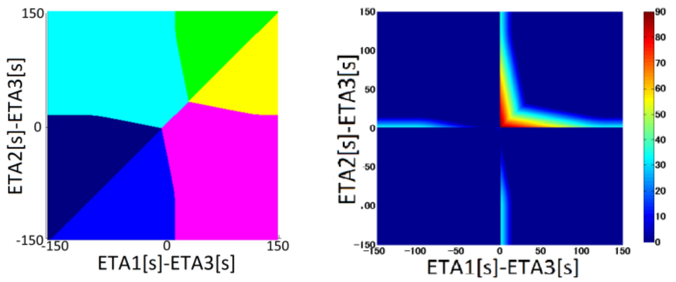
Fig. 3. Intuitional sequence (first come, first served sequence)

However, it can be proven that the optimal sequence depends not only on ETA, but also on the time of aircraft and the distance between the entry waypoint and the exit waypoint. The optimal sequence for a certain scenario from group A (a_i (i=1,2,3)) is shown in Fig.4a. The main difference between Fig.3 and Fig.4a is the change in the sequence when the medium aircraft is "squashed" between two heavy aircraft relatively close together. A set of results from group B is shown in Fig. 5a. Interestingly, the optimal sequence differs from the intuitional one when the heavy aircraft's ETA precedes both medium aircraft, which fly relative close to each other. The difference in the fuel burn between the optimal sequence and the intuitional one is shown in Fig. 4b and 5b. Such graphs can help us decide on the optimal sequence, but the associated time shifts are a complicated function of (a_i (i=1,2,3)) and ETA i (i=1,2,3)). Therefore, such a calculation cannot be done manually by air traffic controllers in real time.



a) Optimal sequence b) Fuel burn difference

Fig.4. Sequencing for two heavy and one medium aircraft



a) Optimal sequence b) Fuel burn difference

Fig.5. Sequencing for two Mmedium and one heavy aircraft

B. *"Mind the Size" Rule*

If the obtained results from our simulations are to be used by air traffic controllers, they should be simplified. A lengthy analysis and numerous simulations led to the following rules.

<u>Sequence:</u>

- Two aircraft (one heavy and one medium)-no changes in the sequence unless the heavy aircraft follows by less than 15 s
- Three aircraft (two heavy and one medium)-no changes in the sequence unless the medium aircraft is between the heavy ones and $|ETA_1\text{-}ETA_2|<k$, where k=60s but is

subject to further analysis.

- Three aircraft (one heavy and two medium)-no changes in the sequence unless the heavy aircraft precedes both medium ones, which are flying soon after, i.e. $|ETA_1\text{-}ETA_3+ETA_2\text{-}ETA_3|<j$, where j=60s but may be subject to change.

<u>Adjusted time of arrival (ATA, flight time shift):</u>

- Two aircraft(one heavy and one medium)- no adjustments to ETA of the heavy aircraft, considering the optimal sequence the medium aircraft's ETA is changed to give ATA.
- Three aircraft (all cases)- ETA of the medium aircraft in the optimal sequence is not changed. ETAs of the other aircraft are adjusted to meet the separation minima.

The essence of these rules is shown in Fig.6.

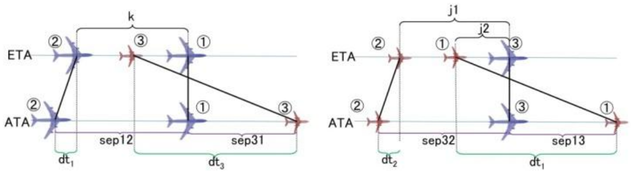


Fig. 6. Sequence change and adjusted time of arrival

C. *Monte-Carlo Simulations*

To verify the suggested guidelines, medium-congested terminal airspace was considered. Monte-Carlo simulations for 10^4 scenarios of 100 aircraft were performed. The aircraft were to enter the terminal area following a normal random distribution, but there was enough time between each batch of three aircraft. First, we considered the fuel savings obtained by following optimal sequences and optimal ATAs. The fuel burn was compared to that of FCFS case when the flight times of the following aircraft are adjusted based on the first one. A histogram of the results is shown in Fig.6. The horizontal axis shows the total fuel savings and the vertical axis shows how frequent such savings were observed. The average fuel saving is 2701 lb (1.18% of the total fuel).

Applying our "Mind the Size" rule, we obtained the analogous results. The average fuel saving was 2144 lb (1.01% of the total fuel burn). Therefore, even though the new rule does not lead to minimum fuel burn, it results in substantial reduce in fuel burn.

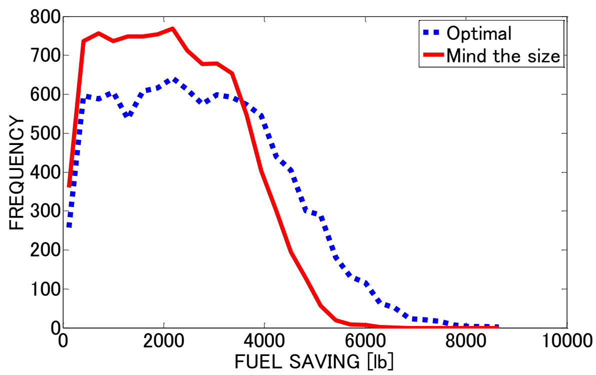


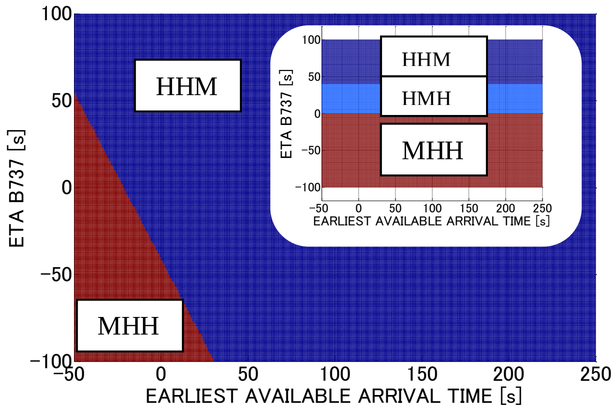
Fig. 7. Monte-Carlo simulations

V. Scenario Simulations With Available Arrival Time Constraints

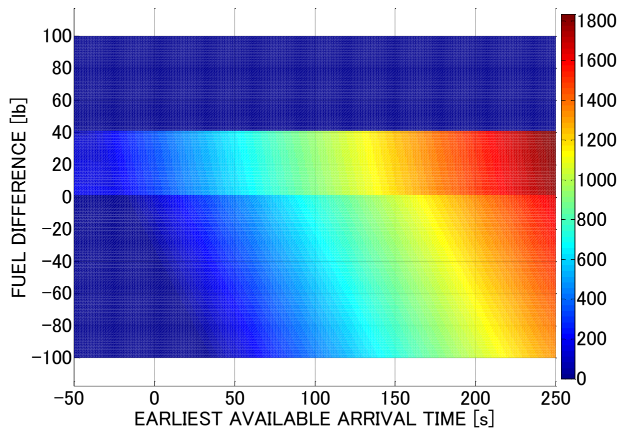
The results from the previous section provided us with hints for the direction of the research. In order to be able to extend the simulations to longer batches of aircraft, the earliest available time was implemented in the simulations. The aircraft were still divided into groups of three based on their ETA. The number of aircraft in each group was set to three because of the number of entry waypoints. Besides by keeping this number small, the simulation can easily be approximated to a real-time one.

A. *Two Heavy and One Medium Aircraft*

The first group of simulations included two heavy and one medium aircraft. The result in one particular case is shown in Fig. 8. ETA of the two heavy aircraft were set at 0 s and 40 s. The vertical axis shows the ETA of the medium aircraft. The horizontal axis shows the arrival time of the first aircraft to pass through the final waypoint relative to the ETA. The FCFS sequence will not depend on AAT and will always be as the sequence shown in the small window in the upper right corner of Fig. 8a. The red zones represent sequence Medium-Heavy-Heavy, the light blue zone shows Heavy-Medium-Heavy and the blue zones show Heavy-Heavy-Medium aircraft. It should be noted that depending on the ETA of the heavy aircraft, the light blue zone might appear in the optimal sequencing, too. However, this region is relatively small. Also, the border line between MHH and HHM areas also depends on ETA of the three aircraft.



a) Sequences depending on the available arrival time (AAT)



b) Fuel burn difference between the AAT and ETA sequences

Fig.8. Sequencing for two heavy and one medium aircraft. ETA of the two heavy aircraft are 0 s and 40 s, whereas ETA of the medium aircraft varies between -100 and 100 s, shown on the vertical axis

Our goal, however, is to find a rule simple enough to be applied in practice, so instead of searching for high accuracy and analyze every single case, we decided to propose some rules regardless of the ETA of the three aircraft in the group.

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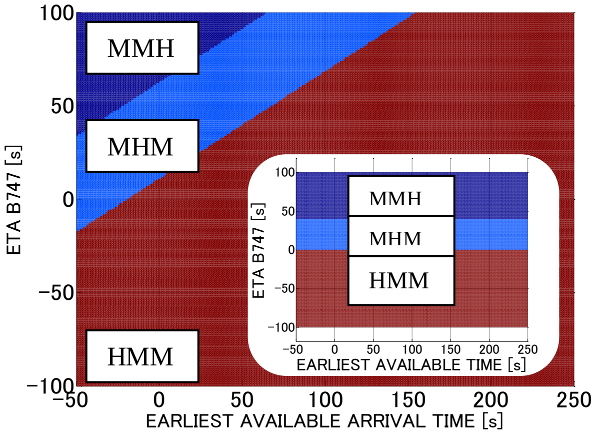
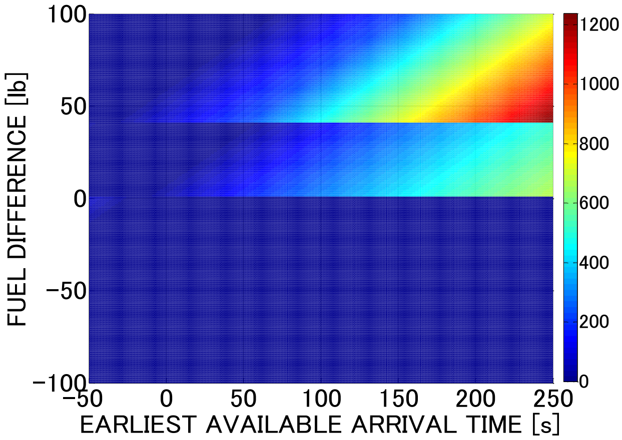
As presented in Section IV, the medium aircraft should go in front when "squeezed" between two large aircraft had there been no arrival time constraints. Looking at the fuel gains shown in Fig.8b, however, we changed the above rule with the following one- move the medium aircraft after the heavy ones. Obviously, the more the aircraft are delayed, the more will be gained by the changed sequence.

B. *Two Medium and One Heavy Aircraft*

The second group of simulations included two medium and one heavy aircraft. Similarly to the results in Section V A, the fuel gains obtained by optimizing the arrival sequence in respect to the available arrival time and ETA are shown in Fig.9. Since the red region occupies most of the optimal seqeunce graph and leads to the highest fuel gains, the new rule was set to be as follows: have the heavy aircraft land first and then clear the medium ones. At first sight this rule differs significantly from the one introduced in the previous section. In reality, however, the two rules do not contradict with each other. The main idea behind the rule which placed the heavy aircraft in the middle of the sequence was to move its descent time as little as possible. Actually, this holds here, too. Because of the introduction of the available arrival time, delays are to be compensated and the first aircraft will suffer the least, i.e. its descent time will be adjusted the slightest. Theerfore, the heavy aircraft should go first in most cases.



a) Sequences depending on the available arrival time (AAT)



b) Fuel burn difference between the AAT and ETA sequences

Fig.9. Sequencing for two medium and one heavy aircraft. ETA of the two medium aircraft are 0 s and 40 s, whereas ETA of the heavy aircraft varies between -100 and 100 s, shown on the vertical axis

C. *"Mind the Size" Revised*

Based on the results obtained by the simulations of scenarios including the available arrival time, the rules proposed in the previous section were revised as shown in Table 3. The arrival time of the first aircraft in the new sequence should be as close as possible to its optimal one and as early as possible in the available window. The highlighted cases represent a need of change in the sequence.

TABLE III
"MIND THE SIZE" REVISED

Rule No.	FCFS sequence	Changed sequence
1	M H H	H H M
2	H M H	H H M
3	H H M	H H M
4	H M M	H M M
5	M H M	H M M
6	M M H	H M M
7	H H H (M M M)	H H H (M M M)

To examine the effect of each of the rules suggested above, Monte-Carlo simulations were conducted. 1000 scenarios in which every 60 min 50 aircraft entered the terminal area were conducted. The ration of medium to heavy aircraft was 1:1. Besides, in accordance with the actual traffic at Tokyo International Airport, 50% of the aircraft entered the terminal area at waypoint A, 20%- at waypoint B and 30% at waypoint C. At each entry point the aircraft met the separation requirements. Their exact ETA were distributed randomly. The results from out Monte-Carlo simulations are shown in Fig.10. Since the mean improvement was observed only in the case of rule 2 and rule 5, a combined scenario where both rules were applied simultaneously was also investigated.

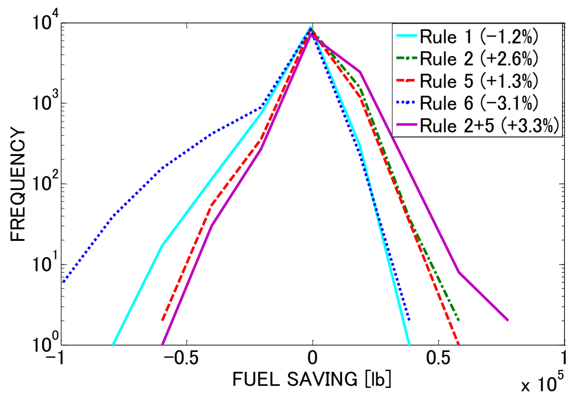


Fig.10. Distribution of the fuel savings obtained when the new rules were applied. The average saving per each scenario in percentage of the total fuel burn is shown in the legend. Plus indicates positive fuel saving (fuel burn decrease) and minus the vice versa. Note that the vertical graph is in logarithmic scale for better visualization.

The total fuel burn was decreased when applying two out of the four rules proposed. When the aircraft was moved by more than one slot in the sequence, the mean fuel burn increased (rule 1 and 6). The reason may be twofold. First, the bigger position shift means bigger average fuel burn increase. Second, if we look closely at these cases, they have increased the necessary time separation between the aircraft within the group from 60s+60s to 90s+60s. Indeed, the separation required before and after each group might have shrunk, but this happened only in some cases so the fuel burn

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increased overall. Therefore, by applying rules 2 and 5 an average fuel saving of 3.3% can be achieved.

D. *"Simple Swap"*

A major disadvantage of the guidelines discussed above is the grouping into three. When looking at the rules which produced the best results, we concluded that changes in the FCFS sequence by one would be sufficient. The sequence should be changed only when the aircraft are in the order heavy-medium-heavy or medium-heavy-medium, as follows:

heavy-medium-heavy→ heavy- heavy-medium
medium- heavy-medium→ heavy-medium-medium

Actually, both cases can be described by one swap between heavy and medium aircraft, i.e. the heavy aircraft goes before the medium one when there is a "squeezed-in" aircraft. Here by a squeezed-in aircraft we mean an aircraft between two other aircraft of different type, i.e. either HMH (M is squeezed-in) or MHM (H is squeezed-in). Besides, when there are more than one possible swap, the earliest one in the FCFS sequence is to be done. This is illustrated in Table IV. The first three aircraft form a "squeezed-in" group, so the heavy one is moved before the medium one. Next, a group can be formed by both (5, 6, 7) or (6, 7, 8). In such a case, consider only (5, 6, 7) as it is before (6, 7, 8) and swap aircraft 5 and 6. Last, consider aircraft (10, 11, 12) and swap 11 and 12. This procedure is referred to as "Simple Swap" rule.

To verify the contribution of the rule "Simple Swap", Monte Carlo simulations under the same conditions as the ones described in Section V (C) were conducted. A histogram of the results is shown in Fig.11. The average fuel saving was 2.8% and the maximum fuel saving for one scenario of 50 aircraft was 34%. The result is extremely promising considering the simplicity of the rule.

TABLE IV
SIMPLE SWAP

	1	2	3	4	5	6	7	8	9	10	11	12
FCFS	M	H	M	M	M	H	M	H	H	H	M	H
Simple Swap	H	M	M	M	H	M	M	H	H	H	H	M

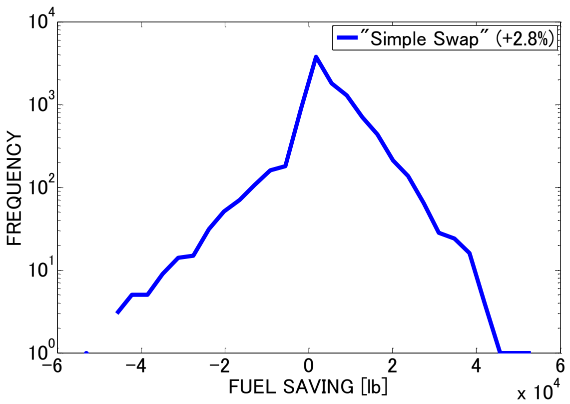

Fig.11. Distribution of the fuel savings obtained with the "Simple Swap" rule. The average fuel saving is 2.8%. Plus indicates positive fuel saving (fuel burn decrease) Note that the vertical graph is in logarithmic scale for better visualization.

VI. Summary and Conclusion

This research laid the grounds for new sequence assignment rules for aircraft entering the terminal area of a hub airport. Taking into account the human-centered nature of air traffic control, the aim was to develop simple yet efficient guidelines. The fuel burn modeling was based on data from previous research on optimized descent trajectories. Aircraft were then divided in batches in which the best order of arrival was investigated. Interestingly, the average fuel gain was higher when available arrival time window was considered. This facts suggests that the effect of the proposed rules will be even more significant at more congested airports or/and time slots. An average fuel saving of 2.8% was observed when applying the simple steps summarized below:

1) Keep the first come-first served sequenced unless there is a "squeezed-in" aircraft, i.e. a medium aircraft between two heavy aircraft or a heavy aircraft between two medium aircraft. In such a case swap the heavy aircraft with the medium one before it.

2) Assign the earliest arrival time plausible for the sequence.

Since the maximum fuel saving was as much as 34%, the rules can further be improved by looking into the structure of the scenarios which were mostly affected by "Simple Swap". Nevertheless, it was demonstrated that by a very simple change in the air traffic operations fuel improvement of 2.8% of the total fuel burn can be easily achieved. We believe that this research gives a valuable insight into the importance of air traffic operation procedures and their potential contribution to the environmental impact abatement of aviation.

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References

[1] GHG Data 2006, submitted under the United Nations Framework Convention on Climate Change (UNFCCC)
[2] Robinson, Sharon, James S. DeArmon, Thomas A. Becher, 2001, "Benefits of RNAV Terminal Procedures: Air/Ground Communication Reduction and Airport Capacity Improvements," 20th Digital Avionics Systems Conference, Irvine, California
[3] Andreeva-Mori A., Suzuki S., Itoh E., "Scheduling of Arrival Aircraft Based on Minimum Fuel Burn Descents", ASEAN Engineering Journal, June 2011, in press
[4] 4 ICAO Doc 4444 (Procedures for Air Traffic Management)
[5] Andreeva A., Suzuki S., Itoh E. : "Flight Management Based On Optimized Descent Trajectories For Minimal Environmental Impact", 47th Aircraft Symposium, 4-6 November 2009, Gifu, Japan (in Japanese)
[6] Air Traffic Controller Manual, http://www.vateud-td.org/handbooks/manual.asp, retrieved on 06/11/2008
[7] ICAO Doc 4444 (Procedures for Air Traffic Management)