論文の内容の要旨

FUEL SAVING SEQUENCING OF ARRIVAL AIRCRAFT

（燃料消費削減のための到着機シークエンシングに関する研究）

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Efficient scheduling of aircraft landings can improve runway throughput and reduce fuel burn. Currently, however, the most common conventional sequencing strategy is the first come, first served one, according to which aircraft are allowed to land in their order of arrival at the runway. The terminal area where most resequencing occurs is a very dynamic environment, so air traffic controllers cannot afford to spend a long time determining an alternative sequence. The goal of this research is to propose aircraft sequencing guidelines for fuel savings.

Outline

This thesis consists of four main parts. Part I presents the necessary background of this research. It gives an overview of air traffic demand scenarios and presents some technological solutions which can improve fuel burn efficiency. After reviewing the present inefficiency of operations, the leading idea of this research is presented.
Part II answers the question "how to model fuel burn?". It states the assumptions on which all simulations in the research are based, starting with the aircraft model, terminal area assumptions and optimization method overview. Single aircraft trajectory optimizations are performed and used as a base for fuel burn modeling. In the third part, which is the essence of this research, sequencing rules are extracted based on analysis of optimal sequencing. The differences between the first come, first served rules are investigated and the statistical performance of the proposed rules is examined. Finally, Part IV summarizes the research and provides suggestions for further study.

Background

At present, aviation accounts for about 3% of all carbon dioxide emissions [1]. Aviation emissions would not have been a discussion matter if it had not been for the continuously increasing demand for air travel. Considerable research has been done on finding new technology solutions which can reduce aircraft fuel burn and thus harmful emissions. Innovations such as lightweight materials, combustion system improvements and technologies which contribute to smooth laminar flow over the aircraft's body can lead to less fuel burn. However, hardware improvements are both cost and time consuming, so this research considers an operational approach only. The author's main goal is to find a substitute to the first come, first served rule commonly used for aircraft sequencing. The motive for this research is "making the most" of the available technology in use already by optimizing operations only without introducing any new hardware and/or software devices at air traffic control centers. The author does not aim at automation of the sequencing process, i.e. the system remains human-centered.

Literature review of the aircraft sequencing problem shows than even though the problem has been studied to some extent, most research is aimed at developing a real-time optimization algorithm and sequencing software rather than introducing something as simple as sequencing rules instead. Therefore, the approach taken in this research is rare, but as seen later can be extremely promising.

Fuel burn modeling

Furthermore, by referring to past research on environmentally-friendly aircraft sequencing, it is observed that for computational simplicity reasons, the fuel burn is mostly modeled by linear functions. Such an approach can contribute to finding analytical and computational solutions to the aircraft sequencing problem, but no prove has been found on its accuracy in the literature. Therefore, before the sequencing problem is formulated, there is a need to determine the fuel burn cost function, i.e. how each single aircraft's fuel burn by changes in the descent times. In order to do that, optimization of single aircraft descents is performed. The aircraft model used in this research is a point mass model. The trajectory is divided into several stages and optimization is performed using Sequential Quadratic Programming method. We consider heavy and medium aircraft as these types are most often used in civil aviation at hub airports which are likely to experience congestion and thus might benefit from improved aircraft sequencing. Here, past operations of the terminal area of Tokyo International Airport (Haneda Airport) are used to model the terminal area, which is shown in Figure 1.

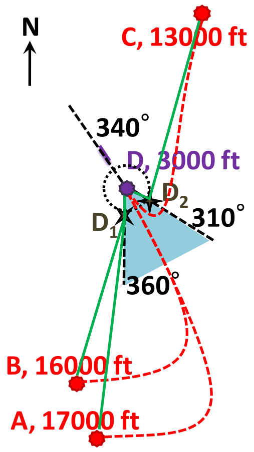


Figure 1. Terminal area

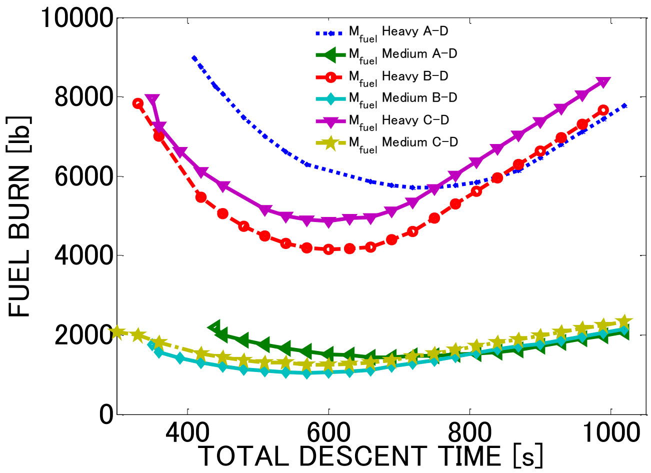


Figure 2. Fuel burn vs. descent time

With all the necessary assumptions being stated, optimization of the trajectory of single aircraft entering the terminal area is performed. First, the optimal descent time and the flight profile associated with it are found. Next, by introducing constraints on the desired deviation from the optimal descent time, the minimum fuel burn as a function of the descent time is determined (shown in Figure 2). The function obtained is used to model the fuel burn when aircraft have to be sped up or delayed in the landing sequence and it substitutes the linear function often used in the literature so far.

Sequencing rule extraction

With a function providing the relationship between fuel burn and flight time available, the next step to the actual sequencing can be made. Operational constraints such as minimum separation, earliest available arrival time, precedence constraints and constrained position shift (CPS) are considered. The minimum separation requirement guarantees that aircraft do not suffer from the wake vortices induced by leading aircraft. Earliest available arrival time accounts for congestions ahead and accumulated delays. Precedence constraints ensure that no overtaking of aircraft entering the terminal area at the same entry point occurs. The position shift constraint reflects the fact that no aircraft can be too far from its original position in the final sequence, i.e. an aircraft can skip ahead or back only a restricted number of positions.

Aircraft sequencing problem should answer two main questions:

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

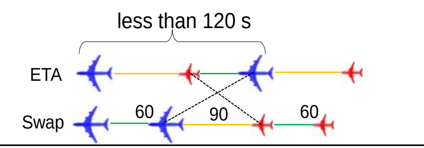
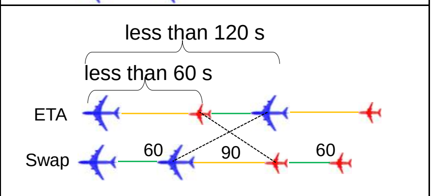
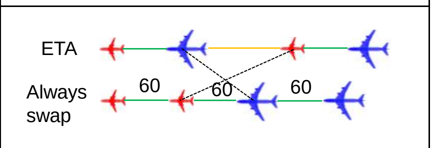
2) How are the expected times of arrival (ETA) changed to achieve the proposed sequence?

It should be kept in mind that the goal of this research is not optimizing the aircraft sequence, but finding a sequence which excels the FCFS sequence in most cases. To do so, simulations are conducted according to the following flow:

1) Group aircraft in batches of 2, 3 or 4
2) Find the optimal sequence
3) Compare the optimal sequence with FCFS sequence
4) Investigate the conditions under which aircraft are swapped
5) Propose sequencing rules based on key swaps
6) Investigate the statistical performance of the rules by Monte-Carlo simulations
7) Finalize the rules

Simulations for ten aircraft entering the terminal area at random times in a predefined time interval are conducted. The ratio of aircraft at each entry waypoint and the ratio of heavy to medium aircraft resemble the actual traffic condition at the model airport. The optimal aircraft sequencing and scheduling is found under the constraints described earlier. A comparison of the optimal sequence and the first come, first served sequence in each simulation reveals the number of swaps in each case. The conditions under which swaps occurred are of interest for defining the swapping, thus sequencing rules.

Table 1. Rules extracted from analyzing batches of 4 aircraft. ETA stands for estimated time of arrival, the figures "60" and "90" show the required separation.

	Configuration
Rule 1	
Rule 2	
Rule 3	

Consider swapping a pair of aircraft. The swap influences the required separation necessary between the pair and the preceding aircraft as well as the separation between the pair and the following aircraft, i.e. four aircraft are considered to monitor the effect of the swap. The parameters which influence swapping are estimated arrival times of all four aircraft, their type (medium or heavy) and the earliest available arrival time. Analyzing the swaps, three rules are extracted. Their essence is shown in Table 1. The statistical performance of the proposed rules is verified by Monte-Carlo simulations. The fuel burn for each sequence is measured by a newly-introduced parameter f_{par}. 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

$fuel_{FCFS.}$ Suppose the total fuel burn increase for all ten aircraft for certain sequencing is $fuel_{seq}$. In such a case, f_{par} is defined as:

$$f_{par} = \frac{fuel_{\ sec} - fuel_{FCFS}}{fuel_{FCFS}}$$

In other words, f_{par} 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 f_{par} 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.

The average values of f_{par} are shown in Table 2. Rule 2 has a slightly better average performance than Rule 1, but since it is more complicated than Rule 1, it is considered that Rule 1 excels overall. Therefore, a simultaneous application of Rule 1 and Rule 3 is suggested. For comparison, f_{par} of the optimal sequence is -35%. Simulation results show an average f_{par} of -17%, with f_{par} for heavy aircraft of -12% and f_{par} for medium aircraft of -22%.

Table 2. Average fuel parameters for the investigated sequencing rules

	Rule 1	Rule 2	Rule 3	Rule 1 and 3
Average f_{par}	-11.1 %	-11.8 %	-12.3%	-17.0%

Fuel savings by the simultaneous application of Rule 1 and Rule 3 are twice less than these by optimal sequencing. The main reason is that 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. Besides, there are aircraft configurations which might be subject to both Rule 1 and Rule 3 resequencing, but because the possible resequencing groups overlap, only one of the rules is applied. However, even though the sequencing rules do not measure up to savings achieved through optimal sequencing, they are remarkably better than the conventional sequencing approach.

Summary

This research suggests guidelines for aircraft sequencing in order to minimize fuel burnt by aircraft in the terminal area. It makes use of information about aircraft type available to air traffic controllers on their radar screen. It was concluded that even though the guidelines do not result in absolute optimal aircraft sequencing, they can contribute to significant fuel savings. It was demonstrated that by a very simple change in the air traffic operations sufficient fuel improvement can be easily achieved. The author believes 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.

[1] J.A. Leggett, B. Elias, and D.T. Shedd, "Aviation and the European Union's Emission Trading Scheme", http://www.fas.org/sgp/crs/row/R42392.pdf, retrieved on 2012/5/30