GUIDELINES FOR FLIGHT TIME MANAGEMENT AND SUSTAINABLE AIRCRAFT SEQUENCING

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Abstract

Aircraft sequencing for greener aviation and increased airport landing capacity has been researched. A sample airport and its surrounding terminal area are considered. First, descent trajectory optimizations of single aircraft are performed for various flight times in the cases of a heavy and a medium aircraft. Speed adjustment and vectoring are implemented as methods to change the descent time. The properties of the optimal trajectories obtained are discussed. Next, multiple aircraft simulations are performed and several sample scenarios are analyzed. The effect of aircraft sequencing on the total fuel burn is observed. Basic guidelines for descending aircraft sequencing are proposed based on the preliminary results obtained so far.

1 Introduction

Aviation is one of the fastest developing industries with an annual forecasted global air-passenger traffic increase of up to 5% [1]. Therefore, the environmental impact and air traffic control capacity have become urgent issues. This research takes into account both problems and suggests practical guidelines for aircraft sequencing based on optimal descent trajectories.

Optimized flight trajectories for noise and CO_2 emission abatement have been a subject of research for some time[2]. In particular, the continuous descent approach has proven to be a superb solution for the environmental problems and thanks to the improved positioning system it is considered to be a feasible solution. However, optimizing a single descent trajectory takes time and therefore it is unrealistic to believe that every time an aircraft is about to land such an optimization will be performed. Besides, air traffic management is a human-centered operation, which requires all implementations to be easy to follow, straightforward and as simple as the popular “first come, first served” rule.

The aim of this research is to develop a system of guidelines for air traffic controllers in order to help them sequence aircraft in descent while reducing the fuel burn. These guidelines are based on optimization results from numerical simulations in various cases.

We consider sequencing after aircraft enter the terminal area of a sample airport at three waypoints. All aircraft are to be properly sequenced, spaced and aligned with the runway before they are transferred to the airport tower control. Furthermore, only the static case is considered, i.e. information about all aircraft landing at the airport is available before they enter the terminal area.

It is expected that this study will be a basis for a new rule for air traffic management for environmentally-friendly flights and decreased workload of the air traffic controllers.

2 Problem Formulation

2.1 Aerodynamic Model

For the purposes of this research, the aircraft has been modeled as a point mass.

The four main forces acting on an airplane are lift, drag, gravity, and thrust.

$$L = \frac{1}{2}\rho V^2 S C_L \quad (1)$$

$$D = \frac{1}{2}\rho V^2 S C_D = \frac{1}{2}\rho V^2 S\left(C_{D0} + K C_L^{\,2}\right) \quad (2)$$

Here, C_L is the lift coefficient and it relates the total lift generated by an aircraft to the total area of the wing of the aircraft.

Let the angle between the velocity vector and the local horizon, i.e. the flight path angle (FPA) be Γ. From the equilibrium in the direction of the thrust vector:

$$T = \frac{1}{2}\rho V^2 S\left(C_{D0} + K C_L^{\,2}\right) + Mg\sin\Gamma \quad (3)$$

$$0 = -\frac{1}{2}\rho V^2 S C_L + Mg\cos\Gamma \quad (4)$$

Furthermore, using empty weight, thrust can be written as:

$$T = C_T M_0 g \quad (5)$$

C_T depends on the engine and is called specific fuel consumption.

The next equation shows how the weight of the aircraft decreases as time proceeds.

$$\frac{dM}{dt} = -\frac{b}{g}T \quad (6)$$

Actually, it is exactly this relationship that has allowed us to define our objective function, which will be discussed in detail later on.

In this paper a three-dimensional trajectory is considered, i.e. the flight path is described by the lateral coordinates *x* and *y*, and the altitude *z*. Furthermore, the trajectory is divided into *N* stages, each of which is characterized by a certain flight time, a variable within a certain range.

Let Δt_i be the flight time of stage *i*. Eq. (6) can be rewritten as:

$$M_{i+1} = M_i - \frac{\Delta t_i \cdot b \cdot T_i}{g} \quad (7)$$

2.2 Optimization Method and Parameters

All optimizations in this research are performed in MATLAB using the gradient method Sequential Quadratic Programming (SQP). We consider a model whose dynamics can be described by differentiable equations. This allows us to apply the SQP method and make good use of the information contained in the derivatives. However, the danger of getting a local rather than a global minimum remains. Furthermore, the robustness of SQP is relatively small and the results depend highly on the initial solutions, especially when the objective function is characterized by numerous local minima. A careful consideration and analysis of the obtained results is needed in order to determine the plausibility of the solution.

3 Numerical Simulation Scenario

3.1 Terminal Area Assumptions

Consider the following terminal area. Suppose aircraft enter the terminal area from one of the three waypoints A, B or C shown in Fig. 1.

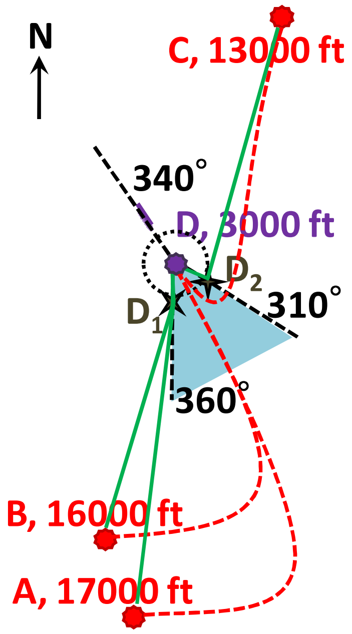

Fig. 1 Waypoints in the terminal area considered

The traffic coming from south is to go through waypoint A at 17000 ft or waypoint B at 16000 ft, whereas the traffic coming from north passes waypoint C at 13000 ft. Furthermore, we assume that 70% of the total traffic comes through waypoints A and B and the remaining 30% enter the terminal area via waypoint C. The final approach waypoint D is at 3000 ft and lies on the line of the runway, at 340 ° (shown in purple). It is known that all aircraft generate vortex wake turbulence, which can cause problems for following aircraft. We assume that the International Civil Aviation Organization (ICAO) separation standards for landing and take-off hold at the final approach waypoint D. Table 1 shows the ICAO wave vortex separation minima [3].

Table 1 ICAO separation standards

Lead / Follower	Heavy	Medium	Light
Heavy W > 136t	4 nm	5 nm	6 nm
Medium 7t < W < 136	3 nm	3 nm	5 nm
Light W > 7 t	3 nm	3 nm	3 nm

Air traffic controllers have to merge the traffic coming from south and north in the terminal area while keeping the separation minima. Once the aircraft is directed to the final approach waypoint D it is transferred to the tower air traffic control and considered out of the scope of the terminal control.

It is assumed that for the aircraft to be safely transferred to tower air traffic control, it needs to approach waypoint D at heading between 310°and 360° (the area shown in blue). Here, two new waypoints, D_1 and D_2 are introduced. They are both at 2000m lateral distance from waypoint D. It is assumed that the aircraft coming from south should pass through D_1 whereas the traffic coming from north goes through D_2. The speed of the aircraft at D_1 (D_2) is set at 230 kt. The FPA in the interval between waypoints D_1 (D_2) and D is 3°.

A common way to direct the air traffic entering the terminal of the kind described above is shown by the red dotted lines in Fig. 1. Even though there is no hard rule, because if the 70%-30% traffic distribution mentioned above, the general approach will be to give priority to the aircraft coming from south and when separation allows merge the traffic from north.

Each aircraft has an ideal descent path that corresponds to its characteristics. However, in reality an aircraft does not always descent in its optimal time. An aircraft might have to wait before it reaches a certain waypoint. This could be due to busy traffic, weather considerations or after-landing management issues. Unlike on the ground an airplane cannot just stop and thus cut its fuel burn. It must keep flying which makes the problem of waiting much more complicated. For the purposes of examining the most fuel-efficient sequencing in our numerical simulations, several new rules described below are introduced.

1) Whenever possible, the aircraft should fly the shortest distance between the waypoint at the entrance of the terminal area (A, B or C) and intermediate waypoint D_1 (D_2).
2) When the above is not feasible, flight time adjustment should be done by speed adjustment and/or vectoring (lengthening the flight path of the aircraft). In previous research[4], it was proven that even though directing the aircraft to a holding pattern before letting it descent lets the controller know at all times the region when the aircraft is flying, an advantage for less experienced controllers, vectoring and speed adjustment can be as much as 19% more fuel efficient than holding patterns.
3) The speed of the aircraft at waypoints A, B and C might vary, but the speed at the final approach waypoint D is fixed at 230 kt.

3.2 Single Aircraft Trajectory Optimization

In our numerical calculations we consider heavy and medium civil aircraft. The medium aircraft is chosen to be the Boeing 737-300, as this is one of the most-widely used aircraft in its category in the civil aviation. From the heavy aircraft group we have chosen the Boeing 747-400, a long-range airplane, which has come to symbolize its class.

3.2.1 Optimal Path

Let the coordinates of the final waypoint D be [0, 0, 3000 ft]. Consider a coordinate system with center [0, 0, 0] with a positive *x* axis pointing east, positive *y* axis pointing north and positive *z* axis pointing upwards (Fig. 2).

Let us give an example with the optimization results obtained for waypoint C-waypoint D path of the heavy aircraft B747-400 in order to illustrate the characteristics of a fuel-optimal descent trajectory. Even though the numbers differ with the starting waypoints and the type of aircraft, the general patterns are common.

The number of stages was set to 5. However, the optimization results showed that one of the stages has a flight time of merely 0.008 sec and it is therefore neglected in the final results.

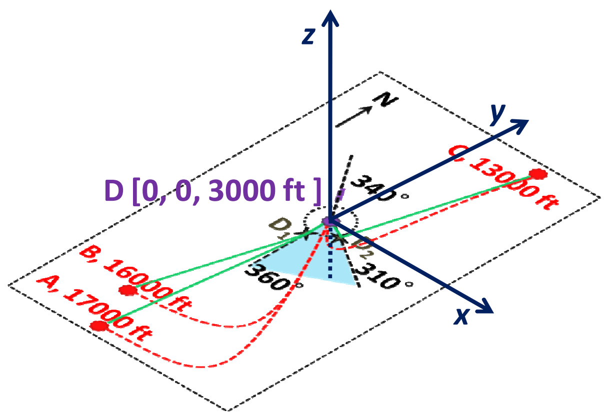

Fig. 2 Definition of coordinates

The three-dimensional trajectory obtained is shown in Fig. 3. As can be seen in Fig. 4, the aircraft does not divert between waypoint C and waypoint D_2, which agrees with the first rule introduced earlier. The altitude profile is shown in Fig. 5. The results confirm the "higher for longer" principle. Below the tropopause, where most commercial aircraft are flown, the air density decreases as the altitude z increases. The lower the air density is, the lower the drag becomes. Consequently, the lower drag results in lower trust necessary, i.e. flying higher for longer leads to lower fuel burn. In the first two stages the aircraft maintains horizontal flight and then descends at the maximum allowed flight path angle 3° (Fig. 6).

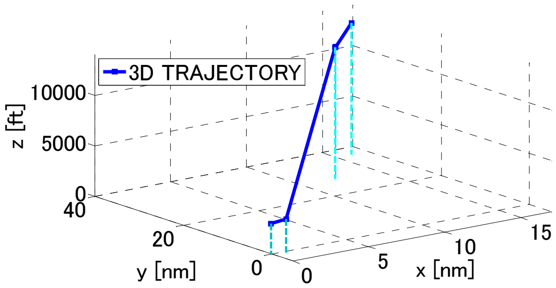

Fig. 3 3D sample descent trajectory

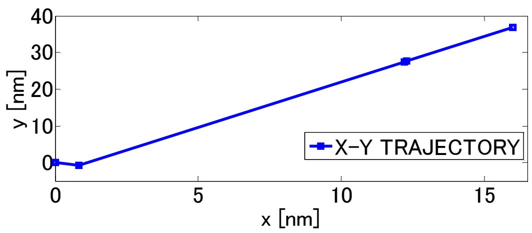

Fig. 4 X-Y sample descent trajectory

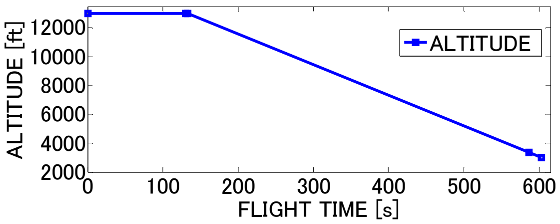

Fig. 5 Altitude- sample descent trajectory

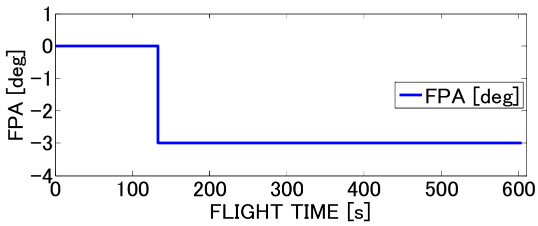

Fig. 6 Flight path angle- sample descent trajectory

3.2.2 Speed profile and thrust analysis

The speed profile of the sample descent trajectory is sown in Fig. 7. The speed in the last phase is set to 230 kt in advance as part of the entry conditions at waypoint D. At present, 250 kt is considered typical descent speed which agrees with our results. It must be noted that aircraft and fuel burn data used is only accurate up to a certain extent and with this research we aim at revealing plausible sequencing procedures rather than absolutely approximation-free numbers.

Besides, as seen in Fig. 8, the thrust coefficient C_T never reaches its minimal allowed value zero. Idle thrust is not achieved, even though theoretically speaking such a value would result in near zero fuel consumption for that stretch. In a lot of papers it is said that the idle thrust is a desirable state for sustainable descent. Looking at the simulation results showing the flight path angle during the descent, it can be concluded that when the 3°constraint on the flight path angle becomes active, C_T is limited to a value higher than zero and idle-power descent is not executed. When the constraints on the flight path angle are weakened, the C_T can reach a lower value and thus the fuel consumption can be decreased. This was confirmed in a series of optimizations letting the maximum allowed descent flight path angle vary from 3 to 4 degrees. The results are shown in Fig. 9. Even in such a short time span considering the descent only in the terminal area, fuel burn reduction of 1% is possible just by having a slightly steeper flight path angle.

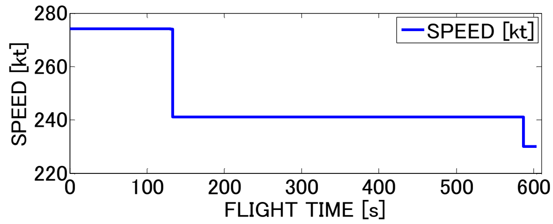

Fig. 7 Speed - sample descent trajectory

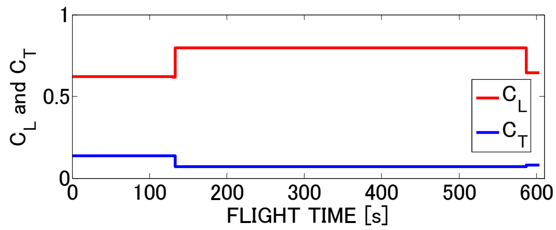

Fig. 8 C_L and C_T- sample descent trajectory

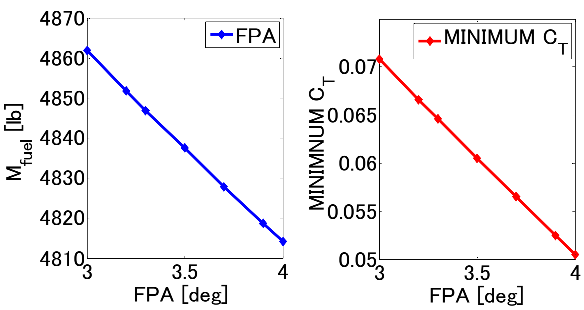

Fig. 9 FPA dependency

3.2.2 Fuel burn and flight time

In reality, an aircraft does not always descent in its optimal time. An aircraft might have to wait before it reaches a certain check point. This could be because the pilot has been told by the air traffic controllers to hold the airplane due to busy traffic. It could also occur due to weather considerations, after-landing management issues (such as passenger services and management of luggage), etc. Unlike on the ground, an airplane cannot just stop and thus cut its fuel burn. It has to keep flying which makes the problem of waiting much more serious and complicated. On the other hand, an aircraft might be asked to arrive slightly earlier, too, considering other flight connections, for example. Therefore, the flight time is crucial when determining an optimal descent trajectory and it poses additional constraints. Numerical simulations with fixed flight time were conducted and the results for B747 and B737 are shown in Fig. 10. These are also used when performing the multiple aircraft optimization. The markers indicate each numerical simulation.

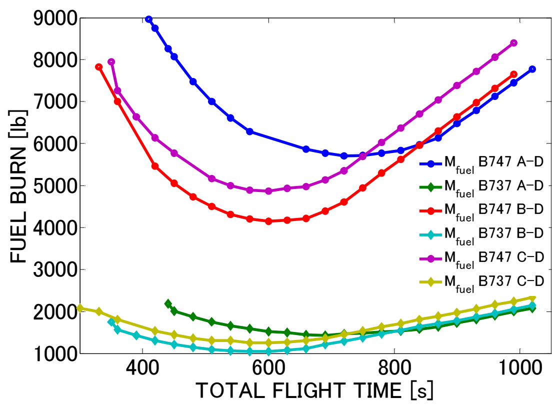

Fig. 10 Fuel burn vs. total flight time

Next, let us consider how the fuel burn is changed in respect to the total flight time. As seen from Fig. 10, each scenario is characterized by a certain optimal flight time, for example the minimum fuel burn for B747 aircraft entering the terminal area at waypoint C happens when the flight time to waypoint D is 600s. In respect to this optimal time, aircraft can either be “early” or “late”. Our optimization results show that the fuel burn is less when the aircraft is “late” by a certain time, rather than “early” by the same time (Fig. 11). The aircraft can arrive faster at the final waypoint flying the same path but adjusting its speed. There is an obvious constraint on how much “catching-up” can be done, too. On the other hand, the aircraft can delay its arrival by speed adjustments and vectoring. Smaller delays can be absorbed by speed adjustments only, but for longer delays no such feasible solutions exist, so vectoring becomes necessary.

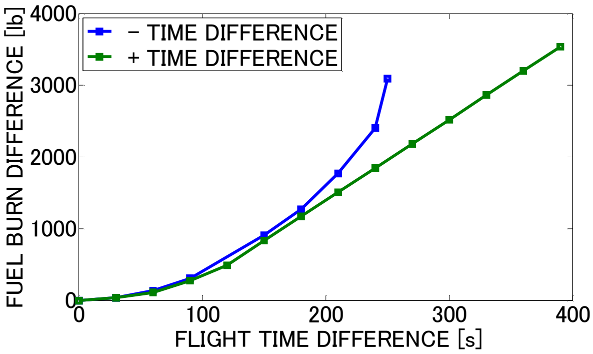

Fig. 11 Fuel burn differences

Some X-Y profiles for waypoint C-waypoint D descent trajectory of B747 are shown in Fig. 12. The longer the flight time becomes, the more vectoring is needed and the intermediate waypoints get further from the optimal trajectory. In this case, delays up to 120s (flight time 720 s) can be compensated by speed adjustments only and still be optimal.

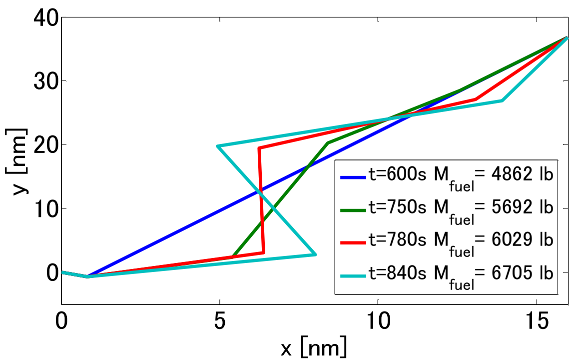

Fig. 12 X-Y descent trajectory profiles

As mentioned in section 2.2, SQP is not a very robust optimization method. The solutions obtained depend highly on the initial solutions.

Fig. 13 shows three different descent trajectories generated for minimum flight time 780 s starting from different initial solutions. The fuel burns also vary slightly, but it is considered this difference is within the error range of SQP. This, however, can be used as an advantage. Similar fuel burn can be generated with various vectoring. Therefore, the air traffic controller is free to choose a trajectory that satisfies their requirements and still get optimal fuel burn.

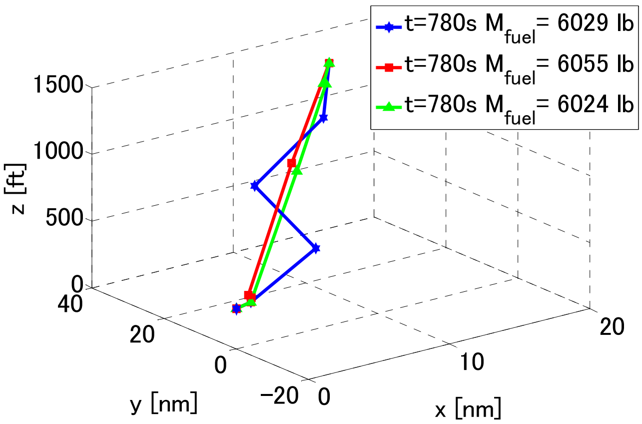

Fig. 13 Trajectory dependency on the initial solution

4 Multiple Aircraft Simulations

Based on the results obtained at the single aircraft trajectory optimization, several multiple aircraft scenarios were considered and analyzed. The flight time was set to take discreet values with a time step of 30 s. Referring to Fig. 10, fuel burn was assigned to each flight time. It should be noted that we are dealing only with the off-line case, i.e. we have complete knowledge of the set of planes that are going to enter the terminal area.

4.1 Scenario I

Consider the following aircraft sequencing configuration (Fig. 14). Two aircraft B747 enter the terminal area at the same time at waypoints B and C respectively.

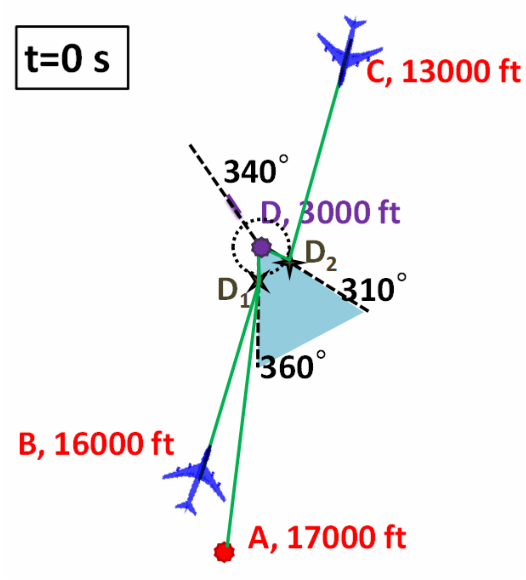

Fig. 14 Scenario I configuration

It should be noted that the optimal descent time of aircraft going through both waypoints is the same and equal to 600 s.

The aircraft are to arrive at waypoint D with a minimum separation of 4 nm (see Table 1). The speed in the last stage is set to 230 kt, so a simple calculation shows that the required time separation should be 62 s. Since we work with discrete values, we assume 60 s of time separation. In the same way Table 1 was converted from nautical miles separation into time separation with approximations done to accommodate the discrete flight time. The result is shown in Table 2.

Table 2 Separation at 230 kt speed

Lead / Follower	Heavy	Medium
Heavy W > 136t	60 s	90 s
Medium 7 t < W ≤ 136	60 s	60 s

Total minimum fuel burn is achieved when the aircraft fly around their optimal flight time. Therefore, four plausible sequencing options exist, presented in Table 3. Here, we varied the flight time, too. The first column shows the descent time for the aircraft entering from waypoint B and waypoint C respectively. The best choices require that the aircraft coming from north be assigned to land prior to the aircraft coming from south. The fuel difference might seem negligible, but it should be kept in mind that this occurs for two aircraft only and thus applying such a strategy to the full air traffic would result in considerable fuel savings.

Table 3 Sequencing options for scenario I

B [s]—C [s]	Mfuel [lb]	Sequence	Difference
600–660	9122	B–C	0.60% (55 lb)
660–600	9078	C–B	0.12% (11 lb)
570–630	9138	B–C	0.79% (71 lb)
630–570	9067	C–B	–

4.2 Scenario II

Next, a sample scenario with 2 aircraft of a different type is considered. The situation is identical with scenario I, but the aircraft coming from the north and passing through waypoint C is B737 instead of B747 (Fig. 15).

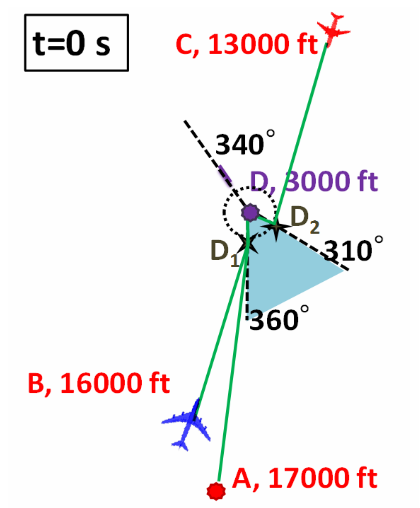

Fig. 15 Scenario II configuration

Both optimal flight times are 600 sec. The sequencing options, their associated flight times and fuel burns are shown in Table 4. It is obvious that the B737 coming from the north should land before the B747 coming from the south, with the most fuel-efficient case being when both flight times are shifted by 30 sec forward and backward respectively. If the B737 lands before the B747, a separation of 90 sec becomes necessary.

Table 4 Sequencing options for scenario II

B [s]—C [s]	Mfuel [lb]	Sequence	Difference
510-600	5751	B-C	6.05% (328 lb)
540-630	5583	B-C	2.94% (160 lb)
570-660	5506	B-C	1.52% (83 lb)
600-690	5517	B-C	1.73% (94 lb)
600-540	5452	C-B	0.54% (29 lb)
630-570	5423	C-B	-
660-600	5470	C-B	0.87% (47 lb)

4.3 Scenario III

Next, consider the aircraft sequencing configuration shown in Fig. 16. Two aircraft B747 enter the terminal area at waypoints A and B respectively, with the aircraft arriving at waypoint B 120 sec later.

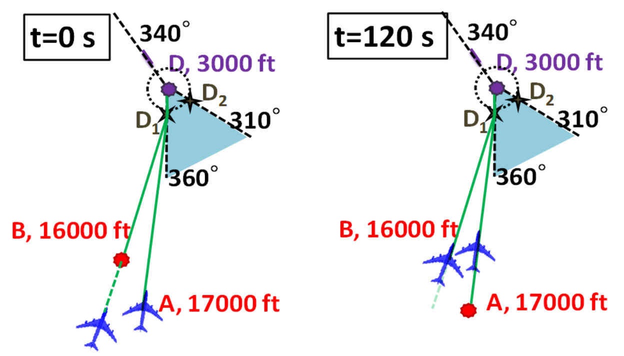

Fig. 16 Scenario III configuration

The candidates for optimal sequencing are shown in Table 5. The fuel burn changes are negligible because the optimal flight times differ exactly by the initial time difference (120 sec) and the aircraft are of the same type. Thus, in this case it can be concluded that as long as the flight times of both aircraft are around the optimal ones, the sequencing is not of much importance.

Table 5 Sequencing options for scenario III

A [s]—B [s]	Mfuel [lb]	Sequence	Difference
720-780	9924	A-B	0.06% (5 lb)
780-720	9919	B-A	-
690-750	9938	A-B	0.19% (19 lb)
750-690	9922	B-A	0.03% (3 lb)

5 Conclusion

In this research, aircraft sequencing based on optimized descent trajectories of aircraft after their entering the terminal area of a sample airport was considered. The preliminary results suggest the following guidelines:

- When two aircraft of the same type (B747) enter through waypoints A and B 120 sec apart, their sequence does not change significantly the total fuel burn, so as long as they are assigned trajectories closed to the optimal ones any order of arrival will suffice.
- When two aircraft of the same type (B747) enter through waypoints B and C at the same time, priority should be given to the aircraft coming from the north.
- When two aircraft of different type (B737 and B747) enter through waypoints B and C at the same time, priority should be given to the medium aircraft, shifting both flight times.

It can be argued that the above guidelines are too specific and refer only to the scenarios discussed earlier, but the authors believe that the approach taken is promising enough and will eventually lead to more generalized rules, a subject of future studies.

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