JOURNAL OF THEORETICAL
AND APPLIED MECHANICS
63, 1, pp. 27-36, Warsaw 2025
https://doi.org/10.15632/jtam-pl/194991

TACTICAL AND STRATEGIC AIR TRAFFIC SEQUENCING WITH MINIMUM-FUEL TRAJECTORIES

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The constantly growing air traffic has a negative impact on the environment, flight safety, and the staff workload. The solution to these problems might be new techniques of air traffic management, especially automatic sequencing of the arriving aircraft combined with optimal flight trajectories. This work aims to analyze the feasibility and optimality of automatic air traffic sequencing by using MILP and large datasets of real air traffic data. The results show that the appropriate formulation of the problem may lead to both suboptimal solutions for tactical planning purposes and optimal solutions for strategic and pre-tactical planning purposes.

Keywords: air traffic, separations, flight dynamics, optimization, sequencing

1. Introduction

The problem of determining the required time of arrival (RTA) value for flights using continuous descent operations (CDO) has been the subject of research, among others in (Park and Clark 2015), and in (Takeichi, 2017) where the nominal flight time was optimized in terms of arrival time planning. Both studies assessed feasible arrival windows for predetermined waypoints, assuming that the arrival time was assigned before the aircraft reached the approach position. Furthermore, the feasible controlled time of arrival (CTA) windows was assessed in (Dalmau and Prats, 2016), assuming the use of energy-neutral CDOs. This study also assumed, unlike previous studies, that the arrival time is assigned after the descent begins. In recent years, researchers' efforts have also focused on the feasibility of operations using CTA and RTA. In (Houston and Barmore, 2009) an assessment of the feasibility of arrival procedures and an assessment of the feasibility of maintaining spacing between aircraft when the RTAs were used was performed. In (de Jong and Bussink, 2017) the use of energy-neutral trajectories was investigated, taking into account the human factor. Prats *et al.* (2016) considers CDOs supported by the use of an electronic flight bag (EFB), so the human-machine interface in the context of CDO is considered. The research results showed that EFB may be a potential solution for communication regarding CDO between the aircraft crew and the air traffic control tower. Mutiple methods for optimizing a set of flights were presented in (Durand *et al.*, 2016), where metaheuristics for optimal air traffic management were described. Methods for optimizing the air route network, managing airspace and airport traffic, allocating departure times, sequencing arrivals, and detecting and resolving conflicts in the airspace were presented. In the case of the arrivals sequencing problem, the need for separations management was highlighted and the problem was formulated in a general form. Also, an overview of possible ways to solve the problem was also presented.

By analyzing the literature, it can be noted that the previous research was aimed at developing theoretical foundations and confirming the correctness and feasibility of the concept and algorithms, but did not focus on using them on a full scale, i.e. using energy-efficient continuous descent trajectories along with assigning the required arrival time to each flight. Therefore, the full-scale feasibility and optimality of these concepts are unknown.

In this work, energy-efficient trajectories using only the idle engine thrust and elevator control, without the use of air brakes, were considered. These trajectories assigned to each flight allow for the determination of time windows using the RTA concept. The resulting time windows were combined with a large set of real arrival traffic data which were input to the aircraft sequencing problem formulated and solved with use of mixed integer linear programming (MILP) techniques.

2. Methodology

2.1. Aircraft sequencing problem

The main goal of the aircraft sequencing problem is to formulate a mathematical problem, the solution of which makes it possible to plan a set of flights in such a way that each aircraft is able to maintain safe separation from other aircraft at a selected navigation point. The problem must also take into account physical limitations, in the form of time windows in which the aircraft can be at a given point. Moreover, to ensure the optimality of the solution, a cost function must be defined that will allow to determine the optimality criterion.

Sequencing methods for aircraft landings had previously been used successfully (Beasley *et al.*, 2000; Briskorn and Stolletz, 2014; Kim *et al.*, 2014; Faye, 2015), but they did not address the concepts of future air traffic management and proposed assigning arrivals to different runways as a conflict resolution measure. In addition, the test scenarios were simplified, differed from reality, and considered a small number of days, usually with low traffic, where the goal was often to test the performance of the algorithm rather than the feasibility of the concept. It is worth noting that for the vast majority of airports, two-runway or three-runway, the issue of landing on multiple runways is not an optimal solution, especially in the contexts of maximizing throughput and minimizing operational complexity. The greatest operational efficiency can be achieved by continuous arrivals to one runway and continuous departures from the other runway. The exception are the largest airports, where dedicated operational methods must be developed (Kim *et al.*, 2014).

In this work, the feasibility of the aircraft sequencing task was examined taking into account the use of a combination of several futuristic concepts: CDO, RTA and time-based separations (TBS) based on the RECAT-EU concepts. Due to the objectives of the task, the following values were defined as the task parameters:

- ETA is the expected arrival time; this is the optimal arrival time obtained for the minimum-fuel trajectory using the energy-neutral CDO method;
- RTA^E is the earliest possible required time of arrival using the energy-neutral CDO method;
- RTA^L is the latest possible required time of arrival using the energy-neutral CDO method;
- $\left\langle \mathrm{RTA}^E, \mathrm{RTA}^L \right\rangle$ is the time window;
- t_{sep} is the minimum required time separation between a preceding and the following aircraft.

Additionally, a decision variable that defines the arrival time obtained after solving the aircraft sequencing problem, the required time of arrival, was defined as RTA. Sets are also defined:

- $\mathcal{A}$ is the set of all arrivals on a given day, where p is a single arrival, $p \in \mathcal{A}$;
- $\mathcal{P}$ is the set of all possible pairs of arrivals on a given day, where (p,q) is a single pair of arrivals, $(p,q) \in \mathcal{P}$, $p \neq q$.

As an optimization criterion, it was assumed that for each aircraft $p \in \mathcal{A}$ the required arrival time RTA should be as close as possible to the expected arrival time ETA. Moreover, it was assumed that the cost factor for the difference between the required and expected arrival time was linear and the same for all aircraft. Therefore, the optimization problem can be defined as

$$
\begin{aligned}
&\min \sum_{p\in\mathcal{A}} (t_p^+ + t_p^-) \\
&\mathrm{RTA}_p^E \leqslant \mathrm{RTA}_p \leqslant \mathrm{RTA}_p^L \qquad \forall p \in \mathcal{A} \\
&\mathrm{RTA}_p^E + t_{sep} \leqslant \mathrm{RTA}_q + L_{p,q}B_{p,q} \qquad \forall (p,q) \in \mathcal{P} \qquad \text{if } p > q \\
&\mathrm{RTA}_p^E + t_{sep} \leqslant \mathrm{RTA}_q + L_{p,q}(1 - B_{p,q}) \qquad \forall (p,q) \in \mathcal{P} \qquad \text{if } p < q \\
&B_{p,q} \in \{0,1\} \qquad \forall (p,q) \in \mathcal{P} \qquad \text{if } p < q \\
&\mathrm{RTA}_p - \mathrm{ETA}_p = t_p^+ + t_p^- \qquad \forall p \in \mathcal{A} \\
&t_p^+ \geqslant 0 \qquad \forall p \in \mathcal{A} \\
&t_p^- \geqslant 0 \qquad \forall p \in \mathcal{A}
\end{aligned}
\tag{2.1}
$$

Additional dependencies

$$
L_{p,q} = \max\{\mathrm{RTA}_p^L - \mathrm{RTA}_q^E, \mathrm{RTA}_q^L - \mathrm{RTA}_p^E\} \quad \forall (p,q) \in \mathcal{P} \quad \text{if } p > q \tag{2.2}
$$

2.2. Aircraft dynamics model in air traffic control

A set of ordinary differential equations can be used to describe the dynamics of aircraft flight (Etkin, 2005). These equations are non-linear and describe various physical phenomena that affect the dynamics of the aircraft, e.g. the influence of elasticity. However, deformations mainly concern the aircraft with significant aspect ratio, e.g. gliders. Therefore, to describe the flight dynamics of a passenger aircraft, a rigid body model with six degrees of freedom (DOF) is usually used (Fischenberg *et al.*, 2012; Seren *et al.*, 2006), making additional assumptions about geometric and mass symmetry in the vertical plane Oxz.

The plane of symmetry of geometry and mass and the assumption of a constant value of gravitational acceleration also enable the decomposition of the equations of motion into two sets: longitudinal and lateral-directional. The aircraft descends in the vertical direction, so only the longitudinal plane can be considered. To determine the aircraft condition for air traffic modeling and sequencing purposes, including calculation and analysis of the flight trajectory, it is necessary to determine such quantities as the route length, height, speed and angle of the flight path. The distance from the target point and the altitude along the flight path are used to determine the aircraft position on the descent path, and the speed and angle of the flight path are used by ATC to estimate how the position on the descent path will change before an update on the aircraft position is received. This means that the spatial orientation of the aircraft is not used, and therefore the equations of motion can be further simplified by adopting a two-dimensional point-mass model with two degrees of freedom, which are the speed and flight path angle (Stengel, 2004). This approach is often used in air traffic control problems, including aircraft sequencing (Vilardaga and Prats, 2015; Dalmau and Prats, 2015). The use of more complex flight dynamics models that would use additional physical quantities, the dynamics of system components (e.g. control system) or the influence of environmental factors would have a minor impact on accuracy. However, the calculation of optimal trajectories would be much longer, and finding a solution in a reasonable time scale would not be possible (Lichota and Ohme, 2014). With the adopted assumptions, the aircraft dynamics model can be expressed as follows

$$
m\dot{U} = F_T - F_D - mg\sin\gamma \tag{2.3}
$$

where F_T is the thrust force, m is mass of the aircraft, F_D is the aerodynamic drag force, g is the acceleration due to gravity, U is the longitudinal velocity, γ is the flight path angle.

2.3. Optimization problem parameters

In this work, a simplifying assumption was made, which consisted in considering one type of aircraft – the Airbus A320. The analyzes showed that approximately 80% of the flights in the dataset used were operated by Airbus A320 (ICAO: A320), Boeing 737-800 (ICAO: B738), Airbus A321 (ICAO: A321) and Airbus A319 (ICAO: A319). These aircraft have similar mass and geometric parameters, and therefore also dynamic properties. All of them are also in category D according to RECAT-EU. Therefore, a uniform time separation of $t_{sep} = 80\,\mathrm{s}$ was assumed.

The time parameters of energy-neutral trajectories were also determined for the Airbus A320 aircraft. For this purpose, Eq. (3) was used because the wing aspect ratio of the Airbus A320 is 10.47 (Airbus, 2016), and therefore the stiffness of the aircraft structure can be neglected. To obtain energy-neutral trajectories, it was assumed that the descent trajectory is controlled only by the flight path angle (in fact, this would be the result of using a control surface, e.g. elevator), and mass changes were neglected due to the fact that the mass change as a result of fuel consumption during descent at idle thrust is negligibly small compared to the weight of the aircraft.

Time windows and trajectories with the minimum fuel consumption as a function of the distance from the destination point for the Airbus A320 aircraft were obtained from the previous studies (Pawełek *et al.*, 2017, 2019). Values for the aircraft aerodynamic and propulsion variables were obtained using accurate performance data received from the manufacturer. Typically, these data are obtained as a result of experimental studies and specified in a tabular form. The data were approximated with continuous functions using B-splines to avoid numerical problems. In addition, the international standard atmosphere model is used, which relates density, pressure and temperature to altitude. Trajectories with minimum fuel consumption were obtained by minimizing the cost function

$$J = \int_{t^0}^{t^{fix}} FF(t)\,dt \tag{2.4}$$

where t^0 and t^{fix} are the relative start and end times of the trajectory, and FF is the fuel consumption function. The earliest possible arrival time was obtained by minimizing the arrival time at the destination, so the cost function was $J = t^{fix,E}$, and for the latest arrival time it was $J = -t^{fix,L}$.

In this work, the synchronization of air traffic at the IF point was considered, and the distance of 250 NM was assumed as the moment of calculating the time window (except for shorter trajectories, where correspondingly smaller distances were assumed), as in preliminary analyzes this value was considered the target value of future TMAs (Ky, 2021). This value is also consistent with the direction of development of the E-AMAN system, where the current horizon is 200 NM, taking into account the possibility of gradual expansion up to 500 NM. Therefore, the time parameters of the aircraft sequencing task were calculated in this work as follows for each aircraft p

- expected arrival time ETA_p was calculated as

$$\mathrm{ETA}_p = T_p^0 + (t_p^{fix} - t_p^0) \tag{2.5}$$

- earliest arrival time RTA_p^E

$$\mathrm{RTA}_p^E = T_p^0 + t^{fix,E} \tag{2.6}$$

- latest arrival time RTA_p^L

$$\mathrm{RTA}_p^L = T_p^0 + t^{fix,L} \tag{2.7}$$

where T_p^0 is the time of day when the plane was 250 NM from the airport threshold. In the case of shorter trajectories, a correspondingly shorter time is used and, therefore, smaller time windows. Additionally, the climb part of the trajectory is not included because CDOs cannot be considered at this stage.

3. Experimental scenario

3.1. Air traffic data

In this work, eleven European airports located in the countries associated with the European Civil Aviation Conference (ECAC) were taken into account. For the airports selected for research, the necessary data were obtained from Aeronautical Information Publications (AIP) of each of the countries in which the selected airports are located. The airports and their respective ICAO codes are presented in the Table 1.

Table 1. Airports selected for the study

Airport	ICAO Code	Airport	ICAO Code
Brussels Airport	EBBR	Barcelona El-Prat Airport	LEBL
Manchester Airport	EGCC	Palma de Mallorca Airport	LEPA
London-Stansted Airport	EGSS	Paris-Orly Airport	LFPO
Copenhagen-Kastrup Airport	EKCH	Roma-Fiumicino Airport	LIRF
Oslo-Gardermoen Airport	ENGM	Zurich-Kloten Airport	LSZH
Warsaw Chopin Airport	EPWA		

Air traffic data were obtained from the Data Demand Repository 2 (DDR2) (EUROCONTROL, 2015) database using the Network Strategic Tool (NEST) (EUROCONTROL, 2016) software. Both DDR2 and NEST are provided by EUROCONTROL.

Current trajectories, in NEST terminology designated CTFM (Computed Traffic Flight Model) or M3, were used for the experimental scenario. M3 is the initial trajectory (last filled flight plan) updated with available radar measurements whenever the flight deviates from the last filed flight plan by more than any of the predefined thresholds: 5 minutes, 7 FL or 20 NM; this trajectory is the best available estimate of the actual flight trajectory as managed by controllers on the day of operation.

In the sequencing problem, the arrival sequence for the entire day was used because outlier observations do not affect the solution, and at the same time, using the full arrival sequence increases the size of the problem, which results in more complex scenarios with a higher traffic intensity, the analysis of which was the purpose of this work.

Time separations at the intermediate fix (IF) point in which the aircraft should already be stabilized on the ILS glide path were analyzed, so IF was the fix variable present in Eq. (2.4). The time at a given distance to airport T_p^0, used in Eqs. (2.5)–(2.7), was calculated using the DDR2 data, by summing segments length from reverse for each trajectory, and where the sum reached the desired value, a linear approximation was used to find the time of day, as passenger aircraft velocity usually changes very slowly.

3.2. Solver configuration

The MILP problem defined by Eq. (2.1) was implemented in the *IBM ILOG CPLEX Optimization Studio 12.9* optimization environment using the Optimization Programming Language (OPL) and solved using the CPLEX solver, which is intended, among others, for solving large-scale mixed-integer linear optimization problems. To solve the problem, the *branch and cut* method was used, based on the *divide and cut* method. This method involves creating a tree of subproblems and searching it to find a solution. MILP problems can have multiple solutions located in different places in the solution tree, and finding all of them can be very time-consuming. The solution of the optimization problem is completed after searching the entire solution tree, and the *divide and cut* method implemented in the CPLEX solver uses several algorithms that cut off the areas of the tree that do not provide an integer solution in order to reduce the problem, heuristic algorithms supporting the solution search process, and other methods to improve the optimization process. A description of all methods can be found in the optimization environment documentation (IBM, 2017).

The calculations were performed on a computer with 16 GB RAM and a Intel® Core^{TM} i7-7500U processor with a base clock frequency of 2.7 GHz. All processor cores were used for calculations.

4. Results

The minimization problem defined by Eq. (2.1) was solved for all days and airports considered in this work in order to assess the feasibility of the concept. Moreover, it was solved also for the scenarios with highest air traffic intensity days in order to search for the optimal solution. The optimality of a solution for such scenarios implies the optimality for scenarios with lower air traffic volumes, because as air traffic volumes increase, the airspace becomes more restricted and therefore there is a greater risk of conflict.

4.1. Feasibility analysis results

To investigate the feasibility of nearly 4000 test scenarios, containing totally over million of flights, the solver was configured so that the calculations ended when the first solution was found. Moreover, in order to be able to analyze all scenarios, it was decided to introduce a time limit of 60 seconds to find a solution. This time was additionally justified by the fact that, as noted in (Durand *et al.*, 2016), for automatic real-time air traffic management, the air situation should be updated at least every 2–3 minutes.

Table 2 presents feasibility analysis results of the arrival traffic sequencing process including CDO, RTA, TBS and RECAT-EU concepts.

Table 2. Results of feasibility analysis

Airport [ICAO Code]	Scenarios with solution [%]	Scenarios without solution [%]
EBBR	92.08	7.92
EGCC	98.63	1.37
EGSS	98.36	1.64
EKCH	99.18	0.82
ENGM	99.18	0.82
EPWA	100.00	0.00
LEBL	99.18	0.82
LEPA	99.18	0.82
LFPO	100.00	0.00
LIRF	60.93	39.07
LSZH	99.73	0.27

It can be observed that the results vary depending on the airport, but for most airports the results can be considered as very good. For EPWA and LFPO all test scenarios had a solution, for

EGCC, EGSS, EKCH, ENGM, LEBL, LEPA and LSZH 98–99% of the scenarios were feasible, and for EBBR approximately 92% of the scenarios were feasible. For LIRF, the results differ from the rest by around 61% of days with the solution. However, it should be emphasized that the results refer to the solution obtained in one minute, so it can be assumed that the results would be better for a longer calculation time. Moreover, it should be noted that this work examined scenarios based on past air traffic in which the planning stages did not take into account new concepts. Quick calculations of feasible solutions can be beneficial at the tactical planning stage, as aforementioned, the air situation should be updated at least every 2–3 minutes, but ideally, to maintain highest levels of safety, it should be performed as frequently as possible. In the future, by solving the air traffic sequencing task in the earlier planning stages, i.e. strategic and pre-tactical, it is expected that tactical scheduling will be used for real-time air traffic management due to weather conditions, delays or other events which were not considered in the sequences planned in advance.

4.2. Optimality analysis

In order to find optimal or better suboptimal solutions, the aircraft sequencing problem was solved with a computation time limit of 21600 s (6 h) and without a limit of the solutions number. Also, the optimality criterion was defined as a relative gap value of less than 0.01%. The relative gap for MILP tasks is defined as the relative difference between the best integer solution found and the best solution to the problem if it were a linear optimization problem (IBM, 2017). For each airport, one day with a very high traffic scenario was selected for the analysis.

The results of the solution obtained after 21600 s of calculations and comparison with the first solution obtained in the feasibility analysis are presented in Table 3, which shows the values of the cost function obtained according to Eq. (2.1) for both cases. For the solution obtained after 21600 s, the value of the cost function which corresponds to the best solution found is presented. The gap value is also presented for this solution. Additionally to the data provided in the table: for EGSS, the optimization problem was solved in 8045 s and for EPWA, the optimization problem was solved in 2 s.

Table 3. Results of the optimality analysis

Scenario	First solution	Solution after 21600 s		
	Cost function value [s]	Number of solutions	Smallest cost function value [s]	Smallest gap [%]
EBBR	31341	38	15164	59.54
EGCC	107594	29	4946	3.17
EGSS	88201	28	3525	<0.01
EKCH	118218	50	8503	31.37
ENGM	108102	41	9057	33.07
EPWA	78924	18	2411	0.79
LEBL	132412	81	16138	51.44
LEPA	159813	68	12269	38.10
LFPO	124099	41	10357	45.26
LIRF	43606	48	14967	54.49
LSZH	119135	54	12673	53.59

By analyzing the results presented in Table 3, it can be seen that the first solution, although obtained very quickly, resulted in most cases in the value of the cost function several times or even several dozen times higher than in the case of a longer optimization time. The smallest relative difference in the cost function values occurred for EBBR and LIRF, where six-hour calculations allowed for obtaining results that were approximately 2 times and 3 times smaller, respectively. The largest relative difference in the value of the cost function occurred in the scenarios for EPWA, EGSS and EGCC, where the results were approximately 33 times, 25 times and 22 times better, respectively, than for the first solution.

It is worth noting that optimal or close to optimal solutions were obtained for EGCC and EPWA scenarios, hence the significant improvement in results. For the remaining scenarios, the solution obtained after six hours is suboptimal, as evidenced by the gap value, but despite this, the obtained solutions were about 10 times better. It should be emphasized here that the gap value of several dozen percent does not always mean that a significant change in the best result is still possible. In some cases, this may mean that there is still a significant part of the solution tree to search, but not necessarily containing feasible solutions to the MILP problem. Therefore, some of the presented solutions may be optimal solutions, but this is not known until a solution is obtained based on criteria other than time.

The significant amount of time needed to search for optimal solutions means that this activity can be carried out at the strategic and pre-tactical planning stages. It is worth noting that properly performed analyzes at the strategic and pre-tactical planning stages may result in tactical planning with solutions close to the solution with the lowest possible value of the cost function. In addition to the value of the cost function, attention should be focused on the number of solutions. For all scenarios, from several to several dozen of solutions were obtained. It was observed that a large part of the solutions were found in the first minutes of calculations, and over time the number of solutions found decreased, however, in some cases, after a long period without new solutions, there was a sudden increase in the number of solutions at various moments of calculations. This was due to the fact that the solver found a region of the tree that had combinations of values which allowed obtaining feasible arrival sequences. Multiple solutions with different characteristics located in different areas of the tree can be an operational advantage. Some solutions may be unsatisfactory, e.g. from the perspective of airline operators or airport operators. Obtaining several dozen solutions for scenarios with a high air traffic intensity makes it possible to consider extending the optimization task with additional constraints to take into account other air traffic management needs.

5. Conclusions

A method for automatic sequencing of arriving air traffic was presented, taking into account continuous descent trajectory techniques, required time of arrival and time-based separations. A feasibility study was carried out using an extensive set of real air traffic data. An optimality analysis was also performed for scenarios with the highest air traffic intensity.

Based on the analyzes performed and the results obtained, conclusions can be drawn. Firstly, in the vast majority of cases, it is possible to solve the problem of sequencing of the arrival traffic in the case of simultaneous use of CDOs, RTA, TBS and initiation of descent trajectory control at a distance of 250 NM from the destination point, through appropriate formulation and solution of a mixed integer linear optimization problem. Secondly, automatic sequencing of arrival traffic may have practical applications in air traffic control, where optimal sequences may be obtained at the strategic and pre-tactical planning stages, and suboptimal sequences may be obtained at the tactical planning stage. Finally, the use of time-based separations creates a room for the development of new robust methods for air traffic control.

Future research may aim to use dynamic models of larger numbers of aircraft to more accurately reflect the airspace situation. In order to assess the feasibility of methods in test scenarios, one target navigation point was considered, in which full air traffic synchronization should be achieved. The methods can be extended to many points on the descent trajectory, which will lead to more control of the situation in the airspace. The future research may also focus on extending the presented methods to include the influence of more factors, e.g. weather conditions.

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Manuscript received October 5, 2023; accepted for publication October 21, 2024