

Engineering Notes

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Aircraft Landing Scheduling Optimization for Single Runway Noncontrolled Airports: Static Case

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Nomenclature

- a_i = time aircraft i lands after the preferred landing time P_i ($i = 1, \dots, N$)
- b_i = time aircraft i lands before the preferred landing time P_i ($i = 1, \dots, N$)
- C = cost coefficient vector defined in the linear programming problem
- E_i = earliest landing time for aircraft i ($i = 1, \dots, N$)
- f_i = penalty cost per unit of time if aircraft i lands before the preferred landing time P_i ($i = 1, \dots, N$)
- g_i = penalty cost per unit of time if aircraft i lands after the preferred landing time P_i ($i = 1, \dots, N$)
- L_i = latest landing time for aircraft i ($i = 1, \dots, N$)
- N = number of aircraft
- P_i = preferred landing time for aircraft i ($i = 1, \dots, N$)
- S_{ij} = separation time requirement between aircraft i and j , where aircraft i lands before j ($i = 1, \dots, N$, $j = 1, \dots, N$, $i \neq j$)
- x_i = landing time for aircraft i
- X = decision variable vector defined in the linear programming problem
- Z = objective function defined in the linear programming problem
- δ_{ij} = 1 if aircraft i lands before aircraft j and 0 otherwise ($i = 1, \dots, N$, $j = 1, \dots, N$, $i \neq j$)

I. Introduction

AIR traffic control automation consists of two basic functionalities: trajectory analysis to provide flight-path predictions, and aircraft scheduling to take advantage of accurate aircraft trajectories to produce efficient landing sequences [1]. In the past decade, researchers at NASA Ames Research Center have been

developing an air traffic control (ATC) automation tool called Final Approach Spacing Tool (FAST) to assist terminal radar approach control (TRACON) controllers in efficiently scheduling arriving aircraft [2]. A similar yet simpler ATC automation tool could potentially enhance the current transportation capabilities of the nation's small airports and thus provide some relief to the congestion at hub airports, particularly in high-density corridors for point-to-point travel [3]. However, within the class G airspace around small airports the pilot is responsible for traffic avoidance even for instrument flight rules (IFR) traffic, and so a "one-in/one-out" or first-come-first-served (FCFS) procedure is enforced. Clearly, capacity at these noncontrolled airports is severely constrained because a single operation can take over 15 min to complete [4]. A new general aviation (GA) concept of operations called the small aircraft transportation system (SATS) is designed to assist pilots in taking responsibility for self-separation during high-volume operations (HVO) within the terminal area of noncontrolled airports, thereby placing the focus on improving aircraft scheduling [5]. In static scheduling the decision is made only once during the entire landing operation at a certain scheduling point, chosen as the time when the first aircraft reaches the waypoint that is 20 n miles from its assigned initial approach fix (IAF). In dynamic or online scheduling, aircraft are rescheduled constantly during the complete landing operation due to changes in the dynamic operational environment, such as the appearance of new aircraft, which is applicable to the case of heavy traffic or emergency situations.

This Note develops a static optimization algorithm for scheduling GA aircraft landing at SATS-type single runway noncontrolled airports. A scheduling model for noncontrolled airports is developed followed by an optimal scheduling algorithm tailored to this model using objective functions and the performance metrics of total cost of deviation, total holding time, and total delay time of the feeder route. Numerical examples are presented for real-time Monte Carlo flight simulation comparisons of a linear programming scheduling algorithm to the FCFS scheduling algorithm, in terms of the performance metrics.

II. Aircraft Landing Scheduling Problem

The aircraft landing scheduling problem is concerned with determining landing times on a runway for a sequence of aircraft, such that each aircraft lands within its predetermined landing time window, while satisfying separation criteria between aircraft. The landing time must lie within a predetermined time window, bounded by an earliest time and a latest time. The aircraft can land at the earliest time if it flies at its maximum airspeed, but it will land at the latest time if it flies at its most fuel-efficient airspeed while also holding for the maximum allowable time [6]. Each aircraft produces its preferred landing time if it flies at its most economical preferred speed, the cruise speed. If the aircraft is required to slow down, hold, or speed up for separation assurance or other incidental reasons, extra cost will be incurred. In general, this cost will grow as the difference between the assigned landing time and the preferred landing time increases. Another issue is the separation criterion assurance. The landing time separation between an aircraft and its successor must be greater than a specified minimum, the *landing separation time*. The landing separation time depends on the type of the aircraft due to wake vortex considerations.

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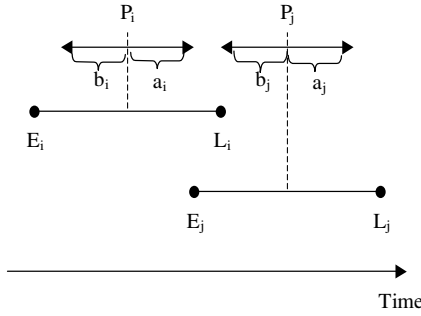


Fig. 1 Example of overlapping landing time windows.

Research on aircraft scheduling can be divided into efficient scheduling algorithms or performance potentials and overall strategies of automated aircraft scheduling [1]. The aircraft landing scheduling problem is usually considered as an application in the field of operations research, and two approaches are often taken: linear/integer programming (LP) and job-shop scheduling. As shown in a later section, the aircraft landing scheduling problem is described as an LP problem by representing the separation requirements of all pairs of aircraft and the landing window constraints of each aircraft in the standard linear/integer programming form [6,7].

III. Aircraft Landing Scheduling Model for Single Runway Noncontrolled Airports

The vast majority of SATS-type noncontrolled airports have instrument approaches designed only for the primary runway, and because only about 1% of the airports are capable of multiple runway operations, only the single runway scheduling model is developed here.

A. Constraints

The landing time window of aircraft i is denoted $[E_i, L_i]$, and $E_i \leq P_i \leq L_i$. Figure 1 is a graphical representation of the constraints developed next showing the overlapping landing time windows of aircraft i and j . The first set of constraints are

$$E_i \leq x_i \leq L_i, \quad i = 1, \dots, N \quad (1)$$

which ensures that each aircraft must land within its predetermined landing time window. Now, considering pairs of aircraft (i, j) provides another constraint:

$$\delta_{ij} + \delta_{ji} = 1, \quad i = 1, \dots, N; \quad j = 1, \dots, N; \quad i < j \quad (2)$$

In words, either aircraft i must land before aircraft j ($\delta_{ij} = 1$) or aircraft j must land before aircraft i ($\delta_{ji} = 1$). The constraints described in the preceding equations mainly deal with the order of pairs of aircraft (i, j) . However, even if the landing order of pairs of aircraft (i, j) is known, it does not necessarily imply the separation constraints are automatically satisfied. For example, if the landing time window for two aircraft i and j are [10,20] min and [30,40] min, respectively, and the separation time is 15 min, the separation constraint is not automatically satisfied; there exist landing times for i and j that violate the separation constraint. Hence, the separation constraint is necessarily defined as

$$x_i + S_{ij}\delta_{ij} - (L_i - E_j)\delta_{ji} \leq x_j, \quad (3)$$

$$i = 1, \dots, N; \quad j = 1, \dots, N; \quad i \neq j$$

Two cases are considered here. First, if $\delta_{ij} = 1$, then i lands before j , and thus $\delta_{ji} = 0$ from Eq. (2). Therefore, inequality (3) becomes $x_j \geq x_i + S_{ij}$, ensuring that the separation requirement is satisfied. Second, if $\delta_{ij} = 0$, then j lands before i , and thus $\delta_{ji} = 1$ from Eq. (2). Therefore, inequality (3) becomes $x_i - x_j \leq L_i - E_j$, and it can be deduced easily starting from the inequality (1). Finally, the constraints that relate the a_i , b_i , and x_i variables are

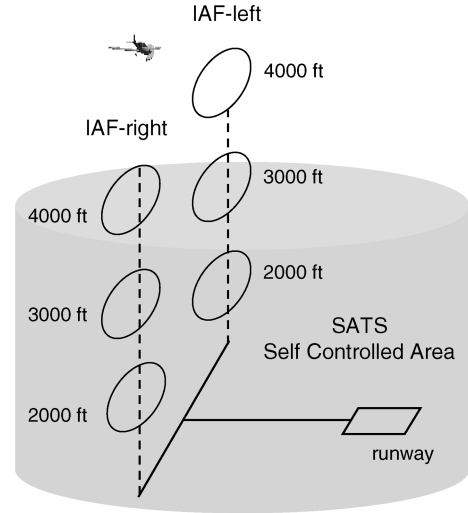


Fig. 2 SATS self-controlled area high-volume operations concept.

$$\max(0, P_i - x_i) \leq b_i \leq P_i - E_i, \quad i = 1, \dots, N \quad (4)$$

$$\max(0, x_i - P_i) \leq a_i \leq L_i - P_i, \quad i = 1, \dots, N \quad (5)$$

$$x_i = P_i - b_i + a_i, \quad i = 1, \dots, N \quad (6)$$

Inequality (4) ensures that b_i is at least the maximum of zero and the time difference between P_i and x_i , and at most the time difference between P_i and E_i (see Fig. 1). Inequality (5) shows a similar meaning for a_i . Equation (6) relates the a_i , b_i , and x_i variables to P_i . It should be noted that, for the i th aircraft in a specified scenario, at least one of the values among a_i and b_i should be equal to zero.

B. Problem Specific Features of Noncontrolled Airports

Noncontrolled airports are always surrounded by uncontrolled airspace (class G airspace), with a ceiling of 700 or 1200 ft above ground level, in which the “one-in/one-out” procedure is enforced during IFR operations. In the SATS self-controlled area (SCA) HVO concept, the SCA is a block of airspace established around noncontrolled airports that enables multiple operations by having aircraft hold in stacks at the IAFs and then follow specified procedures (either vertical entry or lateral entry) to enter the SCA and complete their approaches (Fig. 2). It is assumed for the present work that the prescribed sequences are achieved in the holding stacks with reasonable workload levels and equitable service.

C. Objective Functions and Performance Metrics

Two objective functions based on the special features of the SCA HVO are used as two of the three performance metrics used in the numerical examples. A third performance metric that is not an objective function, i.e., a relation used for optimization, is also introduced.

1) Minimize total cost of deviation (TCD) from the preferred landing time. This is the sum of weighted dynamic time of arrival (DTA) deviation of all aircraft in a scenario, where DTA is the actual arrival time of the flight, as opposed to estimated time of arrival (equivalent to the preferred landing time), which is a time value estimated in advance. Deviation time is calculated as the difference between DTA and the preferred landing time (the flight time from the scenario entry point to the runway, assuming constant holding speed). The weights for DTA are the penalty costs f_i and g_i , and they are set depending on the aircraft type:

$$\text{Minimize} \quad \sum_{i=1}^N (f_i b_i + g_i a_i) \quad (7)$$

Table 1 Numerical results of test scenarios

Number of aircraft in scenario	FCFS solution TCD, min		Optimal solution TCD, min		FCFS solution THT, min		Optimal solution THT, min		FCFS solution TDT _{feeder route} , min		Optimal solution TDT _{feeder route} , min	
	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation
4	13.95	2.12	4.90	0.54	21.11	2.32	9.57	0.79	6.87	1.03	5.32	0.47
6	19.64	2.84	9.15	1.09	30.73	3.00	13.75	1.57	10.65	1.43	7.16	0.69
8	30.17	2.93	13.13	1.18	36.04	4.03	18.08	1.95	15.74	1.92	9.23	1.22
10	36.52	3.28	17.92	1.99	48.55	5.14	24.81	2.26	20.95	2.03	12.54	1.45

2) Minimize total holding time (THT): the sum of delay time of all the aircraft in a scenario during the flight segment of three SATS holding patterns (2000, 3000, and 4000 ft). The holding time for one aircraft is the time from the IAF until it can begin its approach; total holding time is the sum of the holding times for all aircraft. In the context of SCA HVO procedures it measures the total “wasted time” of all aircraft while flying holding patterns above or within the SCA.

3) Total delay time (TDT) of the feeder route: the sum of the delay time of all aircraft in a scenario during the feeder route flight segment (from the scenario entry point to IAF) as a result of implementing the prescribed sequence. This is not an objective function but is introduced here as an important supplementary metric for evaluating flight efficiency because the delay incurred from the scenario entry point to the IAF is not accounted for in the total holding time.

D. Scheduling Point

The scheduler makes its scheduling decision at a certain scheduling point, e.g., the origination airport or the boundary of Center airspace. Because SATS HVO scenarios are used here to evaluate the scheduling algorithms, the scheduling point is chosen as the time when the first aircraft in each scenario reaches the waypoint that is 20 n miles to its assigned IAF.

The complete aircraft landing scheduling model of the single runway case for noncontrolled airports is now established: minimize either total cost of deviation or total holding time subject to equations and inequalities (1–6), and relation (7).

IV. Aircraft Landing Algorithms for Single Runway Noncontrolled Airports

A. First-Come-First-Served Scheduling Algorithm

Instead of using an objective function, the FCFS paradigm is applied as long as constraints (1–6) are satisfied: the first aircraft to reach the scheduling point gets the first slot, the aircraft nearest to the scheduling point (according to the time-based linear projection) gets the second slot, etc. Procedure-based projection is used to calculate the time from the scheduling point until the aircraft lands because the aircraft has to fly specified procedures defined in the SCA HVO to complete an approach. Thus an aircraft must fly the holding pattern in stacks at the IAF before it enters the SCA vertically.

B. Optimal Scheduling Algorithm

The scheduling model developed in the preceding sections is formulated here as an LP problem, which is an optimization of the form

$$\text{Minimize} \quad Z(X) = C^T X \quad (8)$$

$$\text{subject to} \quad AX \geq B \quad (9)$$

where the vector $X = (x_1, \dots, x_n)$, satisfying the inequality set (9), is a feasible solution and Eq. (8) is one of the two objective functions described in Sec. III.C. The LP problem is to find a feasible solution that minimizes (8), and the most popular method for finding this solution is the simplex algorithm [8]. It is an iterative procedure that finds an optimal solution or detects infeasibility after a finite number

of steps, and the current solution being searched is discarded when the cost exceeds the best-known feasible solution.

V. Numerical Examples

The optimal scheduling algorithm is compared with the FCFS scheduling algorithm for landing operations at single runway noncontrolled airports using the performance metrics of total cost of deviation, total holding time, and total delay time of the feeder route. The scheduling model is implemented in the automated safety and training avionics (ASTRA), a real-time computerized airborne expert system and simulation environment that uses multiple intelligent aircraft agents [9]. Each agent is equipped with simulated automatic dependent surveillance–broadcast devices that provide traffic information and scheduling decisions from the scheduler. The agents also implement the SATS conflict detection and resolution (CD&R) algorithm module to plan maneuvers for an optimized and conflict-free trajectory. Complete knowledge of all aircraft to be sequenced is assumed and is defined here as aircraft state information (altitude, longitude, latitude, airspeed, vertical speed, and heading), time stamp, flight-path intent information (the next two waypoints on the intended flight path), fuel status, and emergency priority.

The operational objective for all scenarios is to schedule the landing of between 4 and 10 aircraft over a 1 h time period. Scheduling solution values (performance metrics) for the FCFS approach are found by scheduling each aircraft at its preferred landing time, provided it is feasible. If it is not feasible, then the aircraft is scheduled as early as possible. For the optimal scheduling both the landing sequence and scheduling solution values are determined solely by minimizing the corresponding objective function. Four categories of test scenarios consisting of 4, 6, 8, and 10 aircraft initially placed outside the SCA of Texas State Technical College (TSTC) Waco Regional Airport (KCNW), Waco, Texas, are evaluated. Initial locations are determined randomly according to a Gaussian distribution with a mean distance of 25 n miles to the assigned IAF and a standard deviation of 5 n miles. GA aircraft types used are heavy (e.g., Rockwell Commander 700), medium (e.g., Cessna 182), or light (e.g., Piper Cub) and appear randomly in any scenario with probabilities of 0.2, 0.4, and 0.4, respectively. Each aircraft has a cruise speed, approach speed, and holding speed. Separation time requirements for a scenario are set according to aircraft type, e.g., 5 min for a heavy–heavy case and 2 min for a light–light case. Although the standard wake vortex separation times for GA-type aircraft are of the order of 1 min, for the relatively large number of aircraft (in the SATS sense) used in each scenario here, these larger separation times were found to provide the best overall performance of the CD&R algorithm. Monte Carlo simulation was used on 40 individual scenarios for each of the four scenario classes, run 4 times each for a total of 960 runs. The standard deviation for each performance metric was decreasing by less than 5% per every 10 runs after 960.

Results for the four scenario classes are presented in Table 1. All test scenarios produce converged solutions for both the FCFS scheduling and optimal scheduling algorithms. Compared with the FCFS scheduling, optimal scheduling decreased total cost of deviation by an average of 56.42%, total holding time by an average of 52.16%, and total delay time of the feeder route by an average of 34.21%. Test scenarios that involve more aircraft do not necessarily take more time to complete than those with fewer aircraft, despite the

accumulation of landing operation time. Because the scheduling solution value is found by scheduling each aircraft at its preferred landing time (if it is feasible for the FCFS approach), it is possible for the FCFS scheduling to provide the optimal solution in situations where it obtains the optimal sequence. This results from the randomness introduced in generating the test scenarios.

VI. Conclusions

A static optimization scheduling algorithm using linear programming was developed for automated aircraft landing scheduling at single runway noncontrolled airports and compared with a first-come-first-served scheduling algorithm. Real-time Monte Carlo flight simulation demonstrated that the optimal scheduling algorithm produces significant reductions in total cost of deviation, total holding time, and total delay time of the feeder route.

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