Journal of Air Transport Management 32 (2013) 39–48

Contents lists available at SciVerse ScienceDirect

Journal of Air Transport Management

journal homepage: www.elsevier.com/locate/jairtraman

Greedy algorithms and metaheuristics for a multiple runway combined arrival-departure aircraft sequencing problem

Gulsah Hancerliogullari [a,*], Ghaith Rabadi [a], Ameer H. Al-Salem [b], Mohamed Kharbeche [b]

[a] Old Dominion University, Department of Engineering Management and Systems Engineering, Norfolk, VA 23529, United States
[b] Qatar University, Department of Mechanical and Industrial Engineering, 2713 Doha, Qatar

Keywords:
Aircraft sequencing problem
Sequence-dependent separation times
Greedy algorithms
Metaheuristics
Total weighted tardiness

ABSTRACT

This paper examines the Aircraft Sequencing Problem (ASP) over multiple runways, under mixed mode operations with the objective of minimizing the total weighted tardiness of aircraft landings and departures simultaneously. The ASP can be modeled as a parallel machine scheduling problem with unequal ready-times, target times and deadlines. Furthermore, sequence-dependent separation times on each runway are considered to prevent the dangers associated with wake-vortex effects. Due to the problem being NP-hard, greedy heuristics and metaheuristics are applied in this paper to obtain solutions in reasonable computation times. The algorithms' solutions are compared to optimal solutions and their performances are evaluated in terms of solution quality and CPU time.

1. Introduction

The current capacity of airports is becoming insufficient due to growing air transportation demand and a huge increase in air traffic during the last decade. Therefore, some aircraft cannot land or depart at their preferred target-time. In order to achieve an efficient use of critical resources such as runways, devising appropriate methods for ASP is of great importance and is the main scope of this paper. Airport terminal maneuvering area (TMA) is of great interest to decision-makers since it is a critical link of air traffic operations chain. TMA includes managing air traffic control operations, runway scheduling and taxiway operations. Among these operations, runway scheduling is the one that affects the performance of the TMA the most (Sherali et al., 1992).

The ASP concurrently determines the assignment of each aircraft to a runway, the appropriate sequence of aircraft on each runway, and the departing or landing time on the chosen runway. It is assumed that each runway can accommodate at most one aircraft at any time, runways are reliable, and operate independently. The problem can then be modeled as an identical parallel machine scheduling problem with the runways being machines and the aircraft being jobs that have ready times (release times), target times (due dates), deadlines, tardiness penalties (weights), and sequence-dependent separation (setup) times.

As all aircraft generate wake vortices, a minimum time or a distance is set between aircraft to prevent the adverse effect; this safety buffer is referred as the separation time. Careful sequencing and scheduling can reduce the long separation and operating times. Minimum separation times between consecutive and certain nonconsecutive operations, and specified time-windows during which operations must take place are two of the major requirements of this scheduling effort. Minimizing the total weighted tardiness is a reasonable objective function to schedule landings and departures as close as possible to their target times. A mixed integer linear programming (MILP) model is provided to find optimal solutions. However, since minimizing the total weighted tardiness even for a single machine with all weights being equal is NP-hard (Lawler et al., 1982), ASP is also NP-hard, which means that it is computationally difficult to solve large scale instances in a reasonable amount of time. The initial problem of the paper can be regarded as a case study in which the greedy algorithms and metaheuristics are then customized and applied to the multiple runway aircraft sequencing problem when both arrival and departure flows are considered simultaneously. The greedy algorithms, namely the Adapted Apparent Tardiness Cost with Separation and Ready Times (AATCSR), the Earliest Ready Time (ERT) and the Fast Priority Index (FPI) are proposed. Moreover, metaheuristics, specifically Simulated Annealing (SA) and the Metaheuristic for Randomized Priority Search (Meta-RaPS) are introduced to the ASP to improve the initially constructed solutions by greedy algorithms.

---

* Corresponding author. Tel.: +1 7574720596.
E-mail address: ghancerl@odu.edu (G. Hancerliogullari).

0969-6997/$ – see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.jairtraman.2013.06.001

2. Problem definition

Using the $\alpha|\beta|\gamma$ notation of Lawler et al. (1982), the representation of the problem being researched is $Pm|rj,\delta_j,d_j,s_{kj}$, *time window*$|\Sigma wjTj$. The ASP can be defined as scheduling n aircraft (jobs) on m identical runways (machines) where each aircraft ($j = 1,\dots,n$) has a penalty weight w_j, becomes ready to operate on a runway at ready time r_j (i.e., aircraft cannot be scheduled before r_j), ought to start its operation (land or depart) by target time δ_j (planned latest time of an aircraft to operate) and before deadline d_j. A sequence-dependent separation time s_{kj} is enforced to avoid the dangers of wake-vortex effects when aircraft j operates after aircraft k. s_{kj} values depend on aircraft operations (departures, arrivals) and the size-class of the aircraft (small, large, heavy) (Federal Aviation Administration, 2003, Rabadi et al., 2012). For instance, a heavy aircraft requires a larger separation time before a smaller aircraft can land/depart; on the other hand, a small aircraft generates little air turbulence and, therefore, less separation time is necessary if it is scheduled ahead of a larger aircraft. Note that the wake-vortex separation requirements for departures-only or arrivals-only operations satisfy the triangular inequality, which is $s_{ab} + s_{bc} \geq s_{ac}$, if the separation time required between leading aircraft a and trailing aircraft b is s_{ab}. The implication is that when the spacing requirements between successive aircraft are ensured, the spacing requirements for all pairs of aircraft are met. However, the triangle inequality does not necessarily hold when both arrivals and departures are scheduled simultaneously (Balakrishnan and Chandran, 2010).

The start time of the operation for aircraft j is denoted by t_j, and the tardiness by $T_j = \max(t_{j-}\delta_j, 0)$. Missing the target time for aircraft j is possible at a weighted tardiness cost of w_jT_j if it misses its target-time. Missing the deadline, however, is not permitted where if aircraft j misses d_j, it will not be assigned to a runway, and the aircraft in such case is labeled as "unscheduled" resulting in an infeasible schedule. Target time-to-deadline window is the time window during which weighted tardiness cost is incurred; on the other hand, ready time-to-deadline window is the scheduling window in which aircraft have to operate. The scheduling objective is the minimization of the total weighted tardiness (TWT) which is expressed as $\sum_{j=1}^{n} w_jT_j$.

The minimum separation times adopted in this paper are specified in Table 1. These minimum safety separation times are enforced by the Federal Aviation Administration (FAA), the national aviation authority of the United States. This precaution is necessary because the triangle inequality does not systematically hold for the separation times. It has been noted in Sherali et al. (2010) and Balakrishnan and Chandran (2010) that the separation times in Table 1 do not automatically ensure proper separation between any pair of aircraft having the same operation type that are interspersed with an aircraft operation of the opposite type (e.g., two landings separated by a departure or two departures interspersed with a landing). Referring to Table 1, consider the case where a heavy arrival immediately precedes a heavy departure. This requires a minimum separation time of 40 s. Now, if the latter immediately precedes a heavy arrival, a minimum separation of 50 s is necessary between these two consecutive operations. However, the minimum separation time between the first leading aircraft and the third following aircraft (which are two heavy arrivals) should be $99 > 40 + 50$ s. Therefore, separation standards must be satisfied for consecutive and possibly nonconsecutive aircraft that have the same operation type, and are assigned to the same runway.

Due to the specific separation times used in this paper, which are similar to those in Sherali et al. (2010), it is necessary to ensure the separation of an aircraft between at most 4 consecutive aircraft. By denoting the start time of the aircraft in the kth position by $t_{[k]}$ and the separation time between aircraft at positions k_1 and k_2 by $s_{[k_1,k_2]}$, the start time of an aircraft operation k for up to 4 positions can be obtained by Eqs. (1)–(4).

$$t_{[1]} = r_{[1]}; \tag{1}$$

$$t_{[2]} = \max\left\{r_{[2]}, t_{[1]} + s_{[1,2]}\right\}; \tag{2}$$

$$t_{[3]} = \max\left\{r_{[3]}, t_{[1]} + s_{[1,3]}, t_{[2]} + s_{[2,3]}\right\}; \tag{3}$$

$$t_{[k]} = \max\left\{r_{[k]}, t_{[k-1]} + s_{[k-1,k]}, t_{[k-2]} + s_{[k-2,k]}, t_{[k-3]} + s_{[k-3,k]}\right\}, \quad \forall\, k = 4,\dots,n \tag{4}$$

3. Literature review

Both exact and heuristic algorithms have been proposed for the ASP, with approximate algorithms recently gaining attention due to the fact that for large problems it may take a long time to reach optimal solutions. Bennell et al. (2011) provides a recent survey on ASP where a comprehensive review of operations research techniques is mentioned such as dynamic programming, branch and bound, heuristics and metaheuristics that have been used to schedule aircraft landing and departures.

Early work on ASP dates backs to the early 80s where Psaraftis (1980) investigated a single machine scheduling problem for which a dynamic programming approach was developed and applied in the context of sequencing aircraft arrival operations. Beasley et al. (2000) proposed a mixed integer linear program (MILP) model for the single and multiple runways aircraft sequencing problem, and applied a heuristic algorithm which is a version of First-Come-First-Serve (FCFS) for aircraft landing problems (ALP). Due to the relative priority of landings over departures, the literature mostly focuses on the single runway aircraft landing problem. However, Gupta et al. (2009) presented a MILP for aircraft departures based on operations at Dallas-Fort Worth International Airport. The combined arrival-departure ASP was studied over a single runway by Sherali et al. (2010). The problem was modeled as

Table 1
Minimum separation times (s) from Sherali et al. (2010).

Leading/following	Heavy	Large	Small
Arrival → departure case			
Heavy	40	40	40
Large	35	35	35
Small	30	30	30
Leading/following	Heavy	Large	Small
Arrival → arrival case			
Heavy	99	133	196
Large	74	107	131
Small	74	80	98
Leading/following	Heavy	Large	Small
Departure → departure case			
Heavy	60	90	120
Large	60	60	90
Small	60	60	60
Leading/following	Heavy	Large	Small
Departure → arrival case			
Heavy	50	53	65
Large	50	53	65
Small	50	53	65