An Optimization Framework for Terminal Sequencing and Scheduling: The Single Runway Case

Jitamitra Desai and Rakesh Prakash

Abstract This paper addresses the static aircraft sequencing problem over the entire terminal maneuvering area (TMA) under a mixed-mode, single runway operating scenario. In contrast with existing approaches that only consider the runway as a bottleneck, our approach optimizes flight sequences and schedules by taking into account the configuration and associated constraints of the entire TMA region. This problem is formulated as a 0-1 mixed-integer linear programming problem. Efficient preprocessing and variable fixing strategies, along with several classes of valid inequalities, are derived to tighten the continuous relaxation of the problem. Computational results on illustrative examples show the overall delay in the system can be reduced by nearly a 30 % margin over the default FCFS policy and by nearly 10 % over the runway sequencing policy.

Keywords Aircraft sequencing problem · Terminal sequencing and scheduling · 0-1 mixed integer programming · Runway optimization · Air traffic management · Arrival and departure management

1 Introduction

As global business activities shift their focus towards the Asia-Pacific region, a steep increase in air traffic is expected over the next two decades, with global passenger throughput estimated to touch the nine billion mark by 2025. Air

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transportation systems world-wide are currently operating at (or close to) capacity due to the rapid increase in air traffic demand, leading to severe congestion and delays. According to the Bureau of Transportation Statistics (BTS), in 2014, nearly one-fourth of all flights in the United States arrived late at their destination by at least 15 min, and of these late arrivals, nearly one-third were delayed due to the inability of the *Air Traffic Management* (**ATM**) system to efficiently handle the air traffic demand, and an additional one-third were caused by a concatenated effect of an arriving aircraft's delay on its next scheduled departure. Federal Aviation Administration (FAA) and Eurocontrol forecasts estimate that this imbalance in air traffic demand and existing airport capacity will continue to widen in the years ahead.

This flight delay syndrome is a very serious and widespread problem, and ever-increasing flight delays have placed a significant stress on the entire ATM system, costing airlines, passengers, and the overall economy several billions of dollars each year. In a study on the impact of delay by [1], it was estimated that, in 2007, there were direct losses of US$28.9 billion attributed to aircraft delay alone and moreover, this delay increases nonlinearly as a function of demand. The critical bottleneck within an ATM system is the capacity within a radius of about 50 nautical miles (nm) from an airport, namely the *Terminal Maneuvering Area* (**TMA**). In the United States, terminal area congestion accounted for 13 % of all delays in 2005; this number has been steadily increasing every year, and accounted for nearly 21 % of delays in 2013 (https://www.faa.gov/data_research/aviation_data_statistics/).

There are several possible areas of improvement that can be considered for decreasing or mitigating the flight delay propagation syndrome within the TMA region. The challenge lies in simultaneously achieving safety, efficiency, and equity, which are often competing objectives [2]. Current ATM systems address the issues of passenger safety, runway efficiency, and airline equity independently, and there are few solutions that handle all of these concerns simultaneously. One way of addressing this problem is to invest heavily into airport capacity expansions, but such strategic investments require long lead times and are subject to other national and economic constraints. However, according to [3], significant delay savings can yet be achieved within existing ATM systems by optimizing critical bottleneck operations related to arrivals, departures, runways, and taxiways.

One such aspect is the joint sequencing and scheduling of arriving and departing aircraft, which is commonly referred to in the literature as the *Aircraft Sequencing Problem* (**ASP**). Specifically, in the *static version* of this problem; given a set of aircraft, along with information on the earliest/latest operation time for each aircraft (be it an arrival or a departure), and the minimum safety regulations to protect trailing aircraft from wake vortices generating by leading aircraft; the objective is to determine the optimal sequence that maximizes runway throughput or minimizes the total delay in the system, when operating under a mixed-mode of operations.

Usually, air traffic controllers follow the *First-Come First-Serve* (**FCFS**) rule for sequencing flight arrivals and departures based on their *estimated time of arrival* or *departure* (**ETA** or **ETD**) on the *runway*. But, it is well-known that such a sequencing rule is very inefficient in practice as it induces a lot of delay into the system [4]. Hence, many air traffic management advisory systems such as COMPAS [5], MAESTRO [6], and FAST [7] have been developed to assist controllers better enable procedures in sequencing aircraft by allowing *position shifting* of aircraft with respect to the FCFS sequence. More specifically, these systems implement a *constrained position shifting* (**CPS**) strategy, a concept introduced in [8], wherein an aircraft cannot be shifted by more than k positions (the so-called *maximum position shifting* (**MPS**) parameter) from its initial FCFS-based position.

Recognizing that terminal area scheduling is indeed more realistic (as compared to only runway scheduling), while also affording greater flexibility in managing aircraft, in this research effort, we optimize the sequence of arriving and departing aircraft and determine the optimal flight schedules based on the entire TMA, where the objective is to minimize the total delay in the system. Our approach is a holistic approach (addressing safety, efficiency, and equity) that presents manifold improvements as compared to earlier works, both from a modeling perspective as well as practical considerations, such as: (i) Extension of the ASP to incorporate the configuration of the TMA, thereby accounting for all safety constraints and bottlenecks in the system; (ii) Inclusion of the CPS constraint within the optimization formulation, which forms an important component in maintaining equity amongst airlines; and (iii) Our formulation also yields the advantage of determining exact solutions, as compared to fuzzy logic implementations often seen in practice, thereby attaining minimum delays and improving overall system efficiency.

The remainder of this paper is organized as follows. In Sect. 2, a brief literature review that summarizes some of the prominent works on runway and terminal area scheduling is presented. Then, in Sect. 3, we formulate the aircraft sequencing problem, defined over the entire TMA, as a 0-1 *mixed-integer linear program* (**MILP**), and several variable fixing strategies and different classes of valid inequalities that serve to improve the continuous relaxation of the 0-1 MILP are also derived. Computational results related to an illustrative example are presented in Sect. 4, and finally, Sect. 5 summarizes the contributions of this work and suggests extensions for future research.

2 Literature Review

A recent survey by [4] identifies the following essential attributes of the aircraft sequencing problem: runway operating mode, which can be segregated (only one of landings or departures) or mixed (both landings and departures); single or multiple runways; static or dynamic sequencing; and the different types of objective functions that reflect different stakeholders such as aviation authorities, airlines, airport management, etc. It is worthwhile to note that arrival management has received significantly greater attention in the literature than departure management (possibly due to the critical nature of landings), and there are just a handful of papers that address the joint sequencing problem of both arrivals and departures.

2.1 Runway Sequencing and Scheduling

Most of the existing works in the literature solve the static aircraft sequencing problem by considering only the *runway* as a bottleneck within the ATM system. In such a scenario, the required safety regulations are imposed as *time-based* separation standards between leading and trailing aircraft, which are specified in Table 1. In a pioneering work, [9] modeled the static ASP problem using *general precedence* binary variables as a 0-1 MILP considering precedence restrictions, controller workload, runway workload balancing, and number of landings in a given time period, for single and multiple runways. In [10], the authors present another 0-1 MILP formulation for the same problem using *immediate precedence* binary variables. Furthermore, taking advantage of the underlying network structure and inherent time-window restrictions present in the problem, they prescribe several preprocessing procedures, and as a result, a significant reduction in computational time, in comparison to [9], was achieved for the same data sets.

Other notable works include [11] that deals with a genetic algorithm for scheduling aircraft arrivals at Heathrow airport, and [12] developed a tabu search method for sequencing aircraft departures. [13] modeled the ASP as a shortest path network, wherein aircraft sequences are represented as nodes in the network, edge weights denote the separation times between successive aircraft, and a dynamic programming algorithm is prescribed to solve this problem. [14] proposed genetic algorithms to efficiently schedule aircraft landings and reported empirical results for different scenarios. [15] modeled the static ASP problem as a traveling salesman problem (TSP); [16] presented a MILP formulation for the single runway aircraft landing problem; and [17] modified the earlier work of [15] by taking earliest/latest times into consideration. Finally, [18] studied an aircraft landing problem over a single runway with holding patterns, where an aircraft is assigned a set of disjoint time-windows and the objective function is to minimize the maximum time between consecutive landings.

Table 1 Time-based separation standards enforced at the runway for various cases of leading/following aircraft

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

2.2 Terminal Sequencing and Scheduling

To the best of our knowledge, only the work of [19] has considered solving the aircraft sequencing problem over the entire TMA region. They formulate this problem as a *job-shop scheduling model* with sequence dependent set-up times and release dates to schedule both arrivals and departures. More specifically, in this job-shop model, aircraft at different holding points near the entry fixes are treated as *jobs*, which are waiting to be scheduled and the trajectory segments that lie along a route from an entry gate to the runway, are modeled as a series of *machines*. Once a 'job' is released from its holding stack, it flows freely from one 'machine' to the next until it reaches the runway, which becomes the final machine for arriving aircraft and the initial machine for departing aircraft. However, they do not consider the use of time-windows for scheduling arrivals or departures, which greatly limits the practical applicability of their model. More importantly though, their computational results reveal that a bottleneck can occur anywhere in the TMA and not only on the runway threshold.

During the development of the *Final Approach Spacing Tool* (**FAST**) software, [7] found that merge points within the TMA cannot be ignored from a scheduling perspective because optimal sequencing based solely on runway constraints results in schedules that require heavy conflict detection and upstream resolution tasks. Therefore, the FAST algorithm begins by generating feasible sequences and schedules, and subsequently resolves conflicts that might arise by manipulating the trajectories of the pair of aircraft in conflict. When resolving such conflicts, the algorithm in FAST adds delays to the trailing aircraft and, in an indirect manner, adds to controller workload by issuing vectoring instructions.

Motivated by these earlier works on aircraft sequencing problems, in this paper, we present a mathematical programming framework for solving the joint arrival-departure sequencing and scheduling problem over the entire TMA region, where the objective is to minimize the total delay in the system.

3 Modeling and Analysis

The *Terminal Manoeuvring Area* (**TMA**) is a circular region having a 50 nm radius centered at the airport. At the boundary of the TMA, there are various *way-points* or *fixes*, labeled as entry (or meter) gates, through which traffic enters the TMA. The traffic from the enroute airspace merges at each entry gate and flows into the TMA as *one stream* from each gate. Given a stream, there is a pre-specified route leading to the runway, where a route can be best defined as a series of way-points, and where the sections of a route between two consecutive way-points is said to form a *trajectory segment*. (Multiple routes may share one or more of such trajectory segments.) An incoming aircraft from the enroute airspace either enters into the holding area near the entry gates or proceeds directly along a pre-specified route to its allocated runway. Traffic from different streams merges together at common way-points (merge points) and subsequently flows along the same route. Finally, all traffic designated for the same runway merges into a single stream at the *final approach fix* (**FAF**) and descends into the runway threshold. (This operation is normally performed at a distance of 5 nm from the runway.) Similarly, for departures, aircraft flow together towards the *initial fix* near the runway, and then diverge along different trajectory segments at way-points, finally exiting the TMA from the exit gates.

Once an approach procedure is initiated at the entry gates, a switch in position between aircraft on the same route is not permitted, and furthermore, during this entire approach operation, safety separation standards must be maintained between consecutive and non-consecutive pairs of aircraft. In contrast to the time-based separation standards enforced on the runway (see Sect. 2), the FAA-specified longitudinal safety separation requirements in the TMA region for both arrivals and departures are *distance-based*, which are displayed in Table 2.

As shown in Fig. 1, the TMA region has been represented as a *graph*, where the waypoints are shown as *nodes* or (*vertices*) and the trajectory segments between two consecutive waypoints as *edges*. Arrival traffic enters into the TMA through various entry gates and departure traffic enters into the runway through a holding

Table 2 Distance-based separation standards (in miles) enforced within the TMA for both arrivals and departures

Leading/Following	Heavy	Large	Small
Heavy	4	5	6
Large	3	3	4
Small	3	3	3

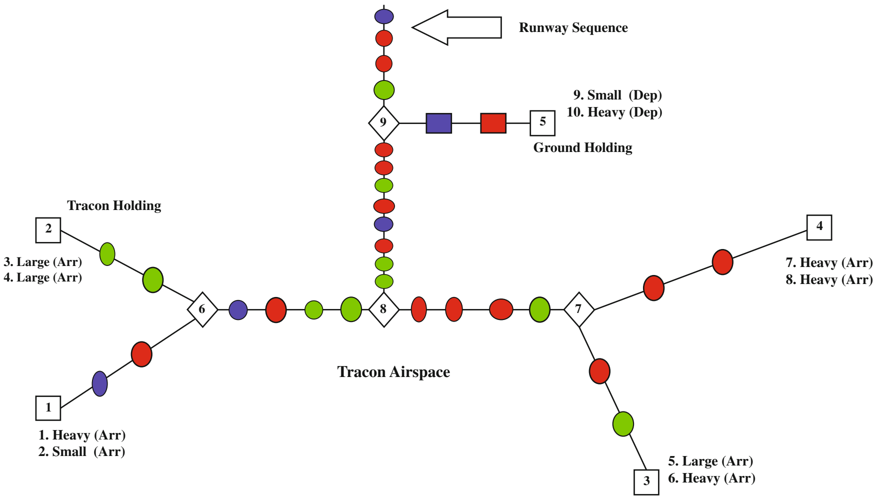

Fig. 1 A graphical representation of a TMA region with four entry fixes, four merge points, and a single runway

area, which is adjacent to the runway. It has been well-established that absorbing anticipated delays at higher altitudes, is always better from fuel consumption, safety, and controller workload viewpoints [20]. Hence, in our model representation, we work under the assumption that delay or earliness is induced in an aircraft before entering the TMA, either by adjusting its velocity or by holding at the entry gates. (For departure traffic, delay is induced on the ground.) As aforementioned, when compiling the final runway sequence, the nominal order of aircraft in the same stream is always preserved, thereby ensuring that overtaking is avoided and a runway closest to the entry fix of the aircraft is allocated.

The aircraft sequencing problem defined over the TMA can now be formulated, where the definitions of the index sets, parameters, and decision variables are given as follows.

Description of Index Sets and Parameters

- $n \in \mathcal{N} \equiv \{1, 2, \ldots, N\}$: Set of all nodes in the graph representing entry gates, merge points, departure holding area, and the runway
- $g \in \mathcal{G}$: Set of all the nodes in the graph representing entry gates, where $\mathcal{G} \subseteq \mathcal{N}$
- $(p, q) \equiv e \in \mathcal{E}$: Set of all the edges (trajectory segments) in the graph, where $p \in \mathcal{N}, q \in \mathcal{N}$
- r: Vertex representing runway
- $f \in \mathcal{F}$: Set of all arriving and departing flights
- v_i^e: Velocity of any flight i in trajectory segment $e \in \mathcal{E}$
- $\mathcal{F}^n$: Set of flights passing through vertex n, where $\mathcal{F}^n \subseteq \mathcal{F}$
- E_i^n: Earliest time of arrival (departure) of aircraft i at (from) vertex n
- T_i^n: Target time of arrival (departure) of aircraft i at (from) vertex n
- L_i^n: Latest arrival (departure) of any aircraft i at (from) vertex n
- Δt_{ij}: Minimum safety separation (in seconds) at runway threshold if flight i is ahead of flight j (see Table 1)
- Δs_{ij}: Minimum safety separation (in miles), if flight i is ahead of flight j (see Table 2)
- ROT_i: Runway occupancy time of aircraft i
- seq_i: Position of flight i based on the FCFS sequence
- k: Specified maximum position shifting (MPS) parameter

Decision Variables

- $x_{ij}^n = \begin{cases} 1, & \text{if flight } i \text{ is ahead of flight } j \text{ in schedule at vertex } n \\ 0, & \text{otherwise} \end{cases}$
- t_i^n = Scheduled time of arrival (departure) of flight i at (from) vertex n

$$\textbf{ASP-TMA} \quad \text{Minimize} \sum_{f \in \mathcal{F}} |t_f^r - T_f^r|. \tag{1a}$$

$$\text{subject to} \quad x_{ij}^n + x_{ji}^n = 1, \ \ \forall i < j, (i,j) \in \mathcal{F}^n, \forall n \in \mathcal{N}. \tag{1b}$$

$$t_i^q = t_i^p + T_i^q - T_i^p, \ \ \forall i \in \mathcal{F}^p \cap \mathcal{F}^q, \forall (p,q) \in \mathcal{E}. \tag{1c}$$

$$t_j^p \geq t_i^p + (\Delta s_{ij}/v_i^e) - M(1 - x_{ij}^p), \ \ \forall i,j \in \mathcal{F}^p. \tag{1d}$$

$$t_j^q \geq t_i^q + (\varDelta s_{ij}/v_j^e) - M(1 - x_{ij}^q), \ \ \forall i,j \in \mathcal{F}^q, \ \forall (p,q) \in \mathcal{E}. \tag{1e}$$

$$t_j^r \geq \max\{\varDelta t_{ij}, ROT_i\} + t_i^r - M(1 - x_{ij}^r), \ \ \forall i,j \in \mathcal{F}. \tag{1f}$$

$$-k \leq (F - \sum_{j \in \mathcal{F}, i \neq j} (x_{ij}^r)) - seq_i \leq k, \ \ \forall i \in \mathcal{F}. \tag{1g}$$

$$x_{ij}^q = x_{ij}^p \ \ \forall i < j, \ (i,j) \in \mathcal{F}^p, \ \forall (p,q) \in \mathcal{E}. \tag{1h}$$

$$E_n^i \leq t_n^i \leq L_n^i \ \ \forall i \in \mathcal{F}^n, \ \forall n \in \mathcal{N}. \tag{1i}$$

$$x_{ij}^n \in \{0,1\}, \ \ t_i^n \geq 0 \ \ \forall i,j \in \mathcal{F}^n, \ \forall n \in \mathcal{N}. \tag{1j}$$

In the above formulation, the objective function (1a) seeks to minimize the total delay; constraint (1b) enforces the order precedence between flights i and j at every vertex; constraint (1c) computes the scheduled time of arrival (or departure) of flight i arriving at node q from node p, where $(p,q) \in \mathcal{E}$, based on the condition of free flow of flights once they enter the TMA; constraint (1d) ensures the longitudinal separation requirement (in miles) between flights departing from each $n \in \mathcal{N} \backslash \{r\}$; constraint (1e) ensures the longitudinal separation requirement (in miles) between flights arriving at each $n \in \mathcal{N} \backslash \{r\}$; constraint (1f) ensures the time-based separation requirement between flights at the runway node r; constraint (1g) imposes the CPS constraint that an aircraft cannot be shifted by more than k positions from its initial (FCFS) position, where $F \equiv |\mathcal{F}|$; constraint (1h) avoids overtaking by maintaining the precedence relationship between two aircraft at succeeding way points; constraint (1i) maintains the scheduled time of arrival (departure) at each vertex to be between the earliest and latest times for each aircraft; and finally constraint (1j) imposes the binary and non-negativity restrictions on the x—and t—variables, respectively.

The ASP-TMA formulation described above can be further enhanced by prefixing some of the variables and by addition of valid inequalities that serve to tighten the underlying linear programming representation of the problem. In the following discussion, we derive several model enhancing features based on time-window restrictions, maintenance of nominal order of aircraft along the same stream, and relative position of an aircraft within the sequence. These strategies potentially help in obtaining a partial convex hull representation, and were therefore found to be very effective in our computations.

Variable Fixing Strategies

Proposition 1 *At any vertex n, consider a pair of aircraft* $i, j \in \mathcal{F}^n$. *If the FCFS sequence positions of i and j satisfy the condition:* $seq(j) - seq(i) \geq 2k$, *where k is the MPS parameter, then we can fix* $x_{ij}^n = 1$. □

Proposition 2 *For a pair of aircraft* $(i, j) \in \mathcal{F}^n$, *if* $E_j^n > L_i^n$, *or more generally, if* $E_j^n + sep_{ji}^n > L_i^n$, *we set* $x_{ij}^n = 1$, *where* sep_{ji}^n *denotes the to-be-maintained separation between a leading aircraft j and a following aircraft i.* □

Proposition 3 *At any entry waypoint g, consider a pair of aircraft* $i, j \in \mathcal{F}^g$ *that belong to the same category. Suppose that the time-window restrictions satisfy the following conditions:*

(i) $E_i^g \leq E_j^g$; *(ii)* $T_i^g \leq T_j^g$ *and (iii)* $L_i^g \leq L_j^g$. *Then, we can set* $x_{ij}^g = 1$. *(It should be noted that this prefixing routine cannot be applied at merge points because flights originating at different entry fixes are in negotiation at each intermediate node.)* □

Valid Inequalities

In order to improve the quality of the lower bound, decrease the required computational effort, and reduce the search space, we derive a set of valid inequalities, that are given below.

- Let $i, j \in \mathcal{F}^n$ be a pair of aircraft such that, $(L_j^n - E_i^n) \equiv \max\left\{t_j^n - t_i^n : \text{constraint } (1\text{i})\right\} > 0$. If $t_j^n - t_i^n > 0$, we can enforce $x_{ij}^n = 1$ by using the following valid inequality:

$$x_{ij}^n \geq (t_j^n - t_i^n)/(L_j^n - E_i^n) \;\; \forall i<j, i, j \in \mathcal{F}^n, L_j^n > E^n, n \in \mathcal{N}. \qquad (2\text{a})$$

- At any vertex n, clearly,

$$\sum_{i \in \mathcal{F}^n} \sum_{i \neq j, j \in \mathcal{F}^n} (x_{ij}^n) = F^n(F^n - 1)/2, \;\; \forall n \in \mathcal{N}, \text{ where } F^n \equiv |\mathcal{F}^n. \qquad (2\text{b})$$

- At any vertex n, given a 3-tuple of aircraft $(i, j, k) \in \mathcal{F}^n$, we can impose the transitive constraints that if aircraft i is ahead of aircraft j, which in turn is ahead of aircraft k, than it implies that i is ahead of k. The following valid inequalities are satisfied by any of the six possible (i, j, k) arrangements of planes.

$$x_{ik}^n \geq x_{ij}^n + x_{jk}^n - 1\,. \tag{2c}$$

$$x_{ik}^n \leq x_{ij}^n + x_{jk}^n \quad \forall i > j, j > k, (i,j,k) \in \mathcal{F}^n, n \in \mathcal{N}\,. \tag{2d}$$

We refer to the ASP-TMA formulation, given by (1a)–(1j), reinforced with all these variable fixing strategies and valid inequalities (2a)–(2d) as RASP-TMA.

4 Computational Results

For the sample TMA configuration shown in Fig. 1, we begin by considering a set of 10 aircraft, belonging to different weight categories, comprising eight arrivals and two departures. The earliest time of arrival (or departure) for all aircraft has been set as 100 s before their respective target time and the latest time is taken to be 1 h beyond the target time. The velocity of heavy, large and small categories of aircraft is given by 260, 160, and 140 nm/h, respectively, and it is assumed to be constant throughout the TMA. Arriving flights either stack up at entry gates (labeled as nodes {1, 2, 3, 4}), or enter the TMA, merging with other streams at merge points (labeled as nodes {6, 7, 8}), before finally merging with scheduled departures (at node labelled {9}), resulting in the final runway sequence.

We tested the relative effectiveness of three different sequencing models: FCFS; optimal runway sequencing (obtained by ignoring the TMA configuration constraints and enforcing only the runway separation standard in ASP-TMA); and the proposed ASP-TMA formulation. Figures 2 and 3 display the optimal sequences and associated delays obtained, using the aforementioned sequencing algorithms, corresponding to the MPS parameter $k = 1$ and $k = 3$ scenarios. As seen in Fig. 2, allowing an aircraft to shift its position by even one unit, with respect to its FCFS sequence-based position, can result in a significant reduction in total delay, and the accrued delay savings increase with an increase in the value of k (see Fig. 3). This result is further validated in Fig. 4, which plots the percentage delay savings obtained by the ASP-TMA model over the FCFS sequence as a function of k, for varying number of aircraft.

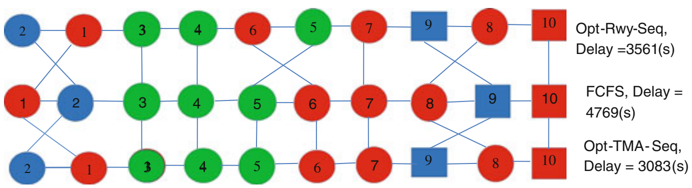

Fig. 2 Optimal sequences obtained by the three sequencing models for the case of k = 1

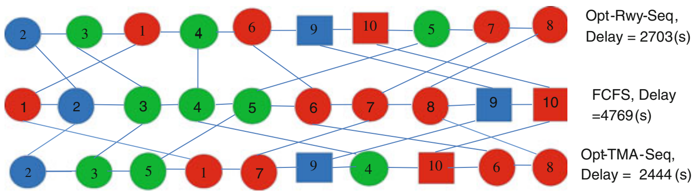

Fig. 3 Optimal sequences obtained by the three sequencing models for the case of k = 3

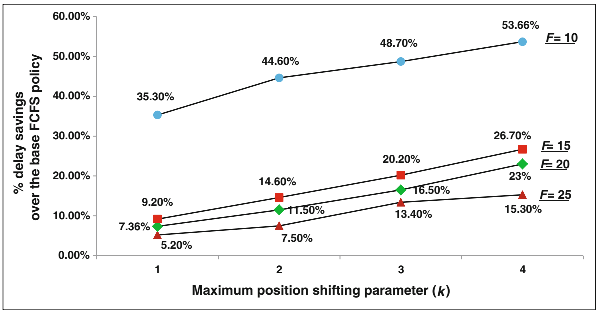

Fig. 4 Percentage delay savings as a function of MPS parameter k for varying numbers of aircraft

Having ascertained the efficacy of the proposed approach, we now examine the strength of the variable fixing strategies and derived valid inequalities by comparing the performance of ASP-TMA and the reinforced RASP-TMA models. Table 3 records various computational parameters, namely the CPU time (in seconds) taken to determine the optimal solution, branch-and-bound nodes enumerated and the LP-IP gap% at the root node, as a function of problem size and the MPS parameter k for these two models. As seen from the results, employing these preprocessing steps, leads to a significant reduction across all measured parameters with the LP-IP gap% having decreased on average to 81.6 from 100 %, when using the enhanced RASP-TMA formulation. Moreover, all of the larger test instances that could not be solved (when using a time limit of 3600 s) using ASP-TMA, were easily solved when reinforced with these additional strategies. Furthermore, it is worthwhile to note that the computational effort required increases significantly with an increase in k, even within data sets having the same number of aircraft. As a practical recommendation, based on our computational experience, we recommend using the RASP-TMA model with no more than a maximum position shifting parameter value of k = 2.

Table 3 Computational comparisons between ASP-TMA and RASP-TMA

		ASP-TMA			RASP-TMA		
No. of aircraft	*k*	CPU time (s)	Nodes	LP-IP gap (%)	CPU time (s)	Nodes	LP-IP gap (%)
10	1	0.07	615	100	0.02	15	55.9
	2	0.34	2037	100	0.06	174	88
	3	0.53	5153	100	0.14	1617	90.3
	4	1.06	13986	100	0.36	3306	92.3
15	1	1.04	2724	100	0.03	126	56.9
	2	6.74	52687	100	0.2	3852	85.6
	3	106.26	1304660	100	1.06	10780	92.3
	4	407.55	6739628	100	3.04	34011	92.3
20	1	4.30	5833	100	0.16	92	55.5
	2	421.74	2045306	100	1.53	10494	87.7
	3	>3600	_	100	8.43	42121	92.7
	4	>3600	_	100	23.39	115008	93
25	1	38.19	29214	100	0.16	1342	55.3
	2	>3600	_	100	1.96	23853	89
	3	>3600	_	100	32.95	41976	95
	4	>3600	_	100	141.87	861072	95.38

5 Conclusion

In this paper, we posed and solved the aircraft sequencing problem over the entire TMA region taking into account several realistic constraints such as longitudinal separations at the runway and in the TMA airspace, CPS constraints, and precedence maintenance requirements, with the objective of minimizing the total delay in the system. This complex problem was formulated as a 0-1 MILP, and several variable fixing strategies and valid inequalities are derived to improve the computational efficiency of the model. Our results indicate that significant delay savings can be achieved over the base FCFS policy schedule and over the runway optimized sequence. Our model is generic enough to be applied to different types of TMA configurations and can handle any mixture of traffic for the single runway case under segregated or mixed-modes of operations.

There are several potential areas of improvement that can be considered for future research, both from modeling and algorithmic perspectives. There are several classes of convex hull defining valid inequalities that can be gainfully employed to improve the model representation. Moreover, our formulation appears amenable to being solved via a Lagrangian dual approach. Furthermore, we can also extend this model to the multiple runway scenario (which is the case in most major airports). We are currently working on all of these improvements, and finally, a realistic computational case study at Changi airport is also being considered.

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