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Cooperative surveillance systems and digital-technology enabler for a real-time standard terminal arrival schedule displacement

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ABSTRACT

As the backbone of Communications, Navigation and Surveillance Systems for Air Traffic Management (CNS/ATM), Automatic Dependent Surveillance-Broadcast (ADS-B) is a surveillance technology and digital-technology enabler relying on the Global Navigation Satellite System (GNSS). The onboard ADS-B Out system broadcasts the aircraft's real-time digital information such as position and ground speed periodically (every 0.5–2 s), which is more frequent than the radar system. Taking this advantage, situational awareness and flight efficiency can be highly improved. In this paper, a novel heuristic search method based on ADS-B is proposed for the Aircraft Landing Problem (ALP) with the objective of reducing flight time while maintaining the time separation standards mandated by the International Civil Aviation Organization (ICAO). The recorded ADS-B data in Shanghai Hongqiao and Pudong international airports are adopted to demonstrate the performance of the proposed method. Results show that there is an obvious decrease in the total flight time. Besides, the heuristic search method can achieve continuous and real-time ALP updates, satisfying the requirements for air traffic control. While highlighting ADS-B-based applications, this study also provides some basic implications for the updated model in air traffic management.

1. Introduction

The civil aviation industry has experienced rapid growth in the past few decades. It is expected that the air transportation market will grow at 4.4% per annum in the next 20 years [1]. This trend contributes to the challenge of simultaneously achieving safety, efficiency, and equity, which are often competing objectives, in a reasonable amount of time [2]. The increasing air traffic demand causes longer flight delays [3,4], higher fuel consumption, and more aircraft emissions [5], which is particularly evident during severe weather occurrences [6]. During peak hours, some aircraft are required to enter a holding pattern to maintain safe separations [7].

Currently, Air Traffic Control Officers (ATCOs) rely on radar system [8,9] to maintain safe separations between aircraft. According to the International Civil Aviation Organization (ICAO) [10], "*a minimum of 300 m vertical separation or a minimum of 5.6 km radar separation shall be provided between aircraft during turn-on to parallel ILS localizer courses and/or MLS final approach tracks in the terminal area airspace*". However, radar performance is related to the power density at the target position, the reflected power, and the antenna gain [11], causing high uncertainty of aircraft positions. If aircraft's positions cannot be obtained accurately, ATCOs would deliberately enlarge the separation distance between aircraft to ensure safe operation. Consequently, there will be a reduction in airspace capacity and flight efficiency [12]. Besides, ATCOs suffer from eyes fatigue after focusing on the eye-tracking system for a long time [13]. In light of potential human failures and operational errors, virtual assistance systems have appeared in the cockpit and on the ground [14] to provide tactical decisions support and alert potential aircraft conflicts.

Considering the radar system's limitations, ICAO proposed the concept of Communications, Navigation and Surveillance Systems for Air Traffic Management (CNS/ATM). Serving as a key component,

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Automatic Dependent Surveillance-Broadcast (ADS-B) can provide aircraft real-time positions accurately and reliably [15]. Fig. 1 shows the schematic diagram of ADS-B application to ATM [16]. The aircraft's position is tracked by the Global Navigation Satellite System (GNSS), then the digital information containing the aircraft's real-time positions (longitude, latitude, and altitude) and other information (ground speed and callsign) will be broadcasted. Other aircrafts equipped with ADS-B In system and ground stations can receive these ADS-B signals. After that, these data are transmitted to the Air Traffic Control (ATC) center to achieve ATM. ADS-B provides more accurate position data than radar because ADS-B messages are updated more frequently with an update interval of 0.5–2 s, compared to the radar at 4–15 s [17]. Therefore, ATCOs will have an increased confidence in aircraft's real-time positions, allowing them to reduce the separation between aircraft without compromising flight safety, which can optimize airspace capacity and improve flight safety [18]. Nowadays, pilots are required to report to ATCOs when entering a new airspace sector [19], such as "*CCA101, 9,500 m maintaining, squawk 1234, 6 miles to FYG*". After that, ATCOs need to acknowledge said report [20], replying with "*CCA101, Shanghai control, radar contact*". In contrast, this communication procedure can be eliminated by using ADS-B, which can save time and energy for ATCOs and pilots.

The transformation to using ADS-B can allow close monitoring of real-time flight activities in the Terminal Manoeuvring Area (TMA). This modern design application supports both the separation distance measurement between aircraft and runway schedule displacement under dynamic situations [21,22]. One crucial issue is that the flight speed and arrival time on the waypoints and runway is subjected to wind direction and intensity, leading to uncertain ground speeds measurements of approaching flights [23,24]. Therefore, it is necessary to combine ATM with contemporary technologies and digital-technology enablers for flight tracking with information from the aircraft's avionic system. With accessibility to real-time flight information using ADS-B, data-driven decisions and flight safety can be significantly improved [25].

ATM can be broadly divided into three levels: (1) the strategic level includes runway expansion or shorter separation standards; (2) the pre-tactical level includes splitting traffic flows and sectors; (3) the tactical level includes sequencing and re-sequencing aircraft during flight operations [26]. Aircraft Landing Problem (ALP) is a dynamic problem at the tactical level which involves sequencing the optimal landing order for arriving flights [27]. Lieder et al. [28] summarized the related works before 2015 and indicated that "*To date, no efficient methods have been proposed in the reviewed literature for the multi-runway ALP that are capable of solving large problem instances*". Table 1 provides an overview of related articles from 2015. The most common objectives can be classified into four parts: (1) minimizing the total deviation time from target time; (2) minimizing the total flight delay; (3) maximizing the total airport throughput; (4) minimizing the makespan for all landing aircraft. The solution methods are mainly intelligent algorithms.

As mentioned above, previous articles about ALP mainly focus on optimizing algorithms without considering aircraft conflict detection and the common operational failure events such as missed approach. Although there are some researches about Unmanned Aerial Vehicles (UAV) using ADS-B [40,41], research gaps still exist in ADS-B application to civil aviation. To better understand digital transformation [42,43] and satisfy the rapid evolution of new service systems [44], a novel heuristic search method based on ADS-B technology is proposed to achieve continuous and real-time aircraft landing time updates and assignments considering the minimum time separation standards induced by wake turbulence. When a new flight enters the TMA, the heuristic search method can immediately generate an updated aircraft landing time with the objective of minimizing the total flight time. Based on the novel and powerful digital technologies, digital platforms, and digital infrastructures, this paper has three contributions:

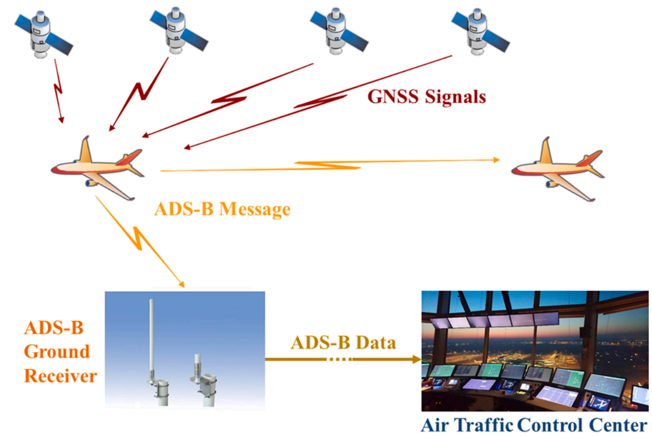

Fig. 1. Schematic diagram of ADS-B application to ATM [16].

Table 1
Overview of ALP articles from 2015.

Source	Objective	Solution method
Lieder et al. [28]	min total delay	Dynamic programming
Ng and Lee [29]	min makespan	Artificial bee colony algorithm
Rodríguez-Díaz et al. [30]	min total delay	Simulated annealing algorithm
Xu [31]	min makespan	Ant colony algorithm
Hong et al. [32]	min total flight time	Particle swarm optimization
Mahmud and Jeberson [33]	min total deviation time	Flower pollination algorithm
Prakash et al. [34]	max total throughput	Data-splitting algorithm
Ikli et al. [35]	min total deviation time	Mixed-integer programming
Lu et al. [36]	min total delay	Genetic algorithm
Wu et al. [37]	min total waiting time	Ant colony algorithm
Salehipour [38]	min total deviation time	Heuristic solution method
Vincent et al. [39]	min total delay	Mixed-integer programming

- Leverage ADS-B data: ADS-B is adopted to solve ALP by reducing communication time and monitoring aircraft's real-time positions.
- Continuous and dynamic scheduling for schedule displacement: The heuristic search method is a fast and effective method for continuous and real-time ALP updates.
- Consideration of operational failure events: The heuristic search method can update landing time when an aircraft is assigned a higher landing priority due to operational failure.

The remaining of this paper is organized as the following. Section 2 presents the proposed aircraft landing model. The schedule displacement heuristic is proposed in Section 3. Section 4 illustrates the case study background and describes the results. In Section 5, we discuss the causes for flight delay and give implications. Finally, conclusions are drawn in Section 6.

2. Problem definition

The proposed heuristic search for ALP is illustrated herein with some of its basic properties. We have considered a single-runway ALP model, which can be applied to a multi-airport TMA, on the condition that flight altitude regulations in flight routes are issued. The scheduling assignment for each flight is determined using the proposed heuristic, considering the hard constraint of sufficient time separation. The following three assumptions are made. First, all flights approach using the standard terminal arrival routes. Second, all flights descend in altitude by a standard rate of descent, aiming to keep a vertical separation between flights and guarantee no conflicts among different flight routes. Third, there is no conflict between arrival flights and departure flights.

For ease of explanation, a schematic diagram of ALP is presented in Fig. 2 [45]. There are three arrival routes from entry points to the runway. The target is to sequence all flights and assign their respective landing time considering the sufficient time separation constraint between two adjacent flights. After detecting flights entering TMA from the entry points using ADS-B, the heuristic solves ALP based on the current flight situation and updates aircraft landing time for all flights within the TMA. The detailed instructions generated from the heuristic are conveyed to pilots to manage air traffic flow.

The ALP mathematical model takes the following input data. Let I be the set of aircraft, and each flight is indexed by j or i, so the number of flights landing on a single runway is denoted by $|I|$. According to ICAO regulation, there should be a minimum time separation (S_{ji}) between two consecutive flights (preceding flight j and following flight i) to avoid the wake turbulence effect generated by the preceding aircraft. According to the Maximum Take-off Weight (MTOW), aircraft categories are divided into light aircraft (MTOW $\leq$ 7t), medium aircraft (7t $<$ MTOW $<$ 136t), and heavy aircraft (MTOW $\geq$ 136t) [46]. The minimum time separation standard S_{ji} relies on the aircraft types and the values are indicated in Table 2. The arrival route of flight i is predefined according to the flight plan, and the flight time F_i is related to flight speed and the distance from the entry point to the runway. From the historical data, F_i is between F_i^{min} and F_i^{max}, where F_i^{min} is the shortest flight time and F_i^{max} is the longest flight time. The time when flight i arrive at the entry point (T_i) can be obtained from ADS-B. Therefore, the assigned landing time is $t_i = T_i + F_i$, which should be within the earliest landing time ($t_i^e = T_i + F_i^{min}$) and the latest landing time ($t_i^l = T_i + F_i^{max}$). Every time when a new flight enters the TMA, the proposed heuristic would solve the ALP and output the updated landing time for each flight, so the decision valuable (t_i) may change several times. The binary decision variable y_{ji} represents the sequence of the schedule. If the landing time of flight j is before flight i, y_{ji} is equal to 1; otherwise y_{ji} is equal to 0.

Given the notations for parameters and decision variables listed in Table 3, we presented the nominal formulation of ALP and assumed all parameters to be deterministic. The objective function (1) is to minimize the total landing time of all arrival flights.

$$\min \sum_{i \in I} t_i \tag{1}$$

s.t.

Table 2
The minimum time separation standard between two consecutive landing flights (in minutes) [10].

		Following aircraft		
		Heavy	Medium	Light
Preceding aircraft	Heavy	2	2	3
	Medium	2	2	3
	Light	2	2	2

Table 3
Notations and decision variables.

Sets with indices	Explanation
I	A set of approaching flights (index i,j)
Parameters	Explanation
i,j	Flight ID$i,j \in I$
F_i	Flight time of flight i from an entry point to landing.
F_i^{min}	The shortest flight time of flight i from an entry point to landing.
F_i^{max}	The longest flight time of flight i from an entry point to landing.
T_i	The arrival time at the entry point for flight i.
M	Large artificial variable.
e_i	The earliest landing time.
l_i	The latest landing time.
S_{ji}	The minimum time separation between aircraft j and i.
Decision variables	Explanation
t_i	The landing time of flight i, $t_i \geq 0, \forall i \in I$.
y_{ji}	1, if flight j lands before flight i (not necessarily immediately); 0, otherwise.

$$F_i = t_i - T_i, \forall i \in I \tag{2}$$

$$t_i \geq t_j + S_{ji} - M\left(1 - y_{ji}\right), \forall i,j \in I, i \neq j \tag{3}$$

$$y_{ji} + y_{ij} = 1, \forall i,j \in I, i \neq j \tag{4}$$

$$F_i^{min} \leq F_i \leq F_i^{max} \tag{5}$$

$$e_i \leq t_i \leq l_i, \forall i \in I \tag{6}$$

$$t_i \geq 0, \forall i \in I \tag{7}$$

$$y_{ji} \in \{0, 1\}, \forall i,j \in I, i \neq j \tag{8}$$

Flight time from entry points to the runway is calculated using constraint (2). Inequality equation (3) indicates that the landing time of the following aircraft i must be larger or equal to the summation of the preceding time t_j and minimum time separation requirement S_{ji}. Constraints (4) ensures either $y_{ji} = 1, y_{ij} = 0$ or $y_{ji} = 0, y_{ij} = 1$. The landing time t_i of each flight must be in the time window ($[e_i, l_i]$) in constraint (6). Constraints (7) and (8) express three decision variables for t_i and y_{ji}.

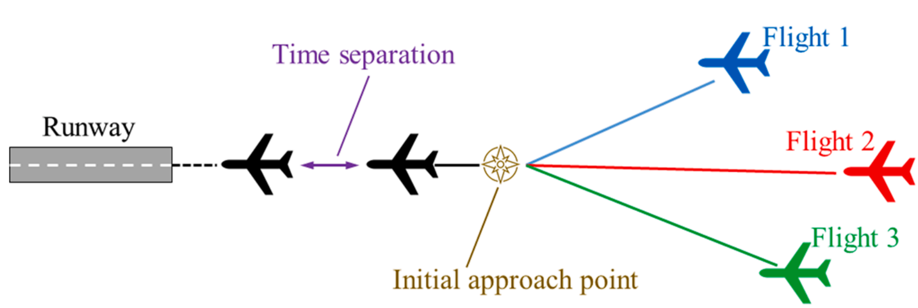

Fig. 2. The schematic diagram of single-runway ALP.

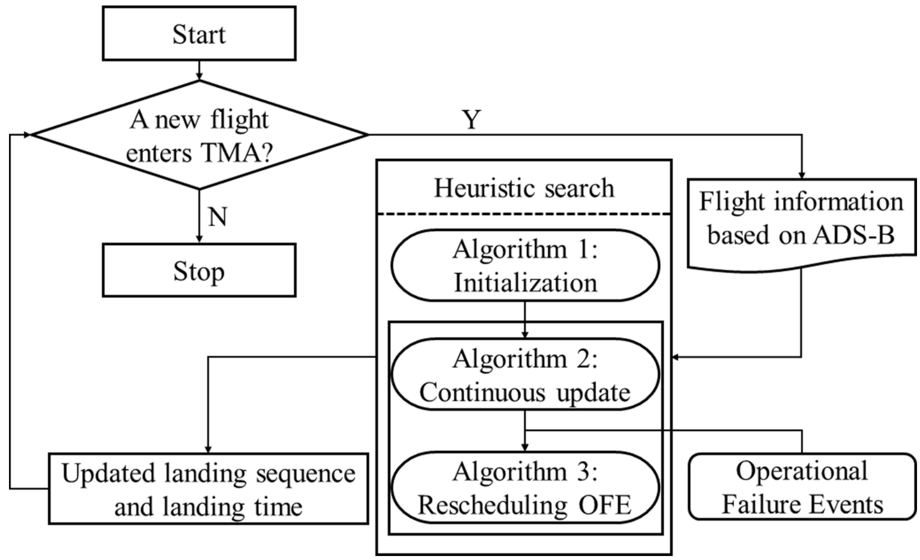

Fig. 3. Heuristic search workflow.

3. Solution approach

As expressed in Section 2, the ALP is a real-time dynamic problem, needing a continuous and efficient solution approach. However, it always takes a relatively long time to provide an ALP solution [28,30,47]. Herein, a novel heuristic search is proposed to solve the ALP timely and quickly. The heuristic workflow is shown in Fig. 3, containing the initialization step and continuous update step.

This section introduces the algorithm of the aircraft landing problem in detail. Firstly, the initialization of the first two flights is introduced, followed by the continuous update heuristics algorithm.

Algorithm 1. Initialization of the first two flights in the decision horizon.

Input	Information of the first two flights j' and i' in the decision horizon: $T_{j'}, T_{i'}$, $j' = 1$ and $j' = i$.
Output	Assigned landing time $t_{i'}, t_{j'}$
1	The 1st flight enters TMA at T_j.
2	Calculate $e_{j'} = T_{j'} + F_{j'}^{min}$, and set $t_{j'} = e_{j'}$.
3	The 2nd flight enters TMA at $T_{i'}$.
4	Calculate $e_{i'} = T_{i'} + F_{i'}^{min}$, and compare $e_{i'}$ and $e_{j'}$.
5	If $e_{j'} < e_{i'}$, set $t_{j'} = e_{j'}$, and $t_{i'} = \max\{e_{i'}, t_{j'} + S_{j'i'}\}$.
6	If $e_{i'} < e_{j'}$, set $t_{i'} = e_{i'}$, and $t_{j'} = \max\{e_{j'}, t_{i'} + S_{i'j'}\}$.

After initialization, we introduce the continuous update algorithm for ALP when a new flight i enters TMA at time T_i. Fig. 4 shows the schematic diagram.

Algorithm 2. Continuous update heuristics.

Input	Information of a new coming flight i:T_i
Output	Assigned landing time on t_i
1	Flight i enters TMA at T_i. Calculate $e_i = T_i + F_i^{min}$.
2	There are two conditions, i.e. (1) or (2). Please see Fig. 4.
3	Condition (1): find a landing time interval (t_j, t_{j+1}) satisfying $t_j < e_i < t_{j+1}$; set $t_i = \max\{e_i, t_j + S_{ji}\}$. Re-schedule the landing time for flights $m+1$ to n, if the landing time separations between two adjacent flights are less than the minimum time separation standards.
4	Condition (2): if $e_i > t_j$, set $t_i = \max\{e_i, t_j + S_{ji}\}$.

In this part, we introduce the ALP algorithm with Operational Failure Events (OFE), e.g., aircraft missed approach. If a flight i cannot land on the runway due to some operational failure problems at T, we will give this flight a higher priority. Based on its current position and speed limit, the earliest landing time is denoted by $\widehat{t}_i$. The optimal scheduled landing time in the deterministic solution t_i will now be the landing time $\widehat{t}_i$ in the rescheduling heuristics. $\widehat{t}_i$ will then be updated when an operational failure event occurs. We define the real-time landing sequence decision as $\widehat{y}_{ji}$, where $\widehat{y}_{ji} = 1$, if flight j lands before flight i (not necessarily

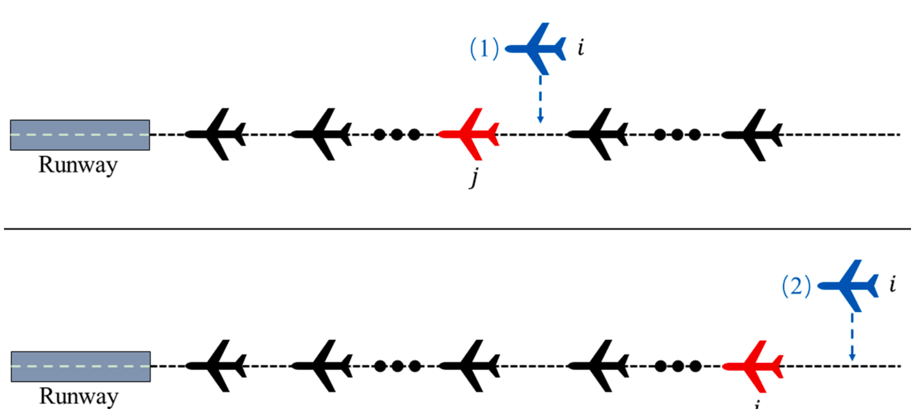

Fig. 4. Schematic diagram of continuous update heuristics.

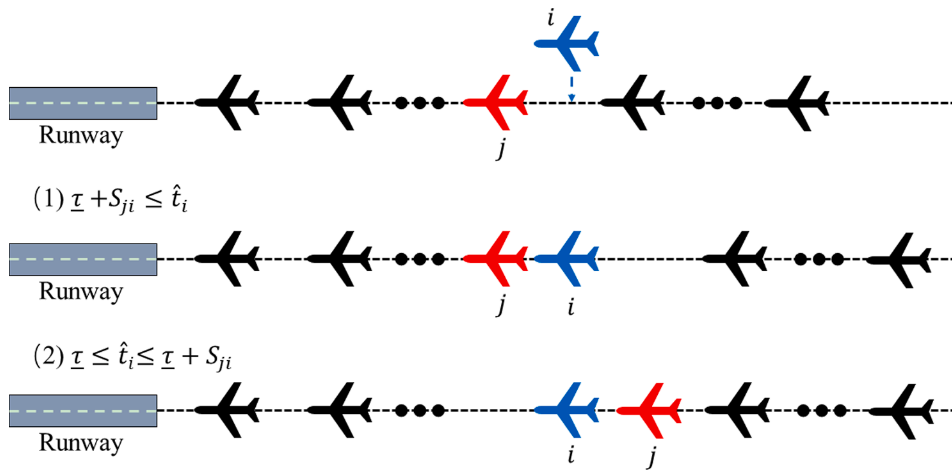

Fig. 5. Schematic diagram of rescheduling heuristics under OFE.

immediately); $\hat{y}_{ji} = 0$, otherwise.

Algorithm 3. Rescheduling heuristics under operational failure events (OFE).

Input	The earliest landing time of OFE-flight (*): $\hat{t}_i$
Output	Landing time for all flights.
1	Find an interval satisfying: $\underline{\tau} \leq \hat{t}_i \leq \overline{\tau}$, where$\underline{\tau} = \max\left\{t_j y_{ji}, \forall j \in I, j \neq i \mid y_{ji} = 1\right\}$ and $\overline{\tau} = \max\left\{t_j y_{ij}, \forall j \in I, j \neq i \mid y_{ij} = 1\right\}$.
2	If $\underline{\tau} + S_{ji} \leq \hat{t}_i$, insert flight i after flight j. The schematic diagram is shown in Fig. 5 condition (1).
3	The landing time of the upcoming flights will be set as $\hat{t}_i = \min\left\{\hat{t}_i, \underline{\tau} + S_{ji}\right\}$ for all the subsequence flights.
4	If $\underline{\tau} \leq \hat{t}_i \cap \underline{\tau} + S_{ji} \geq \hat{t}_i$, swap the positions of flights j and i, and thus, y_{ji} sets to be 0 and $\hat{y}_{ij} = 1$.The updated landing time $\hat{t}_i$ of flight i remains unchanged and the updated landing time of flight j will be $\hat{t}_j = \underline{\tau} + S_{ji}$. The schematic diagram is shown in Fig. 5 condition (2). Update all the subsequence flights in rule 3 and 4.
5	Check until no violation of minimum time separation standards.

As mentioned above, some operational failure events may occur during practical operations and cause flights to not be in the expected position, which increases the risk of violating aircraft separation requirements. Taking advantage of ADS-B, the real-time aircraft positions can be monitored. Pilots can then control flight situations to reduce the deviation from target landing time and target flight routes.

4. Numerical analysis

This section aims to show the performance of the proposed heuristic search. Shanghai terminal maneuvering area is selected because of the complex airspace and high social status. Section 4.2 demonstrates the heuristic application to operational failure events. Continuous and dynamic scheduling of landing time for a whole day is described in Section 4.3.

4.1. Case airports

Shanghai airports are frequently delayed. Such delays and inefficiencies in the ATC system bring about enormous economic impact. Thus, we chose Shanghai airports as the case study subjects. Shanghai owns two airports: Pudong International Airport (ZSPD) and Hongqiao International Airport (ZSSS). ZSPD is a central Chinese aviation hub and mainly serves international flights, while ZSSS mainly serves domestic and regional flights. Fig. 6 shows five entry points: SASAN, DUMET, AND, BK, and MATNU in Shanghai TMA. Table 4 explains the standard flight altitude regulations from entry points to Initial Approach Fixes

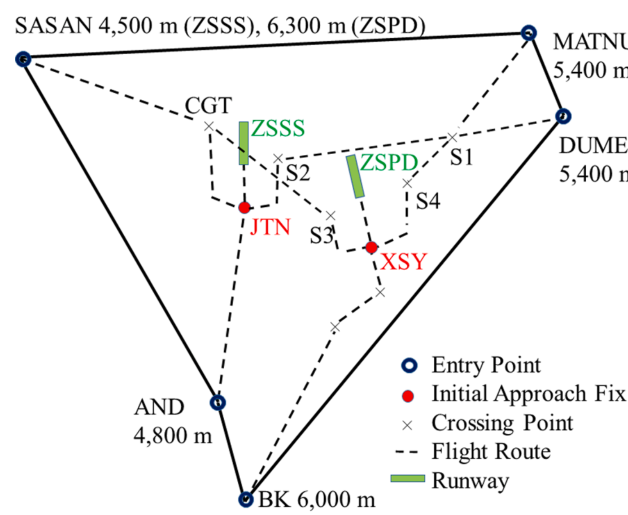

Fig. 6. Standard terminal arrival routes of ZSPD and ZSSS.

Table 4
Standard flight altitude regulations from each entry point to IAF for arrival flights.

Airport	Entry points	Altitude Descent Regulations	
ZSPD	SASAN	SASAN-CGT: 6,300 m-3,800 m	CGT-S3/ XSY: 3,800 m-1,800 m
	BK	BK-XSY: 6,000 m-1,800 m	
	DUMET	DUMET-S1: 5,400 m-3,300 m	S1-S4/ XSY: 3,300 m-1,800 m
	MATNU	MATNU-S1: 5,400 m-3,300 m	S1-S4/ XSY: 3,300 m-1,800 m
ZSSS	SASAN	SASAN-CGT: 4,500 m-3,800 m	CGT-JTN: 3,800 m-1,800 m
	AND	AND-JTN: 4,800 m-1,800 m	
	DUMET	DUMET-S1: 5,400 m-3,300 m	S1-S2/JTN: 3,300 m-1,800 m

(IAF) for arrival flights. For ZSSS, there are three arrival routes: SASAN-JTN (107 km), AND-JTN (90 km), and DUMET-JTN (152 km). For ZSPD, there are four arrival routes: SASAN-XSY (166 km), BK-XSY (127 km), DUMET-XSY (89 km), and MATNU-XSY (118 km). ATCOs must pay more attention to the shared entry points (SASAN and DUMET) because of the high potential for collisions and accidents in those waypoints. Air traffic problems are common during rush hours. As shown in Fig. 7, the

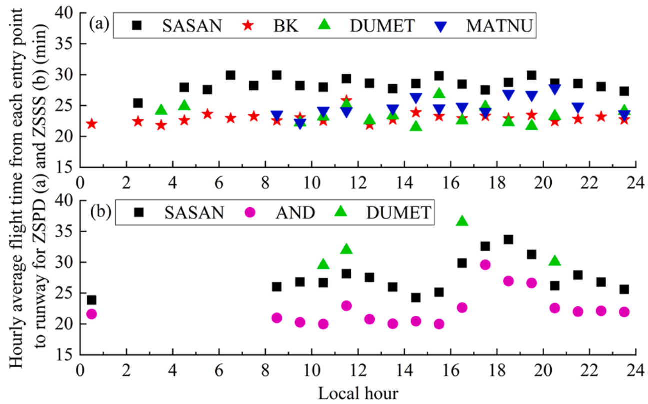

Fig. 7. Hourly average flight time from each entry point to the runway for ZSPD (a) and ZSSS (b).

Table 5
Heuristic implementation procedure.

Entry time (T_i)	ID	ACT	Entry point	F_i^{min}(s)	F_i(s)	Updatedt_i
14:09:47	CES5616	A320	DUMET	21:29	21:29	14:31:16
14:10:47	CCA1215	A321	SASAN	25:08	25:08	14:35:55
14:13:31	DKH1176	A320	BK	18:50	19:45	14:33:16
14:15:05	CSH9462	B737	SASAN	25:08	25:08	14:40:13
14:15:53	CQH8912	A320	BK	18:50	19:23	14:35:16
	CCA1215	A321	SASAN	25:08	26:29	14:37:16
14:17:39	SIA830	A388	BK	18:50	21:37	14:39:16
	CSH9462	B737	SASAN	25:08	26:11	14:41:16
14:18:07	CES788	A332	SASAN	25:08	25:09	14:43:16
14:21:30	CES5600	A321	BK	18:50	23:46	14:45:16
14:33:52	CSN3678	A321	BK	18:50	18:50	14:52:42
14:36:30	CES502	A321	BK	18:50	18:50	14:55:20
14:37:51	CSH9368	B738	MATNU	22:14	22:14	15:00:05

flight time from entry points to the runway increases with a longer distance, and flight time also increases to some extent during the rush hours (12–18 local hours).

4.2. Heuristic implementation steps and flight missed-approach scenario

A fleet landing on ZSPD was selected to demonstrate the implementation procedure of the proposed heuristic using ADS-B under operational failure events. Table 5 shows each flight's information, sequenced by their respective entry time (T_i). The minimum flight time (F_i^{min}) from each entry point to the runway can be obtained from historical flight data (DUMET: 21:29, SASAN: 25:08, BK: 18:50, MATNU: 22:14). Please note: all following entry time and fight information are from ADS-B. At 14:09:47, flight CES5616 entered TMA via DUMET. The landing time of CES5616 (t_i) is assigned to be at 14:31:16 on the condition that the flight time (F_i) from DUMET to the runway is equal to F_i^{min}. Then flight CCA1215 entered TMA at 14:10:47, and the assigned landing time is at 14:35:55. The landing time interval can satisfy the minimum time separation standard, so the updated landing time of CES5616 does not change. At 14:13:31, DKH1176 entered TMA from BK. If DKH1176 adopted F_i^{min}, the landing time would be at 14:32:21. The landing time interval between CES5616 and DKH1176 cannot satisfy the minimum time separation standard, so the landing time of DKH1176 is assigned to be at 14:33:16, from which there is a two-minute landing time interval. Then CSH9462 entered TMA at 14:15:05, and the assigned landing time is at 14:40:13. The landing time interval can satisfy the minimum time separation standard, so the updated t_i of other flights does not change. Then, CQH8912 entered TMA at 14:15:53 from BK. If CQH8912 adopted F_i^{min}, the landing time would be at 14:34:43, causing the landing time interval to be less than the minimum time separation standard. Therefore, the CQH8912 landing time is assigned to be at 14:35:16. Under this condition, CQH8912 would land before CCA1215. The landing time of CCA1215 is reassigned to be at 14:37:16 to satisfy the minimum time separation standard. At 14:17:39, SIA830 entered TMA via BK. If SIA830 adopted F_i^{min}, the landing time would be at 14:36:29, which is earlier than the landing time of CCA1215 (14:37:16). However, because of the First Come First Served (FCFS) regulation, CCA1215 should land before SIA830. Therefore, the landing time of SIA830 is assigned to be at 14:39:16. The landing time of CSH9462 is re-assigned to be at 14:41:16 to satisfy the minimum time separation standard. According to the method mentioned above, the landing time of the other following flights is shown in Table 5. During the heuristic implementation steps, two ADS-B advantages are highlighted. First, the information of arriving flights is relayed to heuristic search automatically, which eliminates some unnecessary communications between ATCOs and pilots. Second, the aircraft real-time positions are visible in a digital format, contributing to improved situational awareness.

Operational Failure Events (OFE) are common during practical operations, causing potential safety hazards and lowering flight efficiency. ATCOs are required to pay extra attention to solve these issues for keeping a smooth flow of flights. To demonstrate the heuristic under OFE, we assume that flight *CES788* cannot land on the runway as planned due to some reasons, and the OFE-time T is at 14:39:00. The position at OFE-time can be obtained via ADS-B instantly, so the next earliest landing time ($\hat{t_i}$) can be calculated for flight *CES788* flying the missed approach route (Fig. 8) and with its flight speed based on historical flight data. Here, the next earliest landing time ($\hat{t_i}$) is set to be at 14:53:00. The OFE-flight *CES788* will be assigned a higher landing priority, so the landing time of flights (CSN3678 and CES502) mentioned in Table 5 should be re-assigned. The updated landing time of CSN3678 and CES502 is at 14:55:00 and 14:57:00, respectively. The landing time of CSH9368 does not need to change because the landing time interval (CES502 and CSH9368) satisfies the minimum time separation standard between two consecutive landing flights (Table 2).

4.3. Continuous update along a 24-hour horizon

A 24-hour dataset on March 7, 2018, was used to evaluate the feasibility and effectiveness of the proposed heuristic for continuous updates. There were 578 aircraft landings for the two airports in Shanghai, 251 for ZSSS, and 327 for ZSPD. The proposed method implementation is carried out in a personal computer with Intel(R) Core (TM) i7-10510U CPU @ 1.80 GHz 2.30 GHz RAM 4.00 GB and Windows 10 OS. As mentioned in Section 2, the heuristic search will run and update again once a new flight enters the TMA. Results show that it takes less than one millisecond for each update, demonstrating the high efficiency of this method. With the numerical results generated from the proposed heuristic, we compared them with the original historical data and defined an equation below to measure the improvement in flight time.

$$\text{improvement} = \sum_{i\in I}\left(F_i^{ORI} - F_i^{OPT}\right) \Big/ \sum_{i\in I} F_i^{ORI}$$

where F_i^{ORI} and F_i^{OPT} are the historical original flight time and the optimized flight time of arrival flight i, respectively, calculated by $t_i - T_i$. Fig. 9 shows the saved flight time ($F_i^{ORI} - F_i^{OPT}$) of each flight. Most flights can save flight time by 3–7 min for ZSPD (a) and 5–10 min for ZSSS (b). The improvement in flight time for ZSPD and ZSSS is 53033/494741 = 10.7%, and 64484/387535 = 16.6%, respectively. However, there are several negative saved flight time, as some flights will have to make sacrifices in order to benefit the whole objective function.

Here, we also define another two parameters: (1) delay time of flight i: $D_i = F_i - F_i^{min}$, where F_i and F_i^{min} is the practical and minimum flight

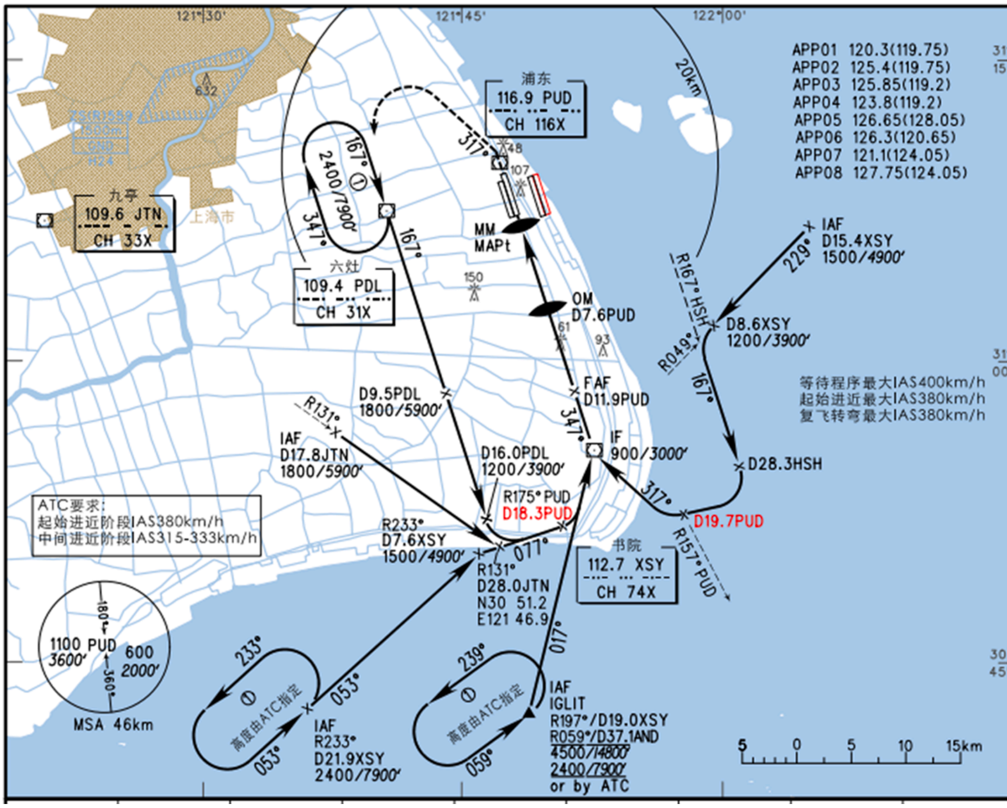

Fig. 8. Instrument approach diagram [48].

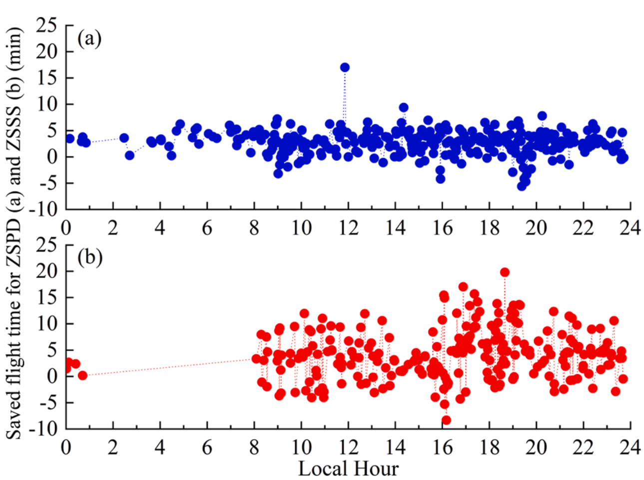

Fig. 9. Saved flight time from entry points to the runway for ZSPD (a) and ZSSS (b) in different local hours.

time from an entry point to the runway, respectively; (2) landing time interval between two consecutive landing flights i and $i+1$: $L_{i,i+1} = t_{i+1} - t_i$, where t_i is the landing time of flight i. Fig. 10 shows the detailed results for ZSPD (left) and ZSSS (right). Fig. 10 (a) shows the hourly number of arrival flights entering the TMA. We can notice that the number of arrival flights reaches the peak during local hours 15–20 (ZSPD) and 16–19 (ZSSS). Fig. 10 (b) presents the landing time interval ($L_{i,i+1}$), ranging from 2 to 10 min for these two airports. Fig. 10 (c) shows the delay time results related to the number of arrival flights entering the TMA. In general, the more arrival flights there are, the higher delay time values will be. In theory, thirty flights can land in an hour with a two-minute separation time interval. However, Fig. 10 (a) shows that the hourly number of landing aircraft is less than thirty, but delay still widely exists, because many flights are planned to land within a short time slot, which causes crowdedness in runway allocation. Therefore, some flights are asked to join holding patterns to maintain a safe separation, causing long flight delays.

5. Discussions and implications

Various factors can cause flight delays, such as weather conditions, airport congestion, and airspace congestion [49]. Therefore, ATC system robustness needs to be improved considering the uncertainty of these factors. In practice, flight delay causes are always inevitable, and in response, some measures should be made to ensure adherence to the scheduled landing time. For example, if flight routes are affected by severe weather or military activities, pilots can apply for a temporary route or a tailwind route with ATC clearance. Satisfying aircraft performance, a faster cruising speed is also recommended although this might result in more fuel consumption. In this paper, the proposed model can reduce the flight time and support ways to realize the scheduled landing time to some extent. The model will run whenever there is a new flight entering the TMA, whenever a new flight enters the TMA, the method will run again, causing the previously generated landing time for some flights to change. Controller Pilot Data Link Communications (CPDLC), an indispensable part of Required Communication Performance (RCP), can then be used to convey the updated landing time to pilots using the data link in a reasonable time.

For traditional radar-based ATC, many unnecessary communications commonly exist, increasing ATCOs' and pilots' workload. However, automatically broadcasted ADS-B signals can solve this problem. Except for the graphical information (blips on the screen), ADS-B can also provide ATCOs with digital information (longitude, latitude, and altitude), which can increase the confidence level of aircraft positions. On this condition, ATCOs can reduce the distances among aircraft without violating separation standards, improving situational awareness and airspace capacity utilization [17]. Using the historical flight data in

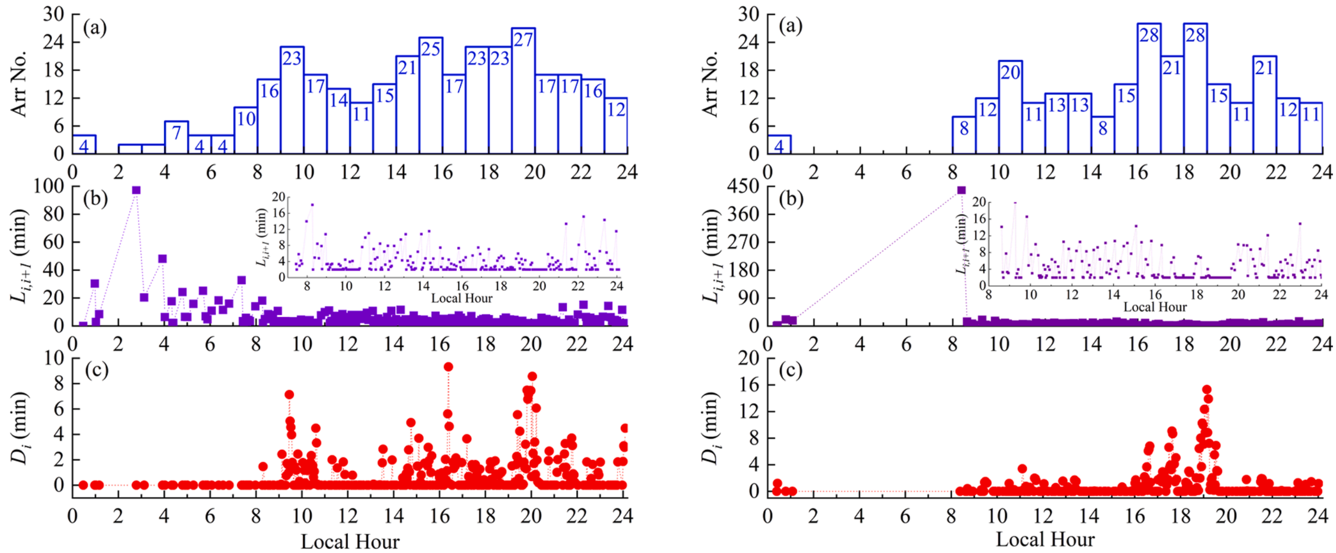

Fig. 10. Results for ZSPD (left) and ZSSS (right). (a). The number of flights entering TMA. (b). The landing time interval between two adjacent aircraft ($L_{i,i+1} = t_{i+1} - t_i$). (c). Delay time ($D_i = F_i - F_i^{min}$).

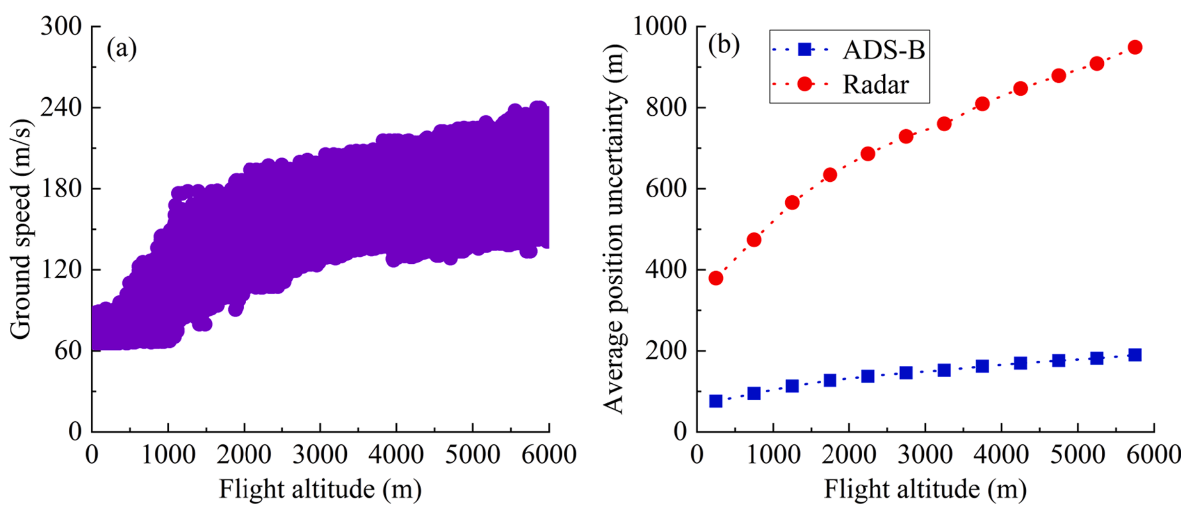

Fig. 11. (a). Ground speed in terms of different flight altitudes. (b). Average position uncertainty based on one-second update interval ADS-B and five-second update interval radar.

Shanghai TMA, we can summarize the relations between ground speed and flight altitude (Fig. 11 (a)). The update rate of ADS-B and radar is assumed to be one second and five seconds respectively, then the average position uncertainty at different flight altitudes can be calculated and is shown in Fig. 11 (b). However, drawbacks of ADS-B should also be noted. ADS-B performance relies greatly on the Global Navigation Satellite System (GNSS), which can be damaged by space weather and ionospheric scintillation [50], so improving GNSS positioning accuracy is also significant [51,52].

At the strategic level, ADS-B has promising applicability. The ground stations can combine the ADS-B data globally and adjust flight plans to avoid unnecessary flight delays and conflicts. As shown in Fig. 10 (c), many flights are delayed because the landing times of these flights are clustered together without satisfying the time separation standard. To be exact, that is due to the unreasonable arrival time (T_i) at entry point. That is also to say if T_i is assigned reasonably, flight delays can be eliminated. Radar has a limited coverage area (~400 km), so it is challenging to combine real-time flight data in remote, oceanic, and lower altitude areas. On the other hand, ADS-B integration can be achieved based on the ADS-B information sharing system utilizing receivers in low earth orbit satellites and on the ground. Herein, we propose a conception based on ADS-B integration to optimize ATM thoroughly, which requires cooperation among ATCOs, airlines, and airports. It involves multiple stakeholders and requires further study.

There are also some deficiencies in this paper. First, the proposed method to solving ALP is a heuristic search, which attempts to optimize a problem by iteratively improving the solution based on a given heuristic function or a cost measure. However, the heuristic search method is not guaranteed to always find an optimal or the best solution but may instead find a good or acceptable solution within a reasonable amount of time and memory space. Air traffic is complex with a continuous flow of departure and arrival flights, so a fast and effective solution is more important than the optimal solution.

6. Conclusions

Air traffic management is experiencing an update to CNS/ATM to reduce aircraft separation and increase aircraft capacity. As a replacement for radar, ADS-B is a digital technology with many advantages based on the GNSS. However, ADS-B-based application to air traffic management is still a novelty. To solve the aircraft landing problem and reduce flight delay, this paper proposes a novel heuristic search method based on ADS-B digital technologies, considering the time separation standards regulated by ICAO. The objective is to minimize the total flight time from entry points to the runway of all landing aircraft. Using the flight data in Shanghai airports, results reveal that the method can solve aircraft landing scheduling efficiently and continuously. Besides, there is a decrease in total flight time due to reasonable landing time assignments.

In the future, the time separation and distance separation standards between aircraft can be reduced with the improvement in the Satellite-Based Augmentation System (SBAS) and Ground-Based Augmentation System (GBAS), which is one of the most studied topics as of late. In addition, as surveillance error for ADS-B is related to GNSS positioning accuracy and latency, more research can be done in terms of GNSS latency as it has not been studied thoroughly. Moreover, the algorithm also needs to be improved to obtain the global optimal results within an acceptable time.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

[1] Airbus, Growing Horizons 2017/2036. Secondary Growing Horizons 2017/2036. Airbus, Toulouse, France, 2017.
[2] I. Anagnostakis, J.-P. Clarke, D. Bohme, U. Volckers, Runway operations planning and control: Sequencing and scheduling, J. Aircraft 38 (2001) 988–996.
[3] C.K.M. Lee, K.K.H. Ng, H.K. Chan, K.L. Choy, W.C. Tai, L.S. Choi, A multi-group analysis of social media engagement and loyalty constructs between full-service and low-cost carriers in Hong Kong, J. Air Trans. Manage. 73 (2018) 46–57.
[4] K. Ng, C.K. Lee, Aircraft scheduling considering discrete airborne delay and holding pattern in the near terminal area, International Conference on Intelligent Computing, Springer, 2017, pp. 567-576.
[5] D. Xue, K.K. Ng, L.-T. Hsu, Multi-objective flight altitude decision considering contrails, fuel consumption and flight time, Sustainability 12 (2020) 6253.
[6] D. Xue, R. Sun, L.-T. Hsu, Optimal assignment of time of departure under severe weather, J. Aeronaut., Astronaut. Aviation 51 (2019) 355–368.
[7] K.K. Ng, K. Keung, C. Lee, Y. Chow, A Large Neighbourhood Search Approach to Airline Schedule Disruption Recovery Problem, 2020 IEEE International Conference on Industrial Engineering and Engineering Management (IEEM), IEEE, 2020, pp. 600-604.
[8] E.M. Argyle, R.J. Houghton, J. Atkin, G. De Maere, T. Moore, H.P. Morvan, Human performance and strategies while solving an aircraft routing and sequencing problem: an experimental approach, Cogn Technol Work 20 (2018) 425–441.
[9] J.W. Ruffner, D.M. Deaver, D.J. Henry, Requirements analysis for an Air Traffic Control Tower Surface Surveillance Enhanced Vision System, Enhanced and Synthetic Vision 2003 (5081) (2003) 124–135.
[10] ICAO, Doc 4444–Procedures for Air Navigation Services: Air Traffic Management, International Civil Aviation Organization Montréal, 2007.
[11] X. Zhang, S. Mahadevan, Aircraft re-routing optimization and performance assessment under uncertainty, Decis. Support Syst. 96 (2017) 67–82.
[12] K.K. Ng, C. Lee, S. Zhang, K. Keung, The impact of heterogeneous arrival and departure rates of flights on runway configuration optimization, Transport. Lett. (2020) 1–12.
[13] H.J. Wee, S.W. Lye, J.-P. Pinheiro, An integrated highly synchronous, high resolution, real time eye tracking system for dynamic flight movement, Adv. Eng. Inf. 41 (2019), 100919.
[14] K. Ng, C. Lee, F. Chan, A robust optimisation approach to the aircraft sequencing and scheduling problem with runway configuration planning, 2017 IEEE International Conference on Industrial Engineering and Engineering Management (IEEM), IEEE, 2017, pp. 40-44.
[15] K. Sampigethaya, R. Poovendran, L. Bushnell, A framework for securing future eEnabled aircraft navigation and surveillance, AIAA Infotech@ Aerospace Conference and AIAA Unmanned... Unlimited Conference, 2009, pp. 1820.
[16] D. Xue, Z. Liu, B. Wang, J. Yang, Impacts of COVID-19 on aircraft usage and fuel consumption: A case study on four Chinese international airports, J. Air Trans. Manage. 95 (2021), 102106.
[17] B.S. Ali, W.Y. Ochieng, R. Zainudin, An analysis and model for Automatic Dependent Surveillance Broadcast (ADS-B) continuity, GPS Solutions 21 (2017) 1841–1854.
[18] F. Kunzi, Reduction of Collisions Between Aircraft and Surface Vehicles Conflict Alerting on Airport Surfaces Enabled by Automatic Dependent Surveillance-Broadcast, Transp. Res. Rec. (2013) 56–62.
[19] R. Li, W.J. Verhagen, R. Curran, Stakeholder-oriented systematic design methodology for prognostic and health management system: Stakeholder expectation definition, Adv. Eng. Inf. 43 (2020), 101041.
[20] F. Li, C.-H. Lee, C.-H. Chen, L.P. Khoo, Hybrid data-driven vigilance model in traffic control center using eye-tracking data and context data, Adv. Eng. Inf. 42 (2019), 100940.
[21] K. Ng, C.K. Lee, F.T. Chan, C.-H. Chen, Y. Qin, A two-stage robust optimisation for terminal traffic flow problem, Appl. Soft Comput. 89 (2020), 106048.
[22] K. Ng, C.K. Lee, F.T. Chan, Y. Lv, Review on meta-heuristics approaches for airside operation research, Appl. Soft Comput. 66 (2018) 104–133.
[23] K.K. Ng, C.-H. Chen, C. Lee, Mathematical programming formulations for robust airside terminal traffic flow optimisation problem, Comput Ind Eng 154 (2021), 107119.
[24] J. Huo, K. Keung, C. Lee, K.K. Ng, K. Li, The Prediction of Flight Delay: Big Data-driven Machine Learning Approach, 2020 IEEE International Conference on Industrial Engineering and Engineering Management (IEEM), IEEE, 2020, pp. 190-194.
[25] H. Lee, G. Li, A. Rai, Chattopadhyay, Real-time anomaly detection framework using a support vector regression for the safety monitoring of commercial aircraft, Adv. Eng. Inf. 44 (2020), 101071.
[26] C. Gwiggner, S. Nagaoka, Data and queueing analysis of a Japanese air-traffic flow, Eur. J. Oper. Res. 235 (2014) 265–275.
[27] K.K.H. Ng, C.K.M. Lee, F.T.S. Chan, Y. Qin, Robust aircraft sequencing and scheduling problem with arrival/departure delay using the min-max regret approach, Transport. Res. Part E: Logist. Transport. Rev. 106 (2017) 115–136.
[28] A. Lieder, D. Briskorn, R. Stolletz, A dynamic programming approach for the aircraft landing problem with aircraft classes, Eur J Oper Res 243 (2015) 61–69.
[29] K. Ng, C. Lee, Makespan minimization in aircraft landing problem under congested traffic situation using modified artificial bee colony algorithm, 2016 IEEE International Conference on Industrial Engineering and Engineering Management (IEEM), IEEE, 2016, pp. 750-754.
[30] A. Rodríguez-Díaz, B. Adenso-Díaz, P.L. González-Torre, Minimizing deviation from scheduled times in a single mixed-operation runway, Comput. Oper. Res. 78 (2017) 193–202.
[31] B. Xu, An efficient ant colony algorithm based on wake-vortex modeling method for aircraft scheduling problem, J. Comput. Appl. Math. 317 (2017) 157–170.
[32] Y. Hong, B. Choi, Y. Kim, Two-stage stochastic programming based on particle swarm optimization for aircraft sequencing and scheduling, IEEE Trans. Intell. Transp. Syst. 20 (2018) 1365–1377.
[33] A.A.A. Mahmud, W. Jeberson, Aircraft landing scheduling using embedded flower pollination algorithm, Int. J. Parallel Prog. (2018) 1–15.
[34] R. Prakash, R. Piplani, J. Desai, An optimal data-splitting algorithm for aircraft scheduling on a single runway to maximize throughput, Transport. Res. Part C: Emerg. Technol. 95 (2018) 570–581.
[35] S. Ikli, C. Mancel, M. Mongeau, X. Olive, E. Rachelson, An optimistic planning approach for the aircraft landing problem, EIWAC 2019:, 6th ENRI International Workshop on ATM/CNS, 2019.
[36] N. Lu, J. Zhang, L. Zhong, Research on the Problem of Sorting Parallel Runway Aircraft in Terminal Area Based on Genetic Algorithm, IOP Conference Series: Materials Science and Engineering, IOP Publishing, 2019, pp. 042040.
[37] L.-J. Wu, Z.-H. Zhan, X.-M. Hu, P. Guo, Y. Zhang, J. Zhang, Multi-runway Aircraft Arrival Scheduling: A Receding Horizon Control Based Ant Colony System Approach, 2019 IEEE Congress on Evolutionary Computation (CEC), IEEE, 2019, pp. 538-545.
[38] A. Salehipour, An algorithm for single-and multiple-runway aircraft landing problem, Math. Comput. Simul 175 (2020) 179–191.
[39] F.Y. Vincent, M. Qiu, H. Pan, T.-P. Chung, J.N. Gupta, An Improved Immunoglobulin-Based Artificial Immune System for the Aircraft Scheduling Problem With Alternate Aircrafts, IEEE Access 9 (2021) 16532–16545.
[40] Z.Y. Zhang, J. Zhang, P. Wang, L. Chen, Research on Operation of UAVs in Non-isolated Airspace, Cmc-Comput. Mater. Con 57 (2018) 151–166.
[41] P. Pierpaoli, A. Rahmani, UAV collision avoidance exploitation for noncooperative trajectory modification, Aerosp Sci Technol 73 (2018) 173–183.
[42] G. Vial, Understanding digital transformation: A review and a research agenda, J. Strateg. Inf. Syst. 28 (2019) 118–144.
[43] P. Zheng, Z. Wang, C.-H. Chen, L.P. Khoo, A survey of smart product-service systems: Key aspects, challenges and future perspectives, Adv. Eng. Inf. 42 (2019), 100973.
[44] Y.-H. Wang, C.-H. Lee, A.J. Trappey, Modularized design-oriented systematic inventive thinking approach supporting collaborative service innovations, Adv. Eng. Inf. 33 (2017) 300–313.
[45] D. Toratani, Application of merging optimization to an arrival manager algorithm considering trajectory-based operations, Transport. Res. Part C: Emerg. Technol. 109 (2019) 40–59.

[46] A. Tobisová, B. Mikula, S. Szabo, D. Blaško, I. Vajdová, E. Jenčová, L. Melníková, V. Němec, The Simulation of Fire and Rescue Services Operations by Airplane Accidents, 2018 XIII International Scientific Conference-New Trends in Aviation Development (NTAD), IEEE, 2018, pp. 144-149.
[47] A. Kwasiborska, Sequencing landing aircraft process to minimize schedule length, Transp. Res. Procedia 28 (2017) 111–116.
[48] Jeppesen, https://ww2.jeppesen.com/wp-content/uploads/2019/05/Introduction-to-Jeppesen-Navigation-Charts.pdf, (2019).
[49] V. Deshpande, M. Arıkan, The impact of airline flight schedules on flight delays, Manuf. Service Oper. Manage. 14 (2012) 423–440.
[50] D. Xue, J. Yang, Z. Liu, The Effect of Space Weather on ADS-B Data in Hong Kong Terminal Airspace, AGU Fall Meeting 2020, AGU, 2020.
[51] R. Sun, G. Wang, W. Zhang, L.-T. Hsu, W.Y. Ochieng, A gradient boosting decision tree based GPS signal reception classification algorithm, Appl. Soft Comput. 86 (2020), 105942.
[52] R. Sun, G. Wang, Q. Cheng, L. Fu, K.-W. Chiang, L.-T. Hsu, W.Y. Ochieng, Improving GPS code phase positioning accuracy in urban environments using machine learning, IEEE Internet Things 8 (2020) 7065–7078.