A Composite Dispatching Rule-Based Method for Multi-Objective Aircraft Landing Problem

Pengli Zhao[1]; Junfeng Zhang[2]; and Lubao You[3]

[1]College of Civil Aviation, Nanjing Univ. of Aeronautics and Astronautics, 29 Jiangjun Ave., P.O. Box 211106, Nanjing, China. E-mail: 727381120@qq.com

[2]College of Civil Aviation, Nanjing Univ. of Aeronautics and Astronautics, 29 Jiangjun Ave., P.O. Box 211106, Nanjing, China (corresponding author). E-mail: zhangjunfeng@nuaa.edu.cn

[3]College of Civil Aviation, Nanjing Univ. of Aeronautics and Astronautics, 29 Jiangjun Ave., P.O. Box 211106, Nanjing, China. E-mail: y1170909149@163.com

Abstract

The high air traffic demand and scarce supply of resources have imposed intense pressure on the air transportation system. In this study, we propose a new method to solve the multi-objective aircraft landing problem quickly. Firstly, we comb the different criteria of the aircraft landing problem, and we choose the average scheduled time, maximum flow time, and maximum delay time as multiple objectives. Secondly, we formulate the model of the multi-objective aircraft landing problem and present the appropriate algorithms to solve the problem. In addition, a new composite dispatching rule is developed to solve the multi-objective aircraft landing problem with high computational efficiency. Finally, the performance of the proposed method is evaluated by a set of benchmark instances and in a real case scenario. The computational results illustrate the efficiency of our approach, which could simultaneously enhance the runway capacity, maximize the cost-effectiveness of airlines, and reduce the workloads of air traffic controllers.

INTRODUCTION

The rapid growth of air traffic has imposed increased pressure on the air transportation system. Such pressure could even result in airport congestion problems with substantial effects on flight delays, fuel consumptions, and pollution emissions. Combined operational management, as one of the most promising countermeasures (Zografos et al. 2017), can improve the airspace system efficiency. In this paper, we mainly focus on tackling the Aircraft Landing Problem (ALP)(Beasley et al. 2000; Bennell et al. 2013, 2017), which has attracted the considerable attention of aviation researchers. In the ALP, model and algorithms play the most important role.

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As far as ALP modeling is concerned, previous research generally focused on one of the following objectives: (1) Minimize the total penalty (Faye 2015; Lieder et al. 2015; Vadlamani and Hosseini 2014; Zhang et al. 2017b), including advanced penalty or delayed penalty, of landing deviations from the target landing time. (2) Minimize the total or average delay of arrival aircraft (Girish 2016; Ji et al. 2016; Sabar and Kendall 2015; Zhang et al. 2017a). (3) Minimize the landing time of the last aircraft (Hu and di Paolo 2011; Zhan et al. 2010) (or, alternatively, maximize runway throughput). All these are typical most common single objective. Furthermore, some of the previous studies also considered two or more objectives simultaneously. Hong et al. (Hong et al. 2017) modeled a multi-objective ALP by minimizing the total flight time and the number of sequence change. Samà et al. (Samà et al. 2017) examined the differences between the solutions regarding various objective functions.

With respect to algorithms, there are several types of algorithms to tackle the ALP. As ALP is an NP-hard problem, the computation time to find an exact solution is likely to grow exponentially with the increase of arrival aircraft. Therefore, the dynamic programming (DP) (Lieder et al. 2015) algorithm, and branch & bound (BB) (Beasley et al. 2000; Wang et al. 2015) algorithm, et al., had been implemented. Moreover, some researchers sought assistance from heuristic and meta-heuristic algorithms, such as simulated annealing (SA) algorithm (Vadlamani and Hosseini 2014), particle swarm optimization (PSO) algorithm (Girish 2016), genetic algorithm (GA) (Hu and di Paolo 2011) and ant colony (AC) algorithm (Zhan et al. 2010).

The previous studies did achieve some significant results. However, there are few focusing on how to solve the multi-objective ALP quickly. In this paper, a new Composite Dispatching Rule (CDR), inspired by the machine scheduling field, and the corresponding algorithm are proposed to tackle the multi-objective ALP.

This paper is organized as follows. In the next section, multi-objective ALP will be defined and described, including different objectives, and then the new CDR and the corresponding algorithm are presented. The simulation and validation results are provided and discussed in the following section. The conclusion will be given in the last section.

MULTI-OBJECTIVE ALP

Problem Description

The multi-objective ALP is an optimization problem, and it can be defined as follows. Given a set of arrival aircraft, the goal is to assign a landing sequence and time for each aircraft by optimizing several given objectives while subject to a variety of operational constraints. The assumptions of ALP are as follows:

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a) The ALP with the single runway is considered in this paper, which could be easily extended to the multiple runway cases.
b) Each aircraft should be assigned at a specific landing time within the landing time window composed by the earliest and latest landing time.
c) The wake-vortex (WV) separation should be respected, which is enforced to avoid the dangers of wake-vortex effects between the leading and following aircraft.

Single runway ALP is similar to a single machine scheduling problem. In the following, the counterparts of a single machine scheduling problem will be described in the brackets. ALP schedules arrival aircraft (jobs) on the runway (machine) where each aircraft is able to land between the earliest landing time (release date) and the latest landing time (deadline). Specifically, the arrival aircraft ought to land on the runway at the target landing time (due date) and should take wake vortex separation (set-up time) into consideration. Moreover, the runway occupied time (processing time) will not be considered in this study. Because once the wake vortex separations have been satisfied, the trailing aircraft will not need to worry about the ROT of the leading landing aircraft. Table 1 summarizes the notation and variables used in this study.

Table 1. Notation and Variables

Notation/ Variables	Single Machine Scheduling	Aircraft Landing Problem
J	a set of jobs	a set of landing aircraft
a_j	Appear time	Entry time
r_j	Release date	Earliest landing time
d_j	Deadline	Latest landing time
δ_j	Due date	Target landing time
s_{jk}	Set-up time	Wake Vortex separation
C_j	Completion time	Scheduled landing time
p_j	Processing time	Runway occupied time
g_j	Earliness weight	Incurred cost for early landing
h_j	Tardiness weight	Incurred cost for late landing
$F_j = C_j - a_j$	Flow time of job	Dwell time in the terminal area
$E_j = \max(\delta_j - C_j, 0)$	Earliness of job	Earliness of aircraft
$T_j = \max(C_j - \delta_j, 0)$	Tardiness of job	Tardiness of aircraft
$q_{kj} = \{0,1\}$	Sequence	Landing sequence

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Objectives of ALP

It is obvious that different stakeholders possess different interests and these different interests could also conflict with each other. The ATC aims to reduce the workload and increase the efficiency of the national airspace system. Airlines focus on reducing operating costs and increasing schedule reliability. Airports pay close attention to making full utilization of runway capacity. The residents' appeal is to mitigate the environmental impacts (noise and air pollution) imposed on the local community.

In ALP, the commonly used objectives are elaborated as follows.

a) Makespan: max C_j. Minimizing makespan implies a high utilization of runway.
b) Total delays: sum T_j. Minimizing total delay could meet the airlines' and passengers' requirements.
c) Maximum delay: max T_j. Minimizing maximum delay is able to prevent the worst violation of the flight schedule.
d) Total cost: sum $(g_jE_j + hT_j)$: Minimizing total cost is the minimizing total weighted earliness plus the total weighted tardiness.

In this paper, a new measurement, dwell time (flow time in machine scheduling field), is introduced into the ALP. The dwell time is defined as the flight time of an arrival aircraft from entering the terminal area at entry fix to landing on the runway. More total dwell time means that air traffic controllers need to pay more attention to monitor and vector aircraft. So, the total dwell time could be treated as a criterion for measuring air traffic controllers' workload. Furthermore, minimizing maximum dwell time makes sure no flight will be kept in the air for too long, whose purpose is to ensure the equity among flights or airlines. Thus, both total flow time and maximum flow time should be included in the objective functions of ALP.

Based on the existence theorems and bounds of bi-criteria scheduling (Wang et al. 2015), we could exclude the objective of maximum flight delay and makespan. Therefore, total delays, total dwell time, and maximum dwell time are chosen as the multiple objectives of ALP.

Formulation of Multi-Objective ALP

The multi-objective optimization problem could be solved by lexicographic ordering strategy or simultaneous optimization strategy. There are no objectives dominant in multi-objective ALP, so we chose a simultaneous strategy for producing the formulation of multi-objective ALP.

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$$\min \quad \alpha\sum_{j=1}^{n}F_j+(1-\alpha)\sum_{j=1}^{n}T_j \tag{1}$$

$$\text{s.t.} \quad F_j \le F_{\max} \qquad \forall j\in J \tag{2}$$

$$r_j \le C_j \le d_j \qquad \forall j\in J \tag{3}$$

$$q_{k,j}+q_{j,k}=1 \qquad \forall k,j\in J; k>j \tag{4}$$

$$C_j \ge C_k + q_{kj}s_{kj} - q_{jk}\left(d_k - r_j\right) \qquad \forall k,j\in J; k\ne j \tag{5}$$

$$E_j \ge \delta_j - C_j \qquad \forall j\in J \tag{6}$$

$$0 \le E_j \le \delta_j - r_j \qquad \forall j\in J \tag{7}$$

$$T_j \ge C_j - \delta_j \qquad \forall j\in J \tag{8}$$

$$0 \le T_j \le d_j - \delta_j \qquad \forall j\in J \tag{9}$$

$$C_j = \delta_j - E_j + T_j \qquad \forall j\in J \tag{10}$$

$$F_j = \delta_j - a_j \qquad \forall j\in J \tag{11}$$

As described earlier, the Eq. (1) and Eq. (2) concern the three selected objectives. Eq. (3) specifies that each aircraft is scheduled within its time window. Eq. (4) and Eq. (5) ensure that the wake vortex separations are assigned. Eq. (6)-(10) define the time window of landing time. Eq. (11) defines the dwell time.

CDR AND ALGORITHM

Composite Dispatching Rules

Exact algorithms can be used to find optimal solutions for the ALP. However, the multi-objective ALP is NP-hard. Therefore, it is necessary to develop an appropriate method to reach a near optimal solution in reasonable computational time. First Come First Service (FCFS) strategy, namely Earliest Ready Date (ERD) rule, is a reasonable alternative, but the scheduling results may be unsatisfactory. Composite Dispatching Rules (CDR), a combination of basic dispatching rules, can perform significantly better.

CDR is a ranking expression that combines a number of basic dispatching rules. Each basic rule in the CDR has its own scaling parameter that is chosen to properly scale the contribution of the basic rule to the total ranking expression. In this paper, we use two dispatch rules to construct the CDR for multi-objective ALP.

a) ERD rule

This rule will select the flight which has the earliest release time to put it into the sequence, which could reduce the average flow time and average tardiness.

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$$F_{ERD}\left(t,j\right)=\exp\left(-\max\left(r_j-t,0\right)/K_1\right) \tag{12}$$

b) Shortest Flow time rule

This rule will select the flight which has the smallest flow time to put in into the sequence, which could reduce the average flow time and the maximum flow time.

$$F_{FLT}\left(t,j\right)=\exp\left(\left(\max\left(r_j,t+s_{ij}\right)-a_j-K_2\right)/K_3\right) \tag{13}$$

So the CDR rule could be

$$I_{CDR}^{i}\left(t,j\right)=\exp\left(-\frac{\max\left(r_j-t,0\right)}{K_1}\right)\times\exp\left(\frac{\max\left(r_j,t+s_{ij}\right)-a_j-K_2}{K_3}\right) \tag{14}$$

The parameter K_1, , K_2 and K_3 is setted refering the study of dispatching rules(Pinedo 2016).

Corresponding Algorithm

In this study, a two-step optimization strategy is used to tackle the multi-objective ALP. The pseudo code of the method is showing as follows.

1. *Set the initial value* $t=0; C_j=0; J=\{1,2,...,n\}; \forall j\in J$
2. *For* $\forall j\in J$ *, get the index using Eq.(14)* $I_{CDR}^{i}\left(t,j\right)$*, set* $s_{ij}=0$
3. *Put* $j=\left\{j\in J\,\middle|\,\max\left\{I_{CDR}^{i}\left(t,j\right)\right\}\right\}$ *on the first place.*
4. *Set* $C_j=\delta_j$ ， $t=C_j$
5. *remove j from Set* J
6. *While* $J\neq\Phi$ *do*
7. *Get the index using Eq.(14)* $I_{CDR}^{i}\left(t,j\right)$ ， $\forall j\in J$
8. *Select* $j=\left\{j\in J\,\middle|\,\max\left\{I_{CDR}^{i}\left(t,j\right)\right\}\right\}$ *to be the next.*
9. *Update* $C_j=\max\left(r_j,C_i+s_{ij}\right)$
10. *update* $t=C_j$
11. *remove j from Set* J
12. *End While*
13. *CPLEX is adopted to get the result*

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In the two-step optimization strategy, firstly, a sequence is obtained by using the CDR method. In such step, the first aircraft is determined by the minimum due dates. Then, the remaining aircraft will be assigned one by one based on the Eq.(14). These steps will be continued until the last aircraft. Secondly, take the sequence into the formulation of multi-objective ALP, in which Eq.(5) should be changed since $q_{k,j}$ has been determined. Finally, CPLEX is adopted to solve the multi-objective ALP.

EXPERIMENTS AND RESULTS

The performance of the proposed CDR-based method for multi-objective ALP was evaluated by a set of benchmark instances and the real case. In these experiments, we tried to formulate and solve the proposed mathematical programming model using CPLEX ((IBM ILOG CPLEX Optimization studio version 12.6) on a PC with 3.30 GHz Intel core I5-4590 processor and 8GB RAM. In addition, the stop limit of CPU computation time of the CPLEX solver is set as 600 s.

Numerical Instances

In this experiment, a set of benchmark instances from the OR Library (could be download from http://people.brunel.ac.uk/~mastjjb/jeb/orlib/airlandinfo.html.) is used, which is the typical benchmark to validate the proposed method for tacking the ALP.

The aircraft landing set contains 13 instances (airland#1-airland#13), involving 10 to 500 aircraft. The airland#9 to airland#12 are used because the WV separation is similar to the real operation. Furthermore, the numbers of aircraft in airland#9 to airline#12 are 100, 150, 200, and 250. And $F_{\max}$ of different instances in Eq.(2) are set to 1,200, 1,300, 1,300, and 1,300, respectively.

The main purpose of this experiment is to carry out the comparison between the results obtained by the proposed method and the results of CPLEX solver imposing on Eq.(1)-Eq.(11). In the former method, landing sequences are obtained based on the composite dispatching rule, as shown in Eq.(14). Then the scheduled landing times are optimized by using CPLEX solver while the landing sequences are determined. In the latter method, both of the sequence and time are optimized by CPLEX solver.

Consider the scenarios and scheduling results of airland#9, as shown in Figure 1, including aircraft appear time (magenta diamond), scheduled time window consisted of earliest and latest landing time (black star line), target landing time (black box), scheduling landing time obtained by CPLEX (red circle), scheduling landing time by our method (blue triangle). Figure 1 provides a clearer display of the scenarios (sorted by appear time) and part results of airland#9.

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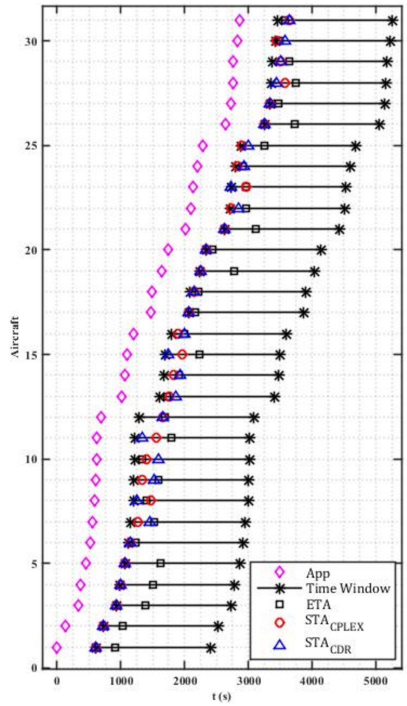

Figure 1.The part optimized results of airland#9.

Furthermore, the computational outcomes are summarized in Table 2, including different objectives. Table 3 compares CPU times of optimizing those instances with multiple objectives. In Table 2, the gap column shows the deviation between the results by CPLEX solver and our proposed CDR+ CPLEX method.

Table 2. The Computational Outcomes

Instances	**Items**	$\sum T_j/n$	$\sum F_j/n$	$\max F_j$	**Multi-objective**
Airland #9	CPLEX	4.02	684.49	1,140.00	344.26
	CDR+ CPLEX	10.03	694.01	1,072.00	352.02
	Gap	6.01	9.52	-68.00	7.76
Airland #10	CPLEX	10.14	700.65	1,232.00	355.39
	CDR+ CPLEX	28.19	726.38	1,231.00	377.29
	Gap	18.05	25.73	-1.00	21.89
Airland #11	CPLEX	0.58	674.06	1,020.00	337.32
	CDR+ CPLEX	11.64	696.48	1,182.00	354.06
	Gap	11.06	22.42	162.00	16.74

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Instances	Items	$\sum T_j / n$	$\sum F_j / n$	$\max F_j$	Multi-objective
Airland #12	CPLEX	3.60	674.85	1,231.00	339.23
	CDR+ CPLEX	11.41	686.68	1,220.00	349.05
	Gap	7.81	11.83	-11.00	9.82

Table 3. The CPU Times of Optimization(s)

Items	Airland #9	Airland #10	Airland #11	Airland #12
CPLEX	629.88	668.06	745.47	844.83
CDR+ CPLEX	13.18	8.08	9.78	10.50

From Table 2 and Table 3, we can find that the proposed method could obtain the approximate optimal results in about 10 seconds.

Real Case

In this experiment, the real case is taken into account. The radar tracks of aircraft taking-off from and landing on Guangzhou Baiyun International Airport (ZGGG) on Dec.15, 2017 are shown in Figure 2. In such real case, a set of arrival aircraft, landing on runway 02R during 10 am to 11 am, is chosen as the samples.

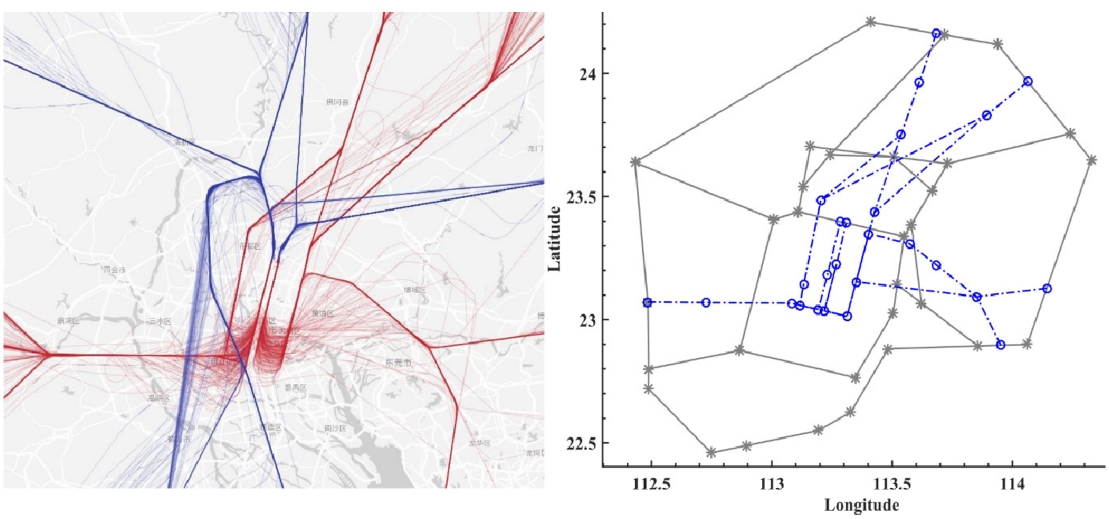

Figure 2. Radar tracks around ZGGG on Dec.15, 2017 (Northbound operation).

Firstly, we reconstruct the scenario of such real case. In this step, the radar tracks are analyzed to get the appearing time, the earliest/target/latest landing time, the aircraft wake vortex type, and the actual landing time. In addition, the maximum dwell time is set to be 1,800s.

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Secondly, through those parameters and constraints, we optimized the landing time by using our proposed method – CDR+CPLEX, in which the landing sequence is determined by using Eq.(14), then the landing times are optimized by CPLEX solver.

Thirdly, we carry out a comparative analysis between the optimized landing time and the actual landing time.

Figure 3 shows the comparison of delay and dwell time of each aircraft. After the optimization, landing time of the last one is 461 seconds earlier than the actual case which means the runway capacity is improved. The average flow time decrease from 1633 to 1209 seconds shows the workload of air traffic controllers is reduced. The average delay decreases 150 seconds, which shows the method can also maximize the cost-effectiveness of the airlines. The computational results illustrate the efficiency of our approach, which could simultaneously enhance the runway capacity, reduce the workloads of air traffic controllers and maximize the cost-effectiveness of airlines.

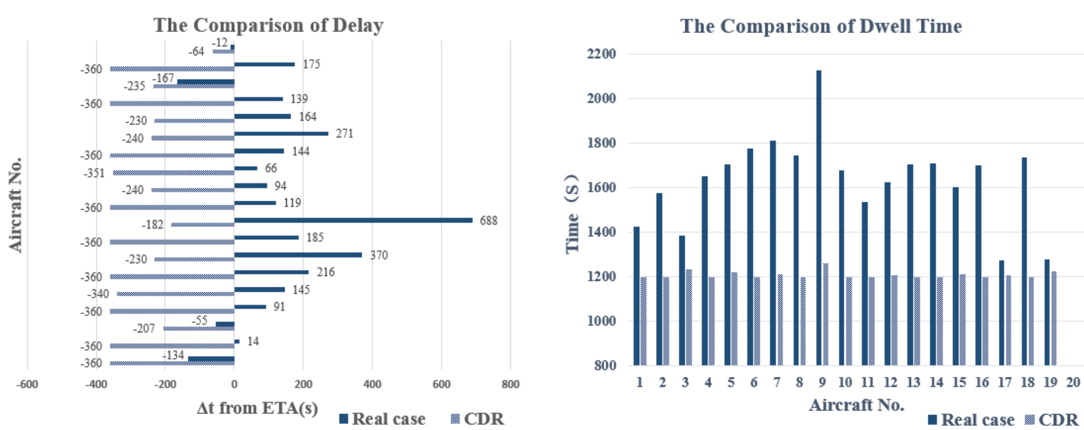

Figure 3. Scheduled results of actual case.

CONCLUSION

In this paper, a new composite dispatching rule and the corresponding algorithm are proposed to tackle the multi-objective ALP. The proposed CDR method contains two parts. First, the proper designed CDR rule is applied to find the landing sequence, and then the scheduled landing time is calculated by CPLEX solver. The most prominent feature of this proposed method is that it could quickly obtain a near-optimal result for the multi-objective ALP. Numerical instance and real case have been successfully adopted to validate the effectiveness and efficiency of our proposed method. The proposed method is fast due to the CDR part getting a good starting sequence for the further optimization part.

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However, the CDR part is a one-off process, the CDR-based method might lead to a suboptimal sequence. In future research, how to combine the CDR-based method and meta-heuristic algorithm to tackle the ALP is worthy of further in-depth study.

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REFERENCES

Beasley, J. E., Krishnamoorthy, M., Sharaiha, Y. M., and Abramson, D. (2000). “Scheduling Aircraft Landings-The Static Case.” *Transportation Science*, 34(2), 180–197.

Bennell, J. A., Mesgarpour, M., and Potts, C. N. (2013). “Airport runway scheduling.” *Annals of Operations Research*, 204(1), 249–270.

Bennell, J. A., Mesgarpour, M., and Potts, C. N. (2017). “Dynamic scheduling of aircraft landings.” *European Journal of Operational Research*, Elsevier B.V., 258(1), 315–327.

Faye, A. (2015). “Solving the aircraft landing problem with time discretization approach.” *European Journal of Operational Research*, Elsevier Ltd., 242(3), 1028–1038.

Girish, B. S. (2016). “An efficient hybrid particle swarm optimization algorithm in a rolling horizon framework for the aircraft landing problem.” *Applied Soft Computing Journal*, Elsevier B.V., 44, 200–221.

Hong, Y., Cho, N., Kim, Y., and Choi, B. (2017). “Multiobjective Optimization for Aircraft Arrival Sequencing and Scheduling.” *Journal of Air Transportation*, 25(4), 115–122.

Hu, X. B., and di Paolo, E. A. (2011). “A ripple-spreading genetic algorithm for the aircraft sequencing problem.” *Evolutionary Computation*, 19(1), 77–106.

Ji, X. P., Cao, X. Bin, and Tang, K. (2016). “Sequence searching and evaluation: a unified approach for aircraft arrival sequencing and scheduling problems.” *Memetic Computing*, Springer Berlin Heidelberg, 8(2), 109–123.

Lieder, A., Briskorn, D., and Stolletz, R. (2015). “A dynamic programming approach for the aircraft landing problem with aircraft classes.” *European Journal of Operational Research*, Elsevier Ltd., 243(1), 61–69.

Pinedo, M. L. (2016). *Scheduling: Theory, Algorithms, and Systems*. Springer International Publishing.

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Sabar, N. R., and Kendall, G. (2015). "An iterated local search with multiple perturbation operators and time varying perturbation strength for the aircraft landing problem." *Omega*, Elsevier, 56, 88–98.

Samà, M., D'Ariano, A., D'Ariano, P., and Pacciarelli, D. (2017). "Scheduling models for optimal aircraft traffic control at busy airports: Tardiness, priorities, equity and violations considerations." *Omega (United Kingdom)*, Elsevier, 67, 81–98.

Vadlamani, S., and Hosseini, S. (2014). "A novel heuristic approach for solving aircraft landing problem with single runway." *Journal of Air Transport Management*, Elsevier Ltd, 40, 144–148.

Wang, F., Zhang, J., Chen, Q., and Sui, D. (2015). "Dynamic Arrival Scheduling Based on Branch and Bound Algorithm." *CICTP 2015*, Beijing, 56–68.

Zhan, Z. H., Zhang, J., Li, Y., Liu, O., Kwok, S. K., Ip, W. H., and Kaynak, O. (2010). "An efficient ant colony system based on receding horizon control for the aircraft arrival sequencing and scheduling problem." *IEEE Transactions on Intelligent Transportation Systems*, 11(2), 399–412.

Zhang, J., Ge, T., and Zheng, Z. (2017a). "Collaborative Arrival and Departure Sequencing for Multi-airport Terminal Area." *Journal of Transportation Systems Engineering and Information Technology*, 17(2), 197–204.

Zhang, J., Zheng, Z., and GE, T. (2017b). "Sequencing approach of arrival aircrafts based on composite dispatching rules." *Journal of Traffic and Transportation Engineering*, 17(3), 141–150.

Zografos, K. G., Madas, M. A., and Androutsopoulos, K. N. (2017). "Increasing airport capacity utilisation through optimum slot scheduling: review of current developments and identification of future needs." *Journal of Scheduling*, Springer US, 20(1), 3–24.

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