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Application of Local Search Algorithm with Constraint Position Shifting in Flight Scheduling

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Abstract. Flight scheduling is a critical issue in airport scheduling, and its effective resolution is of great significance for improving runway capacity and operational efficiency. To tackle this challenge, this paper proposes the ILS-CPS algorithm. The algorithm combines the flexibility and high efficiency of iterated local search to achieve both real-time and optimal flight scheduling. Additionally, by incorporating constrained positional shifts, it ensures the operability and fairness of the scheduling process. Experimental results demonstrate that, compared to the First-Come, First-Served (FCFS) method, the proposed algorithm significantly reduces the total delay time of the flight queue. Even with a large number of flights, it can still find a high-quality solution within a short time, indicating its practical applicability.

Keywords: Iterated Local Search, Constraint Position Shifting, Flight Scheduling

1. Introduction

With the rapid growth of the air transport industry, particularly the increasing volume of business at major cities and hub airports, the complexity of flight scheduling has risen significantly. Flight scheduling involves the allocation of limited resources, such as runway access, gates, taxiways, and parking aprons. Efficiently utilizing these resources while minimizing flight delays is a crucial task in airport operations. Optimizing flight scheduling not only enhances the utilization rate of airport resources but also significantly improves flight punctuality, reducing delays and minimizing the waste of resources.

Currently, the most commonly used scheduling method assigns landing sequences and times based on the Estimated Time of Arrival (ETA) of aircraft, following a First-Come, First-Served (FCFS) strategy. The FCFS strategy is simple and straightforward, but during the peak periods of airport it can lead to significant delays for many aircraft and inefficient use of runways. To address these issues, a growing number of researchers have proposed various optimization algorithms [1]-[5]. However, since this problem is a typical combinatorial optimization problem and belongs to the NP-hard class, it becomes difficult to obtain an effective feasible solution within a short period as the problem scale grows.

The Iterated Local Search (ILS) algorithm was first formally introduced by Martin, Otto, and Felten in their 1992 paper [6], aiming to find global optimal solutions through the extension of local search techniques. ILS can integrate various local search algorithms and is applicable to a wide range of optimization problems. It is simpler to implement than other complex meta-heuristic algorithms, such as genetic algorithms or simulated annealing. The ILS algorithm has demonstrated strong performance in solving problems like the Traveling Salesman Problem, machine scheduling, and vehicle routing.

To achieve operability and fairness in flight scheduling, Dear et al. first proposed the CPS [7]. In the process of scheduling, the constraint control of the aircraft position is used to ensure the stability of the aircraft relative to the initial position after scheduling. The core idea of this strategy is to ensure that the final position of an aircraft deviates from its initial position within an acceptable range, which is typically used to avoid unnecessary delays or to make the scheduling more compliant with certain air traffic management requirements.

This paper proposes a method based on the combination of the Iterated Local Search (ILS) algorithm with the CPS, ILS-CPS, to solve the optimization problem in flight scheduling. By incorporating the CPS

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strategy into the local search process and combining it with perturbation operations, the ILS-CPS algorithm can effectively avoid falling into local optimization and further improve the scheduling performance. This paper explores the feasibility and effectiveness of ILS-CPS in flight scheduling through the establishment of a flight scheduling model and the application of the ILS-CPS algorithm.

2. Model and Constraints of Flight Scheduling Problem

The objective of the flight scheduling problem is to minimize flight delays and optimize resource utilization through efficient allocation of resources. The flight scheduling problem can be formulated using the following mathematical model.

2.1. Problem Definition

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Given a group of flights $F = \{f_1, f_2, ..., f_n\}$ and their initial positions $P = \{p_1, p_2, ..., p_n\}$, the goal is to allocate scheduling locations $Q = \{q_1, q_2, ...q_n\}$ for these flights, so that:

- Each flight is assigned to only one position.
- The CPS requirements: the deviation the assigned position for each flight from its initial position does not exceed a certain maximum allowable value Δd .
- Minimize total delay.

2.2. Decision Variable

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Define binary variables:

$$x_{ij} = \begin{cases} 1, & \text{if flight } f_i \text{ is assigned to position } j \\ 0, & \text{otherwise} \end{cases}$$

where $i = 1,2,...,n;\ j = 1,2,...,n.$

2.3. Objective Function

Minimize total delay: $Minimize\ total\ D = \sum_{i=1}^{n} STAi - ETAi$

Where STA_i denotes the scheduled arrival time of flight x_i, and ETA_i denotes the expected arrival time of flight x_i

2.4. Constraints

- Each flight is assigned to, and only to, one position: $\sum_{j=1}^{n} x_{ij} = 1, \forall i = 1,2,...n$
- Each position can only be assigned to at most one flight: $\sum_{j=1}^{n} x_{ij} \le 1, \forall j = 1,2,...n$
- Constraint Position Shifting:

The Constraint Position Shifting (CPS) means that the aircraft cannot deviate arbitrarily from its original position during the scheduling process. Specifically, the position deviation of an aircraft relative to its initial position in FCFS (First-Come-First-Served) scheduling must not exceed Δd (where Δd is the maximum allowed shift). In other words, for an aircraft with an initial position p_{i,j_0}, its scheduled position p_{ij}, must satisfy the condition $d(p_{ij_0} - p_{ij_1}) \leq \Delta d$. By introducing the CPS, the operational feasibility and fairness of the scheduling are ensured to a certain extent.

For any aircraft I, definition:

p_{ij_0}: The initial position of aircraft i is j_0;

p_{ij_1}: The scheduled position of aircraft i is j_1;

$d(p_{ij_0} - p_{ij_1})$: The distance from the initial position to the final position;

Δd: Preset allowable maximum offset range;

$$d(p_{ij_0} - p_{ij_1}) \leq \Delta d$$

- Variable Definition:

$$x_{ij} \in \{0,1\}, \ \forall i, j$$

3. Implementation of the ILS-CPS Algorithm

3.1. Algorithm Description

ILS (Iterated Local Search) is widely used to solve large-scale combinatorial optimization problems due to its simplicity, ease of implementation, and strong flexibility. This paper makes use of the efficiency and real-time of ILS in solving the flight scheduling problem, and incorporates CPS (Constraint Position Shifting) to make the flight scheduling more realistic. The design idea of the proposed ILS-CPS algorithm is as follows: First, a sequence p is randomly generated, and then the sequence s_best is generated and the total delay d of which is calculated when the FCFS (First-Come-First-Served) strategy is applied to optimize p. Perform local search on s_best as the initial sequence, and use Remove and Reinsert to generate new solutions during the search process. Each solution is checked for the validity of the CPS constraint, and the total delays of the valid solutions are calculated, while invalid solutions are discarded. After the local search is completed, a new sequence s_new is generated. The total delay of s_new is d_new , if d_new <d , then s_best = s_new . After applying a disturbance to s_best , the local search continues. This process is repeated until the stopping condition is met.

The description of the ILS-CPS algorithm is as follows:

Input: Problem instance, stopping criteria

Output: Best solution found

```
p ← RandomSolution()
s_best ←FCFS(P)
s_best ← LocalSearchCps(s_best)
while not StoppingCriteriaMet() do
    s_new ← Perturbation(s_best)
    s_new ← LocalSearchCps(s_new)
    if AcceptanceCriterion(s_new, s_best) then
        s_best ← s_new
    end if
end while
return s_best
```

3.2. Neighborhood Structure

The neighborhood structure is the core of local search algorithms, as it defines the relationships between solutions in the solution space, specifically determining which solutions belong to the neighborhood of a given solution. Commonly used neighborhood structures include Swap Neighborhood, Insertion Neighborhood, Reversion/Reverse Neighborhood, Remove and Reinsert Neighborhood, Adjacency Neighborhood, etc. These neighborhood structures are often employed in problems such as scheduling, route optimization, and facility location.

1. Select positions pi and pj， pj ∈[pi- △ d,pi+ △ d] , pj ≠ pi)

x_{p1}	x_{p2}	…	$x_{pi-\Delta d}$	…	x_{pj}	…	x_{pi-1}	x_{pi}	x_{pi+1}	…	$x_{pi+\Delta d}$	…	x_{pn}
p1	p2	…	pi-△d	…	pj	…	pi-1	pi	pi+1	…	pi+△d	…	pn

2.delete x_{pi}

x_{p1}	x_{p2}	…	$x_{pi-\Delta d}$	…	x_{pj}	…	x_{pi-1}	x_{pi+1}	…	$x_{pi+\Delta d}$	…	x_{pn}	
p1	p2	…	pi-△d	…	pj	…	pi-1	pi	…	pi+△d-1	…	pn-1	pn

3.Insert x_{pi} into position pj

x_{p1}	x_{p2}	…	$x_{pi-\Delta d}$	…	x_{pi}	x_{pj}	…	x_{pi-1}	x_{pi+1}	…	$x_{pi+\Delta d}$	…	x_{pn}
p1	p2	…	pi-△d	…	pj	pj+1	…	pi	pi+1	…	pi+△d	…	pn

Fig. 1: Neighborhood Structure

This paper adopts the Remove and Reinsert Neighborhood to remove an element of the selected solution from the current location and insert it into another location. During the reinsertion process, the Constrained Position Shifting (CPS) constraint in the problem is taken into account. Therefore, the choice of the reinsertion position is controlled accordingly. This approach effectively reduces the search space and improves search efficiency. The specific operation steps are as follows: Assign the maximum value of the Constraint Position Shifting (CPS) as Δd . Select a position pi, then choose a position pj from the interval $[pi-\Delta d, pi+\Delta d]$, where $pj \in [pi-\Delta d, pi+\Delta d]$ and $pj \neq pi$. Remove the element xpi from the current position pi， and then move every element starting from xpi+1 (including xpi+1) one position forward. Next, move all elements from position pj one position backward, and finally insert the element xpi into position pj. The process is shown in Fig. 1.

3.3. Experiments and Results

To validate the effectiveness of the ILS-CPS algorithm in solving flight scheduling problem, this paper calculates the total queue delay obtained by the ILS-CPS algorithm and compares it with the First-Come, First-Served (FCFS) strategy. The number of flights selected for testing are 20, 40, 60, 80, and 100, with the aircraft sequences generated randomly. Among these, H-type, L-type, and S-type flight patterns each account for one-third of the total, and the Expected Time of Arrival (ETA) of the flights obeys normal distribution. The maximum Constraint Position Shifting tested are Δd =5 and Δd =10, the number of iterations of the algorithm is set to max_iterations=n*10, and the maximum number of non-improvement iterations max_no_improvement = max_iterations / 10. We programmed the ILS-CPS algorithm in python on a PC running Windows 10 with a core i7 3.6 GHz CPU and 8.0 GB RAM. The experimental results are presented in Table 1.

Table 1: Comparisons of ILS-CPS algorithm with the FCFS strategy in total delay time of flight queue

Number of Flights	FCFS	ILS-CPS (k=5)			FCFS	ILS-CPS (k=10)		
		Total Delay Time	Time(s)	Improvement in Delays		Total Delay Time	Time(s)	Improvement in Delays
20	17002	13650	0.58	19.71%	17247	12723	1.49	26.23%
40	79156	65414	3.06	17.36%	74932	59017	7.99	21.23%
60	169829	146504	9.15	13.73%	177498	147740	25.77	16.765%
80	312102	262427	94.48	15.91%	304698	253869	51.53	16.68%
100	506498	430561	42.26	14.99%	520787	427663	171.6	17.88%

As shown in Table 1, when Δd =5, the total delay of the ILS-CPS algorithm is reduced by 13% to 19% compared to the FCFS scheduling method. Furthermore,when Δd =10, the total delay of the ILS-CPS algorithm is reduced by 17% to 26% compared to FCFS strategy. These results demonstrate the ILS-CPS algorithm's effectiveness in reducing flight delays. Overall, the experimental results indicate that ILS-CPS can significantly reduce flight delays and improve resource utilization in flight scheduling problems.

In terms of algorithm stability, this paper selects Δd =10 and n=100 to analyze the convergence of the algorithm's minimum total delay, which is as shown in Fig.2. Fig.2 illustrates the variation of the minimum total delay obtained after each iteration. It can be observed that as the number of iterations increases, the curve in the graph descends rapidly and then stabilizes. This indicates that the ILS-CPS algorithm exhibits good convergence in calculating the minimum total delay for flight queues. Additionally, it validates that the experimental choice of maximum iterations max_iterations = n*10 and the maximum number of iterations without improvement max_no_improvement = max_iterations /10 ensures the algorithm reaches a stable state.

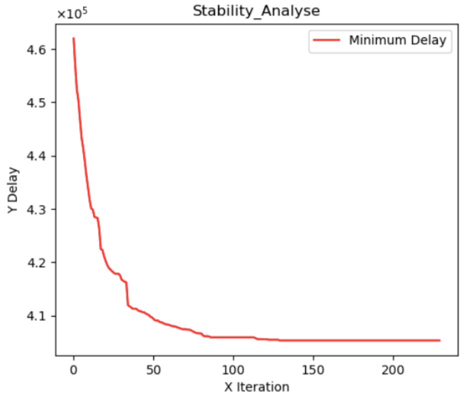

Fig. 2: Algorithm Stability Analysis

In this paper, an optimization method ILS-CPS for flight scheduling based on the Iterated Local Search algorithm with Constraint Position Shifting is proposed, and its effectiveness is verified through experiments. The experimental results demonstrate that the ILS-CPS algorithm is effective in reducing flight delays and improving resource utilization. Future work may explore the integration of other optimization techniques to further enhance the algorithm's performance and tackle more complex scheduling problems. Although the ILS-CPS algorithm has shown promising results in this study, some limitations remain. For instance, in dynamic scheduling and processing of large-scale datasets, the current ILS-CPS algorithm may have longer computation times. Future research could incorporate advanced technologies such as deep learning and reinforcement learning to further improve the algorithm's performance and adaptability.

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