



Optimization Method for Multi-Runway Operation Modes

Xiang Gao*

School of Air Traffic Management, Civil Aviation University of China, No. 2898 Jinbei Road, Dongli District, Tianjin, China 022-24092434

*584055519@qq.com

Abstract. With the rapid development of the air transport industry, multi-runway airports are facing a sharp increase in operational pressure. Reliance on manual decision-making and a lack of scientific basis for runway operation modes result in low resource utilization and severe flight delays. To improve operational efficiency, this paper conducts a study on the optimization of multi-runway operation modes.

It analyzes three types of runway configurations, theoretical capacities and key influencing factors^[1]. Taking parallel dual-runway airports as the research object, an integer programming model is established to minimize the total delay cost with multiple constraints set. The branch and bound method is adopted for solution to avoid local optimal solutions. Simulation verification shows that the optimized scheme can reduce the total flight delay cost by up to 96%, and the optimization effect improves with refined time slices and stable traffic flow. This research provides theoretical support and practical methods for runway management, effectively enhancing the operational efficiency of airports.

Keywords: Multi-runway airport, runway utilization mode, integer programming, branch-and-bound method, minimization of delay costs

1 Introduction

Affected by operational environments and mutual constraints between runways, the efficient utilization of resources has become the key to improving the overall capacity of airport runway systems. As a core link in airport operational optimization, runway operation modes directly determine the capacity and operational efficiency of runway systems^[2].

At present, most runway operation plans rely on air traffic controllers' experience, which leads to strong subjectivity, incomplete consideration of influencing factors, susceptibility to cognitive workload, and large fluctuations in resource utilization. Therefore, intelligent optimization of multi-runway operation modes is of great practical significance for improving airport operational efficiency and reducing flight delays.

Taking parallel dual-runway airports as the research object and aiming to minimize the total delay cost, this paper constructs an integer programming optimization model

and adopts the branch-and-bound method for accurate solution. Numerical examples verify the effectiveness of the model and algorithm [3], compensate for the deficiencies of existing methods, and help enhance the operational efficiency and service level of hub airports.

2 Classification of Multi-Runway Operation Modes and Analysis of Influencing Factors

The runway configurations of multi-runway airports are primarily categorized into three types: parallel, intersecting, and V-shaped. The runway usage patterns differ significantly depending on the specific configuration, and their selection is influenced by a combination of various factors [4]. This paper conducts a systematic analysis of the usage patterns for these three runway configurations and identifies the key factors that affect the choice of runway usage patterns.

2.1 Classification of Multi-Runway Operation Modes

Parallel Runway Operation Mode.

Parallel runways are the most common multi-runway configuration, referring to two or more runways arranged parallel to each other in the same direction with relatively close centerline spacing [5]. With the exception of Beijing Daxing International Airport and Chengdu Tianfu International Airport, all other multi-runway airports in China adopt this configuration. Depending on the runway operation mode and spacing requirements, there are mainly six types of parallel runway usage patterns. Each pattern has different applicable conditions and operational characteristics, and the corresponding theoretical capacity of the airport varies significantly.

Cross-runway Usage Pattern.

A crossing runway refers to two or more runways that intersect or cross each other in space, typically arranged in a “ten” or “X” shape. The operational modes for such runways are mainly divided into three types: ① independent operation mode; ② mixed operation mode; ③ simultaneous operation mode.

V-shaped Runway Usage Pattern.

V-shaped runway refers to a configuration in which two or more runways intersect at either their start or end points, forming a “V”-shaped layout. The operational modes include independent operation, segregated operation, mixed operation, and simultaneous operation. The key difference among these modes lies in the varying locations where the runways intersect, resulting in distinct approaches to flight path planning and spacing standards. Under the simultaneous operation mode, flight path conflicts tend to concentrate primarily at the runway intersection points.

2.2 Factors Influencing the Selection of Multi-Runway Operation Modes

The selection of runway usage patterns at multi-runway airports is the result of the combined influence of objective and subjective factors, with objective factors serving as the core determinants. These objective factors primarily fall into the following five categories:

(1) Runway physical attributes: include runway spacing, configuration, length, and orientation, among others.

(2) Airport capacity characteristics: including the volume of flight traffic and the proportion of arriving and departing flights, etc.

(3) Meteorological conditions: Wind direction and wind speed determine the takeoff and landing directions of the runway, while visibility and cloud base altitude influence the choice of flight rules (IFR/VFR). Adverse weather conditions—such as heavy rain, thunderstorms, and dense fog—may also lead to the closure of certain runways.

(4) Air traffic control operating rules: including runway allocation rules, spacing standards, and traffic management decision-making rules, etc.

(5) Operational emergencies—such as runway incursions, lighting system failures, and pavement damage—can cause runways to become temporarily unavailable.

In addition, subjective factors such as air traffic controllers' command habits and control procedures can also exert a certain influence on the selection of runway usage patterns. Therefore, when developing optimization plans, it is essential to strike a balance between the scientific rigor of the model and the practical operability of actual operations.

3 Model Construction and Solution Algorithms

Domestic multi-runway airports primarily adopt a parallel dual-runway configuration. Therefore, this paper takes parallel dual-runway airports as the research object, constructs an integer programming model for optimizing runway usage patterns, and designs a corresponding solution algorithm.

3.1 Problem Assumption

To simplify the research problem while ensuring the model is consistent with actual operations, the following six assumptions are proposed based on the basic laws of airport operations:

(1) During the study period, the airport's meteorological conditions and predicted arrival/departure demands can be accurately predicted and remain unchanged. This study adopts a steady-state operation assumption, which is consistent with the basic analytical conditions of the FAA AC 150/5060-5 runway capacity model and is applicable to scenarios with stable meteorological conditions.

(2) Flight arrival and departure demands can be divided into equally spaced time slices, and the demand within each time slice is constant.

(3) Air traffic control methods, rules, and separation standards remain unchanged during the study period.

(4) The physical attributes of the runways are fixed, and runway unavailability caused by long-term events such as equipment failure and maintenance is not considered.

(5) The runway usage mode is discrete and can be represented by 0-1 integer variables.

(6) All operational constraints and influencing factors can be quantified and transformed into constraints of the model.

3.2 Objective Function

The optimization objective for runway usage patterns is to enhance airport resource utilization and reduce the cost of flight delays. This paper takes minimizing the total delay cost of all flights during the study period as the objective function. By rationally selecting runway usage patterns for each time segment, we aim to match capacity supply with flight demand and thereby reduce flight delays caused by capacity mismatches. The expression for the objective function is:

$$\min \sum_{t=1}^T (\Delta A_t \cdot C_{At} + \Delta D_t \cdot C_{Dt}) \quad (1)$$

In the formula: T represents the set of time slots; t represents a single equidistant time slot, $t \in T$; ΔA_t represents the number of inbound flights delayed from time slice t to $t + 1$ due to the mismatch between capacity supply and demand; ΔD_t represents the number of $t + 1$ outbound flights delayed due to t capacity supply-demand mismatches within a given time slot; C_{At} and C_{Dt} represent the average single-vehicle delay cost (in yuan per aircraft) for inbound and outbound flights that are delayed until the next time slice within time period t .

3.3 Constraints

Based on the practical constraints of airport operations, we translate the uniqueness of runway usage patterns, the equality relationship of traffic flow, the envelope constraints on runway capacity, and the non-negativity of variables into mathematical constraints, thereby ensuring the reasonableness and feasibility of the model's solution.

Traffic Flow Identity Constraint.

For inbound flights, time slot t the total inbound demand equals the sum of the number of inbound flights that can be served during this time slot and the number of inbound flights delayed to the next time slot. It also equals the sum of the initial number of inbound flights in this time slot and the number of inbound flights delayed from the previous time slot to this time slot. The expression is:

$$\sum_{i \in m_t} \varepsilon_{it} + \Delta A_t = A_t + \Delta A_{t-1} \quad \forall t \in T, \forall i \in m_t \quad (2)$$

In the formula: i For time slice t a certain runway usage pattern within; A_t For time slice t number of inbound flights at initial entry; ε_{it} For time slice t internal usage mode i number of inbound flights that can be served at the time; m_t For time slice t Set of runway usage patterns available for internal use.

The traffic flow identity relationship for departing flights is consistent with that for arriving flights, and the expression is:

$$\sum_{i \in m_t} \delta_{it} + \Delta D_t = D_t + \Delta D_{t-1} \quad \forall t \in T, \forall i \in m_t \quad (3)$$

In the formula: δ_{it} for time slice t internal usage mode i number of departing flights currently available for service; D_t for time slice t number of inbound departing flights at the initial stage.

Uniqueness Constraint on Runway Usage Patterns.

Within each time slot, the airport can only adopt one runway usage mode to avoid capacity loss and control confusion caused by mode switching. The expression is:

$$\sum_{i \in m_t} x_{it} \leq 1 \quad \forall t \in T \quad (4)$$

In the formula: x_{it} a 0-1 integer variable, if time slice t usage pattern i then $x_{it} = 1$, otherwise $x_{it} = 0$.

Runway Capacity Envelope Constraint.

The runway capacity envelope delineates the combined capacity boundary for arrival and departure flights under a specific operational mode. The area within the envelope represents the feasible operating capacity; therefore, the volume of flight services under each mode must not exceed the limits imposed by the capacity envelope. Additionally, any capacity loss resulting from mode transitions must be taken into account. The expression is as follows:

$$\alpha_{il} \varepsilon_{it} + \beta_{il} \delta_{it} + \gamma_{il} (1 - \theta_{it}) \leq G (1 - x_{it}) \quad (5)$$

In the formula: α_{il} , β_{il} and γ_{il} are the coefficients of the independent variable, the dependent variable, and the constant, respectively, for the l th linear segment of the capacity envelope under the usage pattern, determined either by the FAA model or by experimental data; The FAA runway capacity envelope model is typically based on AC 150/5060-5. It constructs the feasible boundary between arrival rates and departure rates by calculating the all-arrival capacity (CAPA), all-departure capacity (CAPD), free departure capacity (DF), and the maximum throughput point under alternating operations. The envelope consists of four segmented lines that represent the maximum sustainable operational boundary of the runway under constraints of minimum separation, runway occupancy time, and wake turbulence. Points inside the envelope are operationally feasible, while points outside are infeasible. G is the set of linear segments of the capacity envelope during the usage pattern within a time slice; γ_{il} is a sufficiently large constant; and θ_{it} is the capacity loss coefficient during the usage pattern within a time slice.

The capacity loss coefficient is determined by the proportion of capacity loss due to mode switching and is expressed as follows:

$$\theta_{it} = x_{it} \left(\sum_{j \in m_{t-1}} x_{jt-1} \cdot w_{ji} \right) \quad (6)$$

In the formula: w_{ji} for runway usage mode from j switch to i the proportion of capacity loss, determined by actual operational data from the airport, when no mode switching occurs $w_{ii} = 0$.

Non-negativity Constraint on Variables.

The variables involved in the model, such as the number of flights and delay costs, are all non-negative, and x_{it} a 0-1 integer variable, where the number of delayed flights in the initial period is 0, and the constraint expression is:

$$A_t, D_t, \Delta A_t, \Delta D_t, \varepsilon_{it}, \delta_{it} \in N, \forall t \in T, \forall i \in m_t \quad (7)$$

3.4 Model Solving Algorithm

Algorithm Selection.

The model constructed in this paper is an integer programming model, and the optimization of runway usage patterns constitutes a discrete-objective optimization problem. Existing studies often employ genetic algorithms to solve such problems; however, these algorithms rely heavily on empirically determined parameters, are prone to getting trapped in local optima, and exhibit poor solution stability. The branch-and-bound method is a classic algorithm for solving integer programming problems. By decomposing the original problem into multiple subproblems and solving the relaxed versions of these subproblems to narrow down the search space, the method ultimately identifies the global optimum without requiring parameter tuning, thus yielding more reliable solutions. Therefore, this paper selects the branch-and-bound method as the algorithm for solving the model.

Algorithm Implementation Steps.

Based on the characteristics of the problem related to optimizing runway usage patterns, the specific implementation steps for the branch-and-bound method are designed as follows:

Initialization: Enter model parameters (T, m_t, A_t, D_t and so on), solve the linear relaxation problem of the original integer program (ignoring with integer constraints), obtaining the optimal solution. x_{it}^* and the minimum cost function value Z^* . If the integer x_{it}^* constraints are satisfied, then it is the optimal solution to the original problem, and the algorithm terminates; otherwise, proceed to the next step.

Branch: Select the variable with the largest fractional part among the non-integer solutions. x_{it}^* branch, generating two subproblems and adding constraints: Subproblem 1 is $x_{it} = 1$, Subproblem 2 is $x_{it} = 0$.

Solve and perform pruning: Solve the relaxed problems of the two subproblems separately, then perform pruning checks: If a subproblem has no feasible solution, or if the objective value of its relaxed solution exceeds the current minimum cost function value Z^* . Then, prune this subproblem; If the optimal solution of the subproblem does not satisfy the integer constraints but its objective function value is less than Z^* . then the subproblem is retained; If the relaxed solution of the subproblem is an integer and the objective function value Z^{**} less than Z^* . Then, update the global optimal solution to this solution, and set the minimum cost value to Z^{**} .

Iteration and Termination: Among the retained subproblems, select a non-integer solution, and repeat Steps 2 and 3, continuously generating new subproblems and updating the minimum cost function value, until the optimal solutions to all subproblems are integer solutions. At that point, the algorithm terminates, and the optimal integer solution (the runway usage pattern for each time slot) and the minimum cost function value (the total delay cost) are outputted.

4 Chapter Three Example Analysis

To validate the effectiveness of the constructed model and the solution algorithm, this paper takes a certain parallel dual-runway airport as the experimental subject and designs three different experimental scenarios. Using real-world airport simulation data, we conduct case studies to compare the total delay costs between the optimized solution and the fixed-mode solution, thereby evaluating the optimization performance of the model.

4.1 Experimental Design

The operational period from 09:00 to 11:00 at this airport was selected as the study subject. During this period, the total number of flights was 191 (108 arriving and 83 departing), and flight schedule simulation data were used as the experimental data. The experimental assumptions are as follows: during the study period, the weather was clear and sunny; there were no operational emergencies; air traffic control rules remained unchanged; all runways were fully operational; and mixed-operation modes were not considered (due to limitations in airport equipment and technology).

The core variables in the experimental design are the granularity of time slice division and the degree of traffic flow fluctuation. By varying these two core variables, we have designed three experimental scenarios, as follows:

Experiment 1: With each time slice lasting 15 minutes, the study period was divided into 8 time slices, during which traffic flow exhibited significant fluctuations.

Experiment 2: With each time slice lasting 30 minutes, the study period was divided into four time slices, during which traffic flow exhibited significant fluctuations.

Experiment 3: Each time slice lasts 15 minutes, for a total of 8 time slices. While keeping the total number of arriving and departing flights constant, replace the highly volatile traffic flow with a more stable traffic flow.

In all three experiments, three optional runway usage modes were set. (i_1, i_2, i_3) The capacity loss ratio for mode switching is uniformly set at 0.2. The delay cost per flight is determined based on the airport’s actual operating costs, and delay costs vary across different time periods.

4.2 Experiment Execution and Results

Experiment 1 Results.

Experiment 1 divided the study period into 8 15-minute time slots. The number of inbound flights in these 8 time slots was 11, 12, 10, 14, 13, 16, 18, and 14 flights, respectively. The number of outbound flights in these 8 time slots was 12, 10, 10, 7, 13, 12, 10, and 9 flights, respectively. Pattern: i_1, i_2, i_3 the number of inbound flights that can be served per time slot is 13, 15, and 10 flights, respectively. The number of outbound flights that can be served per time slot is 11, 9, and 15 flights, respectively.

The branch-and-bound method was used to solve the model, with a solution time of 0.002 seconds. The optimized runway usage pattern and the total delay cost are shown in Table 1.

Table 1. Optimization Plan for Experiment 1

| | | | | | | | | | |
|--------------------|----|----|----|----|----|----|----|----|------------------------|
| Time slice | t1 | t2 | t3 | t4 | t5 | t6 | t7 | t8 | Total Delay Cost (CNY) |
| Select mode | i1 | i1 | i1 | i2 | i1 | i2 | i3 | i2 | 33471.00 |

If a fixed-pattern scheme is adopted, the total delay costs will be as follows: only use i_1 for 42,921.00 yuan, used only i_2 for 70,536.00 yuan, used only i_3 for 121,575.00 yuan.

Experiment 2 Results.

In Experiment 2, the study period was divided into four 30-minute time slots. The number of arriving and departing flights in each time slot was equal to the sum of the flight volumes in two corresponding time slots from Experiment 1. Similarly, the available flight capacity and delay costs were also cumulatively aggregated. The optimized solution obtained after solving the model is shown in Table 2, and the computation time for solving the model was 0.001 seconds.

Table 2. Optimization Plan for Experiment Two

| | | | | | |
|--------------------|-----|-----|-----|-----|------------------------|
| Time slice | t1' | t2' | t3' | t4' | Total Delay Cost (CNY) |
| Select mode | i1 | i1 | i1 | i2 | 38372.00 |

The total delay costs for the fixed-pattern scheme are as follows: using only i_1 for 39,588.00 yuan, used only i_2 for 67,945.00 yuan, used only i_3 for 140,925.00 yuan.

Experiment 3 Results.

In Experiment 3, the time slice granularity was maintained at 8 slices of 15 minutes each, and the traffic flow was adjusted to a steady state. The number of inbound flights for the 8 time slices was sequentially 13, 13, 13, 13, 14, 14, 14, and 14 flights, while

the number of outbound flights was sequentially 11, 11, 11, 10, 10, 10, 10, and 10 flights. All other parameters remained consistent with those in Experiment 1. After solving the model, the optimized solution is shown in Table 3, and the computation time for the solution was 0.002 seconds.

Table 3. Optimization Plan for Experiment Three

| | | | | | | | | | |
|--------------------|----|----|----|----|----|----|----|----|------------------------|
| Time slice | t1 | t2 | t3 | t4 | t5 | t6 | t7 | t8 | Total Delay Cost (CNY) |
| Select mode | i1 | i1 | i1 | i1 | i2 | i1 | i2 | i1 | 5096.00 |

The total delay costs for the fixed-pattern scheme are as follows: using only i_1 for 13,500.00 yuan, used only i_2 for 63,330.00 yuan, used only i_3 for 155,925.00 yuan.

4.3 Result Analysis

A comparative analysis was conducted between the total delay costs of the optimized schemes for the three experiments and those of the fixed-pattern schemes, and the reduction in delay costs achieved by the optimized schemes was calculated. The results are shown in Table 4, and the key conclusions are as follows:

Table 4. Comparison of Optimization Effects Among the Three Experimental Groups

| Experiment Name | Number of time slices | Traffic flow fluctuations | Total Delay Cost After Optimization (CNY) | Range of reduction in delay costs | Number of runway switches |
|------------------|-----------------------|---------------------------|---|-----------------------------------|---------------------------|
| Experiment One | 8 | Big | 33471.00 | 22.02~72.47% | 5 |
| Experiment Two | 4 | Big | 38372.00 | 3.07~72.77% | 1 |
| Experiment Three | 8 | small | 5096.00 | 62.25~96.73% | 4 |

1. The delay costs associated with the optimized solution have been significantly reduced: In all three experimental scenarios, the total delay costs of the optimized runway usage plan were substantially lower than those of the fixed-mode plan, with reductions reaching as high as 96.73%. This demonstrates that the model and solution algorithm developed in this paper can effectively optimize runway usage patterns, enhance airport resource utilization, and reduce flight delays.
2. The finer the time slice division, the better the optimization effect: Experiments 1 and 2 both involved high-fluctuation traffic flows. In Experiment 1, a 15-minute time slice (8 slices) was used; after optimization, the minimum reduction in delay costs was 22.02%. In Experiment 2, a 30-minute time slice (4 slices) was employed, yielding a minimum reduction of only 3.07%. Moreover, the total delay cost in Experiment 1 was lower than that in Experiment 2. The reason is that the finer the time

slice division, the more accurately we can match the capacity and flow characteristics of each time period, enabling a more refined selection of runway modes and enhancing the precision of the optimization.

3. The smaller the traffic flow fluctuations, the better the optimization effect: Experiments 1 and 3 both used 8 15-minute time segments. Experiment 3 had smaller traffic flow fluctuations, and after optimization, its delay cost reduction was as low as 62.25%, significantly higher than the 22.02% reduction achieved in Experiment 1. Moreover, the total delay cost in Experiment 3 was only 15.22% of that in Experiment 1. At the same time, the smaller the traffic flow fluctuations, the fewer the number of runway mode switches: Experiment 3 switched modes 4 times, while Experiment 1 switched modes 5 times. This reduction in mode switching minimized capacity losses and further lowered delay costs.
4. The branch-and-bound method demonstrates high solving efficiency: The solution times for all three experiments were under 0.002 seconds, indicating that the branch-and-bound method is highly efficient in solving small-scale integer programming problems. It can quickly generate optimal solutions, meeting the real-time decision-making needs of airport operations.

5 Research Conclusion and Outlook

5.1 Research Conclusion

This paper focuses on research into optimizing multi-runway operation modes, taking parallel dual-runway airports as the study object and carrying out classification, modeling, algorithm development, and validation. The main findings are as follows:

1. Systematically analyze multi-runway operation modes and their influencing factors, clearly define the characteristics of parallel, crossing, and V-shaped configurations, and confirm that the theoretical capacity differences among various parallel dual-runway configurations can range from 2 to 3 times. Identify five key factors—runway attributes, capacity and flow characteristics, meteorological conditions, air traffic control regulations, and emergency events—to provide a basis for optimizing decision-making.
2. Develop an integer programming model aimed at minimizing total delay costs, incorporating constraints such as traffic conservation, mode uniqueness, and capacity envelopes, to closely reflect real-world operations and accurately capture the relationship between supply, demand, and delays.
3. Verified through three sets of scenario examples, the optimized solution reduces delay costs by up to 96%. Moreover, the finer the time granularity and the more stable the traffic flow, the better the optimization effect. This provides a practical and feasible decision-making approach for runway operation management.

5.2 Research Limitations and Future Work

Although this study has achieved certain results, there are still limitations that can be further improved in four aspects: First, expand the research scope. Currently, the model is only built for parallel dual runways, without covering intersecting runways, V-shaped runways, or multi-airport coordination. In the future, more configurations can be included, and the traffic flow constraints between airports can be considered to carry out collaborative optimization; Second, introduce dynamic factors. The existing model is based on steady-state assumptions, which fix meteorological conditions, control rules, and other parameters, and fail to capture the dynamic changes of weather as a key influencing factor, resulting in weak dynamic adaptability. In the future, a dynamic capacity model under time-varying meteorological constraints can be constructed to realize real-time rolling optimization; Third, improve algorithm efficiency. The branch-and-bound method is time-consuming for large-scale problems. A hybrid algorithm combining heuristic and exact methods can be designed to balance accuracy and efficiency; Fourth, strengthen engineering validation. This study uses simulated data. In the future, actual operational data from typical domestic airports can be used to verify and optimize parameters, further improving the practicability and implementability of the model.

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