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Research Article

Generalized Method of Modeling Minute-in-Trail Strategy for Air Traffic Flow Management

Jinglei Huang, Qiucheng Xu, Yongjie Yan, Hui Ding, and Jing Tian

State Key Laboratory of Air Traffic Management System and Technology,
The 28th Research Institute of China Electronics Technology Group Corporation, Nanjing 210007, China

Correspondence should be addressed to Jinglei Huang; huangjl@mail.ustc.edu.cn

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With the rapidly increasing air traffic demand, the demand-capacity imbalance problem of sector is surfaced gradually. And, minute-in-trail/miles-in-trail (MIT) is an effective strategy to balance the traffic demands and capacity. In this work, we consider the MIT strategy generation problem for the situation that a sector with NC corridors is affected by convection weather for T_{imb} time periods. Given the sector capacity C_w^t, $t = 1, \ldots, T_{\mathrm{imb}}$, under convection weather, we propose a three-phase optimization framework to generate *E-MIT* strategy to achieve the demand-capacity balance. First, we take the sector capacity of T_{imb} time periods under convection weather as a whole, that is, $\sum_{t=1}^{T_{\mathrm{imb}}} C_w^t$, and then a dynamical programming-based method is proposed to allocate $\sum_{t=1}^{T_{\mathrm{imb}}} C_w^t$ for NC corridors such that the capacity resources A_w^i of each corridor COR_i, $i = 1, \ldots, \mathrm{NC}$, can be determined. Second, a 0-1 combination algorithm is used to allocate the capacity resources A_w^i into T_{imb} time periods for each corridor COR_i such that the candidate strategies set CS^i of each corridor can be determined, where a strategy $\mathrm{sol}_j^i \in \mathrm{CS}^i$ is an array with T_{imb} numbers and each number represents the maximum allowed number of flights entering into sector from COR_i in one time period. Finally, a modified shortest path algorithm based on the backtracking method is taken to select the optimal strategy from CS^i for NC corridors such that the total delay cost and air traffic control load are minimized. Additionally, a dynamical programming-based method is proposed to generate *E-MIT* strategy for the special case that the sector capacities of different time periods under convection weather are the same, that is, $C_w^1 = C_w^2 = \cdots = C_w^{T_{\mathrm{imb}}}$, and the generated strategies of T_{imb} time periods for a corridor are also the same. Experimental results show that compared with the proposed three-phase optimization method, rate-based method and need-based method will spend more 8.1% and 6.3% of delay cost, respectively. When considering the special case, the experimental results show that compared with the proposed dynamical programming-based method, the rate-based method and need-based method will spend more 10.2% and 7.5% of delay cost, respectively.

1. Introduction

With the rapidly growing air traffic demands, air traffic control load [1] is increased, and the air traffic problems [2–4], such as air traffic congestion, the demand-capacity imbalance problem [5], and flight delays [6], are surfaced gradually. And, the demand-capacity imbalance problem is often occurred, particularly when capacity has been reduced due to the convection weather.

Generally, the demand-capacity imbalance problem can be dealt with in two ways [7]. One is the long-term strategy through the construction of infrastructure, such as new airports and runways to enlarge capacity. However, this procedure would take a long time and high cost.

The second way is to regulate the traffic flow by using the traffic management initiatives (TMIs) [8], such that the limited capacity can be used efficiently and the impact of unavoidable delays would be reduced [9]. And, the TMIs can be classified into two categories: (1) strategic actions, which are the strategies that taken before the aircraft has been taken off, including ground delay program [10], ground stop [11], airspace flow program [12], minute-in-trail or miles-in-trail [13], and Collaborative Trajectory Options Program [14] and (2) tactical actions, which are the strategies that taken after the aircraft is airborne, consisting of rerouting [15], speed adjustment, airborne holding [16], and fix balancing.

Among these strategies, the minute-in-trail/miles-in-trail is the most frequently used TMI because of its simplicity and ease of implementation [17], which is the strategy that imposes the time/distance spacing restrictions between every two adjacent aircraft flying along a routing path from the same corridor. Because the minute-in-trail strategy and miles-in-trail strategy can be interconverted, this paper focuses on the minute-in-trail strategy, hereafter referred to as MIT.

However, most of traffic managers rely largely on experience to determine the MIT restrictions, and no tool is available to support the traffic managers to balance the interests of all stakeholders, airlines, and passengers, resulting in the larger delay cost. Therefore, it is necessary to study the MIT strategy generation problem.

Many studies have focused on modeling the strategy of MIT. In [17], the authors presented a perspective on the MIT strategy, where the strengths and shortcomings of MIT were discussed in details and proved that MIT is an effective traffic management strategy for high-density sectors. Ostwald et al. [18] proposed an operational concept for arrival MIT restrictions using the MIA capability, where MIA is the tool used to evaluate the impacts of the proposed MIT restrictions on resources and flights before implementing them. Sheth et al. [19, 20] developed a model to compute MIT and pass back restrictions in the NAS for current traffic conditions, and the maximum ground delay and absorbable airborne delay are incorporated in the model.

In [21], the authors proposed a method based on the genetic algorithm for generating the MIT strategy to make full use of the storage capacities of the sector. Unfortunately, the stochastic optimization algorithm would lead to the different MIT strategies in different runs for the same scene; thus, the method cannot be used in the actual control practice. To achieve the goal of demand-capacity balance, Yuanhua and Zhang [22] proposed a method to restrict the interval of every two flights from surrounding areas and the departure time of flights of airports in this area through the strategy of GDP so that the total delay is minimized.

Machine learning has been applied to solve air traffic management problems. In [23], four machine learning algorithms, including support vector machine, random forest, decision tree algorithm, and softmax regression algorithm, are used to evaluate the miles-in-trail. Wang and Grabbe [24] offered an update analysis of the cause, frequency, and duration of historical MIT restrictions and subsequently using machine learning techniques to predict the occurrence of MIT restrictions to manage arrivals into the ATL airport.

However, most of the previous works mainly focused on generating a control strategy to restrict the flights into a sector with minimization of the total delay while the types of aircraft and passengers are not considered, resulting in the larger delay cost. In addition, the generated MIT strategy of the previous work is difficult to operate for air traffic managers because of the frequent change of traffic flow management strategy would lead to higher air traffic control load [25].

In [26], the authors proposed an evolutionary algorithm to generate the MIT strategy, where a traffic flow-capacity matching model based on workload restriction is presented and the stability function for evaluating the strategy in each slot time is defined, and an evolutionary algorithm is proposed to generate the MIT strategy. Unfortunately, the stochastic optimization algorithm would lead to the different strategies in different runs, resulting in the larger air traffic control load.

Motivated by these arguments, we propose a method for generating the *E-MIT* strategy to control the aircraft from different directions heading towards a sector whose capacity is decreased from the normal operation capacity due to the convective weather. The main contributions of this paper are outlined as follows:

(1) Given the sector capacity C_w^t, $t = 1, \ldots, T_{\text{imb}}$, under convection weather, we propose a three-phase optimization framework to generate the *E-MIT* strategy to achieve the demand-capacity balance. A dynamical programming-based method is proposed to allocate the total sector capacity of T_{imb} time periods under convection weather, $\sum_{t=1}^{T_{\text{imb}}} C_w^t$, for NC corridors, and a 0-1 combination algorithm is used to determine the candidate strategies set CS^i for each corridor. Finally, a modified shortest path algorithm based on the backtracking method is taken to select the optimal strategy from CS^i for all corridors with minimization of the total delay cost and air traffic control load.

(2) Additionally, a dynamical programming-based method is proposed to solve the *E-MIT* strategy generation problem for the special case that sector capacities of different time periods under convection weather are the same, that is, $C_w^1 = C_w^2 = \cdots = C_w^{T_{\text{imb}}}$, and the generated strategies of T_{imb} time periods for a corridor are also the same.

Experimental results show that compared with the rate-based method and need-based method, the proposed generalized method can reduce the average cost by 9.1% and 5.2%, respectively. When considering the special case, the experimental results show that compared with the rate-based method and need-based method, the proposed dynamical programming-based method can reduce the average cost by 9.2% and 7.0%, respectively.

The remainder of the paper is organized as follows: Section 2 describes the problem definition. Section 3 gives the details of computing delay cost and air traffic control load. The generalized *E-MIT* strategy generation method is discussed in Section 4. Section 5 discusses the generation method for a special case. Experimental results and conclusions are shown and discussed in Sections 6 and 7, respectively.

2. Problem Description

2.1. Extended MIT Strategy. Minute-in-trail/miles-in-trail (MIT) is the strategy that requires the flights in a flow of air traffic crossing a certain corridor of sector must be separated by a certain number of minutes or miles. Through this strategy, we can control the volume of air traffic into sectors and airports at a safe level.

In the actual control practice, MIT, along with the maximum allowed number of flights, is the frequently used traffic management initiatives to balance the traffic flows and sector capacity under converse weather. That is, the generated strategy includes two restrictions for flights across one transfer-of-control point (or, a corridor) of sector:

(i) The maximum allowed number of flights in a time period

(ii) The minimal time interval between every two adjacent flights from the same corridor

In this paper, we focus on the MIT strategy, along with the maximum allowed number of flights, hereafter referred to as the extended MIT strategy (*E-MIT*).

2.2. Flow Control Time. Table 1 shows some notations used in this paper.

Once the *E-MIT* strategy is issued, the duration time of strategy, i.e., the flow control time T_{fc}, must be attached to the *E-MIT* strategy so that the air traffic managers can control the traffic flows more effectively.

Flow control time T_{fc} is the total time needed to balance the sector capacity and traffic flows using the *E-MIT* strategy, which is defined as follows:

$$T_{\text{fc}} = T_{\text{imb}} + T_{\text{rec}}, \tag{1}$$

where T_{imb} is the duration time periods of convection weather on sector, that is, the time periods of demand-capacity imbalance. Because the sector capacity is decreased from the normal operation capacity due to the convection weather, some planned flights are delayed to the subsequent time periods. And, T_{rec} is the time period to process the delayed flights such that the balance of demand-capacity can be recovered, which is defined as follows:

$$T_{\text{rec}} = \max\left\{T^i_{\text{rec}} \mid 1 \le i \le \text{NC}\right\}, \tag{2}$$

where T^i_{rec} is the time period needed to process the delayed flights and recover the demand-capacity imbalance for corridor COR_i.

Assume that the sector is affected by convection weather during $[t_b, t_e]$, and let $F = \{F_i \mid \text{the flights set across the corridor } \text{COR}_i, i = 1, \ldots, \text{NC}\}$ be the flights scheduled to arrive at this sector during $[t_b, -)$. The time axis can be discretized by subdividing $[t_b, -)$ into a set of consecutive time periods, and the time span τ of each time period can be set any value. However, because of the accuracy of weather forecast, τ is set to 15 minutes, 30 minutes, or 1 hour, practically. For convenience, we define $|F^t_i|$ to be the number of flights across the corridor COR_i during t-th time period.

Thus, the imbalance time periods T_{imb} can be calculated as follows:

$$T_{\text{imb}} = \frac{t_e - t_b}{\tau}, \tag{3}$$

where τ is the time span of a time period, and in this work, we set one hour.

If the maximum allowed number of flights across the corridor COR_i in a time period TP_t $(1 \le t \le T_{\text{imb}})$ is $K^{i,t}_w$ under convection weather and the corresponding normal level is K^i_n in one time period, the demand-capacity recovery time periods T^i_{rec} is the least value that meets the following in-equation:

$$\sum_{t=1}^{T_{\text{imb}}} \left(\left|F^t_i\right| - K^{i,t}_w\right) \le \sum_{t=T_{\text{imb}}}^{T^i_{\text{rec}}} \left(K^i_n - \left|F^t_i\right|\right). \tag{4}$$

Figure 1 shows an example of calculating the recovery time T^1_{rec} for COR_1, where the convection weather occurs from 20:00 to 22:00, and we set each time period at one hour; thus, $T_{\text{imb}} = 2$. In these two time periods, the maximum allowed number of flights across the corridor COR_1 is $K^{1,1}_w = 10$ flights per hour and $K^{1,2}_w = 11$ flights per hour, respectively. And, the maximum allowed number of flights across COR_1 under normal condition K^i_n is 16 flights per hour.

From Figure 1, we can get $|F^1_1| = 16$, $|F^2_1| = 17$, $|F^3_1| = 10$, and $|F^4_1| = 9$. Thus, according to in-equation (4), we can calculate the recovery time periods $T^1_{\text{rec}} = 2$ to recover the left 12 flights of the demand-capacity imbalance periods.

Table 1: Some used notations.

NC	The number of corridors belong to the sector
COR_i	The i-th corridor of sector, $1 \le i \le \text{NC}$
C_n	The sector capacity under normal condition in one time period
K^i_n	The maximum allowed number of flights for corridor COR_iin a time period under normal condition, $1 \le i \le \text{NC}$
C^j_w	The sector capacity of time period TP_junder convection weather condition, $1 \le j \le T$
$K^{i,j}_w$	The i-th corridor capacity resource of TP_j under convection weather condition, $1 \le i \le \text{NC}$, $1 \le j \le T$
A^i_w	The total corridor capacity of COR_i of all time periods under convection weather condition, $A^i_w = \sum_{t=1}^{T} K^{i,t}_w$
t^i_e	Estimated time of takeoff for flight f^i
t^i_c	Calculated time of takeoff for flight f^i
T_{imb}	The duration time periods of convection weather on sector
T_{rec}	The time periods needed to recover the over traffic flows of T_{imb}
T_{fc}	The duration time of *E-MIT* strategy, that is, the total time that needed to balance the sector capacity and traffic flows

2.3. Problem Definition. Based on the above definitions, the problem definition for generating the *E-MIT* strategy is as follows.

Given the following inputs,

(1) The number of corridors NC of a sector, that is COR_i $1 \le i \le \text{NC}$

(2) The sector capacity under convection weather condition, C^j_w, $1 \le j \le T_{\text{imb}}$

(3) The sector capacity C_n of a time period under normal condition

(4) The maximum allowed number of flights K^i_n (or, corridor capacity) of a time period for corridor COR_i, $1 \le i \le \text{NC}$, under normal condition

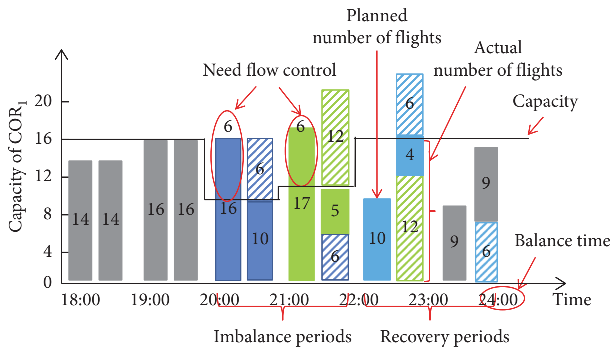


Figure 1: An example of calculating the recovery time T_{rec}^{1} for COR_1.

and the following constraints:

(1) The flights are not allowed to take off in advance, that is, $t_c^i > t_e^i$

(2) The maximum allowed number of flights across COR_i is recovered to a normal level K_n^i once the convection weather is over

(3) The maximum allowed number of flights across a corridor in one time period under convection weather conditions cannot exceed the corresponding normal level, that is, $K_w^{i,j} < K_n^i$

We try to generate an optimal *E-MIT* strategy to control the air traffic flows from different corridors that enter into a sector whose capacity is decreased from the normal operation capacity due to the convective weather. And, the *E-MIT* strategy generally includes two restrictions on flights:

(1) The maximum allowed number of flights across a corridor COR_i in a time period TP_j, i.e., $K_w^{i,j}$

(2) the minimal time interval $t_{\text{int}}^{i,j}$ between every two adjacent flights across the same corridor COR_i in one time period TP_j

Thus, the total flight delay cost and air traffic control load are minimized.

Figure 2 gives an example of the *E-MIT* control strategy for a sector in one hour, where C_w^1 is 31 flights/h, and the maximum allowed number of flights for each corridor in one hour is 8 flights/h, 8 flights/h, 12 flights/h, and 3 flights/h, respectively.

However, once the maximum allowed number of flights $K_w^{i,j}$ of corridor COR_i in time period TP_j is determined, the minimal time interval $t_{\text{int}}^{i,j}$ can be calculated as follows:

$$t_{\text{int}}^{i,j} = \max\left\{\left\lceil \frac{\tau}{K_w^{i,j} * 2} \right\rceil, t_{\text{sep}}^{i,j}\right\}, \quad i \in [1, \text{NC}],\ j \in [1, T], \tag{5}$$

where τ is the duration time of a time period TP_j and $t_{\text{sep}}^{i,j}$ is the minimal separation time between aircraft i and j to ensure safety, which can be calculated according to Table 2. In Table 2, three types of aircraft, small, large, and heavy, are considered [27]. For example, if a heavy aircraft follows a large aircraft, then their minimal separation time must be at least 61 seconds.

Thus, the *E-MIT* strategy generation problem is to determine $K_w^{i,j}$ of corridor COR_i in time period TP_j, $i = 1, \ldots, \text{NC}$, $j = 1, \ldots, T$.

Let Cost^i be the total delay cost of corridor COR_i when $K_w^{i,j}$ of all time periods are determined simultaneously, and let L^i be the air traffic control load of corridor COR_i, which is used to approximate the strategy stability. Therefore, the strategy generation problem can be formulated as a resource allocation problem as follows:

$$\text{minimize} \sum_{k=1}^{\text{NC}} \left(\alpha \cdot \text{Cost}^k + \beta \cdot L^k\right), \tag{6}$$

subject to

$$\begin{aligned} &\sum_{i=1}^{\text{NC}} K_w^{i,j} = C_w^j, \quad \forall j \in [1, T_{\text{imb}}], \\ &K_w^{i,j} < K_n^i, \quad \forall i \in [1, \text{NC}],\ j \in [1, T_{\text{imb}}], \end{aligned} \tag{7}$$

where α and β can make trade-off between the contributing factors.

The first sets of constraints define a limited capacity resource in each time period TP_j for sector, and the second sets of constraints show the limited value of the maximum allowed number of flights for each corridor COR_i in a time period TP_j.

To explain the strategy generation problem more clearly, an example is given in Figure 3, where the sector has four corridors, and the sector capacities of three time periods under convection weather are C_w^1, C_w^2, and C_w^3, respectively. The strategy generation problem is to determine the values of $K_w^{i,t}$, $i = 1, \ldots, 4$, $t = 1, \ldots, 3$, under the constraints that $\sum_{i=1}^{4} K_w^{i,j} = C_w^j$, $\forall j \in [1, 3]$ such that the total delay cost and air traffic control load are minimized. Unfortunately, the delay cost Cost^i and air traffic control load L^i of corridor COR_i can be calculated (discussed in the next section) only if the values of $K_w^{i,1}$, $K_w^{i,2}$, and $K_w^{i,3}$ are given simultaneously.

Therefore, it is very difficult to directly solve this resource allocation problem since $K_w^{i,j}$, $i = 1, \ldots, \text{NC}$, $j = 1, \ldots, T_{\text{imb}}$, cannot be determined simultaneously. And, in this work, a three-phase method is proposed to generate the *E-MIT* strategy.

3. Computation of Objection Function

3.1. Computation of Delay Cost. Once the *E-MIT* strategy is generated, it will be feed back to the collaborative decision-making system of local airport and regenerate the calculated time of takeoff (CTOT) for flights such that the number of flights across a corridor in a time period and the minimal time interval between every two adjacent flights could meet the constraints of *E-MIT* strategy.

Here, we take a corridor, for example, as shown in Figure 3, given the maximum allowed number of flights across COR_1 in one time period under convection weather conditions, that is, $K_w^{1,1}$, $K_w^{1,2}$, and $K_w^{1,3}$, and the CTOT of flight f^i, t_c^i, can be calculated via the ration-by-schedule algorithm [28], which is based on the first-scheduled-first-served principle. The main steps are listed as follows:

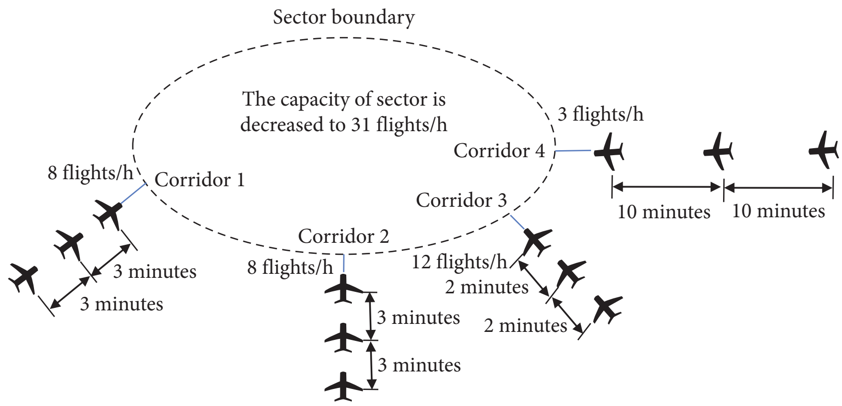


Figure 2: Example of the *E-MIT* control strategy for a sector.

Table 2: Aircraft types and minimum separation time $t_{\text{sep}}^{i,j}$ (in seconds).

		Leading aircraft type		
		Small	Large	Heavy
Trailing aircraft type	Small	59	88	109
	Large	59	61	109
	Heavy	59	61	90

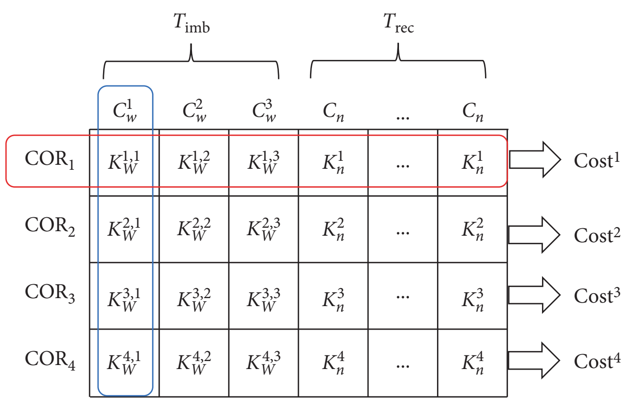


Figure 3: Example of the strategy generation problem.

(a) Determine the number of time slots n_{slot} and the time span of each slot t_{slot}

(b) Sort the flights F^{ctl} according to their estimated time of takeoff t_e^i

(c) Allocate the time slots for the sorted flights in order, and the allocated slot is at or later than the flight's estimated time of takeoff t_e^i

(d) The beginning time of slot is taken as t_c^i

The procedure is repeated until each flight is allocated a time slot. At last, the delay time t_d^i of flight f^i can be determined.

In Step (a), the number of time slots n_{slot} is the maximum allowed number of flights across COR_1 in one time period, and the time span of each slot t_{slot} can be defined as follows:

$$t_{\text{slot}} = \frac{\tau}{n_{\text{slot}}}, \tag{8}$$

where τ is the time span of a time period.

Figure 4 gives an example of calculating t_c^i for flight f^i, where $K_w^{1,1} = 4$, $K_w^{1,2} = 3$, $K_w^{1,3} = 4$, and $K_n^1 = 8$ flights per hour. Because the time span of one time period is one hour, the time span of each slot are $60/4 = 15$ minutes, $60/3 = 20$ minutes, $60/4 = 15$ minutes, and $60/8 = 7$ minutes, respectively. Based on the first-scheduled-first-served principle, we allocate these slot times to the flights according to their estimated time of takeoff t_e^i (which is given as input) as shown in Steps (b) and (c).

As shown in Figure 4, for flight f^2, whose estimated takeoff time t_e^i is 20:07 and through the procedure of allocating time slots, its calculated takeoff time t_c^i is 20:15; thus, the delay time t_d^i is 8 minutes.

Once the delay time t_d^i of flights f^i are obtained, the delay cost Cost^k for corridor COR_k can be calculated as follows:

$$\text{Cost}^k = C_f + C_p, \tag{9}$$

where C_f represents the delay cost of flights and C_p is the delay cost of passengers.

The delay cost of flights C_f depends on the delay time of flights t_d^i, which can be calculated as follows:

$$C_f = \sum_{i=1}^{F^{\text{ctl}}} \alpha^i \cdot t_d^i, \tag{10}$$

where F^{ctl} is the set of affected flights, which can be determined according to the flow control time T_{fc}. α^i represents the delay cost per hour for flight f^i, which depends on the type of aircraft as shown in Table 3, where three types of aircraft are given.

And, the delay cost of passengers C_p can be calculated as follows:

$$C_p = \sum_{i=1}^{F^{\text{ctl}}} \beta^i \cdot n_p^i \cdot t_d^i, \tag{11}$$

where n_p^i represents the number of passengers of flight f^i and β^i represents the delay cost of one people of flight f^i. In this work, we take the cost analysis model [29] to estimate the delay cost of passengers, where the unit delay cost β^i of ordinary passengers is set 50 per hour and the important passenger is 100 per hour.

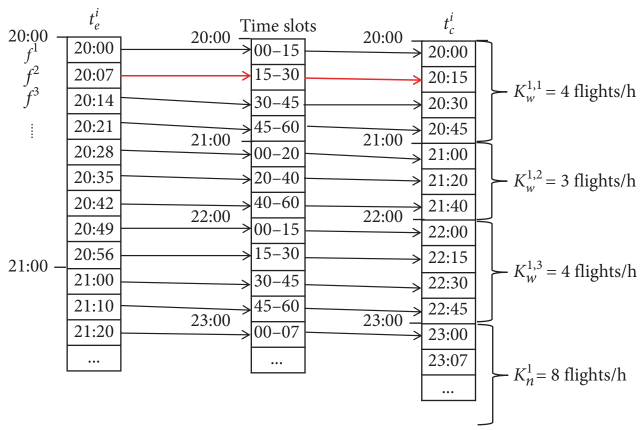


Figure 4: Example of calculating t_c^i for flight f^i.

Table 3: Flight delay cost model.

Aircraft type	H	M	L
Unit delay cost α^i (h^{-1})	4167	2916	208

3.2. Computation of Air Traffic Control Load. In this work, a method similar to [26] is taken to calculate the air traffic control load L^g for corridor COR_g, which is defined as follows:

$$L^g = \sum_{j=1}^{T_{\mathrm{imb}}} \left(K_w^{g,j+1} - K_w^{g,j}\right)^2. \tag{12}$$

What is more, the air traffic control load L^g can also represent the strategy stability, where the bigger value of L^g will cause the less strategy stability.

4. *E-MIT*

Given the sector capacity C_w^t of time period TP_t $(t = 1, \ldots, T_{\mathrm{imb}})$ under the convection weather, a three-phase method is proposed to generate the *E-MIT* strategy for flights with minimization of delay cost and air traffic control load.

4.1. Allocation of Sector Capacity. In this work, we first take the sector capacity of T_{imb} time periods under convection weather as a whole, that is, $\mathrm{SC} = \sum_{t=1}^{T_{\mathrm{imb}}} C_w^t$; thus, the strategy generation problem can be regarded as a classic resource allocation problem that allocates SC for NC corridors with minimization of total delay cost. And, in this work, a dynamical programming-based method is proposed to solve this resource allocation problem such that the capacity resources A_w^i of each corridor COR_i, $i = 1, \ldots, \mathrm{NC}$, can be determined.

Figure 5 shows an example of allocating sector capacity, where the sector has four corridors and $\mathrm{SC} = C_w^1 + C_w^2 + C_w^3$. Our goal is to determine the capacity resources A_w^1, A_w^2, A_w^3, and A_w^4.

If corridor COR_i is allocated to j resources, we can calculate the delay cost v_i^j for corridor COR_i as follows:

(i) Firstly, according to the equation (8), the time span of each slot under convection weather and normal condition can be calculated as $T_{\mathrm{imb}} * \tau / j$ and τ / K_n^i, respectively

(ii) Then, through the procedures of allocating time slots in Section 3.1, the delay time t_d^i of each flight f^i can be calculated

(iii) At last, the delay cost v_i^j for corridor COR_i can be calculated according to equation (9)

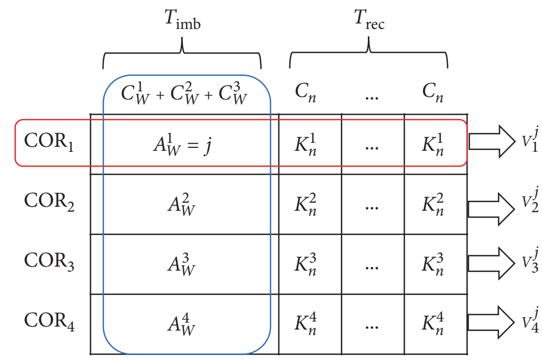


Figure 5: Example of allocating sector capacity.

Let V_i^j be the minimum total delay cost when the first i $(1 \le i \le \mathrm{NC})$ corridors, $\mathrm{COR}_1, \ldots, \mathrm{COR}_i$, are allocated to the total j resources, which can be calculated according to the following two steps:

(1) The first i-1 corridors, $\mathrm{COR}_1, \ldots, \mathrm{COR}_{i-1}$, are allocated to the total m $(m \le j)$ resources

(2) The remaining $j - m$ resources are allocated to corridor COR_i

Thus, the recursive relation formula of dynamical programming can be formulated as follows:

$$V_i^j = \min\left(V_i^j, V_{i-1}^m + v_i^{j-m}\right). \tag{13}$$

Algorithm 1 gives a detailed description of the dynamical programming-based method to allocate the total sector capacity SC for NC corridors.

In lines 2–5 in Algorithm 1, we initialize the values of V_i^0, $i = 1, \ldots, \mathrm{NC}$, and V_1^m. From lines 13 to line 15, we check whether allocating $(j - m)$ flights of T_{imb} time periods to corridor COR_i will violate the constraint (3). If the allocated $(j - m)$ flights meet the constraints and have less delay cost than the current cost recorded by MIN_COST, we will update the minimum delay cost and record the allocated capacity resource for COR_i in lines 17-18.

Once Algorithm 1 is finished, the total allocated capacity resources A_w^i of T_{imb} time periods for each corridor COR_i, $i = 1, \ldots, \mathrm{NC}$, can be determined as shown in line 27.

4.2. Candidate Strategies for a Corridor. Once the total capacity resource A_w^i of T_{imb} time periods for each corridor $\mathrm{COR}_i (i = 1, \ldots, \mathrm{NC})$ is determined, we will use 0-1 combination algorithm to allocate A_w^i into T_{imb} time periods for each corridor COR_i such that the candidate strategies set CS^i of each corridor can be determined, where a strategy $\mathrm{sol}_j^i \in \mathrm{CS}^i$ is an array with T_{imb} numbers, and each number

Input the total sector capacity SC and the number of corridors NC;
Initialize the values V_i^0, $\forall i \in [1, \mathrm{NC}]$;
for $m \longleftarrow 1$ to $\min(\mathrm{SC}, T_{\mathrm{imb}} \cdot K_n^i)$ **do**
    $V_1^m = v_1^m$;
end for
total_cap = 0;
for $i \longleftarrow 2$ to NC **do**
    total_cap+ = $T_{\mathrm{imb}} \cdot K_n^{i-1}$;
    for $j \longleftarrow 1$ to SC **do**
        MIN_COST = INF;
        $m\_\max = \min(j, \mathrm{total\_cap})$;
        for $m \longleftarrow 0$ to $m\_\max$ **do**
            if $(j - m) > T_{\mathrm{imb}} \cdot K_n^i$ **then**
                Continue;
            end if
            if MIN_COST $> V_{i-1}^m + v_i^{j-m}$ **then**
                MIN_COST $= V_{i-1}^m + v_i^{j-m}$;
                $\mathrm{Road}_i^j = m$;
            end if
        end for
        $V_i^j =$ MIN_COST;
    end for
end for
//backtrack output results
$j = \mathrm{SC}$;
for $i \longleftarrow$ NCto 1 **do**
    $A_w^i = j - \mathrm{Road}_i^j$;
    $j = \mathrm{Road}_i^j$;
end for

ALGORITHM 1: Sector_capacity_allocation.

represents the maximum allowed number of flights entering into sector from COR_i in one time period.

To simplify the discussion, the total allocated capacity resource A_w^i of corridor COR_i is relabeled as N; thus, the corridor capacity resource allocation problem can be formulated as the problem of placing $T_{\mathrm{imb}}-1$ baffles between N numbers, which is the combination optimization problem of selecting $T_{\mathrm{imb}}-1$ from $N+1$, and, there has $C_{N+1}^{T_{\mathrm{imb}}-1}$ solutions. In this work, we take the 0-1 combination algorithm to search those solutions, and Algorithm 2 shows the overall flow of the 0-1 combination algorithm.

In line 2 in Algorithm 2, we initialize the array index[ ] with the size of $N+1$, and index[i] is the flag that represents whether the corresponding baffle is placed or not. If index[i] = 1, there is a baffle between the i-th number and the $(i+1)$-th number. Otherwise, the i-th number and the $(i+1)$-th number are allocated to the same time period.

The combination optimization problem is solved in lines 8–26, and the main steps of 0-1 combination algorithm are listed as follows:

(1) Set the first $T_{\mathrm{imb}}-1$ numbers of array index[ ] to 1 as shown in lines 4–6, which corresponds to a solution

(2) Find the first 1-0 combination of array index[ ] and change it to 0-1 combination as shown in line 11–13

(3) Move all 1 of the left of 0-1 combination to the left of array

Repeat Steps 2 and 3 until the last $T_{\mathrm{imb}}-1$ numbers of array index[ ] are 1.

Once the 0-1 combination algorithm is finished, we can get the candidate strategies set CS^i for each corridor COR_i $(i = 1, \ldots, \mathrm{NC})$ according to the values of array index[ ].

Figure 6 shows an example of determining candidate strategies CS^1 for corridor COR_1 using the 0-1 combination algorithm, where $A_w^1 = 3$ and $T_{\mathrm{imb}} = 3$. Firstly, we define an array index[ ] with size of 4, and according to Steps 4–25 of Algorithm 2, we can find $|\mathrm{CS}^1| = 6$ possible solutions for the combination problem of selecting $T_{\mathrm{imb}}-1$ from $A_w^1 + 1$, as shown in Figure 6(a). Secondly, for each solution, according to the values of array index[ ], we can get the positions of baffles placed between numbers. Here, we take the third solution ("0110"), for example, because index[1] = 1, and we place a baffle between the first number and the second number. Similarly, a baffle is placed between the second number and the third number as shown in Figure 6(b). At last, we calculate the numbers between adjacent baffles, and each number represents the maximum allowed number of flights entering into sector from COR_i in one time period.

```
Input the capacity resource N and time periods T_imb;
Initialize the array index[ ]with the size of N+1;
//set the first T_imb−1 of array to 1, which corresponds to a solution;
for i ⟵ 0 to T_imb−1 do
    index[i] = 1;
end for
Store the solution according to the values of array index[ ];
while has Done (index, N, T_imb) do
    for i ⟵ 0 to N+1 do
      //find the first 1-0 combination and change it to 0-1 combination;
      if index[i] = = 1 and index[i] = = 0 then
        index[i] = 0;
        index[i] = 1;
        Store the solution from index[ ];
        //move 1 of the left of 0-1 combination to the left of array;
        int count = 0;
        for j ⟵ 0 to i do
            if index[j] = = 1 then
                index[j] = 0;
                index[count++] = 1;
            end if
        end for
      end if
      break;
    end for
end while
```

Algorithm 2: 0-1 combination algorithm for COR_i.

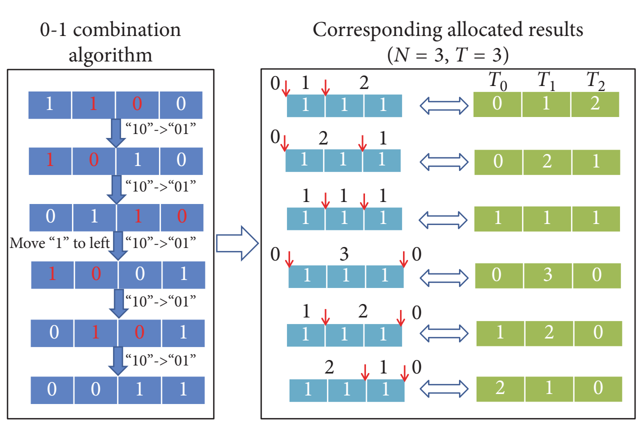


Figure 6: Example of determining candidate strategies for a corridor using the 0-1 combination algorithm.

4.3. Strategy Generation Algorithm. For each corridor COR_i ($i = 1, \ldots, \mathrm{NC}$), there are $|\mathrm{CS}^i|$ ($=C_{A_w^i+1}^{T_{\mathrm{imb}}-1}$) solutions of allocating A_w^i resources into T_{imb} time periods, and different solutions in CS^i will have different delay costs and air traffic control load. In this section, we will introduce a modified shortest path algorithm based on the backtracking method to select the optimal strategy from CS^i for each corridor COR_i such that the total delay cost and the air traffic control load can be minimized.

To represent all the possible candidate strategies of all corridors, a directed search graph $G_s(V, E)$ is constructed, which contains three sets of vertices $V = s \cup V^i \cup t$, where s is the start vertex, V^i is the candidate strategies set of corridor COR_i $i = 1, \ldots, \mathrm{NC}$, and a strategy $\mathrm{sol}_j^i \in V^i$ is an array with T_{imb} numbers, and t is the end vertex. Besides, edge set $E = \{s \longrightarrow V^1\} \cup \{v_{i,k} \longrightarrow V^{i+1} \mid v_{i,k} \in V^i\} \cup \{V^{\mathrm{NC}} \longrightarrow t\}$. In addition, the edge costs are defined as follows:

$$c_{v,u} = \begin{cases} \mathrm{Cost}^g + L^g, & \forall (v,u) \in \{s \longrightarrow V^1\} \cup \{v_{i,k} \longrightarrow V^{i+1} \mid v_{i,k} \in V^i\}, \\ 0, & \forall (u,v) \in \{V^{\mathrm{NC}} \longrightarrow t\}, \end{cases} \tag{14}$$

where Cost^g and L^g are the delay cost and air traffic control load if corridor COR_g uses the strategy that node u represents.

Figure 7 shows an example of a directed search graph $G_s(V, E)$.

Thus, the optimal strategies for each corridor can be determined by finding the shortest path from s to t on $G_s(V, E)$, and each node represents a strategy.

To speed up the search procedure of the strategies for all corridors with minimization of the total delay cost and air traffic control load, we propose a modified shortest path algorithm based on the backtracking method [30] to select the allocation solution for each corridor while meeting the constraint that the corridor capacity of each time period cannot exceed the corresponding normal level, $K_w^{i,j} < K_n^i$.

Once the modified shortest path algorithm [30] is finished, each node in the returned shortest path represents the best solution, that is, $K_w^{i,j}$, $1 \le i \le \mathrm{NC}$, $1 \le j \le T_{\mathrm{imb}}$. And, according to formula (5), we can determine the minimal time interval $t_{\mathrm{int}}^{i,j}$ between every two adjacent flights from the same corridor COR_i and time period TP_j.

5. A Special Case

In this section, we consider a situation that the input sector capacities of the T_{imb} time periods are the same, that is, $C_w^1 = C_w^2 = \cdots = C_w^{T_{\mathrm{imb}}}$, and the generated strategies of different time periods for a corridor are also same (that is, for a corridor COR_i, $K_w^{i,1} = K_w^{i,2} =, \cdots, = K_w^{i,T_{\mathrm{imb}}}$).

Figure 8 shows an example of a special case. For this case, if the strategy of a time period TP_t for each corridor, that is, $K_w^{i,t}$, $i = 1, \ldots, \mathrm{NC}$, is given, the delay cost Cost^i for corridor COR_i, $i = 1, \ldots, \mathrm{NC}$, can be determined.

Thus, this special case can be solved by allocating the sector capacity resource C_w^1 into NC corridors with minimization of total delay cost. And, a dynamical programming-based method similar to Section 4.1 is used to solve this special case.

6. Experiments

6.1. Experimental Setup. The proposed method has been implemented in C language on a Linux 64 bit workstation (Intel 2.4 GHz, 256 GB RAM).

To explore the effectiveness of the proposed algorithm, we construct a case benchmark by referring to the typical operating day of sector 06 in the terminal area of Beijing as shown in Table 4, which has four corridors, COR_1, COR_2, COR_3, and COR_4, and the sector capacity C_n is 48 in one time period under normal condition.

In Table 4, the first row NOC represents the maximum allowed number of flights K_n^i across the corridor COR_i in a time period under normal conditions. The other rows list the traffic flows from each direction across a corridor in different time periods, where the used corridors of flights are predetermined and the sequence of flights are kept unchanged. In addition, the aircraft type, the estimated arrival time of aircraft and the type of passengers are also given.

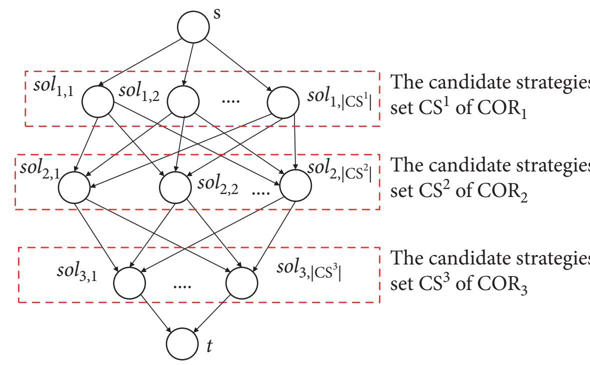


Figure 7: Example of a directed search graph $G_s(V, E)$.

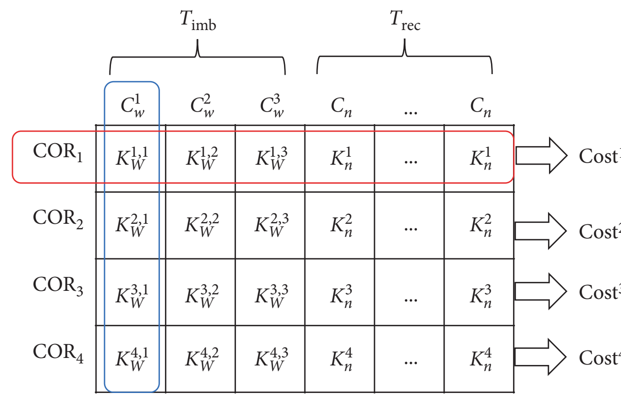


Figure 8: An example of the special case.

6.2. Results and Analysis. To explore the effectiveness of the proposed generalized method, we perform two other methods, rate-based method and need-based method, which are often used in the actual control practice:

(i) Rate-based method: based on the descending ratio of capacity in time period $\mathrm{TP}_j (j = 1, \ldots, T_{\mathrm{imb}})$, $\lambda_j = C_w^j / C_n$ $(\lambda_j < 1)$, the maximum allowed number of flights $K_w^{i,j}$ of corridor COR_i in time period TP_j is set $\lambda_j \cdot K_n^i$.

(ii) Need-based method: let $\beta_{i,j}$ be the rate that the traffic flows of corridor COR_i to the total flows of NC corridors in time period TP_j. That is, for each time period TP_j, $\sum_{i=1}^{\mathrm{NC}} \beta_{i,j} = 1$, the capacity $K_w^{i,j}$ is set $\beta_{i,j} \cdot K_n^i$.

As a baseline situation, we solve the resource allocation problem using an integer linear programming ("ILP"), and the manual in the study of Gurobi [31] is used as the ILP solver to find the optimal solution.

In experiments, we set $T_{\mathrm{imb}} = 2$; that is, the sector in 20:00-21:00 and 21:00-22:00 are affected by the convective weather. And, the sector capacities of these two time periods, C_w^1 and C_w^2, are assumed to be 24 and 28 flights per hour, respectively.

Table 5 shows the experimental results. AF represents the number of affected flights, whose estimated time of takeoff t_e^i is not equal to the calculated time of takeoff t_c^i. The total delay time TD is defined as follows:

Table 4: Information of sector and traffic flows.

Corridor		COR_1	COR_2	COR_3	COR_4
NOC (flights/h)		16	12	15	5
Traffic flow (flight number)	20:00-21:00	16	14	20	6
	21:00-22:00	17	13	16	6
	22:00-23:00	10	5	7	2
	23:00-24:00	9	3	5	2
	00:00-01:00	5	4	6	2
	01:00-02:00	5	4	6	1

Table 5: Comparison with the *rate*- and *need*-based methods under $T_{\text{imb}} = 2$ ($C_w^1 = 24$ and $C_w^2 = 28$).

—		Rate-based method	Need-based method	Three-phase method	"ILP"
Strat.	COR_1	T_0: 8 (4 min/flight), T_1: 9 (3 min/flight) T_2: 16 (2 min/flight), T_3: 16 (2 min/flight) T_4: 16 (2 min/flight)	T_0: 6 (5 min/flight), T_1: 9 (3 min/flight) T_2: 16 (2 min/flight), T_3: 16 (2 min/flight) T_4: 16 (2 min/flight)	T_0: 8 (4 min/flight), T_1: 5 (6 min/flight) T_2: 16 (2 min/flight), T_3: 16 (2 min/flight) T_4: 16 (2 min/flight)	T_0: 9 (3 min/flight), T_1: 16 (2 min/flight) T_2: 16 (2 min/flight), T_3: 16 (2 min/flight) T_4: 16 (2 min/flight)
	COR_2	T_0: 7 (4 min/flight), T_1: 8 (4 min/flight) T_2: 12 (3 min/flight), T_3: 12 (3 min/flight) T_4: 12 (3 min/flight)	T_0: 7 (4 min/flight), T_1: 8 (4 min/flight) T_2: 12 (3 min/flight), T_3: 12 (3 min/flight) T_4: 12 (3 min/flight)	T_0: 4 (8 min/flight), T_1: 9 (3 min/flight) T_2: 12 (3 min/flight), T_3: 12 (3 min/flight) T_4: 12 (3 min/flight)	T_0: 4 (8 min/flight), T_1: 6 (5 min/flight) T_2: 12 (3 min/flight), T_3: 12 (3 min/flight) T_4: 12 (3 min/flight)
	COR_3	T_0: 7 (4 min/flight), T_1: 9 (2 min/flight) T_2: 15 (2 min/flight), T_3: 15 (2 min/flight) T_4: 15 (2 min/flight)	T_0: 8 (4 min/flight), T_1: 8 (4 min/flight) T_2: 15 (2 min/flight), T_3: 15 (2 min/flight) T_4: 15 (2 min/flight)	T_0: 9 (3 min/flight), T_1: 11 (3 min/flight) T_2: 15 (2 min/flight), T_3: 15 (2 min/flight) T_4: 15 (2 min/flight)	T_0: 8 (4 min/flight), T_1: 4 (8 min/flight) T_2: 15 (2 min/flight), T_3: 15 (2 min/flight) T_4: 15 (2 min/flight)
	COR_4	T_0: 2 (15 min/flight), T_1: 2 (15 min/flight) T_2: 5 (6 min/flight), T_3: 5 (6 min/flight) T_4: 5 (6 min/flight)	T_0: 3 (10 min/flight), T_1: 3 (10 min/flight) T_2: 5 (6 min/flight), T_3: 5 (6 min/flight) T_4: 5 (6 min/flight)	T_0: 3 (10 min/flight), T_1: 3 (10 min/flight) T_2: 5 (6 min/flight), T_3: 5 (6 min/flight) T_4: 5 (6 min/flight)	T_0: 3 (10 min/flight), T_1: 2 (15 min/flight) T_2: 5 (6 min/flight), T_3: 5 (6 min/flight) T_4: 5 (6 min/flight)
Total cost		1156187 (1.081)	1136662 (1.063)	1069118 (1.0)	1053433 (0.985)
AF		121	121	118	123
TD (min.)		4981	4899	4852	4830
AD (min.)		41.2	40.5	41.1	39.3

$$\text{TD} = \sum_{i=1}^{\text{AF}} t_d^i. \tag{15}$$

And, the average delay time AD is defined as AD = TD/AF.

As shown in Table 5, compared with the proposed three-phase optimization method, the rate-based method and need-based method will spend more 8.1% and 6.3% of delay cost, respectively, which shows the effectiveness of the proposed method. In addition, the proposed three-phase optimization method can reduce the affected flights AF of 3 aircraft and 3 aircraft on average when compared to the rate-based method and need-based method, respectively.

In Table 5, the delay cost obtained by the proposed method is a litter higher (1.5%) than the baseline situation of "ILP," which demonstrates the effectiveness of the proposed method.

Table 5 also lists the strategy generated by the proposed three-phase method for each directions to control the maximum allowed number of flights and the minimal time interval between every two adjacent flights in different time periods, and the minimal interval between every adjacent flights is determined according to formula (5). Here, we take corridor 2, for example, whose flow control time is five hours and the strategies are listed as follows in detail:

(i) 20:00 to 21:00: the maximum allowed number of flights is 4 flights/h, and the minimal time interval between adjacent flights is 8 minutes

(ii) 21:00 to 22:00: the maximum allowed number of flights is 9 flights/h, and the minimal interval between adjacent flights is 3 minutes

(iii) 22:00 to 23:00: the maximum allowed number of flights is 12 flights/h, and the minimal interval between adjacent flights is 3 minutes

(iv) 23:00 to 00:00: the maximum allowed number of flights is 12 flights/h, and the minimal interval between adjacent flights is 3 minutes

(v) 00:00 to 01:00: the maximum allowed number of flights is 12 flights/h, and the minimal interval between adjacent flights is 3 minutes

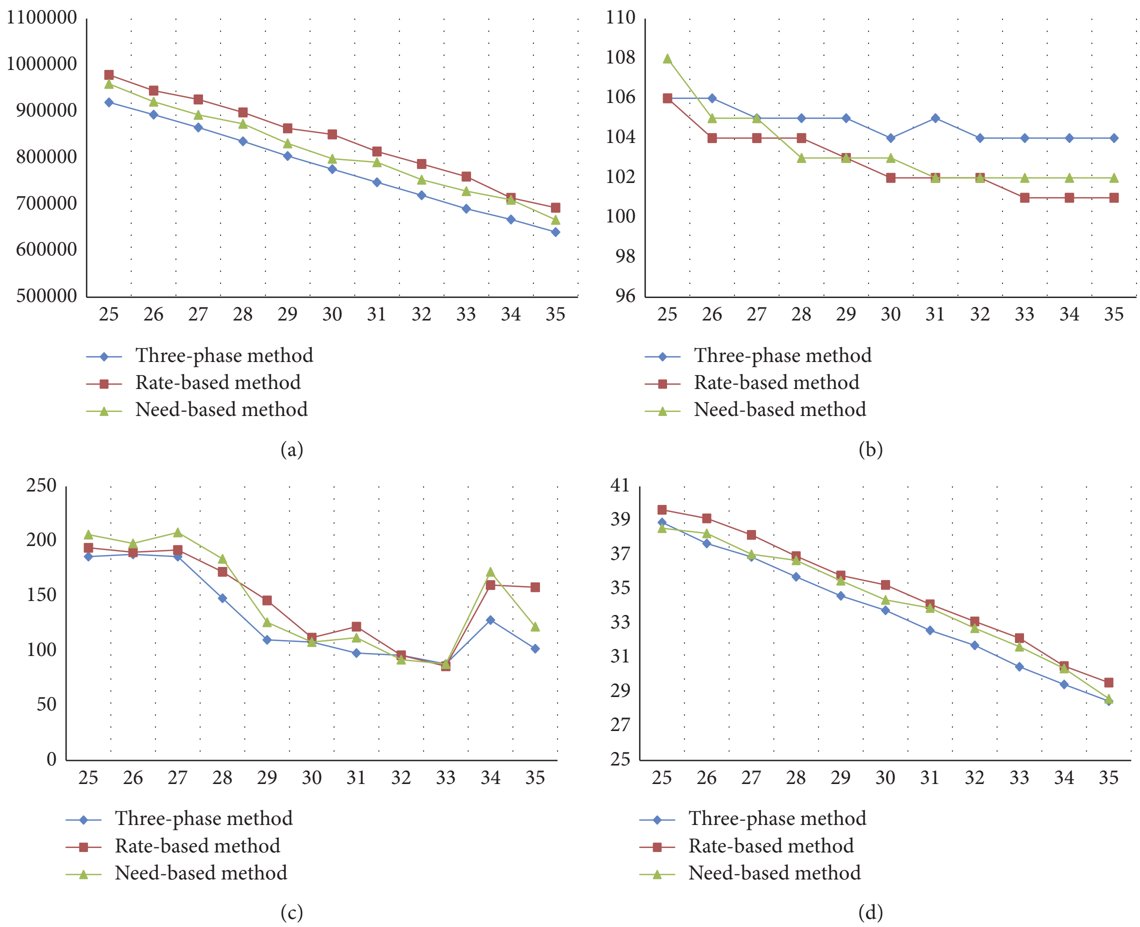


Figure 9: The comparison results of (a) delay cost, (b) the number of affected flights, (c) air traffic control load, and (d) average delay time under the different sector capacity, where K_w^1 is set to 30 and K_w^2 is ranged from 25 to 35.

6.3. Impacts of Sector Capacity on E-MIT. Further to demonstrate the effectiveness of the proposed three-phase optimization method, we perform the comparison experiments on different sector capacities of these two time periods, where C_w^1 is set to 30 and C_w^2 is ranged from 25 to 35. Figure 9 shows the changing trend of the delay cost, the number of affected flights, air traffic control load, and average delay time with changing C_w^2 under the same C_w^1. Form Figure 9, it can be seen that the proposed three-phase method can generate the control strategy with the least delay cost and the least air traffic load when compared to the rate-based method and need-based method. And, as shown in Figures 9(b) and 9(d), the proposed three-phase method can achieve the least average delay time with a little more of affected flights.

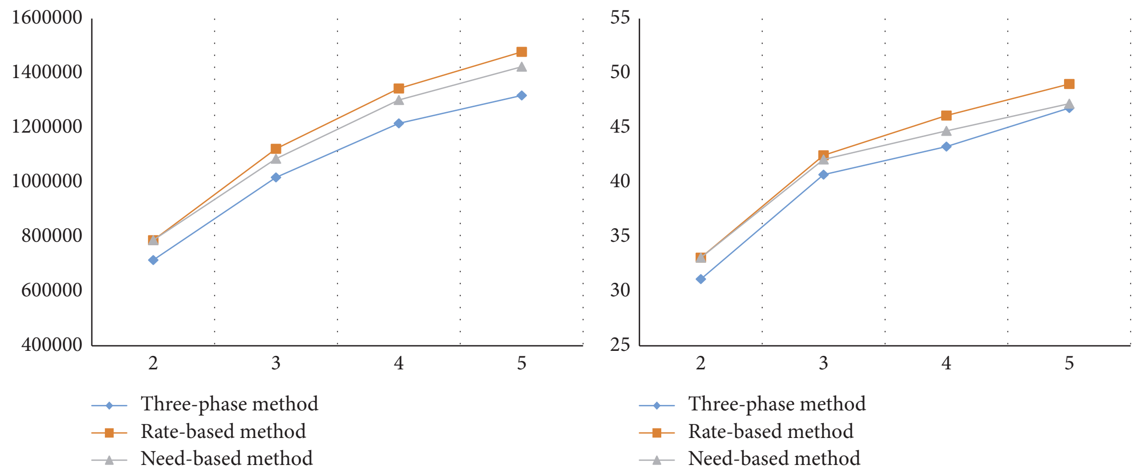
6.4. Impacts of T_{imb} on E-MIT. To evaluate the impact of T_{imb} on the generated strategy *E-MIT*, we perform the experiments on the test benchmark as shown in Figure 10, where the duration time periods of convection weather T_{imb} ranged from 2 to 5, and in each time period, the sector capacity C_w^t, $t = 1, \ldots, T_{\text{imb}}$, is set to 31.

As shown in Figure 10, with the increasing T_{imb}, the delay cost and average delay time are increased, which is consistent with the actual situation. What is more, compared with the rate-based method and need-based method, the proposed three-phase optimization method can achieve the least delay cost and delay time.

6.5. Results of the Special Case. In this section, to demonstrate the effectiveness of the proposed dynamical programming-based method for the special case, we perform experiments with the rate-based method and need-based method as shown in Table 6, where the sectors in 20:00-21:00 and 21:00-22:00 are affected by the convective weather, and the corresponding sector capacity of these two time periods are both set to be 31 flights per hour.

From Table 6, it can be seen that, compared with the proposed DP-based method, the rate-based method and need-based method will spend more 10.2% and 7.5% of delay cost, respectively, which shows the effectiveness of the proposed method for the special case. In addition, the proposed DP-based method can save the average delay AD of 2.0 minutes and 1.6 minutes on average when compared to the rate-based method and need-based method, respectively.

In addition, we also compare the DP-based method with the proposed three-phase method as shown in Table 7. In



(a) (b)

Figure 10: Impacts of T_{imb} on the generated strategy *E-MIT*, where T_{imb} ranges from 2 to 5. (a) The results of delay cost. (b) The results of delay time.

Table 6: Comparison with the *rate*- and *need*-based methods under $T = 2$ for the special case ($C_w^1 = 31$ and $C_w^2 = 31$).

—		Rate-based method	Need-based method	DP-based method
Strategy	COR_1	T_0: 10 (3 min/flight), T_1:10 (3 min/flight) T_2: 16 (2 min/flight), T_3: 16 (2 min/flight)	T_0: 10 (3 min/flight), T_1: 10 (3 min/flight) T_2: 16 (2 min/flight), T_3: 16 (2 min/flight)	T_0: 8 (3 min/flight), T_1: 8 (3 min/flight) T_2: 16 (2 min/flight), T_3: 16 (2 min/flight) T_4: 16 (2 min/flight)
	COR_2	T_0: 9 (4 min/flight), T_1: 9 (4 min/flight) T_2: 12 (3 min/flight), T_3: 12 (3 min/flight)	T_0: 8 (4 min/flight), T_1: 8 (4 min/flight) T_2: 12 (3 min/flight), T_3: 12 (3 min/flight)	T_0: 8 (4 min/flight), T_1: 8 (4 min/flight) T_2: 12 (3 min/flight), T_3: 12 (3 min/flight) T_4: 12 (3 min/flight)
	COR_3	T_0: 9 (4 min/flight), T_1: 9 (4 min/flight) T_2: 15 (2 min/flight), T_3: 15 (2 min/flight)	T_0: 10 (3 min/flight), T_1: 10 (3 min/flight) T_2: 15 (2 min/flight), T_3: 15 (2 min/flight)	T_0: 12 (3 min/flight), T_1: 12 (3 min/flight) T_2: 15 (2 min/flight), T_3: 15 (2 min/flight) T_4: 15 (2 min/flight)
	COR_4	T_0: 3 (10 min/flight), T_1: 3 (10 min/flight) T_2: 5 (6 min/flight), T_3: 5 (6 min/flight)	T_0: 3 (10 min/flight), T_1: 3 (10 min/flight) T_2: 5 (6 min/flight), T_3: 5 (6 min/flight)	T_0: 3 (10 min/flight), T_1: 3 (10 min/flight) T_2: 5 (6 min/flight), T_3: 5 (6 min/flight) T_4: 5 (6 min/flight)
Total cost		787041 (1.102)	768141 (1.075)	714464 (1.0)
AF		101	101	104
TD (min.)		3341	3307	3236
AD (min.)		33.1	32.7	31.1

Table 7: Comparison with the proposed three-phase method.

C_w^1	C_w^2	DP-based method					Three-phase method				
		T.Cost	A.Flight	T.Delay	A.Delay	Load	T.Cost	A.Flight	T.Delay	A.Delay	Load
15	15	2028187	141	8907	63.2	0	1986784	141	8912	63.2	615
16	16	1931099	141	8491	60.2	0	1899271	139	8512	61.2	500
17	17	1834914	140	8074	57.7	0	1810957	139	8099	58.3	467
18	18	1739630	140	7660	54.7	0	1721609	133	7657	57.6	444
19	19	1650660	136	7318	53.8	0	1633627	130	7317	56.3	525
20	20	1561976	138	6869	49.8	0	1535481	130	6857	52.7	308
21	21	1473005	134	6527	48.7	0	1447824	126	6496	51.6	279
22	22	1385355	131	6140	46.9	0	1368293	124	6129	49.4	238
23	23	1298882	130	5759	44.3	0	1275632	122	5801	47.6	223
24	24	1216527	129	5471	42.4	0	1193387	120	5376	44.8	238
25	25	1137924	127	5143	40.5	0	1107526	118	5046	42.8	227
26	26	1061984	117	4748	40.6	0	1043709	117	4731	40.4	218
27	27	983381	115	4420	38.4	0	970058	109	4369	40.1	159
28	28	910680	113	4102	36.3	0	914595	108	4076	37.7	122

Table 7: Continued.

C_w^1	C_w^2	DP-based method					Three-phase method				
		T.Cost	A.Flight	T.Delay	A.Delay	Load	T.Cost	A.Flight	T.Delay	A.Delay	Load
29	29	843689	112	3835	34.2	0	848398	106	3785	35.7	111
30	30	778042	105	3526	33.6	0	775967	104	3511	33.8	108
31	31	714465	104	3236	31.1	0	708205	103	3251	31.6	101
32	32	651009	103	2982	29.0	0	643665	102	2974	29.2	104
33	33	587866	101	2695	26.7	0	578850	101	2691	26.6	87
34	34	526066	98	2454	25.0	0	518742	98	2390	24.4	108
35	35	476363	94	2180	23.2	0	468282	96	2139	22.3	69
Average		1.0	121	5263.7	41.9	0	0.98	117	5243.7	43.2	249.5

this experiment, the sector capacities C_w^1 and C_w^2 are set to the same values, which are ranging from 15 to 35 flights per hour. As shown in Table 7, compared with the DP-based method, the proposed three-phase method can save 2% delay cost because it could explore larger solution space, while the DP-based method assumes that the generated strategies of different time periods for a corridor to be same; thus, the air traffic control load is zero as shown in Table 7.

7. Conclusion

In this work, we consider the MIT strategy generation problem for the situation that a sector with NC corridors is affected by convection weather for T_{imb} time periods. Given the sector capacity C_w^t, $t = 1, \ldots, T_{\text{imb}}$, under convection weather, we propose a three-phase optimization framework to generate $E\text{-}MIT$ strategy to achieve the demand-capacity balance. Firstly, we take the sector capacity of T_{imb} time periods under convection weather as a whole, that is, $\sum_{t=1}^{T_{\text{imb}}} C_w^t$, and then a dynamical programming-based method is proposed to allocate $\sum_{t=1}^{T_{\text{imb}}} C_w^t$ for NC corridors such that the capacity resources A_w^i of each corridor COR_i, $i = 1, \ldots, \text{NC}$, can be determined. Secondly, a 0-1 combination algorithm is used to allocate the capacity resources A_w^i into T_{imb} time periods for each corridor COR_i such that the candidate strategies set CS^i of each corridor can be determined, where a strategy $\text{sol}_j^i \in \text{CS}^i$ is an array with T_{imb} numbers, and each number represents the maximum allowed number of flights entering into sector from COR_i in one time period. Finally, a modified shortest path algorithm based on the backtracking method is taken to select the optimal strategy from CS^i for NC corridors such that the total delay cost and air traffic control load are minimized. Additionally, a dynamical programming-based method is proposed to generate the $E\text{-}MIT$ strategy for the special case that the sector capacities of different time periods under convection weather are the same, that is, $C_w^1 = C_w^2 = \cdots = C_w^{T_{\text{imb}}}$, and the generated strategies of T_{imb} time periods for a corridor are also the same. Experimental results show that compared with the proposed three-phase optimization method, rate-based method and need-based method will spend more 8.1% and 6.3% of delay cost, respectively. When considering the special case, the experimental results show that compared with the proposed dynamical programming-based method, the rate-based method and need-based method will spend more 10.2% and 7.5% of delay cost, respectively.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Disclosure

This manuscript is an extension of our previous publications [32, 33].

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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