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Research Article

Cost-Effective Flight Sequencing and Gate Assignment Considering Transfer Time under Pandemic Conditions

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An efficient hub-and-spoke network (HSN) can reduce operating costs and passenger delays at hubs through proper sequencing of flights and assignment of gates. Typically, batches of flights are scheduled to arrive within brief time windows. By considering aircraft sizes/loads and locations of the available gates, there is a considerable potential for reducing the total cost. During pandemic conditions, passenger transfer time and aircraft dwell time significantly increased because of outbreak controls (e.g., COVID-19 and its variant). In addition to walking time between connecting flights, there is a significant delay for the airport staff to validate passengers' proper travel documents. The objective of this study is to minimize the total cost by optimizing the flight sequencing and gate assignment and by considering the realistic transfer delay under pandemic situations. A genetic algorithm with an elite selection strategy is developed to search for the optimal solution, which significantly reduces the total cost by 25% compared with that under existing operations, and the relations between optimized solutions and various model parameters are explored.

1. Introduction

The pandemic (e.g., COVID-19) has posed a risk to our health, economies, and travel restrictions. Some countries have raised the infectious disease alert to the highest level, which adopted a combination of containment and mitigation activities, such as travel restrictions.

The COVID-19 pandemic has caused an unprecedented crisis for the world's airline industry [1]: airline capacity was down 70 to 80 percent in April 2020 compared to April 2019, and multiple large airlines had temporarily ceased operations. Almost 60 percent of the global fleet was grounded in early April 2020 as per McKinsey report [2]. The unprecedented decrease in passenger demand (together with country-wise flight bans) led to the halt of most airlines. Companies had to cease the majority of their operations and ground entire fleets [3], and many airports have closed the runways to free up space for aircraft parking [4].

The constraints of pandemic situations have led to changes in passenger handling. Currently, airlines aim to protect passengers and crews from COVID-19 and see wearing masks as one mandatory action for passengers onboard [5]. There are further key elements to efficiently reduce the transmission risk, such as temperature and symptom screening, cleaning and disinfection, or COVID-19 testing [6]. With new virus variants, social distancing, including quarantine and travel restrictions, is the main tool used.

In March 2022, industrywide revenue passenger kilometers grew by 76% year-on-year (YoY). Although this is lower than the strong 115.9% rise in February YoY, volumes are now the closest to the 2019 prepandemic levels, that is, below 41% [7]. Air travel sustains a positive trend in 2022, while airport operations still need to follow procedures to check documents, which would increase passenger transfer and flight dwell time. Flight departure delays due to "immigration, customs, and health" have increased significantly, which is 10–20% of all primary delays, mostly at check-in (e.g., destination needs, combination of tests, and vaccination certificates) [8].

The HSN concept has been applied to reduce the cost of operation; however, the passenger transfer delay increases. Batch arrivals and departures of flights are desirable for minimizing the delay cost but are stretched over time by the runway capacity, apron capacity, and maximum connecting time [9], which limits the arrival and departure dates, especially under pandemic situations. Passenger transfer time and aircraft dwell time significantly increased because of outbreak controls (e.g., COVID-19 and its variant).

Considering the various sizes of aircraft and temporal-spatial passenger demand, sequencing flight arrivals at a hub are expected to improve service level (e.g., transfer delay) and reduce operation costs. Transfer time, in general, is affected by the walking distance between connecting flights and walking speed. Thus, gate assignment is a critical task for the effectiveness of an HSN in reducing transfer delay as well as gate occupancy time. The size of the aircraft is related to passenger load, especially for long-run scheduling purposes. For example, larger aircraft implies more expensive aircraft with higher passenger loads. Therefore, reducing dwell time and transfer time through proper landing sequence and gate assignment may significantly reduce total cost.

The effectiveness of such an operation was affected by several factors, including the batch of aircraft arrivals, aircraft sizes, the number of available gates, transfer demand between pairs of flights, and transfer claim time. The outbreak control policies (e.g., COVID-19 and its variant) at airports may change the transfer procedures and can increase the claim time, which would deteriorate the system's performance and level of service.

This paper intends to optimize flight sequencing and gate assignment at a hub airport under pandemic conditions by considering the realistic transfer time under different outbreak control policies. It is difficult to jointly optimize the sequence for a batch of arrivals/departures and gate assignment at a hub within a time window because the feasible solution spaces exponentially increase as the numbers of flights and gates increase. An efficient genetic algorithm is developed to solve the study problem, which will be discussed later in this paper.

2. Literature Review

The coordination of passenger transfers at a hub airport (HA) by sequencing flight arrivals and departures may significantly reduce transfer time while improving HA's productivity and reducing airliners' cost of operation. Few studies focused on the joint optimization of flight sequencing and gate assignment under pandemic situations.

Bianco et al. [10] formulated an aircraft sequencing problem as a combinatorial optimization problem, which was considered an n-job (i.e., landing or take-off) and one-machine (i.e., runway) scheduling problem. Subsequently, some studies reduced delays [11–13] and improved runway utilization [14] and capacity [15, 16] by optimizing flight sequencing. Eun et al. [17] developed a linear programming model to optimize the sequence of arrival flights, which minimized the delay. Later, Serhan et al. [18] optimized flight scheduling to minimize the airport surface and terminal delays. Jamili [19] developed a mixed integer programming model to determine the integrated aircraft routing, scheduling, and fleet assignment plan. Munari and Alvarez [20] optimized the aircraft routing, which minimized the operational costs. Pternea and Haghani [21] proposed an integrated framework for reassigning flights to airport gates in case of schedule disruptions. Ho et al. [22] proposed a multilevel optimization framework for the distribution of aircraft movements among the departure routes. Cecen and Aybek Çetek [23] optimized the total conflict resolution time and total airborne delay for aircraft landing problems with an area navigation route structure. For the coupling problem of resources and flights, Tian et al. [24] proposed a heuristic algorithm based on multidimensional flight priority for slot division and flight ranking.

Airport gate assignment is the process of designating gates for arrival and departure flights, which directly affects the transfer distance. Gate assignment is a combinatorial problem even when all flight arrivals and departures are known precisely in advance. Several studies optimized the gate assignment problem (GAP), focusing on minimizing passenger transfer distances [25–28]. Some studies [29, 30] suggested that a GAP may be optimized by considering multiple objectives. Genc et al. [29] optimized a GAP that maximized gate preference and then minimized the walking distance. By considering schedule robustness, facility and personnel costs, and passenger satisfaction (i.e., transfer distance), Yu et al. [30] optimized the gate assignment. Ali et al. [31] developed a passenger-centric model to analyze the effect of turnaround times, minimum connection times, and stochastic delays on missed connections of self-connecting passengers. Zhang et al. [32] proposed gate allocation of transit flights under the constraints of maximizing gate utilization and minimizing transit time. Lin et al. [33] proposed a bilevel programming model to minimize the overall variance of slack time between two consecutive aircrafts at the same gate and passenger transfer time. Yuan et al. [34] presented a continuous time formulation for the GAP to optimize passenger transfer time and the robustness of airport operation schedules. Çiftçi and Özkır [35] introduced the airline bank optimization problem for improving flight connection times, aiming to minimize the total connection times for transfer passengers.

In the global post-epidemic period, airports still implement corresponding outbreak controls to prevent the further spread of the epidemic, which changes the check-in procedure and even increases the transfer time. These studies discussed the abovementioned optimized flight sequence and gate assignment without outbreak controls. Since the relationship between outbreak controls and transfer claims was not considered, the optimal results might not be yielded in actual operations. Recent studies focused on the multi-objective optimization of gate assignments [36, 37]. In the optimization goal of gate assignment research, Cai et al. [36] modeled the GAP as a biobjective constrained optimization problem, where the two objectives were the total walking distance of passengers and the total robust cost of the gate assignment. Furthermore, Bi et al. [37] solved the GAP, where the objective is to maximize the number of passengers through a jetway.

Several studies focused on the joint optimization of flight sequence and gate assignment [38–42]. Xiao et al. [38] minimized the total cost by optimizing flight sequence and gate assignment, while considering transfer speed, transfer demand, aircraft size, gate size, and terminal configuration. L'Ortye et al. [39] modeled a flight-to-gate assignment problem that considers both airside and landside constraints on the capabilities of facilities such as check-in, security, and transfer to handle passengers. Li et al. [40] modeled the airport flight-to-gate assignment problem, where the goal is to minimize the on-ground portion of arrival delays by optimally assigning each scheduled flight to a compatible gate. To solve the NP-hard problem of combined aircraft turnaround time and airport gate allocation optimization, Asadi et al. [41] developed a hybrid metaheuristic algorithm. She et al. [42] addressed the problem of assigning a number of flight activities, including arrival, parking, and departure, to different gates during the operating period. A robust strategy is developed, considering the airport operators' tow-averse attributes. However, the realistic transfer time resulting from the outbreak control policy at airports was not considered.

Few studies considered the effect of realistic transfer time of passengers, which will significantly affect the dwell time of flights and connection time of passengers, especially under pandemic conditions. In the paper, we focus on developing an operation that minimizes the cost of users and suppliers by considering the transfer delay during the pandemic, while flight sequence and gate assignment that would affect queuing formation, dissipation, delay, and transfer time are explored.

3. Methodology

A general hub-and-spoke network consisting of a hub airport and a set of connecting spoke city airports is considered. A set of connecting flights N are assigned to a set of gates G within a cycle period in which $|G| \geq |N|$. The cycle period is the total time from landing to take-off of flight batches, which equals to the time interval between the first landing and the last take-off of the n connecting flights. The dwell time of a flight at a gate is determined by unloading/loading passengers/baggage, cleaning, refueling, provisioning, inspecting, passenger transfer time, and other procedures.

Transfer passengers from the gate of an arrival flight need to walk to the gate of a departing flight. The connection time of transfer passengers consists of transfer time (including walking time and transfer claim time) and wait time at the pickup gate of the departure flight. The walking time is dependent on the walking distance between gates and walking speed, while transfer claim time is affected by the outbreak control policies. All transfer passengers need to follow clearance procedures at the transfer hall (TH), such as checking documents (i.e., nucleic acid test report, safe healthy code, and personal travel history) depending on the different outbreak control policies, concerning the transmission risk of the pandemic. Passenger wait time is defined as the flight departure time which is less than the passenger arrival time at the gate.

The proposed model considers an HA with multiple domestic connecting flights. The objective is to develop an operation by optimizing flight sequencing and gate assignment of the HA, which minimizes the total cost considering its effect on realistic transfer time. To formulate the model, the following assumptions are made:

(1) The available gates are sufficient to serve a batch of connecting flights with different sizes.
(2) Flight safety checkup time is from the end of the last passenger boarding to the time when the flight disengages from the gate.
(3) The transfer time of passengers between the connecting flights depends on the distance between gates, walking speed, and transfer claim time. The walking distance is determined by the locations of gates and TH. In this study, we consider a very conservative walking speed to prevent missing flights.
(4) Considering a batch of flight arrivals in a short time window, the passenger's arrival rate at TH is the number of transfer passengers divided by the queue formation time T_f as shown in Figure 1, which is the duration between the first and the last passenger arrival times.

3.1. Model Formulation. The objective of this study is to reduce the total cost, denoted as C, which is the sum of the supplier cost C_s and the user cost C_u, that is,

$$C = C_s + C_u. \tag{1}$$

The variables and parameters used to formulate the objective function are shown in Table 1.

3.1.1. Supplier Cost (C_s). Supplier cost, denoted as C_s, is the sum of flight operating cost and gate cost. Flight operating cost is the flight dwell time (f_i) multiplied by the unit dwelling cost (v_{fi}), while gate cost is the usage time multiplied by the unit gate cost (v_{uk}). Note that, the gate usage time is equal to the flight dwell time. Thus,

$$C_s = \sum_{i=1}^{n} v_{fi} \cdot f_i + \sum_{k=1}^{g} \sum_{i=1}^{n} X_{\mathrm{ki}} \cdot v_{\mathrm{uk}} \cdot f_i, \tag{2}$$

where g = number of gates; i, j = index of flights and $i, j = 1$, 2, and . . ., n; k, l = the assigned gates for flights i and j, and k,

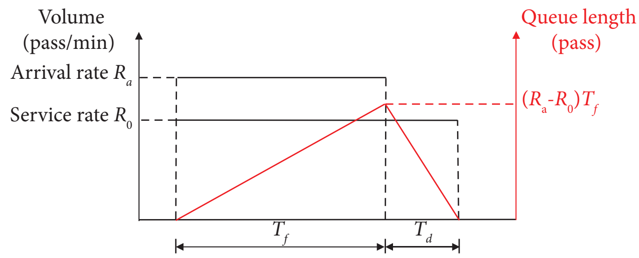

Figure 1: Queuing processes and delays.

Table 1: Notations.

Variables	Descriptions	Units
A_i	Arrival time of flight i	hh:mm
C	Total cost	\$/cycle
C^*	Minimized total cost	\$/cycle
C_s	Supplier cost	\$/cycle
C_u	User cost	\$/cycle
f_i	Dwell time of flight i	min
D_i	Departure time of flight i	hh:mm
d_k	Transfer distance between gates k and TH	m
G	Set of available gates	—
g	Number of gates	—
i,j	Index of flights	—
K	Number of servers	Servers
k,l	Index of gates	—
N	Set of connecting flights	—
n	Number of flights	Flights
O	Arrival time of the first flight in a batch	hh:mm
P	Total transfer demand	pass
P_i	Number of transfer passengers of flight i	pass
p_{ij}	Transfer demand from flight i to j and $p_{ij}=p_{mij}+p_{sij}$	pass
p_{mij}	Number of passengers who missed connecting from flight i to j	pass
p_{sij}	Number of connecting passengers from flight i to j	pass
R	Average service rate per service channel	pass/min
R_a	Arrival rate	pass/min
R_0	Service rate	pass/min
T_c	Transfer claim time	min
T_d	Queue dissipation time	min
T_f	Queue formation time	min
T_q	Queuing delay	min
T_s	Flight safety checkup time	min
t_{ai}	Elapsed time from O to the arrival time of flight i	min
t_{di}	Elapsed time from O to the departure time of flight i	min
V_p	Walking speed	m/min
V_m	Mean walking speed	m/min
v_{fi}	Unit dwelling cost of flight i	\$/min
v_m	Penalty per passenger who missed a connection	\$/pass
v_p	Value of transfer walking time	\$/pass-min
v_{uk}	Unit cost of gate k	\$/min
v_w	Value of wait time	\$/pass-min
W_{ij}	Transfer time from the gate of flight i to the gate of flight j	min
w_{ij}	Wait time of passenger from flight i at the gate of flight j	min
X_{ki}	Binary variable; $X_{ki}=1$ if flight i docks at gate k; otherwise, 0	—

$l=1$, 2, and … g, respectively; $n=$ number of flights; $X_{\text{ki}}=$ binary variable; and $X_{\text{ki}}=1$ means that gate k is assigned to flight i; otherwise, $X_{\text{ki}}=0$.

The dwell time of a flight i (f_i) is the elapsed time from the arrival of a flight i (A_i) at a gate to its departure from that gate (D_i). The arrival time of a flight i, denoted as A_i (in hh: mm), is the arrival time of its preceding flight plus an arrival headway. The flight departure time can be determined similarly. The departure time of a flight i, denoted as D_i (in hh:mm), can be determined by the departure time of its preceding flight plus a departure headway. By setting the arrival time of the first flight in a batch as the reference time point, denoted as O, D_i (in hh:mm), and A_i (in hh:mm) can be represented by t_{di} and t_{ai}, respectively. Therefore, f_i (in minutes) is equal to t_{di} minus t_{aj} (e.g., $f_j = t_{\mathrm{dj}} - t_{\mathrm{aj}}$).

The flight departure time depends on the expected passenger transfer time and departure sequence, subject to practical constraints. As discussed earlier, transfer time is affected by the flight arrival time (t_{aj}), walking speed (V_p), transfer claim time (T_c), and the distance between the gates of the connecting flights. Assuming that flights i and j are assigned to gates k and l, respectively, the elapsed time from O to the departure time of a flight i can be determined by the following equation:

$$t_{\mathrm{di}} = \max_{j=1}^{n}\left(t_{\mathrm{aj}} + \frac{d_k + d_l}{V_p} + T_c + T_s\right), \forall i, j \in N, i \neq j, \tag{3}$$

where i, j = index of flights, k, l = index of gates, t_{di} = elapsed time from O to the departure time of the flight i (min), d_k = transfer distance between gate k and TH (m), d_l = transfer distance between gate l and TH (m), and T_s = flight safety checkup time (min).

Departure time t_{di} is determined by the maximum transfer time considering the conservative walking speed, which minimizes the probability of missed connection. The first two terms in equation (3) represent the time for the last passenger arriving at the gate k (e.g., flight i) from gate l (e.g., flight j), and equation (3) represents the earliest departure time for the flight i.

The duration of transfer claim time is determined by the passenger arrival rate and the service rate of the TH as shown in Figure 1. The arrival rate of passengers is denoted by R_a, which is equal to the total transfer demand of P (e.g., $P = \sum_{i=1}^{n}\sum_{j=1}^{n} p_{\mathrm{ij}}$, where p_{ij} = transfer demand from flight i to j) divided by the transfer queue formation time. The queue formation time T_f lasts from the beginning to the end of the queue activity. The average service rate per service channel (e.g., server), denoted as R, depends on the average processing time per passenger and passenger volume. Considering K servers in TH, the service rate R_0 (= $K{\cdot}R$) is the product of the number of servers (K) and the average service rate per server (R). If the arrival rate R_a exceeds R_0, a queue will form, which dissipates as $R_a < R_0$.

The queue dissipation time (T_d) is the maximum queue length divided by the service rate R_0, that is,

$$T_d = \frac{(R_a - R_0)T_f}{R_0}. \tag{4}$$

The queuing delay T_q incurred by passenger arrivals can be estimated by using the following equation:

$$T_q = \frac{1}{2}\left(T_f + T_d\right)(R_a - R_0)T_f. \tag{5}$$

The transfer claim time per passenger, denoted as T_c, equals to the queuing delay divided by transfer demand P, that is,

$$T_c = \frac{T_q}{P} = \frac{1}{2}\left(\frac{P}{KR} - T_f\right). \tag{6}$$

3.1.2. User Cost (C_u). User cost, denoted as C_u, consists of connection and missed connection costs. Connection cost is the product of the number of connecting passengers (p_{sij}) multiplied by connection time and the value of time, while missed connection cost is the product of passengers who missed connections (p_{mij}) and penalty per passenger (v_m). Nontransfer passengers, including those originating from or terminating at the HA, are excluded from the total cost. Connection time is the elapsed time from the arrival time of flight i to the departure time of flight j, which is the sum of transfer time W_{ij} and wait time w_{ij}. Thus, we have

$$C_p = \sum_{i=1}^{n}\sum_{j=1}^{n} p_{\mathrm{sij}}\left(v_p W_{\mathrm{ij}} + v_w w_{\mathrm{ij}}\right) + \sum_{i=1}^{n}\sum_{j=1}^{n} p_{\mathrm{mij}} v_m, \tag{7}$$

where v_p = value of transfer time (\$/pass-min) and v_w = value of wait time (\$/pass-min).

The first term in equation (7) represents the connection cost incurred by transfer passengers, while the second term represents the missed connection cost that can be ignored if the probability of a missed connection is minor.

The transfer time W_{ij} is equal to the sum of time for walking and transfer claim time which depends on the outbreak controls. Thus,

$$W_{\mathrm{ij}} = \frac{d_k + d_l}{V_m} + T_c, \forall i, j \in N. \tag{8}$$

Note that, walking time is determined by walking distance, that is, the sum of d_k and d_l, divided by the mean walking speed V_m.

w_{ij} represents the mean passenger waiting time at the gate for boarding, which varies with the schedule of connecting flights i and j and can be determined by the following equation:

$$w_{\mathrm{ij}} = t_{\mathrm{dj}} - t_{\mathrm{ai}} - W_{\mathrm{ij}}, \forall i, j \in N. \tag{9}$$

Note that, the objective total cost function (i.e., equation (1)) is minimized and is subject to constraints to ensure that each gate is assigned to one flight or less (i.e., equation (10)) and that each flight is assigned to one gate only (i.e., equation (11)). Thus,

$$\sum_{i=1}^{n} X_{\mathrm{ki}} \leq 1, \forall k \in G, \tag{10}$$

$$\sum_{k=1}^{g} X_{\mathrm{ki}} = 1, \forall i \in N. \tag{11}$$

3.2. Solution Algorithm. The optimization problem formulated here is combinatorial. The solution spaces of the numerical example are tremendous because of the number of flights (n), the combination of flight arrival/departure sequences (e.g. $n!n!$), and the number of gates (g), as well as the sizes of flights and types of gates. As discussed in the paper, the solution spaces are $(\mathrm{x}n!n!d!(e+d-a)!(f+d+e-a-b)!/(d-a)!(e+d-a-b)!(f+d+e-a-b-c)!)$. Where a, b, and c represent the number of large, medium, and small flights, while d, e, and f represent the numbers of large, medium, and small gates, respectively. Note that, the combination of gate assignments is $(d!(e+d-a)!(f+d+e-a-b)!/(d-a)!(e+d-a-b)!(f+d+e-a-b-c)!)$. The maximum solution space is enormous and may be up to $n!n!g!$ For example, with 10 flights (e.g., 3 large, 4 medium, and 3 small ones) and 12 gates (e.g., 4 large, 5 medium, and 3 small) situations, the feasible solutions are (10!10!4!6!5!/2!2!). However, it is computationally expensive to find the solution with an exhaustive search method.

According to a previous study [43] discussing metaheuristics, the genetic algorithm (GA) can deliver more consistent solutions than simulation annealing and tabu search, albeit GA may consume more computation time. Considering large feasible solution spaces, an elite GA is efficient for optimizing flight sequencing and gate assignment. Thus, an elite genetic algorithm (GA) is developed. Figure 2 shows the step-by-step procedure for executing the GA.

The candidate solution (also called chromosome) consists of three integer encoded strings, representing flight arrival sequence, departure sequence, and gate assignment. Both arrival and departure sequence strings are encoded by n cells with integers between 1 and n, while the gate assignment string is represented by n cells with integers between 1 and g.

Three operators, including elitist selection, two-point crossover, and two-point mutation, are executed to evolve the chromosomes of new generations. A predetermined portion of the existing solutions with a high fitness is selected to breed a new generation. Specifically, the optimal individual solution of the current generation is directly copied to the next generation. The fitness function is used to measure the quality of the solution; therefore, the solution with the minimum total cost is deemed as the maximum fitness. A new generation of chromosomes is determined through crossover and mutation.

To exclude infeasible solutions, an enormous penalty is included in the fitness function. Note that, the realistic transfer claim time is computed by using equation (6) as soon as the provisional flight arrival times and gates are determined.

4. Numerical Example

A numerical example is used to demonstrate the proposed model's applicability. The studied HA is Xianyang International Airport (also labeled as XIY), located in Xi'an, China, consisting of three terminals with 127 gates and two runways. The configuration of Terminal 3, a main terminal for domestic flights, which is analyzed here, is shown in Figure 3. This is a general terminal with no remote stands, no interairport terminal transportation, and no levels to separate arriving from departing passengers. The gates are renumbered in an ascending order of distance to TH.

Within the studied cycle at XIY, with 11 available gates (i.e., 2 large, 6 medium, and 3 small), there is a batch of 10 flights (i.e., 1 large, 6 medium, and 3 small) arriving between 16:00 and 16:18 with a 2-minute headway. The unit dwelling cost varies with flight size, that is, 8.33 \$/min, 6.33 \$/min, and 3.33 \$/min for large, medium, and small flights, respectively. Similarly, the unit cost of a gate is 5 \$/min, 4.17 \$/min, and 3.33 \$/min for large, medium, and small gates, respectively.

All transfer passengers will merge and head to TH at Terminal 3. The processing time per passenger from cities with high- and low-risk levels are 0.5 min and 2 min concerning the procedure during pandemic conditions. The number of transfer passengers from cities with high- and low-risk levels are 411 and 943, respectively, and thus the service rate per server is 1.04 pass/min. For a 20-server TH, the service rate is 20.9 pass/min. The flight safety checkup time is 10 min. The conservative walking speed and mean walking speed are 36 m/min and 60 m/min, respectively. The value of transfer time v_p is 0.168 \$/min based on the average monthly salary of high-income persons, while the value of wait time is 80% of v_p (i.e., 0.134 \$/min). The numbers of transfer passengers on all connecting flights are shown in Tables 2 and 3.

Note that, flight indices are sorted in a descending order based on the number of transfer passengers. Flight and gate characteristics are shown in Tables 4 and 5. The gates are sorted in an ascending order based on the distance to TH.

The proposed GA was developed by using MATLAB R2014a. The case study is executed on a personal computer with 2.7-GHz Intel Core CPU and 8.0 GB of RAM. The parameters are set as follows: the initial solution size is 2,000, the selection rate is 0.8, the crossover rate is 0.75, the mutation ratio is 0.75, and the number of total generations is 1,000.

4.1. Scenario-Based Analysis. A benchmark analysis was conducted by considering the following three scenarios:

(i) Scenario I: do nothing (existing operation)
(ii) Scenario II: optimization with fixed transfer claim time
(iii) Scenario III: optimization with realistic transfer claim time

For scenario I, Table 6 shows the flight sequence and gate assignment under existing operations. The total cost is 28,982 \$/cycle, which is determined by the scheduled arrival and departure times and preassigned gates. Large gates 5 and 10 are assigned to flights 1 and 2 with large number of transfer passengers, respectively. Passenger transfer cost is 17,327 \$/cycle, which is 59.8% of the total cost. As shown in Figure 3, gate 9 is far away from TH, hence, it is vacated to reduce the transfer costs.

By considering the fixed transfer claim time (e.g., 23.7 min) in scenario II, the optimized flight sequence and gate assignment are shown in Table 7. We found that the total cost reduces from 28,982 \$/cycle (scenario I) to 21,249 \$/cycle. Flights with more transfer passengers (e.g., flights 3

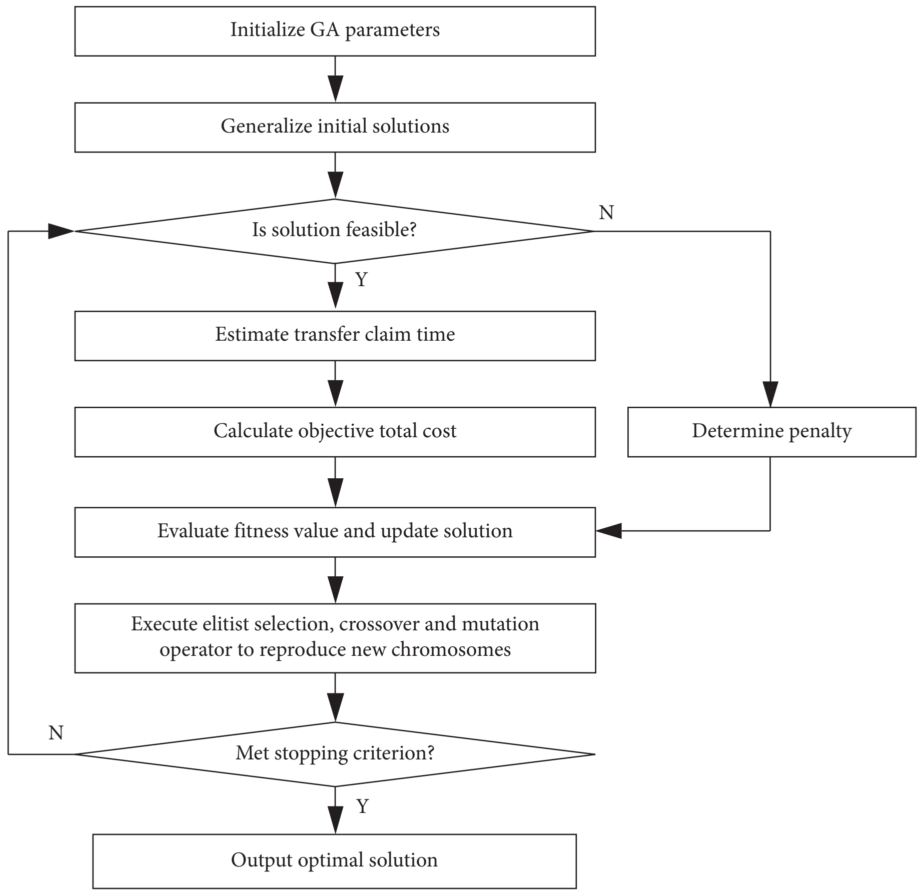

Figure 2: The flow chart of GA.

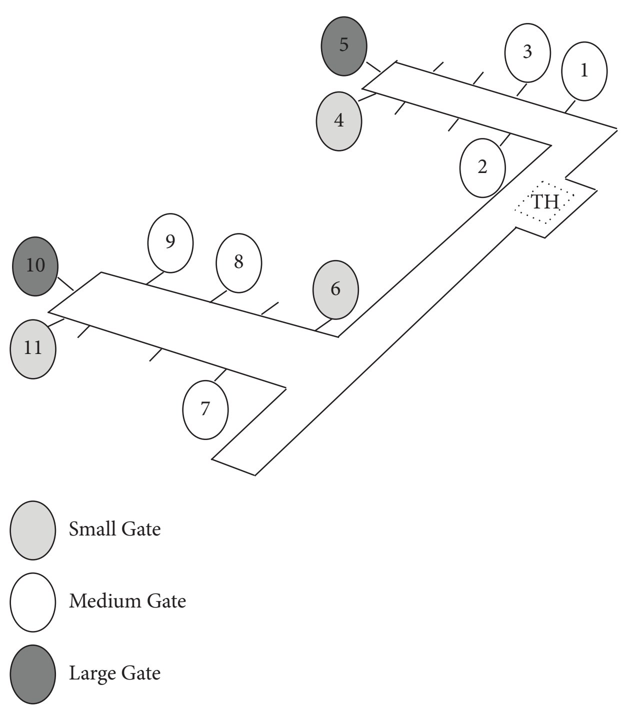

Figure 3: Terminal layout and gate locations.

Table 2: Baseline values of transfer passengers from flight i to j.

	i	j 1	2	3	4	5	6	7	8	9	10
p_{ij}	1	0	26	61	32	28	27	39	7	21	13
	2	67	0	12	15	13	16	22	8	11	14
	3	39	18	0	18	6	20	17	19	4	3
	4	46	31	12	0	3	6	3	9	2	11
	5	34	16	25	22	0	28	7	11	9	5
	6	48	16	19	2	10	0	11	4	13	8
	7	33	25	2	8	10	13	0	8	5	6
	8	6	12	12	17	18	4	9	0	11	9
	9	3	15	2	13	10	7	5	16	0	16
	10	7	11	12	15	3	6	3	13	2	0

Table 3: Baseline values of transfer passengers of flight i.

Flight index i	1	2	3	4	5	6	7	8	9	10
P_i	537	348	301	265	258	258	226	193	165	157

Note. P_i is the number of transfer passengers of flight i, $= \sum_{j=1}^{n} (p_{ij} + p_{ji})$.

Table 4: Baseline values of flight characteristics.

Flight index i	1	2	3	4	5	6	7	8	9	10
A_i (hh:mm)	16:16	16:18	16:12	16:06	16:08	16:14	16:10	16:04	16:02	16:00
D_i (hh:mm)	17:29	17:31	17:41	17:37	17:35	17:33	17:39	17:47	17:43	17:45
f_i (min)	73	73	89	91	87	79	89	103	101	105
k	5	10	7	8	1	3	2	4	11	6
Size	L	L	M	M	M	M	M	S	S	S
Risk level	H	LO	LO	LO	H	LO	LO	LO	LO	LO

Note. A_i, arrival time of flight i; D_i, Departure time of flight i; k, assigned gate to flight i; L, large; M, medium; S, small; H, high-risk level; LO, low-risk level.

Table 5: Baseline values of gate characteristics.

Gate index k	1	2	3	4	5	6	7	8	9	10	11
Size	M	M	M	S	L	S	M	M	M	L	S
d_k (m)	112	150	165	300	303	310	342	437	479	502	509

and 4) tend to land later and depart earlier than those with fewer passengers (e.g., flight 9) so as to reduce the dwell time, and the assigned gates are closer to TH to reduce the walking time. Note that, flight 1 serves more transfer passengers, assigned to gate 5, dwells longer than flights 2, 3, and 4 and the walking distance from gate 5 to TH is long. It is worth noting that the average transfer claim time varies with the passenger arrival rate and the TH's service rate. The optimized flight sequence and gate assignment result in a longer transfer claim time (e.g., 26.0 min > 23.7 min) and a higher total cost, 22,532 \$/cycle. The average flight dwell time is 67.7 min.

For scenario III with the realistic transfer claim time, the optimized results are shown in Table 8. Compared with scenarios I and II, the optimal arrival sequence and gate assignment are justified, which reduces the dwell time at gates. On one hand, flight 4 shall land first and be served by gate 2 (a closer gate to TH), which may reduce the passenger arrival rate at TH because of the increased queue formation time. Considering the fixed service capacity at TH, the transfer claim time can be shortened. On the other hand, the two small flights 8 and 9 are assigned to gates 4 and 6 to reduce the user cost. With this operation, the transfer claim time reduces from 26.0 min to 23.7 min, which yields the minimized total cost of 21,686 \$/cycle, which is less than the total cost in scenario II (e.g., 22,532 \$/cycle).

Figure 4 shows the flights' dwell time for the three scenarios. For flight 10, the dwell time significantly decreases from 105 min under the scenario I to 84 min and 79 min with an optimized flight sequence and gate assignment under scenarios II and III, respectively. The mean (deviation) dwell times per flight are 89 [11] min and 65 [9] min for scenarios I and III, separately, and the dwell time increases as the number of transfer passengers increases.

Table 9 shows the minimized total cost and its components for scenarios I through III. Compared with scenario I, both supplier and user cost decreases significantly in scenarios II and III.

Table 6: Flight sequence and gate assignment for scenario I.

Time		Scenario I																			
		$T_c = 24.8$ min										$C^* = 28{,}982$ \$/cycle									
		16:00	16:02	16:04	16:06	16:08	16:10	16:12	16:14	16:16	16:18	17:29	17:31	17:33	17:35	17:37	17:39	17:41	17:43	17:45	17:47
Assigned gate	6	**10**																		**10**	
	11		**9**																**9**		
	4			**8**																	**8**
	8				**4**											**4**					
	1					**5**									**5**						
	2						**7**										**7**				
	7							**3**										**3**			
	3								**6**					**6**							
	5									**1**		**1**									
	10										**2**		**2**								

Note. The bold numbers in the table are the indexes of flights.

Table 7: Optimized flight sequence and gate assignment for scenario II.

Time		Scenario II																			
		$T_c = 23.7$ min (26.0 min)										$C^* = 21{,}249\$/\text{cycle}$ (22,532 \$/cycle)									
		16:00	16:02	16:04	16:06	16:08	16:10	16:12	16:14	16:16	16:18	17:05	17:07	17:09	17:11	17:13	17:15	17:17	17:19	17:21	17:23
Assigned gate	11	**10**																		**10**	
	6		**9**																		**9**
	9			**7**														**7**			
	8				**6**												**6**				
	5					**1**									**1**						
	7						**5**									**5**					
	4							**8**											**8**		
	3								**4**					**4**							
	2									**3**			**3**								
	1										**2**	**2**									

Note. The bold numbers in the table are the indexes of flights. The actual transfer claim time and the total cost are in brackets.

Table 8: Optimized flight sequence and gate assignment for scenario III.

Time		Scenario III																			
		$T_c = 23.7$ min										$C^* = 21{,}686$ \$/cycle									
		16:00	16:02	16:04	16:06	16:08	16:10	16:12	16:14	16:16	16:18	17:05	17:07	17:09	17:11	17:13	17:15	17:17	17:19	17:21	17:23
Assigned gate	2	**4**												**4**							
	11		**10**																	**10**	
	9			**7**														**7**			
	8				**6**											**6**					
	7					**5**											**5**				
	5						**1**								**1**						
	6							**9**													**9**
	4								**8**										**8**		
	3									**3**			**3**								
	1										**2**	**2**									

Note. The bold numbers in table are the indexes of flights.

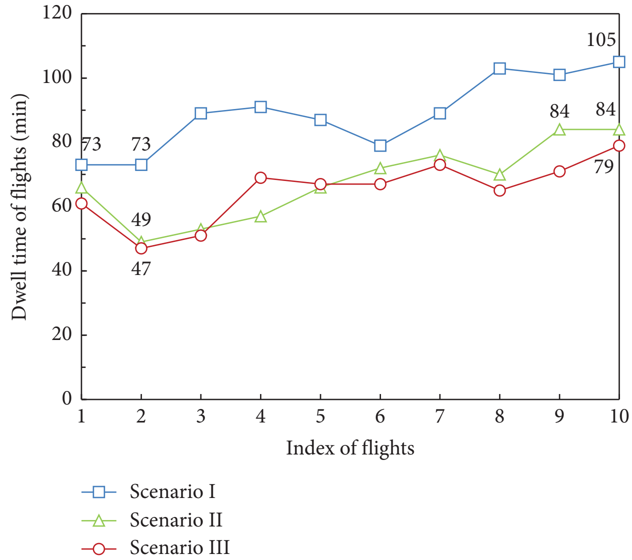

Figure 4: Flight dwell time for scenarios I-III.

Table 9: Minimized total cost and its component for scenarios I through III.

Scenario	Supplier cost C_s (\$/cycle)	User cost C_u (\$/cycle)	Minimized total cost C^* (\$/cycle)
I	11,655	17,327	28,982
II	8,798	13,733	22,532
III	8,501	13,185	21,686

The total cost incurred by the provisional solution at each iteration is shown in Figure 5. It was found that the total cost was reduced effectively before iteration 50 and then gently converged. The minimum total cost was yielded at the 132nd iteration.

4.2. Sensitivity Analysis. This section aims to explore the relations among model parameters (i.e., transfer demand, mean walking speed, and service rate) and decision variables (i.e., flight sequence and gate assignment) for scenario III with realistic transfer claim time.

The study XIY experienced reduced travel demands during the pandemic. Figure 6 shows the optimal results with a 40% demand reduction, resulting in a reduced transfer claim time from 23.7 min to 10.1 min. The mean dwell time is reduced by 12 min. The cycle period of all connecting flights decreased from 83 min to 71 min. The minimized total cost is 13,098 \$/cycle.

In another situation, if a specific spoke city implements travel restrictions, for example, the transfer passengers of flight 5 decrease by 20% from 258 to 227 pass, while the demand on the other flights remains the same, then the optimal results are shown in Figure 7. The transfer claim time reduces slightly from 23.7 min to 21.5 min, which reduces the mean dwell time of flights and usage time of gates by 10 min. The minimized total cost is 20,965 \$/cycle. Note that, flight 5 is arranged to arrive early and take-off later because of a reduced demand.

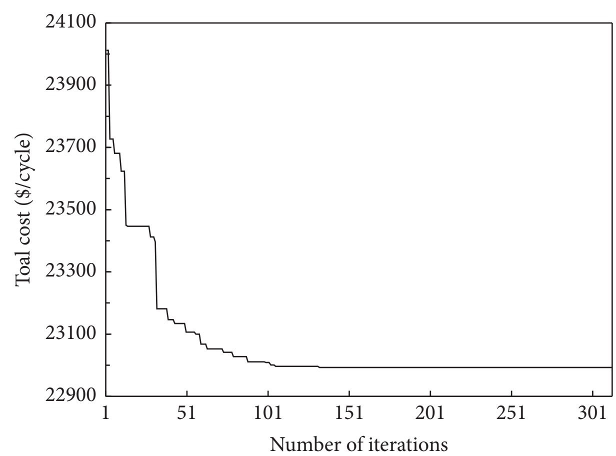

Figure 5: Total cost vs. iteration of the elite GA.

Keeping social distance is important for safety during COVID-19, which may slow down the mean walking speed V_m (e.g., from 60 m/min to 50 m/min), and this will affect the optimal flight sequence and gate assignment as shown in Figure 8. Flight 2 served at gate 2 is arranged to land last and depart first, which results in the average dwell time being prolonged to more than 1 minute. The minimized total cost slightly increased by 1.16% from 21,686 \$/cycle (scenario III) to 21,938 \$/cycle.

Increasing the number of servers (e.g., service channels at TH) will increase service rates, which can reduce the transfer claim time and dwell time as shown in Figure 9. When the number of servers K increases from 22 to 30, the service rate R_0 increases from 23.0 pass/min to 31.4 pass/min, which reduces the transfer claim time from 23.7 min to 12.1 min per passenger. This would slightly change the optimal flight sequence and gate assignment. The latest arrival, that is, flight 2 is assigned to gate 3, a bit far from TH (e.g., usually served close to gates 1 and 2), which reduces the transfer claim time and may slightly increase the flight dwell

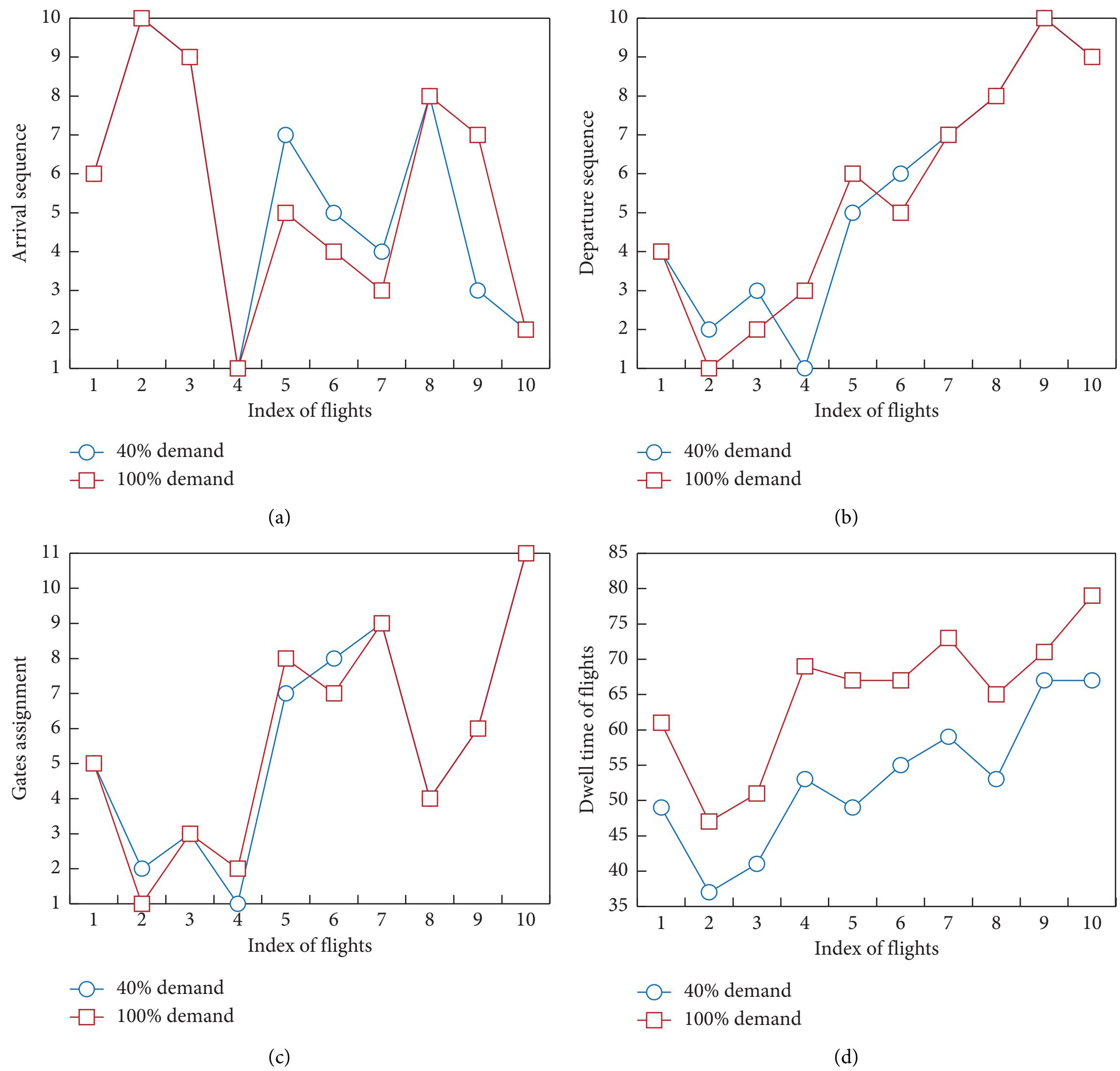

Figure 6: Optimal results with different travel demands.

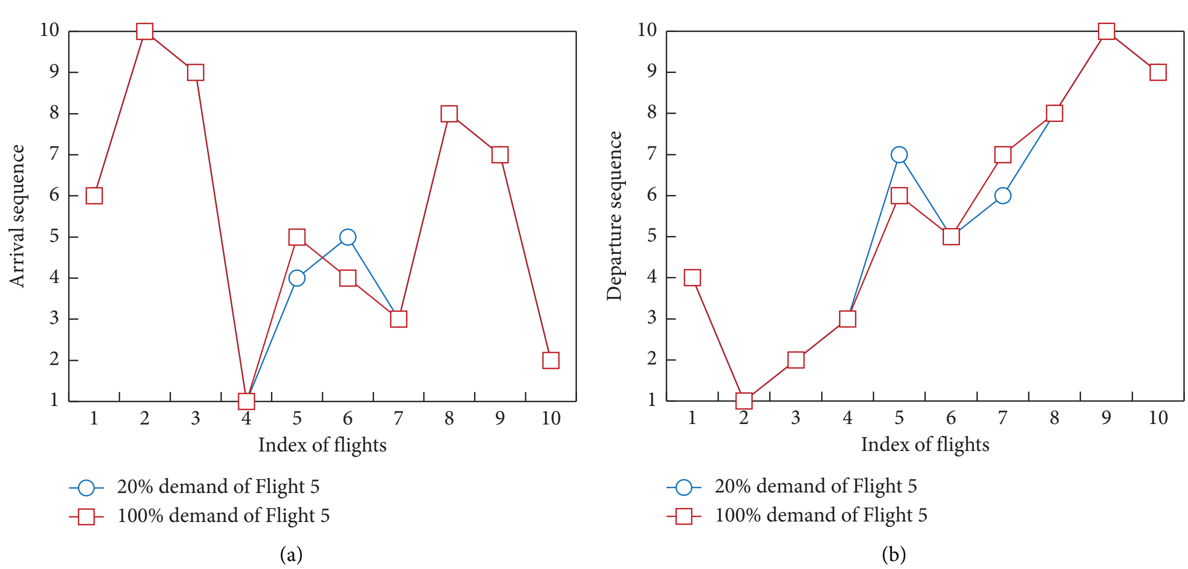

Figure 7: Continued.

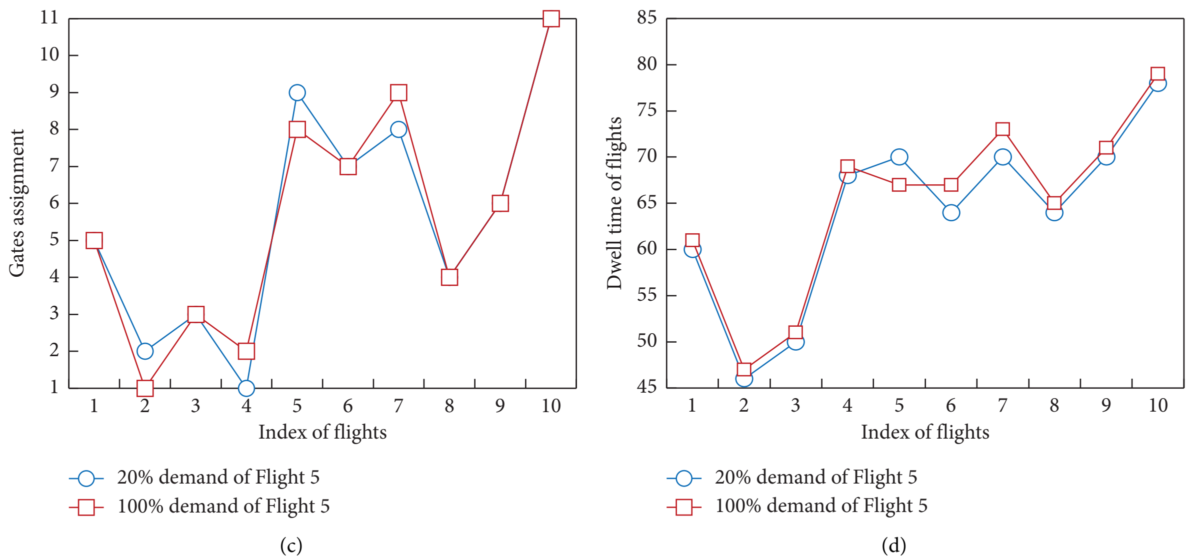

Figure 7: Optimal results with different transfer passengers of flight 5.

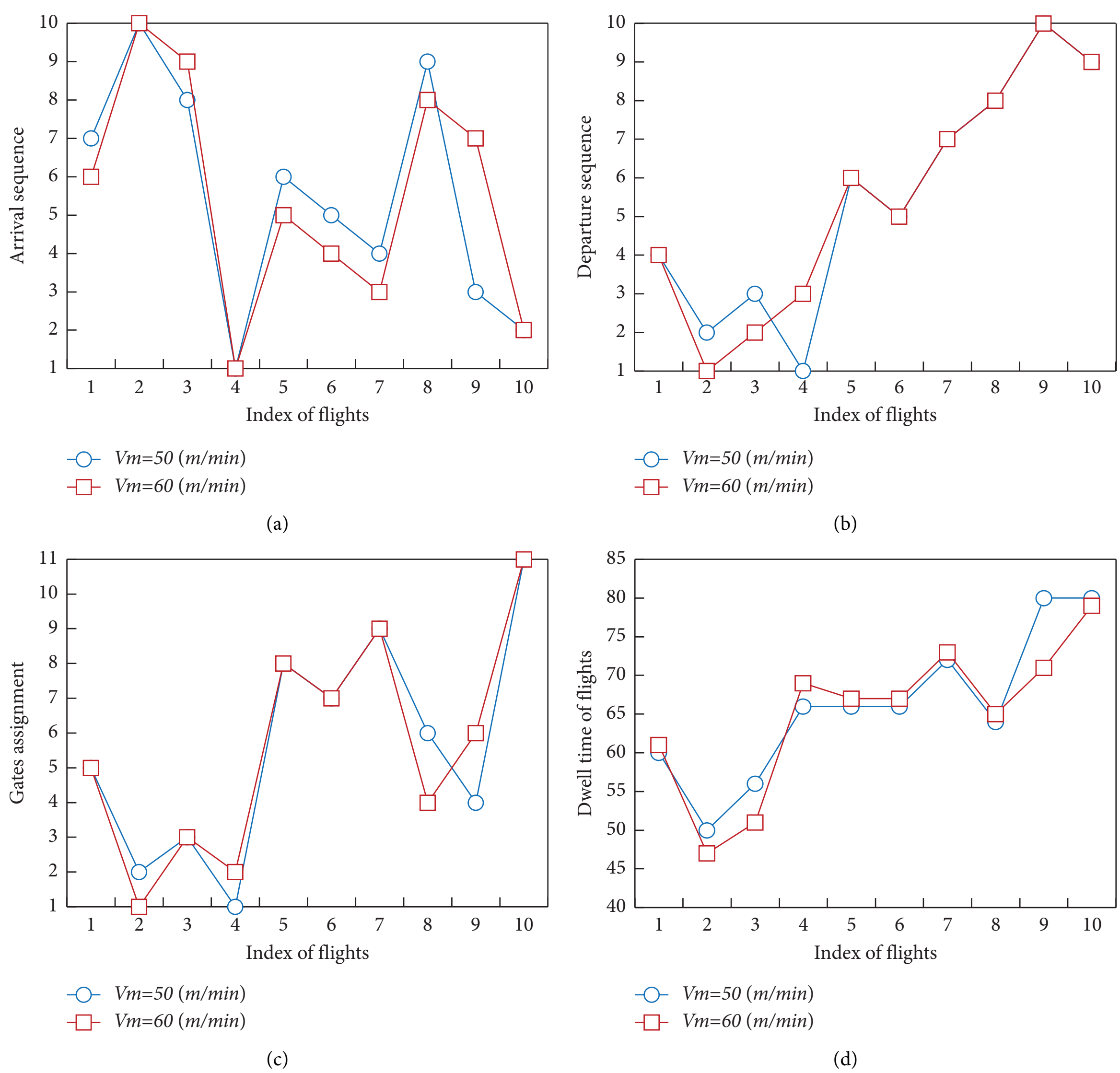

Figure 8: Optimal results for different mean walking speeds.

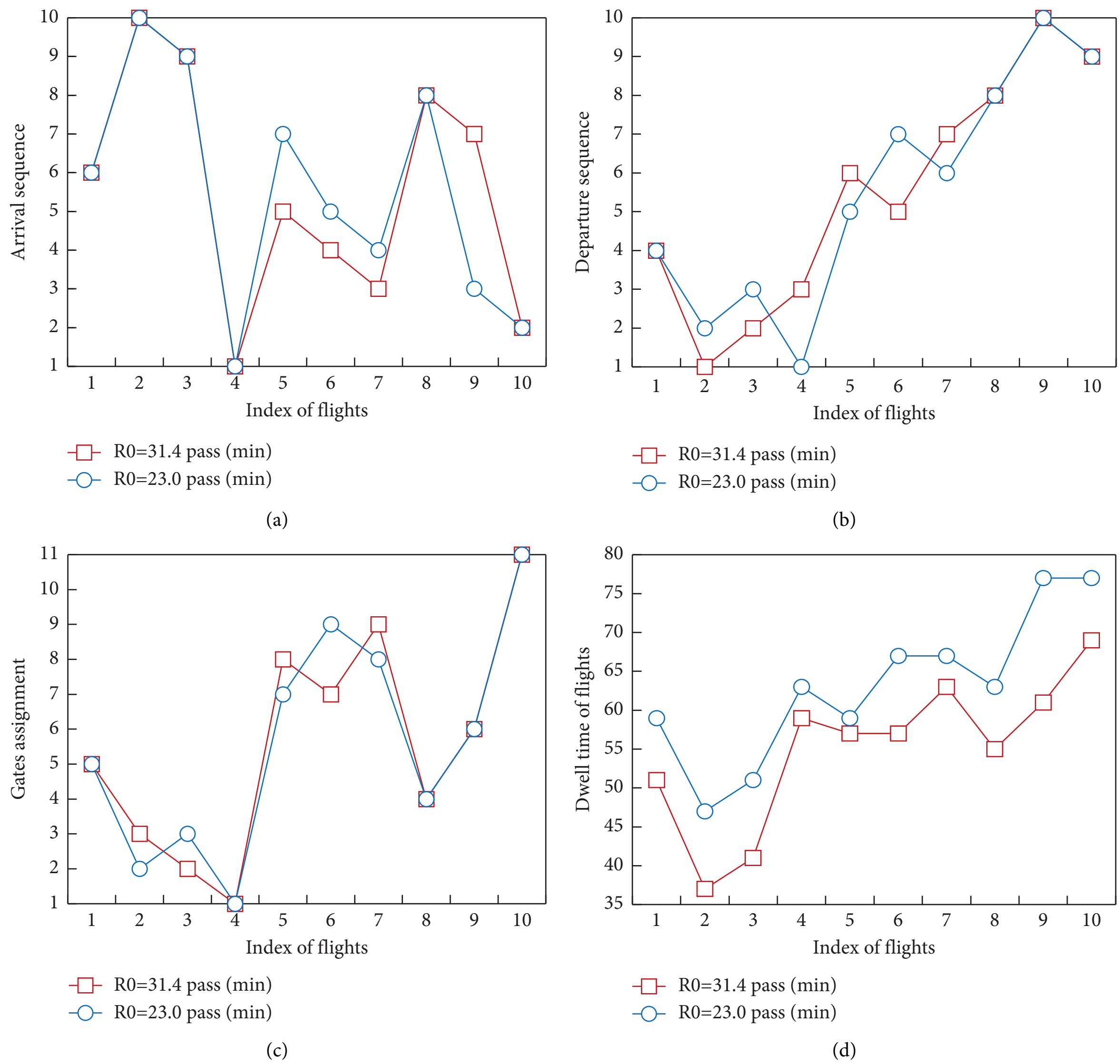

Figure 9: Optimal results with different service rates.

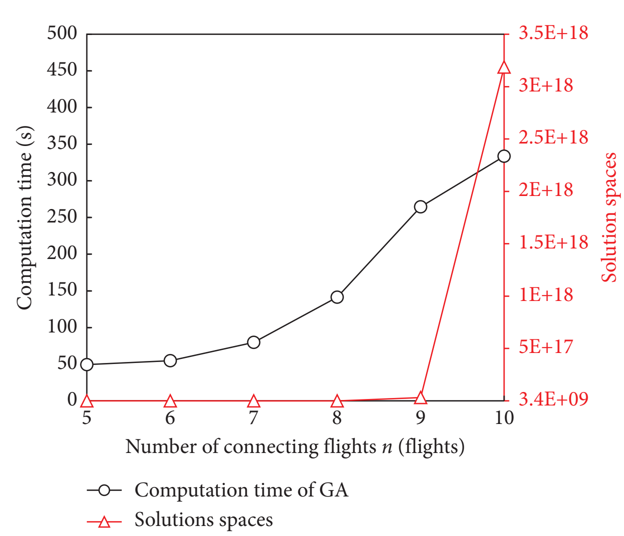

Figure 10: Computation time and solution spaces vs. the number of connecting flights.

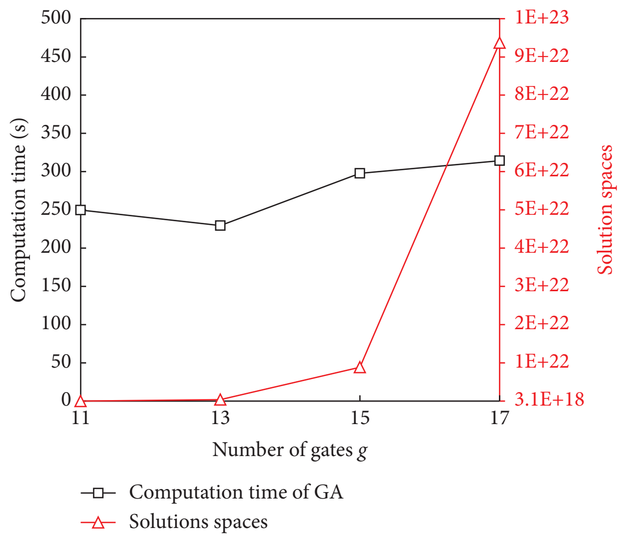

FIGURE 11: Computation time and solution spaces vs. the number of gates.

time. The cycle is shortened by 10 min, and the minimized total cost decreases to 18,038 \$/cycle.

For the eleven available gates, Figure 10 shows that as the number of connecting flights increases, the size of the solution space expands exponentially; however, the computation time tends to increase linearly. While fixing the number of connecting flights (e.g., $n = 10$) with the varying number of gates, Figure 11 shows comparable results as those shown in Figure 10. As the number of gates increases, the size of solution spaces expands exponentially, and computation time tends to increase linearly. Figures 10 and 11 show that the performance of the elite GA is promising.

5. Conclusions

A mathematical model is developed in this study to optimize flight sequence and gate assignment for a hub-and-spoke connecting transfer considering realistic transfer time under pandemic conditions. The proposed methodology can effectively estimate the delay of transfer claims affected by passenger flows. The study hub is XIY in Xi'an, China, which connects flights from spoke cities.

The minimized total cost is yielded by the optimal flight sequence and gate assignment. It was found that those flights with more transfer passengers should be arranged to arrive later and depart earlier. Reducing transfer claim time can shorten dwell time, which can be achieved by assigning the gates closer to TH for earlier flight arrivals and those gates farther from TH for later flight arrivals.

The results of a sensitivity analysis suggest that transfer demand influences the sequence of flights. In general, flights with more passengers should arrive later and depart earlier. The optimal gate assignment and flight sequencing will be affected by the service rate at TH, which is related to the level of outbreak controls, passenger walking speed, and travel policies. Improving the service rate can reduce the transfer claim time, dwell time, and total cost. Increasing walking speed can reduce transfer costs, which would slightly affect the optimal solution.

Future extensions of this study will include, but not be limited to, (1) improving the current method for estimating transfer claim time considering multiple THs at terminals, (2) developing a more efficient solution algorithm for more connecting flights in a multi-hub HSN, and (3) developing a hybrid algorithm (e.g., NGSA-II) to solve a multiobjective optimization problem (e.g., minimizing operating cost and maximizing service level).

Data Availability

The raw data required to reproduce these findings cannot be shared at this time as the data also form part of an ongoing study.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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