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Research Article

Multiobjective Gate Assignment Based on Passenger Walking Distance and Fairness

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Passenger walking distance is an important index of the airport service quality. How to shorten the walking distance and balance the airlines' service quality is the focus of much research on airport gate assignment problems. According to the problems of airport passenger service quality, an optimization gate assignment model is established. The gate assignment model is based on minimizing the total walking distance of all passengers and balancing the average walking distance of passengers among different airlines. Lingo is used in the simulation of a large airport gate assignment. Test results show that the optimization model can reduce the average walking distance of passenger effectively, improve the number of flights assigned to gate, balance airline service quality, and enhance the overall service level of airports and airlines. The model provides reference for the airport gate preassignment.

1. Introduction

Airport gate is a main component of airport resource. Rational and efficient gate assignment is an important way to improve airport operation efficiency and passenger service level. Airport gate is divided into contact gate (a gate with an aerobridge) and remote stand (on the apron). The type and layout lead to different distance from gate to security check, baggage hall, and transit counters. The distance between different areas has a direct impact on passenger activities in the terminal. How to optimize the gate assignment from the perspective of passengers becomes a hot research area at home and abroad.

At present, the main research findings of gate assignment from the perspective of passengers took the shortest passenger walking distance and the minimum embarking and transit time as objective function to optimize gate assignment; for example, Braaksma, [1], Babic et al. [2], Mangoubi and Mathaisel [3], Yan and Huo [4], Bolat [5], Yan et al. [6], and Cheng's [7] research findings showed that reasonable gate assignment could reduce passenger walking distance appropriately. In 1998, Haghani and Chen [8] took the number of transfer passengers of different flights and the distance between different gates into account comprehensively while minimizing passenger walking distance in a terminal. Assuming that all passengers were converted into transit passengers and had taken the shortest transit time as the objective function, Xu and Bailey [9] established quadratic mixed 0-1 integer programming model of gate assignment through virtual assumption. In further research, some scholars began to consider minimizing the number of flights, which are assigned to remote stands, and the passenger walking distance/time, such as Pintea et al. [10], Ding et al. [11, 12], and so on; some scholars considered minimizing walking distance together with delay costs, like Zhu et al. [13], balancing usage of airport gates, like Wei and Liu [14, 15], passenger waiting time, like Hu and Paolo [16], and fuel consumption of aircraft taxiing, like Maharjan and Matis [17], respectively.

Optimization gate assignment from the perspective of passengers can reduce passenger walking distance and improve passenger service levels to a certain extent. However, there are some deficiencies in research findings. Firstly, in some large hub airporsts, the proportion of transit passengers is large and the actual walking distance of transit passengers is not equal to the actual distance between two gates. The walking distance is related with the layout of transit counters and transit halls. In the research, ignoring transit passengers can cause the model to be inaccurate. Secondly, civil airport service quality issued by the Civil Aviation Administration in 2006 requires that the number of passengers embarking/disembarking through aerobridges should be above 80%. But in most current research, the proportion of passengers is not taken into account. Thirdly, most current researches do not consider the balance of passenger walking distance between different airlines, which can lead to reducing the passenger service level and can be unfair for some airlines, especially for small airlines.

Optimizing gate assignment can improve passengers' satisfaction and balance the service quality of each airline. In this research, we propose a new model which is different from previous researches; the gates are categorized into contact gate and remote stand in the mode, the proportion of passenger embarking/disembarking through aerobridges is taken into account, and the model considers the fairness between airlines besides reducing the overall passengers' walking distance.

The paper is organized as follows. The gate assignment model is detailed in Section 2. Section 3 briefs the simulation software and analyzes the results under different conditions in detail. Some conclusions are drawn in the last section.

2. Gate Assignment Model

2.1. Description of Gate Assignment. Gate assignment is to arrange a reasonable gate for each arrival-departure flight timely according to the flight plan, which is submitted by every airline. Safety operation of aircraft and gate is the premise of gate assignment.

Passenger walking distance in a large airport is composed of three parts: arrival passenger walking distance, departure passenger walking distance, and transit passenger walking distance. The arrival passenger walking distance refers to the distance from gate to baggage hall; the departure passenger walking distance refers to the distance from security check to gate; the transit passenger walking distance refers to the distance from gate to transit counter and then to the next flight gate. The arrival-departure transit passengers are known collectively as transit passengers in the paper. The walking distance of transit counter passengers includes the arrival passengers' distance from gate to transit counter and the departure passengers' distance from transit counter to gate.

Minimizing and balancing the walking distance of all passengers from different airlines are goals to model gate assignment in the paper. Then Lingo software is adopted to verify the effectiveness of a model in order to improve the service level of airport and airline.

2.2. Model Assumptions

(1) Gate assignment is a continuous operation course. In order to reduce the scale of the problem, the paper selects some time intervals for gate assignment.

(2) The capacity of gates can meet the demand of all flights in the research time; it means that every flight can be assigned to a gate.

(3) The arrival-departure flight performed by the same aircraft is assigned to the same gate and it used the same flight number.

(4) All information, such as flight plan, aircraft basic information, the usage status of gates, and so on, is known in research time.

(5) Only the gate assignment of domestic flights is considered in the paper.

2.3. Symbol Definition

F: flight set, $F = \{f_1, f_2, \ldots, f_m\}$, m is the total number of flights in research period. f_i $(1 \leq i \leq m)$ is flight number which is ordered by the arrival time of flights; the bigger i means the later flight f_i arrives at the airport.

c_{f_i}: size of the aircraft which executes flight f_i. The bigger c_{f_i} is, the larger aircraft is. The smaller c_{f_i} is, the smaller aircraft is.

L: airline set, $L = \{l_1, l_2, \ldots, l_q\}$, q is the total number of airlines in research period. l_a $(1 \leq a \leq q)$ is airline code.

F_{l_a}: the flights set of airline l_a.

G: gate set, $G = \{g_1, g_2, \ldots, g_n\}$, n is the total number of gates. g_k $(1 \leq k \leq n)$ is gate code.

Assuming that the number of gates is x, if $k \leq x$, it means that g_k gate is a contact gate; otherwise, it is a remote stand.

c_{g_k}: size of gate g_k; the bigger c_{g_k} means the larger aircraft can be parked on the gate; the smaller c_{g_k} means the smaller aircraft can be parked.

a_{f_i}: arrival time of flight f_i; the unit is minute.

d_{f_i}: departure time of flight f_i; the unit is minute.

T: minimum time interval of two flights which are assigned to the same gate; the unit is minute.

$S^a_{g_k}$: distance of arrival passenger walking from gate g_k to baggage hall.

$S^d_{g_k}$: distance of departure passenger walking from security checking to gate g_k.

$S^m_{g_k}$: distance between gate g_k and transit counter.

$N^a_{f_i}$: number of arrival passengers of flight f_i.

$N^d_{f_i}$: number of departure passengers of flight f_i.

$N^m_{f_i}$: number of transit passengers of flight f_i.

Consider

$$y_{f_i,g_k} = \begin{cases} 1, & \text{if flight } f_i \text{ is assigned to gate } g_k, \\ 0, & \text{otherwise,} \end{cases}$$
$$z_{f_i,f_j} = \begin{cases} 1, & \text{if flight } f_i \text{ and } f_j \text{ are assigned to the same gate,} \\ 0, & \text{otherwise.} \end{cases} \quad (1)$$

2.4. Modeling. Minimizing the total walking distance of all passengers in research period is one of the goals in the paper.

Consider

$$\min Z_1 = \sum_{f_i \in F} \sum_{g_k \in G} y_{f_i,g_k} \left(N^a_{f_i} S^a_{g_k} + N^d_{f_i} S^d_{g_k} + N^m_{f_i} S^m_{g_k} \right), \quad (2)$$

where $N^a_{f_i} S^a_{g_k}$ represents the total walking distance of arrival passengers of flight f_i walking from gate g_k to baggage hall; $N^d_{f_i} S^d_{g_k}$ represents the total walking distance of departure passengers of flight f_i walking from security checking point to gate g_k; $N^m_{f_i} S^m_{g_k}$ represents the total walking distance of transit passengers of flight f_i.

According to the objective function (2), gate assignment may result in longer walking distance of some airlines' passengers while some others are shorter. The objective function (2) can lead to unbalanced passenger walking distance among airlines and reduce the airlines' service quality. Therefore, in order to improve the service quality of the entire airport, it is necessary to balance passenger walking distance of each airline from the viewpoint of airline fairness.

Consider

$$\min Z_2 = \max_{l_a \in L} Z_{S_{l_a}}, \quad (3)$$

$$\overline{S_{l_a}} = \frac{\sum_{f_i \in F_{l_a}} \sum_{g_k \in G} y_{f_i,g_k} \left(N^a_{f_i} S^a_{g_k} + N^d_{f_i} S^d_{g_k} + N^m_{f_i} S^m_{g_k} \right)}{\sum_{f_i \in F_{l_a}} \left(N^a_{f_i} + N^d_{f_i} + N^m_{f_i} \right)}, \quad (4)$$

$$\overline{S} = \frac{\sum_{f_i \in F} \sum_{g_k \in G} y_{f_i,g_k} \left(N^a_{f_i} S^a_{g_k} + N^d_{f_i} S^d_{g_k} + N^m_{f_i} S^m_{g_k} \right)}{\sum_{f_i \in F} \left(N^a_{f_i} + N^d_{f_i} + N^m_{f_i} \right)}, \quad (5)$$

$$Z_{S_{l_a}} = \frac{\left| \overline{S_{l_a}} - \overline{S} \right|}{\overline{S}}, \quad l_a \in L. \quad (6)$$

The objective function (3) is to minimize the ratio between the difference and the average walking distance of all passengers, where $\overline{S_{l_a}}$ represents the average passenger walking distance of airline l_a in research period; $\overline{S}$ represents the average walking distance of all passengers in research period; $Z_{S_{l_a}}$ represents the ratio of the difference and walking distance of all passengers, where the difference is the average passenger walking distance of airline l_a and all passengers.

Subject to

$$\frac{\sum_{f_i \in F} \sum_{k \le x, g_k \in G} y_{f_i,g_k} \left(N^a_{f_i} + N^d_{f_i} + N^m_{f_i} \right)}{\sum_{f_i \in F} \left(N^a_{f_i} + N^d_{f_i} + N^m_{f_i} \right)} \ge 0.8, \quad (7)$$

$$\sum_{g_k \in G} y_{f_i,g_k} = 1, \quad \forall f_i \in F, \quad (8)$$

$$y_{f_i,g_k} \in \{0, 1\}, \quad (9)$$

$$z_{f_i,f_j} = \sum_{f_i \in F} \sum_{j>i, f_j \in F} \sum_{g_k \in G} \left(y_{f_i,g_k} \times y_{f_j,g_k} \right), \quad (10)$$

$$a_{f_j} - d_{f_i} + \left(1 - z_{f_i,f_j} \right) M \ge T, \quad i < j, \quad (11)$$

$$c_{f_i} \le c_{g_k} + \left(1 - y_{f_i,g_k} \right) M, \quad (12)$$

$$i, j, a, q, k, x \in Z^+. \quad (13)$$

Equation (7) is to restrain the proportion of passengers who are required to embark/disembark aircraft through aerobridges. Civil airport service quality, which was issued by the Civil Aviation Administration in 2006, requires that the number of passengers that embark/disembark through aerobridges should be above 80%.

Equations (8) and (9) indicate that each flight has one and only one gate to be assigned. That is, for flight f_i, in the gate set G, there is only one gate g_k to make $y_{f_i,g_k} = 1$.

Equation (10) is used to judge whether the two flights are assigned to the same gate. When $y_{f_i,g_k} \times y_{f_j,g_k} = 1$, $z_{f_i,f_j} = 1$, it indicates that the later arrival flight f_j and the front flight f_i are arranged in the same gate; otherwise, $z_{f_i,f_j} = 0$.

Equation (11) requires that the two flights which were assigned to the same gate should meet certain safety interval. According to (10) when $z_{f_i,f_j} = 1$, it needs to meet $a_{f_j} - d_{f_i} \ge T$; the front and later flights should meet the minimum safety interval. When $z_{f_i,f_j} = 0$, the two flights are not assigned in the same gate; it need not meet safety interval. Therefore, value M, which is big enough, is introduced to ensure the inequality holds.

Equation (12) means that the gate type should match the aircraft type. When $y_{f_i,g_k} = 1$, flight f_i is assigned to gate g_k; it should meet $c_{f_i} \le c_{g_k}$. When $y_{f_i,g_k} = 0$, there is no relationship between flight f_i and gate g_k.

Equation (13) is a positive integer constraint.

3. Simulations

The decision variables in the gate assignment model are 0 and 1, belonging to 0-1 planning of integer programming problem. Due to nonlinear constraints involved in the model, the model is called integer nonlinear programming (INLP). The paper uses Lingo software to simulate and verify the model. The Global (global optimization algorithm) and Multistart (more initial point algorithm) built-in Lingo are specifically used to solve nonlinear programming (Scharge [18]). In addition, Lingo can be connected with EXCEL, database, and other software conveniently; it also can easily input and output the simulation results. Another important superiority of Lingo is convenient to describe large-scale optimization problems concisely and intuitionisticly. Therefore, the paper uses Lingo software to simulate and verify the effectiveness of the model.

The simulation data of domestic flights to be assigned in a typical time interval (8:00–11:00) in a large airport is shown in Tables 1 and 2. The minimum time interval $T = 15$ minutes; this is the time when the two flights are to be assigned to the same gate continuously. The constant value $M = 300$.

Table 1: Domestic flight to be assigned from 8:00 to 11:00.

Flight no.	Type	Airline	Arr. time	Dep. time	Number of arr. passengers	Number of dep. passengers	Number of transit passengers	Total passengers
F101	M	A1	08:00	08:55	35	48	174	257
F102	M	A2	08:15	09:20	129	142	36	307
F103	L	A4	08:30	09:50	132	136	169	437
F104	M	A3	08:45	09:55	97	101	86	284
F105	M	A1	09:00	10:10	106	89	128	323
F106	L	A2	09:10	10:30	206	189	64	459
F107	M	A1	09:15	10:20	72	96	72	240
F108	S	A2	09:30	10:15	41	46	98	185
F109	M	A3	09:40	10:40	128	114	29	271
F110	M	A4	10:00	11:30	154	146	65	365
F111	S	A3	10:05	10:55	49	63	32	144
F112	M	A2	10:20	11:20	143	136	40	319
F113	M	A3	10:30	11:25	98	92	108	298
F114	L	A2	10:35	11:55	246	238	63	547
F115	L	A4	10:55	12:00	182	168	57	407
F116	M	A2	11:00	11:50	118	115	20	253

Note: L, M, and S represent large, middle, and small aircrafts, respectively. A1~A4 represent different airlines.

Table 2: Data of available gates.

Gate no.	Gate size	Distance to the baggage hall (unit: m)	Distance to the security check points (unit: m)	Distance to the transit counter (unit: m)	Average distance (unit: m)	Contact gate or remote stand
G001	M	150	245	215	203.3	C
G002	L	240	270	245	251.7	C
G003	M	220	260	230	236.7	C
G004	M	190	235	210	211.7	C
G005	L	135	170	115	140.0	C
G006	S	530	585	440	518.3	C
G007	M	520	580	425	508.3	C
G008	L	400	220	230	283.3	C
G009	L	920	960	975	951.7	R
G010	L	1000	1100	1050	1050.0	R

Note: L, M, and S represent large, middle, and small gates, respectively.

The paper uses Lingo 11.0 and selects Global Solver (Global optimization solve) and Global set strategy (Branching: Rel Violation; Box Selection: Worst Bound; Reformulation: High) to verify the effectiveness of models.

The paper uses Lingo to simulate the results of the random assignment, the objective function (2) (Z_1 optimal) and the objective function (3) (Z_2 optimal), respectively. The simulation result is shown in Table 3, where Z_1 and Z_2 represent the value of the objective function (2) and the objective function (3), respectively. The smaller Z_1 is, the shorter passenger walking distance is. The smaller Z_2 is, the fairer between airlines is. Q represents the proportion of passengers embarking/disembarking through aerobridge (referring to passing rate); the larger Q is, the more passengers embarking/disembarking through aerobridge are. S represents the overall average passenger walking distance. S_{A1}–S_{A4} represents the average passenger walking distance of four airlines, respectively. $S_{\max}$ represents the maximum difference of average passenger walking distance between airlines. (the unit of Z_1, S, S_{A1}–S_{A4}, and $S_{\max}$ is meters.)

With Table 3 and Figures 1 and 2, we can draw the conclusions.

(1) When Z_1 is optimal, the value of Z_1 is a minimum. It means that the total passenger walking distance is the shortest. The maximum value of Q is 1, which means the passing rate is 100%. But the difference of average passenger walking distance between four airlines is

Table 3: Comparison of simulation results between random assignment, optimization Z_1, and optimization Z_2.

Results	Z_1	Z_2	Q	S	S_{A1}	S_{A2}	S_{A3}	S_{A4}	S_{max}
Random assignment	2089750	0.238	0.831	410.1	351.1	351.9	461.2	507.6	156.5
Z_1 optimal	1244430	0.299	1.000	244.2	206.9	243.6	317.3	210.2	110.4
Z_2 optimal	2165555	0.003	0.800	425.0	423.8	424.4	426.1	425.7	2.3

comparatively large and the value of Z_2 (0.299) is also the largest; it means that the ration between the average and total passenger walking distance of airlines is large; the largest ration is approaching 30%.

(2) When Z_2 is optimal, the value of Z_2 is approximately zero and the average passenger walking distance of four airlines (Figure 2) is basically flat. That is, the gate assignment is the fairest. But the average passenger distance is 180.8 meters higher than the value of optimal Z_1. and the passing rate is only 80% (Q = 0.800), which is the lowest in the three simulation groups.

(3) The three values of Z_1, Z_2, and Q in random gate assignment are relatively concentrated. But compared with the value of optimal Z_1, the value of Z_1 in random gate assignment is high and the value of Q is low. Compared with the value of optimal Z_2, the value of Z_2 in random gate assignment is high. And the difference of average passenger walking distance between airlines is the largest, which is 156.5 meters. The gate assignment schedule is much unfair to airline A_4 because the average walking distance is larger than other airlines distinctly.

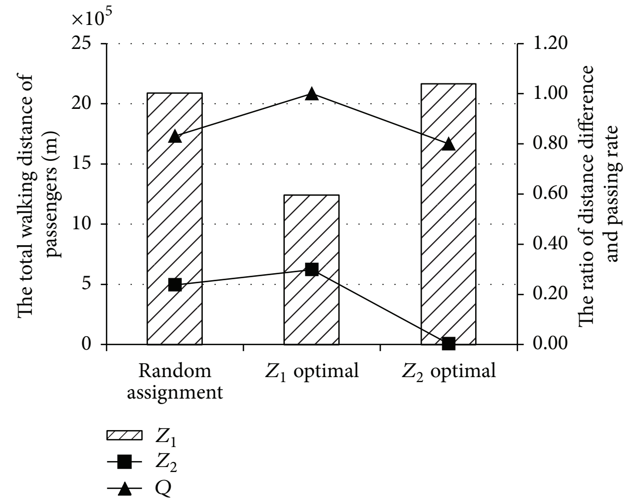

Figure 1: Comparison of Z_1, Z_2, and Q.

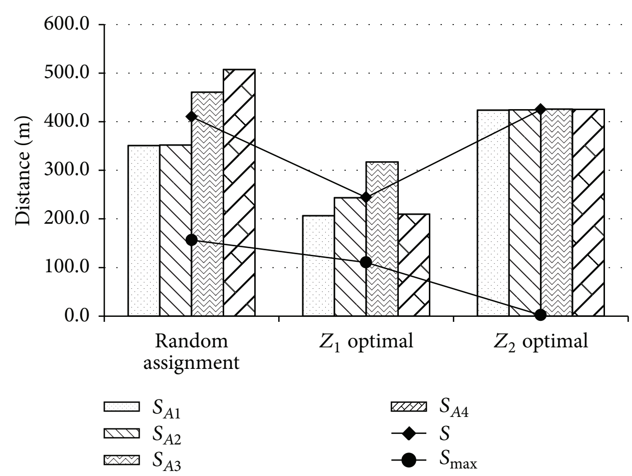

Figure 2: Comparison of S and S_{A1}–S_{A4}.

From the above simulation results, the three groups all have shortcomings. To find a set of ideal solution, the paper takes the objective function (2) as primary objective and transfers the objective function (3) into constraint. Assuming $Z_2 \leq 0.10$ and $Z_2 \leq 0.20$, the simulation results can be acquired (Table 4).

According to Table 4 and Figures 3 and 4, when the objective function (2) is the objective and $Z_2 \leq 0.10$, all the indexes of simulation are in the state of ideal according to the five group simulation results. Compared with the random gate assignment, the simulation result of $Z_2 \leq 0.10$ is as follows. (1) The total walking distance of passengers is 1,368,320 meters and decreases by 34.5%; (2) the passing rate is 96.4% and improves by 13.3%; (3) the total average passenger walking distance is 268.5 meters and decreases by 141.6 meters; (4) the simulation results show that it is relatively fair among airlines. The largest difference of average walking distance among airlines is only 20.3 meters; it is more inferior to the random gate assignment.

Flight Gantt chart of the random gate assignment and the situation of $Z_2 \leq 0.10$ are shown in Figures 5 and 6. Distribution of passengers and the average distance of gate are shown in Figure 7.

It is convenient for passengers to embark/disembark the aircraft through aerobridge because the distance is close and passengers will not be influenced by weather. The average distance from gate to baggage hall, security check, and transit counter is shorter; the total walking distance of passengers assigned to the gate is shorter. Thus the passenger will feel comfortable. We can draw the conclusions from Figure 5 to Figure 7: (1) the number of flights assigned to the remote stands (G009, G010) is only one, and this gate assignment schedule can improve the passing rate; (2) two flights are reduced to be assigned to gate which is near the remote stand; one flight is added to be assigned to G001, G003, G004, and G008 gate, respectively; (3) the gate, where the average walking distance is short, is assigned efficiently. Making

Table 4: Comparison of simulation results under five different conditions.

Results	Z_1	Z_2	Q	S	S_{A1}	S_{A2}	S_{A3}	S_{A4}	$S_{\max}$
Random assignment	2089750	0.238	0.831	410.1	351.1	351.9	461.2	507.6	156.5
Z_1 optimal	1244430	0.299	1.000	244.2	206.9	243.6	317.3	210.2	110.4
Z_2 optimal	2165555	0.003	0.800	425.0	423.8	424.4	426.1	425.7	2.3
$Z_2 \leq 0.10$	1368320	0.041	0.964	268.5	278.1	267.7	275.6	257.6	20.5
$Z_2 \leq 0.20$	1272690	0.199	1.000	249.7	204.0	252.0	222.5	299.3	95.3

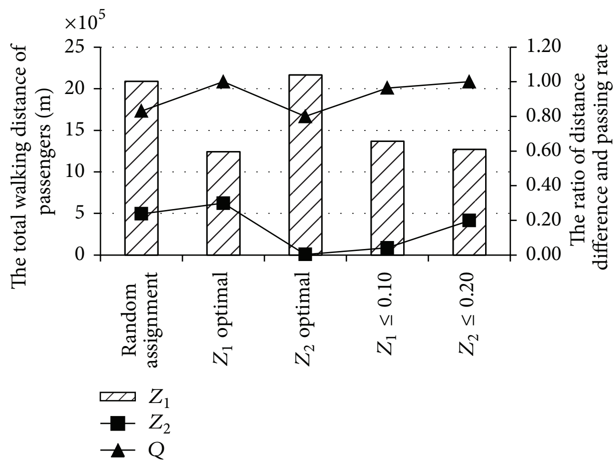

Figure 3: Comparison value of Z_1, Z_2, and Q in five groups.

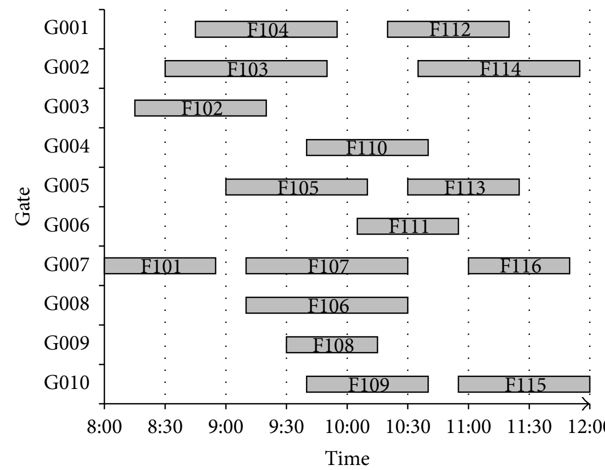

Figure 5: The flight Gantt chart of random gate assignment.

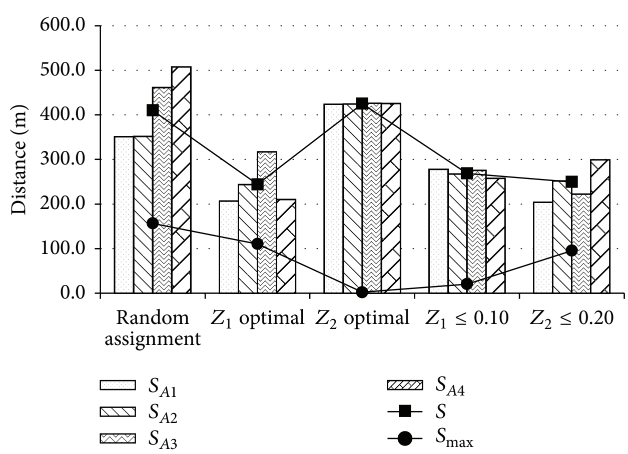

Figure 4: Comparison value of S, S_{A1}–S_{A4}, and $S_{\max}$ in five groups.

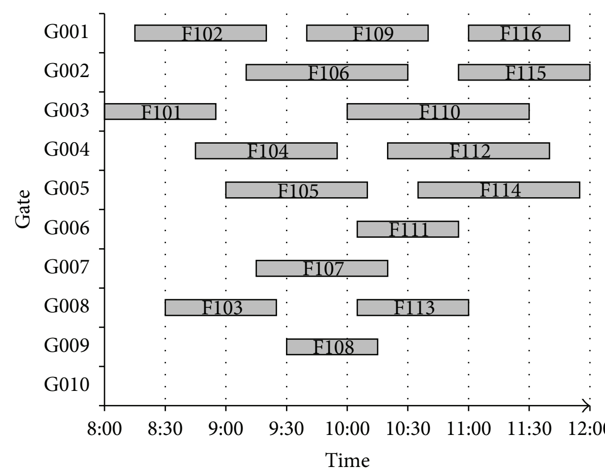

Figure 6: The flight Gantt chart of $Z_2 \leq 0.10$.

effective use of a gate can reduce the walking distance and improve the service level of passengers.

In summary, the simulation optimization results can not only reduce the average passenger walking distance effectively and improve passing rate, but also reduce the difference of average walking distance of passengers among airlines and enhance the overall passenger service quality of airports and airlines.

4. Conclusions

The paper presents a new idea for the airport gate assignment problem. Unlike the previous researches, it takes the restraint of passenger passing rate and airlines' fairness into account under the premise of airport safety operation. Combining with the objective of minimizing the whole passengers' walking distances, the paper builds a multiobjective optimization model of gate assignment. Lingo software is used to verify the effectiveness of model by simulating a large airport gate

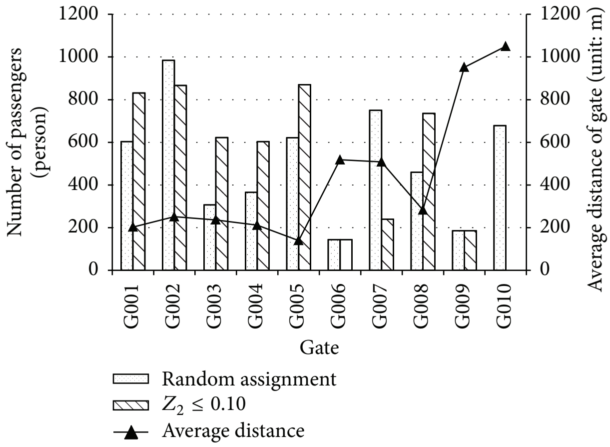

Figure 7: Distribution of passengers and the average distance of gate.

assignment. According to the test results, we can draw some conclusions.

(1) The assignment can ensure the passengers passing rate by setting (7).

(2) The two objectives are interactional between each other. And decision makers can get a set of suitable results by adjusting the value range of the second objective.

(3) Compared to the random assignment, this model can reduce the whole passengers' walking distances and improve the fairness between airlines at the same time.

(4) The research scope of the paper is only part of the domestic flights. How to combine with international flights and effective resource schedule should be further researched.

Acknowledgments

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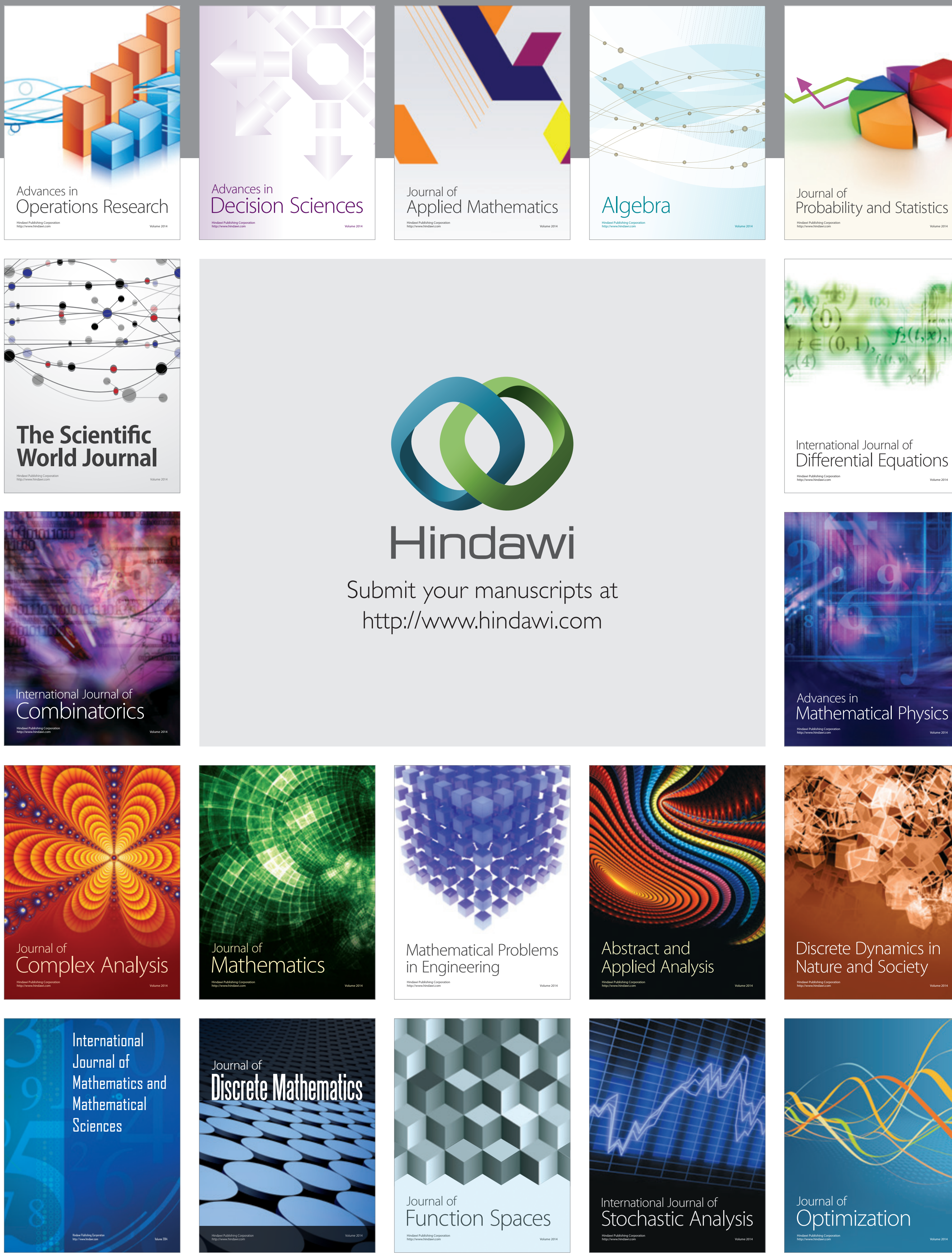
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