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Optimizing Airport Gate Assignment with Operational Safety Constraints

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Abstract—**This paper makes a comprehensive review of existing approaches and presents an optimization model for the airport gate assignment problem (AGAP) considering operational safety constraints. The main objective is to minimize the dispersion of gate idle time periods (robust assignment) while dealing with the problem of aircraft size mismatching with its gate type and avoiding the potential hazard caused by gate apron operational conflict. Genetic algorithm is adopted to solve the problem. An illustrative example is given to show the validity of the model and algorithm.**

Keywords-AGAP; operational safety constraints; robust assignment; mismatching; genetic algorithm

I. INTRODUCTION

Due to the tremendous growth of air traffic volume for the last decades, the yearly throughput of most hub airports in Europe has approximately increased more than twice as much as that of the previous stage in early 1990s [9]. As an overall trend in the world, the airport operators nowadays have to keep on facing the serious bottleneck situation based on the limitation of existing airport configuration and capacity, which will strongly affect the development of airport operation efficiency. However, in short term, it is impractical to increase the number of gates by redesigning the layout of current terminal buildings or simply enlarge the involving apron areas, not only because the gate is one of the most precious and expensive facilities in airport, but also the plan to expand existing airport is a very time-consuming procedure. Hence, with economic consideration, airport operators or terminal managers have to use the limited gates available at airport in a more appropriate way for daily operations.

Airport gate assignment is a key activity and static pre-planned strategy of airport operations in air traffic management (ATM). It involves the task of assigning a given set of flights from different airlines with normally specified arrival and departure times and other important information including the sizes and types of the serving aircrafts, the numbers of passengers, etc., to the fixed number of gates available at airport while satisfying some operational requirements and specific constraints [1], which is usually on the basis of one day, a week or even a month ahead of the scheduled flight slots and predictable weather report to ensure the success of flight services for each airline. Therefore, as a typical hub airport usually handles hundreds of domestic and international flights in each day [2], unreasonable assignments may result in flight delays, poor feedback of customer satisfaction, disproportion of gates utilization, surface congestion and safety issues with potential hazards caused by aircraft push-back or taxi conflicts near adjacent gate areas, and even extra cost of fuel for both arriving and departing aircrafts that may increase the exhaust emission as well, especially when the airport capacity is nearly saturated by its present configuration.

Apparently, as a combinatorial optimization topic, gate assignment problem is easy to understand but difficult to solve, because it cannot be accomplished independently without considering or dealing with a wide range of different resources running on the airport surface [2], including aircrafts, gates, gate facilities, and various types of service vehicles (cargo, food, fuel, de-icing vehicles and towing tug, etc.) of ground crews. Thus, any decision making for the usage of these interdependent resources will bring different degrees of influence on each section of the overall operation. Moreover, although the gate assignment problem is a static and predetermined operation, it has to handle some temporary changes (flight delays and emergency flights) and unexpected events (mechanical fault of aircrafts, manually operated errors and severe weather conditions) under the dynamic and uncertain environment of airport in the last-minute phase. For instance, a significant delayed arrival of one specific flight may generate a series of problems and lead to a ‘domino effect’ or traffic standstill throughout the whole corresponding sections of airport operations [3] and [7]. In this case, from the view of practical aspect, an optimal or more efficient gate assignment should be flexible for compensating the minor delays or temporary changes subject to the uncertainty. As mentioned above, it is clear that AGAP is more complicated than many traditional scheduling problems to some extent because it needs high level of evaluation on decision making in order to achieve multiple objectives and simultaneously improve the smooth operation performance by considering various factors.

The paper is organized as follows: First of all, a literature review is presented in the next section. In Section 3, a formal description of the problem and a corresponding formulation will be provided. The basic idea of the genetic algorithm used to solve the problem is introduced in Section 4. In Section 5, the significance and influence on whether considering the safety issues of AGAP or not is discussed and demonstrated using an illustrative example. Finally, a conclusion is given in Section 6.

II. LITERATURE REVIEW

In previous research, many mathematical models and techniques have been developed with different objectives and corresponding realistic rules and restrictions (either hard or soft) in AGAP. A basic version is modelled as a quadratic assignment problem and proved to be NP-hard [21]. For a comprehensive review, the original objectives of AGAP can be classified into either passenger-oriented or airport-oriented [6]-[13]. On the purpose of increasing passengers' satisfaction, AGAP are mainly focusing on minimizing the total walking distance of all the passengers for both arriving and departing aircrafts and the number of flights assigning to remote apron stand (un-gated area far away from the terminal building). On the contrary, the airport-oriented objectives in AGAP concentrate on improving gate utilization and the ability of robust assignment in dealing with the problem of sudden changes or stochastic flight delays.

A. Minimizing the Total Passenger Walking Distance

As the first attempt, Braaksma and Shortreed [5] use quantitative analysis method to describe and simulate the problem of minimizing passenger walking distance with critical path. Babic et al. [4] propose a 0-1 binary integer programming model and use the branch and bound framework to solve the problem, but the component of transferring passengers is not included. Later, Mangoubi and Mathaisel [19] take into account transferring passengers' walking distance based on the previous model. In addition, they also try to convert this model as a mixed integer programming (MIP) problem and solve it by using linear programming relaxation and greedy heuristic methods. After that, another consideration of minimizing the un-gated flights has appeared [6] [10]. However, the basic model with objective of minimizing the overall walking distance (distance between check-in counter and boarding gate; disembarking gate and baggage claim; two flights for transferring passengers) has been generated and become more mature and fixed. Thus, due to these combined factors, other researchers then turn to focus on using different methodologies to improve the computational efficiency of the same problem. For example, Xu and Bailey [10] present their mixed 0-1 quadratic assignment model and solve it using tabu search algorithm. Similarly, there are some discussions about the performance of meta-heuristic algorithms applied widely in AGAP [2]-[6]. Ding et al. [6] use simulated annealing (SA) and tabu search (TS) by considering the over-constrained element of assigning aircrafts to remote apron stand with similar model in [10].

B. Robust Gate Assignment

Unexpected disruptions including early or late arrivals and late departures in AGAP have a major impact on the smooth performance of pre-determined plan indeed. Therefore, instead of using inherent random input parameters to represent the stochastic disruptions, some concepts of generating robustness of gate assignment are proposed in literatures [16]-[18], such as idle time, buffer time, gate conflict, etc. Mangoubi and Mathaisel [19] state that if only considering minimizing the total passengers walking distance in real-time gate assignment problem, then the highly utilized gates may have the weakest performance on absorbing the early or late arrival aircraft, which may also lead to the gate conflict problem for every flight pre-assigned to the same gate with estimated gate occupation time. Yan and Chang [20] also argue the importance of adding a buffer time between flights into the model to demonstrate that it is useful in improving the punctuality of robust schedule between the two consecutive flights assigning to the same gate. Alternatively, Bolat [18] considers the objective of minimizing the variance of the idle time. The purpose of his approach is to improve the possibility of uniform distribution for gate utilization, while maintaining the robustness in gate assignment problem at the same time. Later, Lim et al. [6] propose the proportional penalties for the delayed flights which are not available to be assigned to the original position in a specific time window.

C. Other Approaches

Different from the most common objectives, other approaches also bring some new ideas of traditional gate assignment problem. Cheng [13] first defines push-out conflict and considers relevant influence on ground movement near gate apron area in the AGAP with objective of minimizing the delays, based on the network simulation results. With the inspiration of his achievement, some following works also consider avoiding the potential hazard in push-back conflict. Some other researchers [12]-[14] point out that there is rare attention on improving both safety and efficiency by comparing the existing studies of multi-objective optimization problem in AGAP. Then, Kim et al. [14] present a simulation model to predict and reduce the operation time in order to minimize the ramp congestion. Moreover, Atkin and Burke [11] and Newman and Atkin [15] demonstrate that the major problem of this push-back conflict will affect the further step of taxi operation in ATM by various test data and they also evaluate the final allocation results by introducing a novel towing constraint which can solve the problem of ground movement conflicts.

III. PROBLEM DESCRIPTION AND FORMULATION

According to the definition of push-back conflict by previous study, we try to expand the condition of conflicts in three types: conflict between push-back and taxi-in, conflict between taxi-in's, and conflict between push-out's.

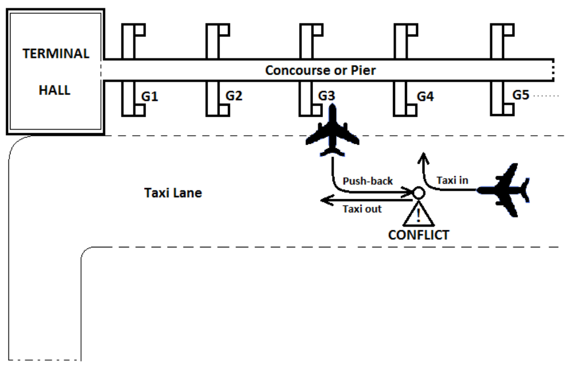

Figure 1. Conflict between push-back and taxi in

In Fig. 1, there is an overlapping ground movement time between two aircrafts that are assigned to adjacent gates 3 and 4. In this case, a high potential of conflict will happen by the simultaneously operation for both the arriving and departing aircrafts. This condition is obviously not allowed in our optimization model.

Similarly, the other two types of conflicts will also bring the hazards of collision to disturb the smooth operation and original gate assignment plan. An incident is considered an accident when there is a loss of life or severe damage. Normally, there were no casualties of passengers reported in the conflicts between the push back and taxi in aircrafts, because the speed restrictions will limit the operation of aircraft taxiing or being towed on airport surface. However, this kind of low speed collision will bring tremendous cost of aircraft damage, and of course it might be blamed on the carelessness and incorrect operation of assistant operators from ground crew. After all, the major reason will be exposed by the effects of improper gate assignment section. If no two aircrafts are assigned to the very closed, two adjoining gates for taxiing concurrently, then the possibility of potential hazards in push-back conflicts will be reduced markedly.

A. Notations and Constraints

From most of the former studies [2]-[3], the classic constraints can be recognized as either hard or soft (particular airport layout, airline specified gate area, priority of gate occupation for emergency flight, etc.). Normally, there are two hard constraints, but in this paper, we also consider the safety constraints as a hard one.

- Every flight must be assigned to one and only one feasible gate.
- No two flights with overlapping gate occupation times are assigned to the same gate simultaneously (gate conflict avoidance).
- No two flights with overlapping taxi-in or push back times are assigned to the adjacent gates (aircraft conflict avoidance).

The notations we use for formulating the AGAP are shown as follows:

N: the set of flights arriving at and/or departing from airport per day;

M: the set of gates available at airport;

A_j: arriving time of flight *j;*

D_j: departing time of flight *j;*

α: minimum conflict avoidance time;

β : buffer time between two consecutive flights assigned to the same gate;

S_{ik}: the idle time of gate k before flight *i*;

u_i: parameter indicating the type of flight *i*;

$u_i = 1$ if it denotes the large flight, else $u_i = 0$.

v_k: parameter indicating the type of gate *k*;

$v_k = 1$ if it denotes the large gate, else $v_k = 0$.

w_{ik}: 0-1 indicator variable for mismatch between flight type and gate type;

$w_{ik} = 0$ if the small or middle type of flight *i* is assigned to small type of gate *k*, or the large type of flight *i* is assigned to large type of gate *i* (i.e. $u_i = v_k$);

$w_{ik} = 1$ if the small or middle type of flight *i* is assigned to large type of gate *k* (i.e. $u_i < v_k$);

The mismatch of $u_i > v_k$ is strictly forbidden here. Because we stipulate that large type of flight cannot be assigned to small type of gate.

x_{ik}: 0-1 decision variable;

$x_{ik} = 1$ if flight *i* is assigned to gate *k*, else $x_{ik} = 0$.

z_{ijk}: 0-1 indicator variable;

$z_{ijk} = 1$ if both flight *i* and flight *j* are assigned to gate *k*, and flight *i* is followed by flight *j*, else $z_{ijk} = 0$.

z_{0jk}: flight *j* is the first flight assigned to gate *k*;

T: the fixed close time of all gates after daily utilization;

F_k: the departure time of the last flight of each gate.

B. Objective Function and Model Formulation

The main objective is minimizing the dispersion of idle time periods on the basis of solving mismatching problem between flight size and gate type and considering safety issues as the hard constraint as well. The original objective function can be denoted as

$$\sum_{k=1}^{|M|}\sum_{i=1}^{|N|}(S_{ik}-\bar{S})^2$$

Since the total available time of gates and the ground time of flights are known as a constant, whereas the specific slack time for each gate is independent of the way that flights are assigned, but the total idle time for all available gates at airport in one day is fixed as well. In this case, the function $\sum_{k=1}^{|M|}\sum_{i=1}^{|N|}S_{ik}^2$ can be used as a surrogate.

In general, there should be an immediately preceding idle time before each aircraft arrives. While for each gate, the final idle time of a day should be considered as well, which usually refers to the duration between the last aircraft leaves or being towed away for maintenance and the close of gate. In a word, the overall number of idle times can be concluded as $|\mathrm{N}| + |\mathrm{M}|$.

Therefore, the objective function of the variance of idle times can be formulated as follows:

$$min \quad F = \sum_{k=1}^{|M|}\sum_{i=1}^{|N|}S_{ik}^2 + \sum_{k=1}^{|M|}(T-F_k)^2$$

The related constraints are illustrated as follows:

$$\sum_{k\in M} x_{ik} = 1, \ \forall i \in N \tag{1}$$

$$x_{ik} + x_{jk} \le 1, \tag{2}$$

$$if \quad (D_j - A_i)(D_i - A_j) > 0,\ \forall i,j \in N,\ \forall k \in M$$

$$\sum_{k \in M} \sum_{i \in N \cup \{0\}} z_{ijk} = 1, \forall j \in N \quad (3)$$

$$x_{ik} + x_{jk} - 2z_{ijk} \geq 0,\ \forall i,j \in N,\ \forall k \in M \quad (4)$$

$$x_{jk} - z_{0jk} \geq 0,\ \forall j \in N,\ \forall k \in M \quad (5)$$

$$A_j - D_i \geq \beta z_{ijk},\ \forall i,j \in N,\ \forall k \in M \quad (6)$$

$$(v_k - u_i)x_{ik} \leq w_{ik},\ \forall i \in N, \forall k \in M \quad (7)$$

$$\sum_{i \in N} \sum_{k \in M} w_{ik} \leq w_0 \quad (8)$$

$$S_{ik} \leq A_j - D_i z_{ijk}, \forall i,j \in N,\ \forall k \in M \quad (9)$$

$$S_{ik} \geq A_j z_{ijk} - D_i z_{ijk}, \forall i,j \in N,\ \forall k \in M \quad (10)$$

$$F_k \geq \sum_{i \in N} D_i\, x_{ik},\ \forall k \in M \quad (11)$$

$$\begin{cases} |D_i - D_j| \geq \alpha x_{ik} x_{j,k+1} \\ |D_i - A_j| \geq \alpha x_{ik} x_{j,k+1} \\ |D_j - A_i| \geq \alpha x_{ik} x_{j,k+1} \\ |A_i - A_j| \geq \alpha x_{ik} x_{j,k+1} \end{cases}, \forall i,j \in N,\ \forall k, k+1 \in M \quad (12)$$

$$x_{ik}, z_{0jk}, z_{ijk}, w_{ik} \in \{0,1\},\ \forall i,j \in N,\ \forall k \in M \quad (13)$$

$$S_{ik}, F_k \geq 0, , \forall i \in N,\ \forall k \in M \quad (14)$$

Constraints (1) indicate that every flight must be assigned to only one gate. Constraints (2) ensure that one gate can serve at most one aircraft at a time. Constraints (3) and (4) give an exact description of variable z_{ijk}. Constraints (5) define z_{0jk} variables for the special case where a flight is the first one allocated to a gate. Constraints (6) stipulate that there must a buffer time between the departure of a flight and the arrival of the next flight assigned to the same gate. Constraints (7) define the mismatch between flight type and its gate type. The total mismatch can be minimized as an objective. In this paper we limit the number of mismatches in constraint (8). Constraints (9) and (10) calculate the idle time of each gate before each flight. Constraints (11) obtain the departure time of the last flight of each gate, which is used to calculate the last idle time of each gate in the objective function. Constraints (12) guarantee the minimum time between the arriving and departure of two flights assigned to the adjacent gates to avoid conflict. Constraints (13) and (14) are binary and non-negativity constraints for the variables.

IV. SOLUTION METHOD

As seen from literature review, both exact and heuristic methods have been proposed to find the optimal or near-optimal solution for improving the operation performance. In general, exact algorithms are particularly applicable for solving the small scale problems. For example, using branch and bound algorithm [4]. However, as a matter of fact, in most of the major city airports, there are usually over 50 gates available for scheduling daily [2], In this case, traditional exact methods are unable to solve the realistic problems effectively due to the large problem sizes. Therefore, most of the previous research solves the AGAP using meta-heuristic methods (genetic algorithm, tabu search, simulated annealing, swarm intelligence and their hybrid approaches). As an attempt, we use genetic algorithm to solve the problem and check the effect of adding safety constraints to the original gate assignment problem. Generally, GA has better performance on global searching and we expect it to be effective for this problem.

A. Chromosome Coding and Initialization

Using an integer string to present the chromosome is a direct way to express the flight-to-gate relations. The length of the string is |N| and each bit corresponds to a flight, while the specific number in that gene bit refers to the gate number this flight assigned to. For example, the string $\boxed{5164532}$ represents a solution of assigning seven flights to six gates successively, where flight 1 and flight 5 are both assigned to gate 5.

The genetic algorithm maintains a population of chromosomes or individuals for each generation. Each chromosome represents a solution to the problem at hand. The first step of GA is creating an initial set of solutions. The solutions in the initial population are generated randomly to ensure diversity. Solutions generated this way may be infeasible because AGAP is highly constrained. In the process of generating the initial population, infeasible solutions are discarded.

B. Genetic Operations

a) Selection: Selection provides the driving force in a genetic algorithm. The game method is adopted as the selection operator, such that chromosomes with better fitness (objective) will have higher chance to be selected. Using this method two chromosomes are selected each time to produce offspring through crossover and mutation for the next generation. Repeating the progress P times, we will obtain a new population with P chromosomes. By preventing the good chromosomes to be destroyed at crossover and mutation, some best chromosomes as the substitute of those worst chromosomes of offspring population. Of course, the number of best chromosomes is comparatively small to prevent them to dominate the selection process.

b) Crossover: Crossover and mutation are common GA operators. Crossover Operates on two chromosomes at a time and generating offspring by combining both chromosomes' features. One-cut point method crossover is adopted in the paper. A random point i is first generated where $i < N$. Then the parts to the right of bit i of the two parents are exchanged to generate offspring. Those two offspring chromosomes may be infeasible, so a checking and modifying process is promoted as follows. For the child chromosome f, whose cut point is i. Because those genes before it are feasible, then checking begins from $i+1$. For the gene $i+1$ (flight $i+1$): first get the present condition of gates; and then check if the gate assignment of the current flight is feasible or not; if feasible then turn to next gene; if not, reassign a gate for it and update the condition of gates; then turn to next gene.

c) Mutation: The general mutation will not be used in the AGAP. A random exchange method is adopted to implement the operator. Two genes are randomly chosen from the chromosome and their values are exchanged to obtain a muted chromosome. In case it is infeasible, the checking and modifying method is applied as described above.

V. TESTING RESULTS

Table 1 shows the test example data containing 40 flights are assigned to 10 gates (6 large gates and 4 small gates) and an extra un-gated apron stand in one day operation between AM 8:00 and PM 8:00. However, as an initial stage, the case of over-constrained problem is not considered in this paper, which means we assume that the gate resources are enough for the assignment. At present, our model is basically focusing on the airport-oriented part while in the practical application of ATM, sometimes the remote apron stand is also well in use. However in many other literatures, e.g., [6] and [10], un-gated area is regarded as just one point for minimizing utilization rather than considering it with its own configuration. In this way, the point of un-gated apron stand should be taken into account more seriously and comprehensively.

TABLE I. FLIGHT DATA INFORMATION

Flight number	Arriving time (min)	Departure time (min)	Type of flight
1	0	55	M
2	8	72	L
3	24	96	L
4	35	110	M
5	48	108	M
6	66	135	M
7	87	152	L
8	104	164	S
9	115	182	L
10	137	191	M
11	144	210	M
12	156	227	M
13	160	220	L
14	168	225	M
15	168	253	L
16	183	302	L
17	192	278	M
18	224	289	L
19	230	295	M
20	252	309	S
21	268	348	M
22	276	385	L
23	293	359	M
24	320	387	M
25	332	395	L
26	347	402	M
27	360	429	S
28	369	435	L
29	384	447	M
30	411	480	M
31	425	489	M
32	436	500	S
33	461	543	M
34	489	540	M
35	495	599	L
36	535	620	M
37	528	599	M
38	550	645	M
39	560	677	L
40	620	700	L

The buffer times are chosen as $\alpha = 5$ and $\beta = 15$ minuets respectively. The parameters of GA are set as follows:

Population size: 20

Crossover probability: 0.9

Mutation probability: 0.05

Maximum generation: 200

The results of flight-to-gate assignment with and without considering the safety constraints are presented in Fig. 2 and Fig. 3, respectively. According to the test data, flights 35 and 37 have extremely overlapping ground movement time. In Fig. 2, these two flights are assigned to the adjacent gate 2 and 3 without considering safety constraint: the deviation of the same departure time is obviously smaller than the minimum conflict avoidance time α. The results also show another potential hazard of push-back and taxi- in conflict between flights 31 and 34 with extremely overlapping ground movement time at 489. Similarly, this kind of conflict sometimes happens on the assignments of flight 6 and 10, flight 18 and 23, flight 10 and 17, and flight 23 and 27 as well, based on their specific overlapping arriving or departing times shown in the table above.

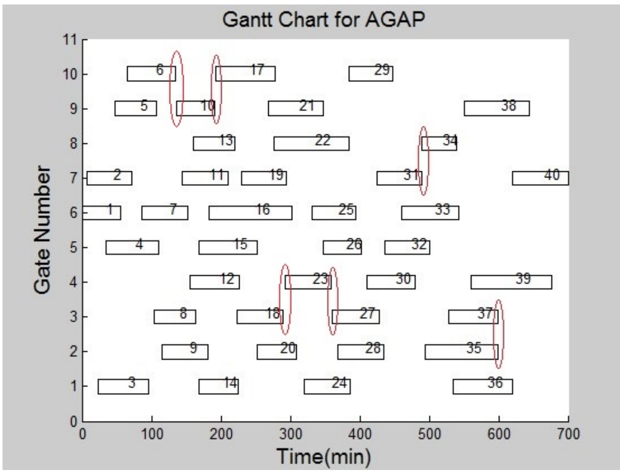

Figure 2. Gantt chart of gate assignment without safety constraints

The result in Fig. 3 has avoided flight conflict by the strict forbidden constraints: no two flights with overlapping ground movement times can be assigned to the adjacent gates. We can notice that because of this constraint, the gate assignment of many other flights is also different.

Due to the scale of test data set, it is worth noting that accompanying with the objective function in Fig. 4, the line curve of population mean value has declined quickly. Moreover, the solution shows that it will be convergent after approximate 10 iterations.

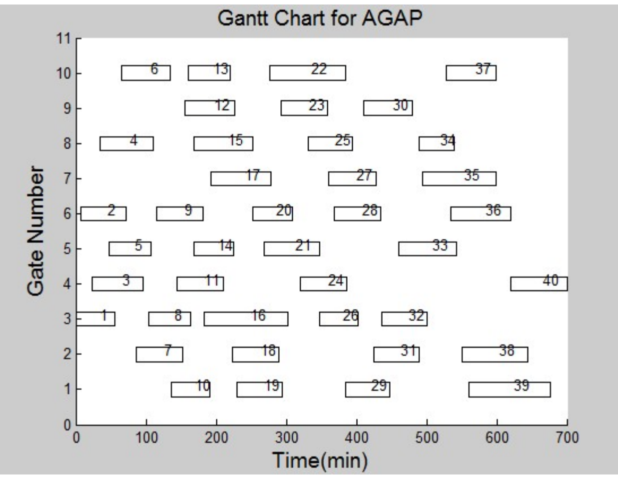

Figure 3. Gantt chart of gate assignment with safety constraints

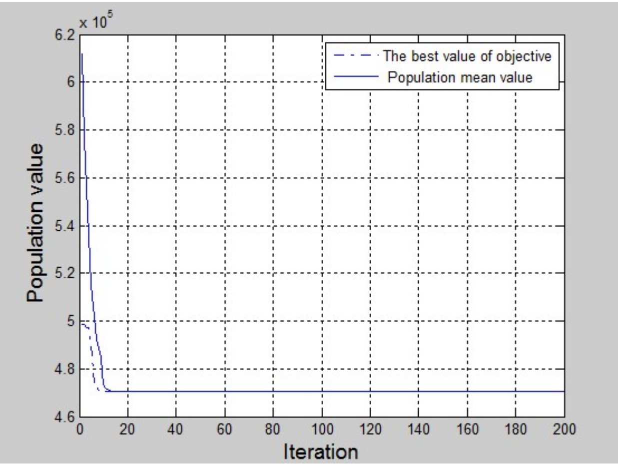

Figure 4. Output the optimal solution

VI. CONCLIUSION

In this paper, we have studied airport gate assignment problem and formulated a model by embedding the safety constraints. The objective function of robust assignment was considered to minimize the dispersion of idle time periods. Genetic algorithm has been used to solve this gate assignment problem. Moreover, the illustrative example is used to show the running of algorithm and the effect of the safety constraints. It is worth noting that the solution space can be decreased due to the existence of safety constraints. In this case, the next major phase of work will turn to solve the problem with operational safety constraints under the over-constrained scenario. Moreover, future work will also focus on multi-objective optimization combining different two or three objectives together based on the decision making preference. Another major work is the dynamic approach with operational safety constraints, i.e., real-time reassignment to deal with the flight delays or temporary changes.

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