Arrival and Departure Scheduling at Hub Airports Considering Airlines Level

A. Nourmohammadzadeh, and R. Tavakkoli- Moghaddam

Abstract—As the air traffic increases at a hub airport, some flights cannot land or depart at their preferred target time. This event happens because the airport runways become occupied to near their capacity. It results in extra costs for both passengers and airlines because of the loss of connecting flights or more waiting, more fuel consumption, rescheduling crew members, etc. Hence, devising an appropriate scheduling method that determines a suitable runway and time for each flight in order to efficiently use the hub capacity and minimize the related costs is of great importance. In this paper, we present a mixed-integer zero-one model for scheduling a set of mixed landing and departing flights (despite of most previous studies considered only landings). According to the fact that the flight cost is strongly affected by the level of airline, we consider different airline categories in our model. This model presents a single objective minimizing the total sum of three terms, namely 1) the weighted deviation from targets, 2) the scheduled time of the last flight (i.e., makespan), and 3) the unbalancing the workload on runways. We solve 10 simulated instances of different sizes up to 30 flights and 4 runways. Optimal solutions are obtained in a reasonable time, which are satisfactory in comparison with the traditional rule, namely First-Come-First-Serve (FCFS) that is far apart from optimality in most cases.

Keywords—Arrival and departure scheduling, Airline level, Mixed-integer model

I. INTRODUCTION

AIR traffic has experienced a major increase in the world during the last decade. It can be resulted from growing air transportation demands (i.e., passenger, cargo) because of its comfort, foundation of new airlines, more advertisement for air travels, and the like. According to global traffic forecast executed by Airports Council International (ACI), this increase of the total passenger and freight traffic is going to continue to reach over 9 billion passengers and 214 million tons by year 2025 [1]. Figure 1 depicts this forecast for the total annual passengers and freights following the data of the previous years.

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(a) Annual passengers (million)

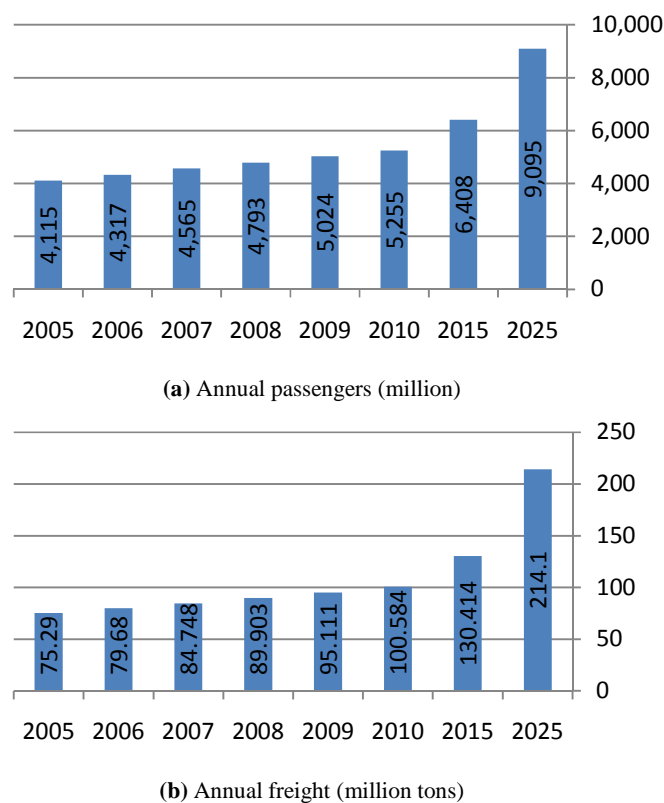**(b)** Annual freight (million tons)

Fig. 1 Forecast for the total annual passengers and freights

It is clear that by such rising in amount of passengers and cargo, the number of flights, which meet airports to land or depart, increase simultaneously. This phenomena result in congested airports. The reason is that airports facilities (e.g., runways, taxiways, gates and terminals) are limited resources and have a bounded capacity. The most critical resources in an airport are runways because building new runways at existing airports is not simply possible due to environmental, financial and geographical constraints. Therefore, devising an appropriate method for scheduling flights, which are going to depart or land on airport runways, is of great importance and the main scope of this paper.

The final result of such a schedule determines for each flight a suitable runway, departing or landing time on the chosen runway and gives for each runway its appropriate sequence of flights.

As a landing aircraft enters the radar range of an airport, the aircraft's flight number, altitude and speed are transmitted to controllers in the air traffic control tower [9]. Based on this

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obtained information the controllers consider a time window for the aircraft to land within it. This time window consists of a lower bound called, the earliest time defined as the time the aircraft can land on the runway if it flies at its maximum airspeed and an upper bound called the latest time, defined as the time the aircraft can land on the runway if it flies at its most fuel efficient airspeed while holding for the maximum allowable time. Each landing aircraft has also a preferred or target time, that is the time the aircraft can reach the runway if it flies at its most economical, preferred speed, referred to as the cruise speed [2], [9], [12]. These times can be defined for a departing aircraft in a similar way. Such that the earliest time is the time when the aircraft can take off if it becomes embarked and directed to the runway as quick as possible, the latest time is the time when the aircraft can take off if it becomes embarked and directed to the runway as late as possible and with maximum holding, and finally the preferred or target time is the time when the aircraft reaches the take off runway if it becomes embarked and directed to it at the time, in which no extra cost incurs. It is obvious that if the aircraft scheduled to land or depart before or after its target time, the extra cost will incur. This cost increases as the difference between assigned time and the target time grows.

An airport is used by different airlines. Some airlines are the home carriers, which have large number of flights and transfer passengers. At some airports home carriers have private facilities even their own terminal to make comfort for the passengers using them. Flights operating by these airlines have higher priority to schedule near to their target times as much as possible. This is because of several apparent reasons, such as having large number of transfer passengers, which may lose their connecting flights or have to wait for extra time to get on them, or often these carriers belong to the country the airport located in and so much attempt is made to protect them to absorb more passengers and gain larger revenue. The other category are usual airlines, often belonging to other countries, they may have also transfer passengers but much fewer than home carriers. Therefore, the priority for this category of airlines is smaller than the first one or hub owners. The third category of airlines using the airport is a group of carriers that operate low price or charter flights. These airlines have approximately no transfer passengers, and deviating them from targets is not so important. Hence, they have the smallest priority in scheduling.

The crucial task of air controllers is to ensure safety on the runways. This can be achieved respecting an elapsing time between two successive flights using a same runway because all aircrafts create wake vortices at the back of themselves. These vortices have a chaotic evolution and can cause serious turbulence to a closely following aircraft; even it can cause a crash [2], [12]. This elapsing time is refereed as the separation time between two aircrafts that depends on several elements, such as the type of the leading and following aircrafts or environmental conditions. The separation times are the most critical limiting factors that reduce the capacity of runways [9].

The problem of scheduling landing and departure flights can have different objectives, often used separately by the previous studies carried out in the literature. The objective function used widely is to minimize the sum of deviations (or weighted deviations) of all flights [2], [3], [9-10], [12-13]. By this work, we enter the airline category or level of the flight into this objective to come closer to a real situation. Another objective applied much fewer [4], [6] is to minimize the time required all flights to be done (land or depart) or the time of the last flight, which is known also as makespan by scheduling problems. It is totally clear that if we reduce this time the constant cost imposed to airport for the corresponding set of aircraft also decreases. The other objective considered by the current study is to balance the workload between all runways. If we construct new runways but they are not be used as much as we investigate them or accumulate most of flights on a few number of runways, it yields the cost in the system. Hence, we take the objective of minimizing the unbalancing of the runways. These objectives will be further explained clearly in Sections III and IV. Now, we have three objectives and for the sake of simplifying the problem considering a weight for each one related to the importance of it. Schedulers can choose alternatively these weights according to significance that they have assumed for each of the above-mentioned objectives.

II. PREVIOUS LITERATURE

Most of the previous studies are concentrated in scheduling only the landing and considering just one objective (often sum of deviations from targets). The previous papers can be categorized by different aspects. However, we review them in terms of their solution methodologies, which can be either exact or heuristic methods. Exact methods are based on predetermined fixed structures rather than random or probabilistic selection. They start from an initial solution and try to reach a better one by each new iteration so the final solution is always the same (i.e., the same solution obtained running them for each time). On the other hand, heuristic methods are based on making random or probabilistic changes in the solution in each iteration to obtain maybe a better solution in the next iteration. Therefore, they result in different final solutions by each time, running them which are appropriate if they fall near to the optimal solution.

A. Exact Methods

Models proposed by Beasley *et al* [2] are widely used by researchers. The problem of scheduling landings is considered and a mixed-integer zero-one formulation for the single runway case is presented and extended to a multiple case. They strengthen the linear programming relaxations of these formulations by introducing additional constraints. Moreover, they discussed how the formulation can be used to model a number of issues emerge in practice. This problem is solved optimally using linear programming based tree search. The computational results were presented for a number of test problems. Bojanowsky *et al* [4] considered a multiple runways problem with the goal of minimizing the total landing time (i.e., makespan). They presented an algorithm, which provides

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a polynomial-time feasibility condition. Xiangwei *et al* [13] presented a mixed-integer formulation based on the previous literatures originally proposed by Beasley *et al* [2]. A sliding window method is applied for solving the given. The sliding window algorithm divides the time into equal segments and considers a number of the segments to use information within it, but only scheduled the times assigned to aircraft within the specific segment by each iteration.Wen [12] proposed again a mixed-integer model based on Beasley *et al* [2]. A branch and price exact algorithm which was the combination of column generation and the branch and bound algorithm is used for solving the model. It was the first attempt to develop such an algorithm for aircraft land scheduling problem. The branch-and-bound method was developed to find the optimal integer solution for the problem. The total branch and price algorithms is implemented and tested with instances up to 50 aircrafts and 4 runways. Sharma [11] presented a problem of assigning the scheduled times of arrival to the aircraft such the separation time between two successive aircraft, which land on a single runway and the time windows were followed. Under these constraints, the total delays of aircraft at the single runway are to be minimized. The problem is solved optimally using the GAMS/CPLEX software.

B. Heuristic Methods

Beasley *et al* [2] also presented a heuristic, which is a

are implemented. The computational results are presented showing that feasible solutions of good quality can be produced relatively quickly. The results indicated that the bionomic algorithm outperformed the scatter search for the non-linear objective. However, on the other hand for the linear objective, that is totally vice versa. Capri *et al* [5] presented a new innovation for air traffic scheduling problem considering the departing flights into the aircraft sequence. A dynamic model is setup to take account of time-varying variables, and a specific genetic algorithm was used to solve the aircraft sequencing problem. Hansen *et al* [7] aimed to develop a solution procedure based on a genetic local search (GLS) algorithm for solving the ALP with runway dependent attributes. The objective function was to minimize the total delays. Zhan *et al* [14] applied for the first time the ant colony optimization (ACO) algorithm to land scheduling problem. This algorithm was applied with the aim of receding horizon control techniques (RHC) and suitable results were obtained.

At the end of this section, we compare our paper with other previous studies to make the contribution of this paper more clear. Table I shows this comparison in terms of different characteristics.

TABLE I
COMPARISON OF CHARACTERISTICS OF THE PREVIOUS
STUDIES AND THIS PAPER

	Flight	Runway	Objectives (to be minimized)	Solution methodology
Beasley *et al* [2]	Landing	Single, multiple	Sum of deviations	Exact and heuristic
Beasley *et al* [3]	Landing	Single	Sum of squared deviations	Heuristic
Bojanowsky *et al* [4]	Landing	Multiple	Makespan	Exact
Capri *et al* [5]	Landing and departing	Single	Sum and maximum of delays	Heuristic
Harikiopolo *et al* [6]	Landing	Single	Makespan	Exact
Hansen *et al* [7]	Landing	Multiple	Sum of delays	Heuristic
Yu-Hsin Liu *et al* [8]	Landing	Multiple	Sum of delays	Heuristic
Pinol *et al* [9]	Landing	Single	Sum of (also squared) deviations	Heuristic
Soomer *et al* [10]	Landing	Single	Sum of deviations	Heuristic
Sharma [11]	Landing	Single	Sum of delays	Exact
Wen [12]	Landing	Multiple	Sum of deviations	Exact
Xiangwei *et al*[13]	Landing	Multiple	Sum of deviations	Exact
Zhan *et al* [14]	Landing	Single	Sum of delays	Heuristic
This paper	Landing and departing	Multiple	Sum of deviation+makespan+unbalance	Exact

version of FCFS, modified for multiple runway cases. It sorts the aircrafts according to ascending targets and then begins to search on runways for a runway with minimum cost to assign the aircraft to it. By this method, all the flights are assigned at or after their targets.

The use of evolutionary heuristics become recently common due to the complexity of large-sized air traffic scheduling problems [3], [5], [7-9], [14]. Pinol *et al* [9] considered the multiple runway case of the static aircraft landing problem. A mixed-integer zero-one formulation is used with two different objective functions, once linear and the other time non-linear one. The two population heuristic techniques, namely scatter search and bionomic algorithms,

III. PROBLEM DESCRIPTION

In this section, we return to the concepts in the introduction section to give additional problem specific explanation and make them more understandable.

As mentioned before, we consider a set of aircrafts (flights) to be of both landing and departing status. A main question here is that what the differences between scheduling parameters of a landing and departing flight are. A landing flight is in the air by the earlier step, so forcing it to reach the runway sooner or later than predetermined target time yield much extra cost than a departing flight that stand just at a gate or on a taxiway. Moreover, a departing aircraft has a smaller flexibility to be scheduled before its target because the planning at airports is so, that the aircraft cannot be embarked

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much sooner that the determined target. On the other hand, the departing flight has larger flexibility to be delayed and scheduled after its target than a landing one. Hence, we consider a time window with a target approximately in the middle of it for a landing flight, but a wider time window with a target near to the lower bound (earliest time) for a departing flight. The cost of each flight by different scheduled times can be considered as a function. Figure 2 depicts this function for landing and departing flights.
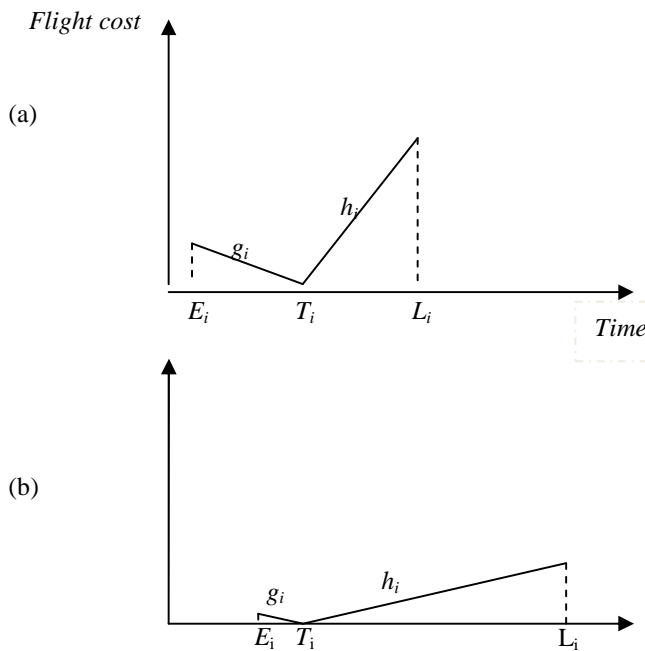

Fig. 2 (a) Cost function of a landing flight, and (b) Cost function of a departing flight, where
E_i: earliest time of flight i; T_i: target time; L_i: latest time
g_i: earliness cost per unit; h_i: delay cost per unit

As we know, delaying a flight annoys passengers and airline so much, but also earliness of a flight can yield cost for airline and airport, although it is not so bothering for passengers or even provide more pleasure for them. Therefore, we consider larger penalty (cost) per a unit of delay than a unit of earliness. Comparing g_i and h_i in Figure 2 also demonstrates this fact.

The other fact, which affects the flight cost and should be embedded in the cost function, is the type of airplane operated the flight because a larger aircraft has more passengers, so deviation of it causes higher disturbance. In this paper, we consider three types of aircrafts like most of the previous studies, but more types can be regarded in real. We assume that each aircraft in the set of flights is small (e.g. Boeing 737, Airbus 320), large (e.g., Airbus 330, Boeing 777) or heavy (e.g., Airbus 380, Boeing 747).

Another critical factor in air traffic scheduling that is related to the aircrafts type is a minimum separation time between two aircrafts that use an identical runway. As it is notated, this is the most limiting factor for capacity of runways. These separation times should be respected in scheduling for the

safety reasons that have been explained before. Here for the sake of simplifying, we assume that the separation times are only dependent on the type of leading and following flights that use a same runway and do not mention whether the two flights are either landing or departing. We consider the standard separation times that are used by [7-8], [12]. These separation times are shown in Table II.

TABLE II
MINIMUM SEPARATION TIME REQUIRED BETWEEN TWO FLIGHTS THAT USE AN IDENTICAL RUNWAY ACCORDING TO THEIR TYPE

Leading	Trailing		
	Small	Large	Heavy
Small	1	1	1
Large	1.5	1.5	1
Heavy	2	1.5	1

As explained before, another factor that has major influence on the cost of a flight, scheduled after or before its target, is the category of the airline that operated it. Here, we consider three types of airlines, namely home carriers that the airport is their hub, usual carriers and charter or low price carriers. To implement the effect of airline levels (types), we consider a specific coefficient for each airline level and multiply the cost of each flight by it.

The objectives are to minimize (1) the total cost of delay or earliness of all flights, (2) the time required the whole set of aircraft to land or the makespan, and (3) unbalancing between runways. Then, we choose a weight for each objective according to the importance of it and add the weighted objectives together to make a single total objective. It is worth to note that we should pay much attention in choosing the weights by considering several factors that can be different at each airport and determine an appropriate weight for each objective. Here we think that the first objective has the most significance after that are the second and third objectives.

In the next section, we present our mathematical model for air traffic scheduling based on the explained concepts and assumptions.

IV. MATHEMATICAL MODEL

In this section, a mixed-integer zero-one programming model is given. First, we introduce the notations that are used in the model and then the mathematical formulation of the model is presented.

A. Notations
Parameters:

P	number of flights
R	number of runways
i,j	indices corresponding to flights $i, j \in \{1, 2, …, P\}$
r	index corresponding to runways $r \in \{1, 2, …, R\}$
T_i	target time of flight i
T_{max}	maximum of target times
E_{ir}	earliest time of flight i on runway r
L_{ir}	latest time of flight i on runway r
AL_i	airline level of flight i
wl_i	the workload of flight i on each runway

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S_{ij} minimum separation time required between flight i and j if j comes after i and on a same runway

C cost of delaying the last flight per unit

B cost for unbalancing of the maximum and minimum workload on runways per unit

w_1, w_2, w_3 weights that reflect the importance of the objectives

Decision variables:

x_i scheduled time for flight i

α_i earliness of flight i

β_i delay of flight i

γ maximum scheduled time of all flights (i.e., $\max\{x_i\}$)

λ_{ir} binary variable equals to 1 if flight i assigned to runway r ; 0, otherwise

z_{ij} binary variable equals to 1 if flights i and j use a same runway and 0 otherwise

δ_{ij} binary variable equals to1 if flight j comes after i

E_i earliest time of flight i on the chosen runway

L_i latest time of flight i on the chosen runway

zz_{max} maximum amount of workload between runways

zz_{min} minimum amount of workload between runways

B. Formulation

$$\text{Min } w_1 \sum_{i=1}^{P} AL_i(g_i\alpha_i + h_i\beta_i) + w_2 C(\gamma - T_{max}) + w_3 B(zz_{max} - zz_{min}) \quad (1)$$

s.t.

$$E_i \le x_i \le L_i \quad ; \forall i \quad (2)$$

$$\delta_{ij} + \delta_{ji} = 1 ; \forall i, j \text{ and } i \neq j \quad (3)$$

$$x_j \ge x_i + z_{ij}S_{ij} - (L_i - E_j + S_{ij})\delta_{ji} \quad ; \forall i, j \text{ and } i \neq j \quad (4)$$

$$z_{ij} \ge \lambda_{ir} + \lambda_{jr} - 1 \quad ; \forall i, j \text{ and } i \neq j; ; \forall r \quad (5)$$

$$z_{ij} = z_{ji} \quad ; \forall i, j \text{ and } i \neq j \quad (6)$$

$$\sum_{r=1}^{R} \lambda_{ir} = 1 \quad ; \forall i \quad (7)$$

$$E_i = \sum_{r=1}^{R} \lambda_{ir} E_{ir}, L_i = \sum_{r=1}^{R} \lambda_{ir} L_{ir} \quad ; \forall i \quad (8),(9)$$

$$x_i = T_i - \alpha_i + \beta_i \quad ; \forall i \quad (10)$$

$$0 \le \alpha_i \le T_i - E_i \quad ; \forall i \quad (11)$$

$$\alpha_i \ge T_i - x_i \quad ; \forall i \quad (12)$$

$$0 \le \beta_i \le L_i - T_i \quad ; \forall i \quad (13)$$

$$\beta_i \ge x_i - T_i \quad ; \forall i \quad (14)$$

$$zz_{max} \ge \sum_{i=1}^{P} \lambda_{ir} wl_i \quad ; \forall r \quad (15)$$

$$zz_{min} \le \sum_{i=1}^{P} \lambda_{ir} wl_i \quad ; \forall r \quad (16)$$

$$\gamma \ge x_i \quad ; \forall i \quad (17)$$

$$x_i, \alpha_i, \beta_i \ge 0 \quad ; \forall i \quad (18)$$

$$\lambda_{ir}, z_{ij}, \delta_{ij} \text{ binary} \quad ; \forall i, j \text{ and } i \neq j; ; \forall r \quad (19)$$

Constraint (1) is the objective function of the model that consists of the sum of the three weighted objectives. The first term multiplies the earliness or delay of each flight by their unit cost and again multiplies this later amount by the coefficient related to airline level of the flight. The second term minuses the time assigned to last flight from the maximum of target times and multiplies it by the unit corresponding cost. It is obvious that if the latest scheduled time is before the maximum target the amount of the second term becomes negative and causes our total cost to decrease. Finally, the third term counts the difference between maximum and minimum workload of the runways and multiplies this value by its unit cost.

Constraint (2) forces the scheduled time of each flight to be within its time window determined later by (8)-(9) according to runway chosen for it. Constraint (3) demonstrate either j comes after i (i.e., δ_{ij} =1) or vice versa(i.e., δ_{ji}=1). Constraint (4) is very significant constraint in the model, because it ensures respecting the separation time between two flights assigned to a same runway. If flights i and j are assigned to a same runway and j comes after i (i.e., z_{ij}=1 and δ_{ij} =1), then the equation is converted to $x_j \ge x_i + S_{ij}$. It ensures the separation time between the two flights. In other combinations of z_{ij} and δ_{ij} this constraint becomes always true and satisfied. Constraint (5) ensures that if flights i and j are assigned to the identical runway r , i.e. l_{ir} =1 and l_{jr}=1 , then z_{ij}=1.Constraint (6) enforces z_{ij} and z_{ji} to be equal. Equation (7) forces each flight to be assigned to only one runway. Equations (8) and (9) determine the amount of earliest (E_i) and latest time (L_i) of flight i according to the runway it has been assigned to. Constraints (10)-(14) set the amounts of α_i and β_i to be the earliness and delay of flight i in from its target time. Constraints (15) and (16) ensure that zz_{max} and zz_{min} are the values of workloads corresponding to the most loaded and the least loaded runways. Constraint (17) ensures that γ is the maximum of scheduled times, i.e. $\gamma = max\{x_i\}$. Finally, (18) and (19) demonstrate the positive and binary variables in the model.

V. COMPUTATIONAL RESULTS

A. Simulation and Creating Instances

In this section we should generate test problems of different sizes to be solved with appropriate solver software. So judgment about the merit of our model and solution methodology can be made. For this purpose we decided to have instances of 10, 20, 30 flights and solve each one with

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different number of runways. The parameters of problems with different sizes have been created using the following simulation:

We randomly generate 10, 20 and 30 integer numbers from [5, 20], [5,30] and [5,40], respectively. In addition, we consider them as the target times of instances with 10, 20 and 30 flights. Then, we generate the same number of integers from [0,1] that considers as the status of flights. So, if 0 is generated for a flight, we assume that it is a landing one and 1 is corresponding to a departing one. To determine the type of flights, we consider that a flight is with probabilities of 0.2, 0.6 and 0.2 for small, large and heavy aircrafts, respectively. To determine airline levels the probabilities 0.6, 0.3, 0.1 are corresponding to home carriers, usual carriers, and low price carriers, respectively. The considered coefficients for them are 1.5, 1 and 0.5. The workload assumed for each flight is according to its type. So, we consider 1, 2 and 3 for small, large and heavy, respectively. We determine the unit cost for earliness and delay in the order of flight types 0.5, 1, 1.5 and 1, 2, 3. We generate the earliest and latest times on each runway randomly with paying attention to its status. At last, we choose the objective weights w_1=0.6, w_2=0.3 and w_3=0.1.

B. Comparing the Results

After creating the required instances we solved our problem with them using the GAMS/CPLEX solver. The model is coded for each instance with the created parameters and implemented in 1.83GHz Intel Pentium computer with 0.99GB of RAM. We solve 10 instances and summarize the results in Table III. In this table, the size of each problem, which consists of number of flights and number runways, are tabulated in the first and second column. For realizing the advantageous of our solution approach, we compare the result of the traditional FCFS method with our results. These two solutions are presented in third and forth columns. The last column shows the CPU time of solving the each problem with the GAMS software.

The data given in Table III depict that for the first instance the optimal solution is obtained very quickly (in less than 4 seconds). This solution is much better than FCFS (about 66% decrease). The second instance is implemented with parameter of the first one but another runway is added to it. Only little improvement is observed (about 4%). It can be related to generated parameter that put the FCFS at ease to solve it as good as an optimal solution. Adding the third runway decreases the amount of objective. Again in this case, the FCFS can gain a near-optimal solution.

As the number of flights increases, we can guess that FCFS loses its efficiency. In firth instance we can easily observe that the solution provided by FCFS is far apart from our optimal solution (about 86%). By considering the second and third runway superiority of optimal solution is still observable (by about 60 and 75%). A strange result that obtained in fifth instance in comparison with the forth one is increasing the objective (from 8.25 to 8.55). It was unexpected because when we add one runway, we think that additional resources cause always smaller cost. But it is not always true, because adding

an extra runway in some situation has no influence on the delays and also increases unbalancing that yields more cost. This fact was again happed by instances with 30 flights. In these instances the optimal solutions still overcome the FCFS (by about 40, 25 ,20 and 22%). we have to mention that by increasing the size of problem the CPU time increases simultaneously to over 40 seconds, but it is still applicable. It should be noted that by the last instance we have taken the concept of runway restriction into account that may emerge in practice due to specific features of runways. So the forth runway can only be used by small and large aircrafts.

It is realized from computational results that the optimal solution is much better than traditional FCFS method by problems that can be solved in suitable time. A recommended approach for problem of larger size could be dividing them to smaller sub-problems and solving the sub-problems to optimality.

VI. Conclusion

In this paper, we considered the problem of scheduling landing and departing flights in a hub airport with taking the effect of airline levels into account. A mixed-integer zero-one formulation was presented according to our assumptions. The model is solved using GAMS/CPLEX for a set of simulated test problems, and the results were compared with the traditional FCFS method. The comparison demonstrated that using our approach for different instances is very satisfactory.

More investigation should be conducted for modification this model to improve its capability for solving the problem of larger sizes in appropriate time. One suggestion is to divide the whole problem into smaller sub-problems; however, a precise structure is needed.

Another recommendation is to solve our problem with a suitable heuristic method for large-sized problems. The chosen heuristic should provide near-optimal solutions in a short time.

TABLE III
COMPARISON BETWEEN THE RESULTS OF OUR METHOD (OPTIMAL SOLUTION WITH GAMS) AND TRADITIONAL FCFS METHOD

Number of flights	Number of runways	FCFS solution	Optimal solution with GAMS	CPU time (s)
10	1	18.9	6.45	3.812
10	2	6.25	6	5.313
10	3	2.9	2.85	3.719
20	1	59.45	8.25	4.438
20	2	20.38	8.55	7.078
20	3	10.15	2.55	15.937
30	1	89.27	54.975	16.09
30	2	73.46	54.975	33.541
30	3	69.73	55.275	35.272
30	4 (the forth runway only for *Small* and *Large aircraft*)	70.39	55.275	40.172

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