Determination of the Aircraft Landing Sequence by Two Meta–Heuristic Algorithms

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Abstract

Due to an anticipated increase in air traffic during the next decade, air traffic control in busy airports is one of the main challenges confronting the controllers in the near future. Since the runway is often a bottleneck in an airport system, there is a great interest in optimizing the use of the runway. The most important factors in aircraft landing modeling are time and cost. For this reason, Aircraft Landing Scheduling Problem (ASLP) is a typical hard multi-constraint optimization problem and finding its efficient solution would be very difficult. So in real applications finding the best solution is not the most important issue and providing a feasible landing schedule in an acceptable time would be the preferred requirement. In this study a three objectives formulation of the problem proposed as a mathematical programming model on a runway in static mode. Problem is solved by multi-objective genetic algorithm (NSGA-II) and multi-objective Particle Swarm Optimization Algorithm (MOPSO). Considering a group of 20 aircrafts, this problem is solved and landing sequence determined and we are shown the obtained sequence does not follow First Come First Serve law for sequencing as well. Finally by comparing results, conclusion and suggestions are proposed.

Keywords: Aircraft landing scheduling problem, Expected Landing Time (ELT), Scheduled Landing Time (SLT), NSGA-II Algorithm, MOPSO Algorithm.

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1. Introduction

During the past few decades, air traffic operations have experienced unprecedented and massive growth. Compared to 2010, the number of air travelers around the world increased up to %5.3 in 2011 and %11.9 compared to its earlier year; it has reached 5.44 billion passengers [ACI releases world airport traffic report for 2010, Aug 2011]. According to records of International Association of Airports, it is found that total incoming aircrafts in an airport radar range is significantly high and this requires a strong management to schedule aircrafts landings.

When an aircraft reaches the airport, radar range requires landing permit, landing time and appropriate runway (if it is available) from air traffic control. aircrafts cannot descend earlier than a certain time because airplanes have an specific maximum speed and cannot stay in the sky longer than that specified time since the fuel per aircraft is limited. A target landing time is defined within this time window that is the preferred landing time according to airline. If it lands on runway with the cruise speed (the most economical aircraft speed), the same time that is announced to the passengers, would be the landing time. Any deviation (early or late) from target landing time will disturb airport program. Consequently, with any deviation before or after target landing time, penalty fees is considered separately for fuel, parking, apron, etc. Therefore, the goal is to minimize total time landing sequence (or maximize runway efficiency) as well as minimizing the total fine costs including:

- Vertical and horizontal separation of standard flights that keeps them apart is one of the most important security tools for air traffic control (ATC). Minimum required separation creates minimum allowable distance between aircrafts approaching runway. In general, the required separation (WV) between aircrafts depends on aircraft type. Therefore, this problem is also related to arrangement.
- Each aircraft should land within a predetermined time window (the earliest landing time plus the required holding time and the latest landing time).

In single- runway situation, decision making on the adopted landing sequence is often based on FCFS method. The first aircraft entering the radar range should land first and the second one should land later, etc… In general, many studies have been conducted on the ALSP in the field of operation research. Normally, aircrafts are scheduled by FCFS method [Harikiopoulo and Neogi, 2004; Saraf and Slater, 2006; Chandran and Balakrishnan, 2007]. When multi-runway situation is discussed, FCFS method often is used; so that the aircrafts land on the runway assigned to them and in sequence that appear in the radar range. In the works conducted on this topic, both meta-heuristic and optimization methods including meta-heuristic method based on initial population, simple heuristic method, genetic algorithm etc.. have been developed to solve ALSP. Although, more than 60 papers in the field of optimizing aircrafts landing have been provided in the past three decades, most of the proposed methods have never been used in the studies [Mesgarpour and Bennell, 2010].

Since ALSP can simultaneously include optimization of multiple dependent objectives, also due to lack of optimization with more than two objective functions in the topic literature, the requirement to deal with this type of optimization has been felt strongly for a more satisfactory evaluation as well as creating the ability to modify relevant coefficients, depending on the environment where the model is used.

In this paper, an attempt was made to introduce a three-objective mathematical model of aircraft landing problem to satisfy the needs of different stockholders in air transportation including Aircraft Traffic Control (ATC), airlines, runway and government. Also, it has been tried to investigate the applicability of two samples of the most applicable meta-heuristic algorithms available in the area of solving optimization problem and to provide the results.

2. Mathematical Formulation

In this section, for ASLP static condition on a runway, a new mathematical formulation will be provided:

2.1. Abbreviations

Decision variable

SLT_i: The scheduled landing time of each aircraft i, calculated by trajectory synchronizer equipment after entering the aircraft into the radar range.

Parameters

n: The number of aircraft to be scheduled.

X_{ij}: Defined to be 1 if aircraft i land before (not necessarily immediately) aircraft j and otherwise 0.

ELT_i: The expected) or target (landing time of aircraft i, based on the assigned time slot which is normally specified in flight plan.

$TELT_i$: Aircraft type i in size category based on three different types of aircraft in small, medium and large.

Δ_{ij}: The minimum time separation between aircrafts i and j, if aircraft i lands before aircraft j.

CAT_i: Airline cost per unit of time (except fuel factor) for landing of aircraft i after ELTi.

CBT_i: Airline cost per unit of time (except fuel factor) for landing of aircraft i before ELTi.

FCD_i: Average required fuel burn cost per minute for aircraft I to be delayed.

FCA_i: Average required fuel burn cost per minute for aircraft I to be advanced.

EAT_i: The earliest possible arrival time for aircraft i, subject to technical and operational restrictions.

LAT_i: The latest possible arrival time for aircraft i, which is usually determined from fuel limitation and maximum allowable delay.

Th: The time for a plan to circle for one loop when waiting its turn to land.

ea_i: The allowed earliness for aircraft i to land before ELTi , from the moment the wheels touch the ground to reach the parking lot (including across the taxiways).

da_i: Allowed lateness for aircraft i to land after ELTi , from the moment the wheels touch the ground to reach the parking lot (including across the taxiways).

e_i: The earliness for aircraft i,(max(0,ELTi-SLTi)).

d_i: The lateness for aircraft i, (max(0,SLTi-ELTi)).

2.2 Objective functions

- Maximizing runway throughput. Total landing times can be equally minimized instead maximizing the number of aircrafts that land on the runway; this is the same runway throughput.

Minimize

$$Minimize \sum_{i=1}^{n} SLT_i \tag{1}$$

Minimizing apron and parking and other costs that are imposed on the airline by additional stay of aircraft at the airport through minimizing the delay time and allowable earliness.

$$Minimize \sum_{i=1}^{n} \{|SLT_i - ELT_i| - B\} A \tag{2}$$

In which:

$$A \begin{cases} CAT_i \text{, if } SLT_i > ELT_i & (2.4) \\ 0 \text{, if } SLT_i > ELT_i & (2.5) \\ CBT_i \text{, if } SLT_i > ELT_i & (2.4) \end{cases} \qquad B \begin{cases} da_i \text{, if } SLT_i > ELT_i & (2.1) \\ 0 \text{, if } SLT_i > ELT_i & (2.2) \\ ea_i \text{, if } SLT_i > ELT_i & (2.3) \end{cases}$$

Minimizing fuel consumption cost and therefore minimizing carbon dioxide pollution of the air. Fuel consumption depends on different factors including pilot flying techniques, height, wind speed, aircraft model, aircraft weight (including passengers' weight and cargo) and fuel inside tanks. Consequently, additional fuel cost resulting from late arrival and fuel cost saving because of early arrival should be considered.

Minimize

$$Minimize \sum_{i=1}^{n} \{|SLT_i - ELT_i|\} C \tag{3}$$

In which:

$$\begin{cases} FCD \text{ , if } SLT_i > ELT_i & (3.1) \\ 0 \text{ , if } SLT_i = ELT_i & (3.2) \\ FCA \text{ , if } SLT_i < ELT_i & (3.3) \end{cases}$$

2.3 Constraints

A variety of operational constraints can exist for ALSP; having a look at the real world, the most practical of these for using in a runway are given below. All scheduled landing times (SLT) should be determined and calculated according to the following constraints:

2-3-1 Runway use restrictions

$$X_{ij} + X_{ji} = 1 \qquad \forall_{ij} = 1, 2, \ldots, n \tag{4}$$

Each runway can be used by only one aircraft at the same time. So, the aircraft i lands before the aircraft j or vise versa.

2.3.2 Guarantee Limit for Minimum Separation Distance (separation VW)

$$SLT_j - SLT_i \geq \Delta_{ij} \tag{5}$$

Aircraft should be in a safe distance from other aircrafts to avoid turbulence created by aircraft ahead.

2.3.3 Time limit

$$EAT_i + Th \leq SLT_i \leq LAT_i \tag{6}$$

Based on technical and operational assumptions such as limited fuel, wind speed etc... ,each aircraft has a minimum and maximum allowable air time. This restriction should be considered as a serious limitation. According to this problem, it is possible that the runway is blocked in the time allocated to aircraft landing or the aircraft is obliged to wait due to traffic saturation, poor visibility, weather conditions or lost time points, therefore, a soft time is added to the beginning of time interval for aircraft bypass in an air loop, to avoid changing sequence scheduling in this situation.

2.3.4 Positivity Constraint of Scheduled Time for Each Pair of Aircrafts (outrider and follower)

$$(ELT_i - ELT_i)(SLT_i - SLT_j) > \cdot \tag{7}$$

2.3.5 Restrictions related to earliness or lateness

$$\cdot \leq e_i \leq ELT_i - EAT_i \tag{8}$$

$$\cdot \leq d_i \leq LAT_i - ELT_i \tag{9}$$

Early or late landing of the aircraft i is always a function of the defined time window and also the expected landing time for this aircraft.

2.4 Penalty Functions

Penalty function solution is a method for finding reasonable responses through valuation and also determining the role of constraints as a criteria , moving towards responses with less errors and eventually to an appropriate area. This method is very popular among all techniques, to justify the constraints.

This method, constrains violation is constrained and multiplied by penalty parameter ($R_k=10^6$) and its result is added to the value assigned by each of the target functions. Note that the value of R_k will be positive in minimizing the functions.

In the restrictions in which decision variable (SLT) exists, penalty has been determined as follows:

2.4.1 To limit guarantee for minimum separation distance

$$max\left(\text{٠},\left(\frac{\Delta_{ij}+SLT_i}{SLT_j}-1\right)\right)^2 \times R_k \quad (10)$$

2.4.2 For time limit

$$\begin{cases} max\ (\text{٠},(\dfrac{SLT_i}{LAT_i}-\text{١}))^2 \times R_k & (11) \\ max\left(\text{٠},\left(1-\dfrac{SLT_i}{Th+EAT_i}\right)\right)^2 \times R_k & (12) \end{cases}$$

2.4.3 To Limit Positive Scheduled Time max

$$\max\ (\text{٠},\left(\frac{ELT_i-ELT_j}{SLT_j-SLT_i}-\text{١}\right)^{\text{٢}}) \times R_k \quad (13)$$

2.4.4. For restrictions related to earliness or lateness

$$\begin{cases} \max\left(\text{٠},\left(\dfrac{ELT_i-SLT_i}{ELT_i-EAT_i}-\text{١}\right)\right)^{\text{٢}} \times R_k & (14) \\ \max\left(\text{٠},\left(\dfrac{SLT_i-ELT_i}{LAT_i-ELT_i}-\text{١}\right)\right)^{\text{٢}} \times R_k & (15) \end{cases}$$

2.5 Problem Implementation

In this problem, a linear matrix has been used as follows, for expected landing time (ELT), for consecutive series including 20 incoming aircrafts in the sequence they enter the radar range of the airport:

ELT_{20} = [8.05 8.00 8.20 8.15 8.10 8.45 8.50 8.60 8.75 8.80 9.05 9.10 9.20 9.35 9.40 9.65 9.80 10.00 9.70 9.95]

In some references such as [Anagnostakis and Clarke, 2002], aircrafts are classified in several groups in terms of weight and separation time matrices formed due to the group that both pairs of consecutive aircrafts belong to, like what is given in (table 1). In this matrix, aircrafts have been assigned to three small (S), medium (M) and heavy (H) groups [Salehipour et al, 2009]. Columns (indices i) represent follower aircraft and rows (indices j) represent outrider aircraft.

Table 1. Separation time matrix

	S_j	M_j	H_j
S_i	5	3	3
M_i	8	5	3
H_i	15	8	5

The following matrix indicates that in terms of dimensions, to what group do the aircrafts coming to the radar range of the airport (in entering sequence) belong, (S, M, H).

$TELT_{20}$=['1S' '2M' '3H' '4S' '5M' '6H' '7S' '8M' '9H' '10H' '11H' '12S' '13S' '14S' '15M' '16H' '17H' '18H' '19S' '20M'].

For consecutive arrival in a series of 20 aircrafts, time interval have been considered between 8 to 10 (total time interval is 2 hours, means that a landing operation each 6 minutes).

3. Model solution using the second version of NSGA-II algorithm

3.1 Multi-objective Evolutionary Algorithms

By changing the basic evolutionary algorithms, it would be possible to maintain parts of optimum Pareto in each generation of evolutionary algorithms. Therefore, the necessity of multiple run in a classical method to find a Pareto response in each run can be eliminated. In other hand, a unique feature of evolutionary algorithm in solving optimization problems is access to a diverse set of non-dominated responses with appropriate distribution and utilization of an operator to establish this distribution [Deb, 2001].

3.2 NSGA-II Algorithm

This algorithm was provided in 2002 by Deb et al [Deb et al, 2002] to solve multi-objective optimization problems and in this paper, a new formulation using a Non-dominated Sorting Genetic Algorithm (NSGA) was introduced, because of its ability to handle multi-objective optimization and multiple constraints [Xue et al, 2012]. NSGA-II algorithm is an elitist multi-objective evolutionary algorithm. In addition to having a proper strategy to keep a better response, this algorithm has a clear mechanism to maintain population diversity. The steps conducted in each iteration of NSGA-II algorithm is shown in figure 1.

3.4 Implementing Parameters of NSGA-II Algorithm for the Problem

To adjust the algorithm parameters by entering the variables and the response levels, creating a Taguchi design the software minitab16 is used. In this method, the average rate of the signal to noise (S/N) and the average robust parameter design (RPD) for each parameter for each level has been achieved and considering the impact of each factor algorithm, the following values have been considered:

Maximum number of iteration algorithm for a series of 20 aircrafts is equal to 1000 and the number of initial population (nPop) equal to 50; Percentage of people who work in company crossover (pCrossover) is equal to 0.7 and the mutated population (pMutation) equal to 0.4; mutation rate is also considered equal to 0.02.

4. Results for NSGA-II Algorithm

Pareto optimal region obtained for series of 20 aircrafts is shown in the figure 2.

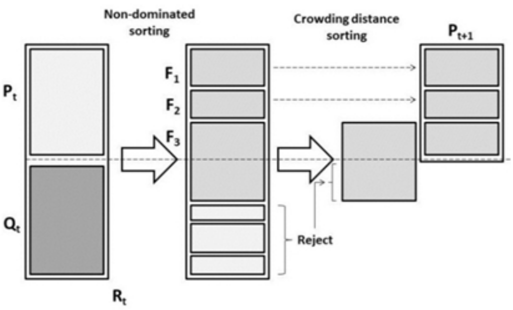

Figure 1. The steps conducted in each iteration NSGA-II algorithm

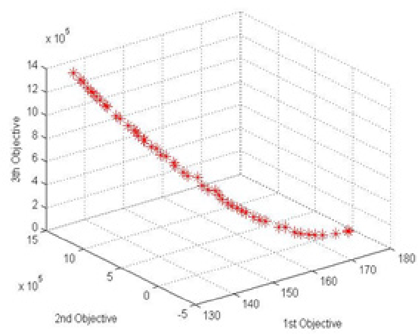

Figure 2. Pareto optimal region obtained for a series of 20 aircrafts

The obtained expected landing times (ELT) and the scheduled landing times (SLT) for sequencing of 20 aircrafts is shown in table 2 where α indicates absolute value of the difference between these two times:

The sequence obtained for a series of 20 aircrafts is shown in figure 3.

Values of each target function taken from the first members of the first front are also as follows:

For a series of 20 aircrafts $\begin{cases} f_1 = 179.26 \\ f_2 = 0.92 \\ f_3 = 19.78 \end{cases}$

5. Model Solution using (MOPSO) Algorithm

5.1. PSO Optimization Algorithm

PSO algorithm was first proposed by Eberhart and Kennedy in 1995. This method was inspired from group flight of birds and group

Table 2. ELT and SLT obtained for a series of 20 aircrafts

Aircraft number	ELT_i	SLT_i	α	Aircraft number	ELT_i	SLT_i	α
1	8.05	8.05	0	11	9.05	9.04	0.01
2	8.00	8.00	0	12	9.10	9.10	0
3	8.20	8.19	0.01	13	9.20	9.19	0.01
4	8.15	8.15	0	14	9.35	9.34	0.01
5	8.10	8.10	0	15	9.40	9.38	0.02
6	8.45	8.45	0	16	9.80	9.79	0.01
7	8.50	8.49	0.01	17	9.65	9.65	0
8	8.60	8.60	0	18	10.00	9.98	0.02
9	8.75	8.75	0	19	9.70	9.72	0.02
10	8.80	8.79	0.01	20	9.95	9.94	0.01

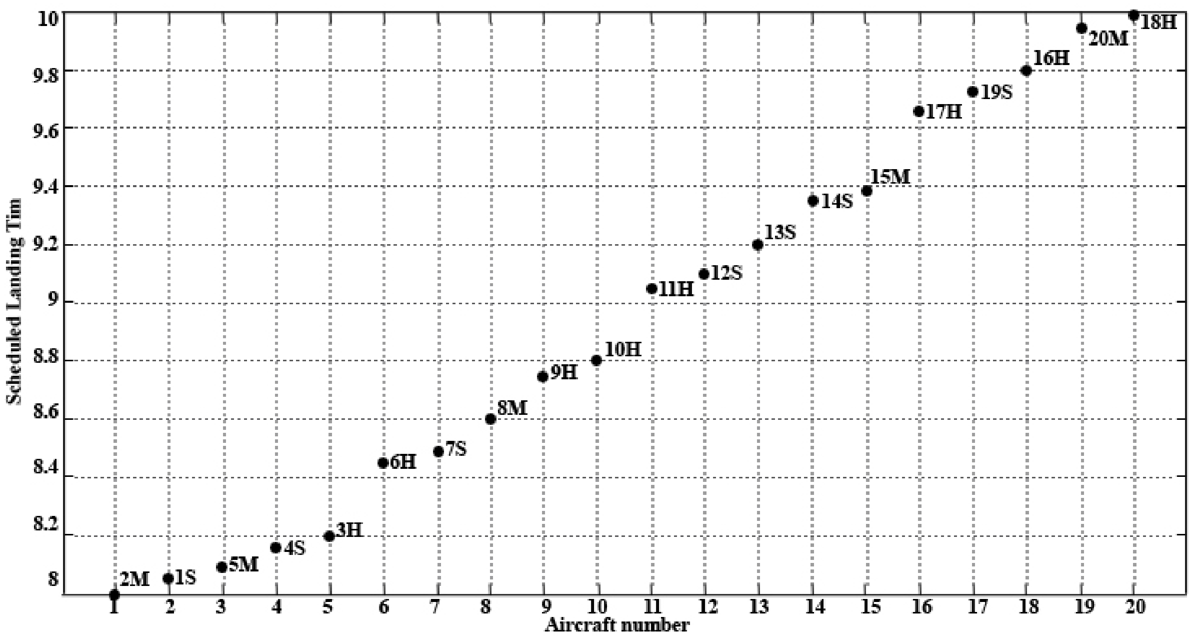

Figure 3. The sequence obtained for a series of 20 aircrafts for NSGA-II algorithm

swimming of fishes and their social life, and formulated using a series of simple equations. Like all other evolutionary algorithms PSO also starts with a random distribution of people. In fact, every particle provides a point of solution space. The difference between PSO and other evolutionary algorithms is a method by which the created populations move in the researching space. It is based on the principle that in any moment, each particle adjusts its location in the researching space due to the best place has ever had and the best place in the whole neighborhood.

Flowchart of steps done in each iteration of MOPSO algorithm is shown in figure 4.

5.2. Implementation of MOPSO Algorithm Parameters for the Problem

Maximum number of algorithm iteration for series of 20 was equal to 1500; number of initial population was considered 200 and for parameters related to inertia coefficient movement 0.5; for nostalgia coefficient equal to 0.75 and the coefficient of the best collective memory considered 1.5. Also, mutant population was considered equal to 0.1.

5.3. Results Obtained from MOPSO Algorithm

The values obtained for a sequence of 20 are

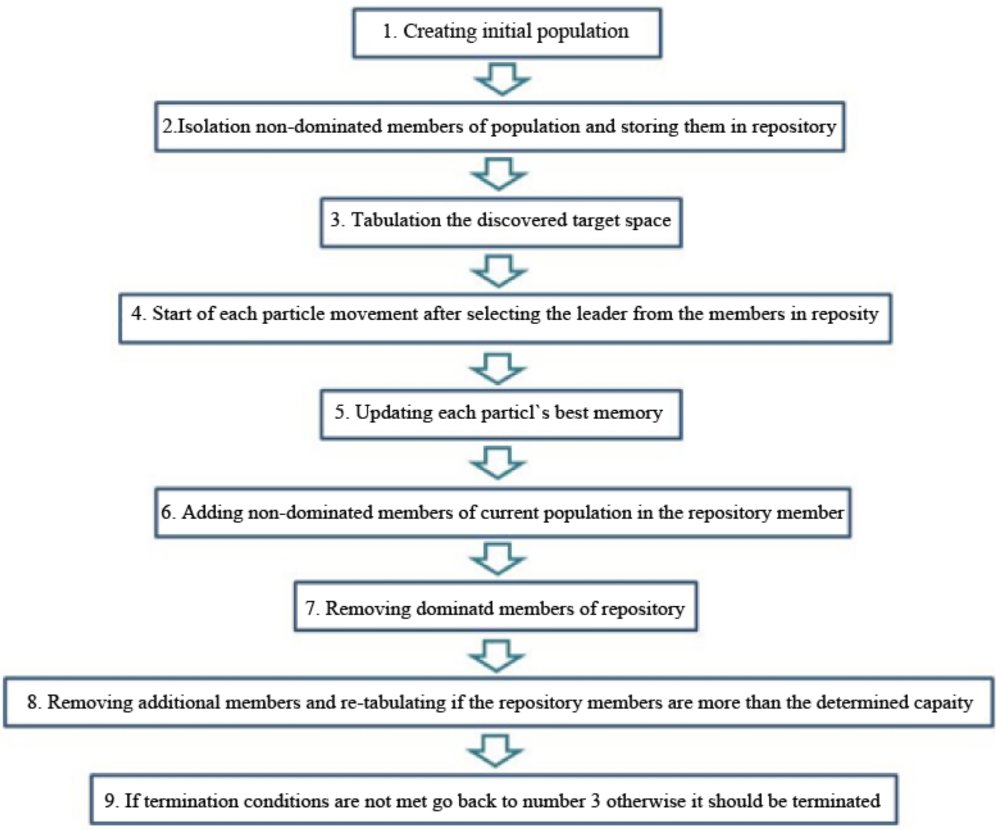

Figure 4. Flowchart of steps done in each iteration of MOPSO algorithm

shown in table 3.

The sequence obtained for a series of 20 aircrafts is shown in figure 5.

Values for each target function obtained from the first members available in repository, are also as follows:

6. Discussion and Conclusions

In this paper, it has been tried to cover many basic problems and factors emphasized by air traffic controllers. Parts of these factors are as follows:

- Taking into account operational and functional limitations in order to achieve a practical and not merely a theoretical model.
- Obtaining proper sequence in an acceptable time. Optimal solutions that arise from long computation times have little use in practice.

Table 3. ELT and SLT obtained for a series of 20 aircrafts for MOPSO algorithm

Aircraft number	ELT_i	SLT_i	α	Aircraft number	ELT_i	SLT_i	α
1	8.05	8.04	0.01	11	9.05	9.04	0.01
2	8.00	8.00	0	12	9.10	9.12	0.02
3	8.20	8.16	0.04	13	9.20	9.15	0.05
4	8.15	8.22	0.07	14	9.35	9.31	0.04
5	8.10	8.10	0	15	9.40	9.39	0.01
6	8.45	8.44	0.01	16	9.80	9.79	0.01
7	8.50	8.52	0.02	17	9.65	9.65	0
8	8.60	8.60	0	18	10.00	9.96	0.04
9	8.75	8.77	0.02	19	9.70	9.76	0.06
10	8.80	8.80	0	20	9.95	9.90	0.05

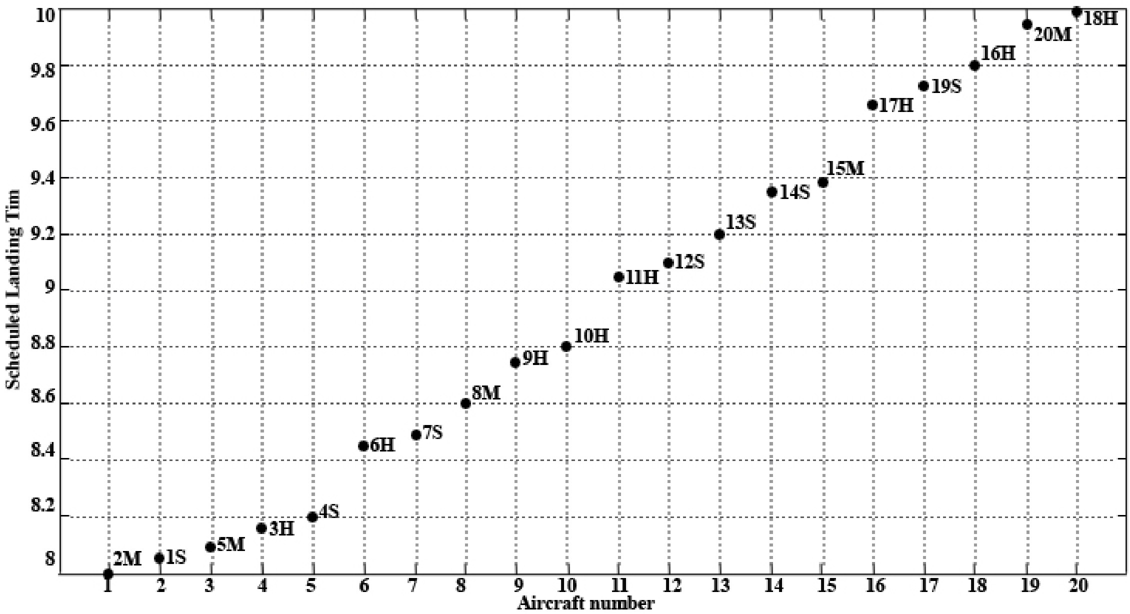

Figure 5. The sequence obtained for a series of 20 aircrafts for MOPSO algorithm

- Selection of a proper target function for ALSP is controversial and stakeholders likely have conflicting criteria. Therefore, the first important step for the running model is the selection of multiple objectives that can meet interests of all parties or provide an acceptable compromise.

Looking at the results obtained from model solution by two algorithms that are shown in tables 2 and 3, and due to value of parameter α that shows distance rate of scheduled landing time from expected arrival time, it is understood that accuracy of solving model by NSGA-II algorithm to obtain optimal sequence was more than the MOPSO algorithm. So in solving the model with NSGA-II algorithm, the worst result obtained for series of 20 aircrafts was about % 2 far from optimal result and this value for MOPSO algorithm was about %7. Also, NSGA-II algorithm reached to optimum response with less number of iteration.

However it is not the case in range of investigated responses and also in solution time.

A parameter called NFE was used to determine that how many responses were investigated by each algorithm in solution process to reach optimum response; so in each iteration, the values investigated by each algorithm are calculated. NSGA-II algorithm investigated 88080 responses during 1000 iterations, MOPSO algorithm 400500 responses during 1000 iterations and 600200 responses to reach optimum sequence which 1500 iterations were considered for it.

According to the obtained results, it is clear that MOPSO algorithm examines a greater range of target space in less time compared to NSGA-II algorithm, in order to achieve optimum response, but the accuracy of solution and response quality obtained by NSGA-II algorithm is more satisfactory.

Selection of algorithm to solve the problem depends on severity of decision-making conditions and criteria of. Hence, it cannot be definitely remarked on the efficiency of algorithms for solving similar problems. But according to problem modeling which its goal is simultaneous reduction of time and cost in sequence determination, accuracy of obtaining responses is more important because it directly affects the costs.

In conclusion, due to existing 20 sequences for the five first aircrafts and the five last aircrafts in expected times, there are times substitution in radar range of the airport in arrival arrangement. Based on the results obtained for landing times in table (2) and (3), it is clear that many aircrafts change their scheduled landing time compared to the number of entries. number. This shows that scheduled landing time, is just based on expected landing times and does not follow First Come First Serve law for sequencing. This kind of sequences results more optimal sequencing and also reduces the costs imposed to system and fuel costs.

For future works, more investigation should be conducted for modification of this model to improve its capability for solving the problem of larger sizes in appropriate time. One suggestion is developing the proposed three-objective model in landing and take-off conditions together. Another recommendation is to solve this problem for dynamic situation.

7. Endnotes

1- Wake vortex

2- Non-dominated sorting genetic algorithm

3- Multi-objective particle swarm optimization

4- Number of Function Evaluation

5- Wake Vortex

8. References

- Anagnostakis, I. A. and Clarke, J. P. (2002) “Runway operations planning: A two-stage heuristic algorithm”, AIAA Aircraft, Technology, Integration and Operations Forum. Los Angeles, October 1st-3rd.

- Chandran, B. and Balakrishnan, H. (2007) “A dynamic programming algorithm for robust runway scheduling”, In Proceedings of the American Control Conference, pp. 1161-1166.

- Deb, K. (2002) “A fast and elitist multi objective genetic algorithm: NSGA-II”. In IEEE Transactions on Evolutionary Computation Conference; 6(2): pp.182-197.

- Deb, K. (2001) “Multi-objective optimization using evolutionary algorithms”, 1st edition. John Wiley and Sons

- Eberhart, R. and Kennedy, J. (1995) “A new optimizer using particle swarm theory”, Proceedings of the 6th International Symposium on Micro Machine and Human Science, Nagoya, Japan. NJ, pp.39-43.

- Gittens, A. (2011) “ACI releases world airport traffic report for 2010”, Airports Council International. Available at: URL:http://www.internationalairportreview.com/

- Harikiopoulo, D. and Neogi, N. (2004) “Polynomial time feasibility condition for Multi-Class Aircraft Sequencing on a single runway airport”, In AIAA 1st Intelligent Systems Technical Conference, 20-22, Chicago, Illinois, USA.

- Kennedy, J. and Eberhart, R. (1995) “Particle swarm optimization”, Proceedings of IEEE International Conference on Neural Network, Perth, Australia, IEEE Service Center Piscataway NJ,pp.1942-1948.

- Julia, A., Bennell., Mesgarpour, M.and Chris N. Potts, Chris N. (2011) Airport runway scheduling. Invited Survey. Springer, 4OR-Q J Oper Res 9:115–138.

- Mesgarpour, M. Potts, C.N., Bennell, J.N. (2010) “Models for aircraft landing optimization",. In Proceedings of the 4th. International Conference on Research in Air Transportation (ICRAT 2010), Budapest, Hungary.

- Salehipour, Amir. Moslemi, Leila. Kazemipoor, Hamed. (2009) Scheduling aircraft landings by applying a variable neighborhood descent algorithm:Runway-dependent landing time case. Journal of Applied Operational Research, 39–49 ISSN 1735-8523.

- Saraf P.and Slater L. (2006) "An efficient combinatorial optimization algorithm for optimal scheduling of aircraft arrivals at congested airports". IEEE aerospace Conference, 4-11.

- Xue, Min. Zelinski, Shannon. (2012) "Optimal integration of departures and arrivals in terminal airspace". Navigation, and Control Conference (AIAA, 2012), Minneapolis, Minnesota.