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## A New Approach in Airport Capacity Enhancement Based on Integrated Runway Assignment and Operations Planning Model

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**Abstract:** This research, for the first time presents the Flexible Flow Shop (FFS) model of scheduling method for considering runway assignment and operations planning together. One of the advantages of the developed model is considering the procedures of air routes in terminal airspace which is very similar to the real world condition. The model is analyzed with both exact method (LINGO) and meta-heuristic SA algorithm which runs in PASCAL language. This approach can be used as an aid for decision making, delay reduction and improving the available runway throughput.

**Key words:** Assignment, operations planning, scheduling, sequencing, integrated model, simulated annealing, FFS

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### INTRODUCTION

Nowadays, Airport capacity is a bottleneck in the air traffic system. Many airports operate at their maximum capacity (for some hours of the day). Runways are critical resource of an airport. Airport runway capacity is subject to large changes, mainly because of weather and visibility conditions. Therefore, large arrival and departure delays occur frequently. Capacity should be used in an efficient way. This can be done by creating efficient landing and departure sequences and allocating an optimum assignment to runway system.

It should be noted that airport capacity is mostly expressed as sum of landing and take off operations (Jason *et al.*, 2007). Current and predicted levels of air traffic demand raise the need for airport capacity enhancements, as well as reduction of the environmental impact (engine emissions) and the costs incurred by operational inefficiencies (fuel burn). In an effort to satisfy such a need, the presence of an automated decision support system, which includes planning and control algorithms, has a significant contribution (Anagnostakis *et al.*, 2000).

One of the ways of runway capacity enhancement is increasing the number of runways. Because of heavy costs and requires occupying urban lands, construction of new runways often is not possible. Moreover, increasing the number of runways without optimum operations planning and assignments will not be undertaken completely. Using which runway, for which operation, in which time plays an important part in the

runways system capacity. For example, in an airport with the single runway, the following parameters have their own influential rules in determining operations planning: configuration of runways, arrival and departure volumes, volume and place of fixes in a time, place and number of apron gates, place and number of taxiways and exit rapid taxiways, mix of aircrafts, etc. An increase of the number, geometric complexity, runway's orientation and location, runway crossing points and final approach of runways, workloads of the controllers is so important that without optimum operations planning and assignments, most of the capacity of the runways and ultimately the airside capacity, will not be used. In addition, strong delays, wasting of economic resources and dissatisfaction of the airport users, among the passengers and airlines, are of the other consequences.

This research, for the first time presents the scheduling method for considering runway assignment and operations planning together which is similar to the real world condition. The airport runway is a scarce resource that must be shared by different runway operations (arrivals, departures and runway crossings). The runway system, as a resource shared by all aircraft, is a significant flow bottleneck due to many causes that either limit the effective capacity of the airport or increase the demand for runway service. A new generic method to represent the structure of the Air Traffic Management (ATM) system is introduced in the following sections.

In some researches, a new structure for ATM has been proposed which is the base of this research. Such a structure can be useful in any effort to design and build

decision-aiding systems for air traffic controllers, because it describes the links and dependencies between the three main traffic elements of ATM arrivals, departures and ground traffic. Runway Operations Planning (ROP) belongs to Runway Operations Management (ROM), which in turn is a part of the overall ATM System and is affected by decisions made in other parts of ROM. The main tasks of ROM are:

- Runway configuration management
- Runway assignment management, which determines the runway to be used by each aircraft
- Runway operations planning, i.e., the tactical planning of runway usage by different arriving and departing flights

Although some researchers have explained these three tasks hierarchically, but in this study, Runway Assignment Management and Runway Operations Planning have been considered together (Anagnostakis *et al.*, 2001).

Planning the allocation of runway time to the various types of runway operations can be a challenging task, in any busy airport. Planning and control function are the two main tactical tasks that must be conceptually distinguished from each other, without overlooking the interrelations and links between the corresponding tasks.

These links are usually neither obvious nor easily observable because, in many cases, one controller mentally performs both planning and control tasks at the same time. In an airport, both planning and control are performed in a distributed fashion. Consequently, a successful design of an automated ROP system that will be under airport-wide use must provide the necessary integration between the different objectives, constraints, controls and inputs from all parties involved in airport ground operations. Then the Runway Operations Planning problem is an optimization problem that is affected by the operational and financial interests of several involved parties, such as the airport users (airlines, passengers) and the ATM service providers (airport authority, air traffic controllers) (Anagnostakis *et al.*, 2001). Generally in literature, regarding objectives and constraints, operations planning is modeled and solved just for arrivals or departures.

Assignment of aircrafts (arrivals and departures) to the runways is one of the main concerns of the controllers; because sometimes in high demands they should make immediate and optimal decisions which sometimes don't lead to overall use of available runways

capacity. Most of the assignments are done for the arrivals. Runway assignment of arrival aircraft is a tactical decision made by controllers. Strategic reassignments, or allocations, assist in balancing controller workload and reducing delay, but are difficult for controllers because of the high workload already associated with the traffic load. As terminal area controllers become consumed with the task of separation, strategic runway allocation becomes neglected. During high workload periods, controllers simply assign runways to fill available landing slots when aircraft are well within TRACON airspace. This process of tactical adjustments to the arrival schedule requires coordination between controllers and ultimately leads to higher workload and increased delay. For runway assignment, knowledge based runway allocation flowchart and decision Tree are used. There is a similar process for the departures. However arrival and departure assignments are done independently.

#### **REQUIREMENT OF INTEGRATION OF ROP AND RAM**

Runway assignment is not a problem in single runway airports and just operations planning for arrival and departure are important. With greater demands for capacity enhancement, number of runways would be increased, but an increase in the number of runways calls for their tactical planning; otherwise it is not possible to use the enhanced capacity in a suitable manner, comparing to the increase in the number of the added runways. Compared with increase in the number of runways, operations planning would be even more complicated because of increase in demand for terminal airspace. This complexity often brings about high workloads for the air traffic controllers which leads to selecting simple methods for runway assignments (for example in parallel runway systems, one runway is assigned for arrivals and one for departures). This decision is not necessarily an optimal planning and may not lead to the optimal runway usage. Runway assignment is not an independent task, because in this case arrivals and departures are assigned regarding to closeness gate and fix locations of the runways.

Some of the undertaken researches are devoted just to the arrival operations planning, considering airlines costs. Because of the dependencies between arriving and departing flights, it is expected that additional cost savings can be accomplished if arrivals and departures are considered simultaneously. Therefore, considering arrival and departure operations planning with runway assignments to increase airport throughput is a must.

**SCHEDULING APPROACH FOR PROBLEM ANALYSIS**

Scheduling is the allocation of resources over time to perform an allocation of tasks. The process of scheduling in general requires both sequencing and resource allocation decisions (Baker, 1974). In order to the objective function be satisfied, not only the sequencing of the arrival and departure operations in each runway but also in runways generally should be distribute optimally. Objective function can include following performance measures: minimizing average runway occupancy time, minimizing maximum runway occupancy time, minimizing average aircraft tardiness from time table, minimizing maximum aircraft tardiness from time table, minimizing number of tardy aircrafts and so on.

**Model formulation:** In modeling of this problem, the Hybrid Flow Shop is used. One of the major advantages of this model to the previously presented models is that the previous model has been considered as a Real World Problem model. In this model the separation time of aircrafts and also the ready time of arrival or (departure) to (or from) the fixed points have been considered. One of the major objectives of airport officials is minimizing delays; therefore selected target function is formulated for 2 Stage Flow Shop with Ready Time as follows that minimizing the delays is usually the goal of the airport authorities; then:

$$\text{Min } Z = \sum_{j=1}^n w_j T_j \tag{1}$$

Subject to:

$$\sum_{k=1}^z X'_{kj} = 1, \forall j: 1 \leq j \leq n, \tag{2}$$

$$\sum_{i=1}^m X_{ij} = 1, \forall j: 1 \leq j \leq n, \tag{3}$$

$$C_{j1} \geq \sum_{k=1}^z P'_{kj} X'_{kj} + r_j, \forall j: 1 \leq j \leq n, \tag{4}$$

$$C_{j2} \geq C_{j1} + \sum_{i=0}^m x_{ij} p_{ij}, \forall j: 1 \leq j \leq n, \tag{5}$$

$$C_{j1} + M \times (3 - X'_{kj} - X'_{kl} - Y'_{lj}) \geq C_{j1} + P'_{kj}, \tag{6}$$

$\forall j, l: 1 \leq j, l \leq n, \forall k: 1 \leq k \leq z,$

$$C_{j1} + M \times (2 - X'_{kj} - X'_{kl} + Y'_{lj}) \geq C_{j1} + P'_{kl}, \tag{7}$$

$\forall j, l: 1 \leq j, l \leq n, \forall k: 1 \leq k \leq z,$

$$C_{j2} + M \times (3 - X_{ij} - X_{il} - Y_{lj}) \geq C_{j2} + P_{ij}, \tag{8}$$

$\forall j, l: 1 \leq j, l \leq n, \forall k: 1 \leq k \leq z,$

$$C_{j2} + M \times (2 - X_{ij} - X_{il} + Y_{lj}) \geq C_{j2} + P_{il}, \tag{9}$$

$\forall j, l: 1 \leq j, l \leq n, \forall k: 1 \leq k \leq z,$

$$T_j \geq C_{j2} - d_j, \forall j: 1 \leq j \leq n, \tag{10}$$

$$C_j, T_j \geq 0, \forall j: 1 \leq j \leq n, \tag{11}$$

$$X_{ij}, Y_{ij} \in \{0,1\}, \forall j, l: 1 \leq j, l \leq n, \forall i: 1 \leq i \leq m. \tag{12}$$

In which:

- $j, l$  : Aircraft subscript (Job)
- $I$  : Runway subscript (Machine)
- $k$  : Approach or departure procedure index
- $n$  : No. of Aircrafts
- $m$  : No. of Runways
- $z$  : No. of approach or departure procedure
- $P_{ij}$  : The processing time of aircraft  $j$  on runway  $I$  (form fix to exit of runway or inversely)
- $P'_{kj}$  : The processing time of aircraft  $j$  on Approach or departure procedure  $k$  (form fix to exit of runway or inversely)
- $w_j$  : Weight factor of aircrafts
- $r_j$  : Ready time of  $j$ th aircraft (in fix)
- $d_j$  : Due date of the aircraft  $j$
- $C_{j1}$  : The completion time of aircraft  $j$  in 1st stage
- $C_{j2}$  : The completion time of aircraft  $j$  in 2nd stage
- $M$  : Large number
- $X_{ij}$  : A Binary variable: 1 if flight  $j$  assigned to runway  $i$  and 0 otherwise
- $X'_{kj}$  : A Binary variable: 1 if flight  $j$  assigned to procedure  $k$  and 0 otherwise
- $Y_{kj}$  : A Binary variable: 1 if flight  $l$  lands earlier than flight  $j$  (in the 2nd stage) and 0 otherwise
- $Y'_{lj}$  : A Binary variable: 1 if flight  $l$  lands earlier than flight  $j$  (in the 1st stage) and 0 otherwise
- $S_i$  : Runway  $i$  approach procedures set
- $T_j$  : Tardiness of aircraft  $j$

Regarding Hybrid 2 stage based on separation time Model, the model is formulated as follows:

It is assume objective function and constraints till constraint is same as 1 to 5.

$$C_{j1} - P'_{ij} + M \times (3 - X'_{kj} - X'_{kl} - Y'_{lj}) \geq C_{j1} - P'_{kl} + S_{i,j}, \tag{13}$$

$\forall j, l: 1 \leq j, l \leq n, \forall k: 1 \leq k \leq z,$

$$C_{i1} - P'_{i1} + M \times (2 - X'_{ij} - X'_{il} + Y'_{ij}) \geq C_{ij} - P'_{ij} + S_{ij,l}, \quad (14)$$

$$\forall j,l: 1 \leq j,l \leq n, \forall k: 1 \leq k \leq z,$$

$$C_{j1} + M \times (3 - X'_{ij} - X'_{il} - Y'_{ij}) \geq C_{j1} + S_{i,j}, \quad (15)$$

$$\forall j,l: 1 \leq j,l \leq n, \forall k: 1 \leq k \leq z,$$

$$C_{i1} + M \times (2 - X'_{ij} - X'_{il} + Y'_{ij}) \geq C_{j1} + S_{j,l}, \quad (16)$$

$$\forall j,l: 1 \leq j,l \leq n, \forall k: 1 \leq k \leq z,$$

$$C_{j1} + M \times (3 - X'_{ij} - X'_{il} - Y'_{ij}) \geq C_{i1} + P'_{ij}, \quad (17)$$

$$\forall j,l: 1 \leq j,l \leq n, \forall k: 1 \leq k \leq z,$$

$$C_{i1} + M \times (2 - X'_{ij} - X'_{il} + Y'_{ij}) \geq C_{j1} + P'_{il}, \quad (18)$$

$$\forall j,l: 1 \leq j,l \leq n, \forall k: 1 \leq k \leq z,$$

$$C_{j2} - P_{ij} + M \times (3 - X_{ij} - X_{il} - Y_{ij}) \geq C_{i2} - P_{il} + S_{i,j}, \quad (19)$$

$$\forall j,l: 1 \leq j,l \leq n, \forall i: 1 \leq i \leq m,$$

$$C_{i2} - P_{il} + M \times (2 - X_{ij} - X_{il} + Y_{ij}) \geq C_{j2} - P_{ij} + S_{i,l}, \quad (20)$$

$$\forall j,l: 1 \leq j,l \leq n, \forall i: 1 \leq i \leq m,$$

$$C_{j2} + M \times (3 - X_{ij} - X_{il} - Y_{ij}) \geq C_{i2} + S_{ij}, \quad (21)$$

$$\forall j,l: 1 \leq j,l \leq n, \forall i: 1 \leq i \leq m,$$

$$C_{i2} + M \times (2 - X_{ij} - X_{il} + Y_{ij}) \geq C_{j2} + S_{j,l}, \quad (22)$$

$$\forall j,l: 1 \leq j,l \leq n, \forall i: 1 \leq i \leq m,$$

$$C_{j2} + M \times (3 - X_{ij} - X_{il} - Y_{ij}) \geq C_{i2} + P_{ij}, \quad (23)$$

$$\forall j,l: 1 \leq j,l \leq n, \forall i: 1 \leq i \leq m,$$

$$C_{i2} + M \times (2 - X_{ij} - X_{il} + Y_{ij}) \geq C_{j2} + P_{il}, \quad (24)$$

$$\forall j,l: 1 \leq j,l \leq n, \forall i: 1 \leq i \leq m,$$

$$Y'_{ij} + Y'_{il} \leq 1, \quad \forall j,l: 1 \leq j,l \leq n, \quad (25)$$

$$Y_{ij} + Y_{il} \leq 1, \quad \forall j,l: 1 \leq j,l \leq n, \quad (26)$$

$$T_j \geq C_{j2} - d_j, \quad \forall j,l: 1 \leq j,l \leq n, \quad (27)$$

$$C_j, T_j \geq 0, \quad \forall j,l: 1 \leq j,l \leq n, \quad (28)$$

$$X_{ij}, Y_{ij} \in \{0,1\}, \quad \forall j,l: 1 \leq j \leq n. \quad (29)$$

**Constraint description**

- (2) : Every aircraft assign to a procedure.
- (3) : Every aircraft assign to a runway.
- (4) : Completion time of aircraft j in procedure k is greater or equal than ready time plus process time of aircraft j in the procedure stage.
- (5) : Completion time of aircraft j in runway i is greater or equal than completion time of aircraft j in procedure stage plus process time of aircraft j in the runway stage.
- (12, 13): Start time between two subsequent aircrafts in procedure stage is greater or equal than Separation time.
- (14, 15): Completion time between two subsequent aircrafts in procedure stage is greater or equal than Separation time.
- (16, 17): Completion time of leading aircraft, between two subsequent aircrafts in procedure stage is greater or equal than completion time of trailing aircraft plus process time of leading aircraft.
- (18, 19): Start time between two subsequent aircrafts in runway stage is greater or equal than Separation time.
- (20, 21): Completion time between two subsequent aircrafts in runway stage is greater or equal than Separation time.
- (22, 23): Completion time of leading aircraft, between two subsequent aircrafts in runway stage is greater or equal than completion time of trailing aircraft plus process time of leading aircraft.
- (24) : Priority constraint in procedure stage for aircrafts j,l.
- (25) : Priority constraint in runway stage for aircrafts j,l.
- (26) : Tardiness constraint: Tardiness of aircraft j is greater or equal than due date of aircraft j subtract of completion time of same aircraft.

**ANALYSIS OF THE SOLUTION**

Because all of the above issues are generalization of  $1 || \sum w_j T_j$  model, all issues are NP-hard. Therefore, to solve them, it is unavoidable to use heuristic techniques (Lawler, 1977; Lenstra, 1977).

For solving this problem, two type methods are used: heuristic method that is the method of adjacent pair wise interchange and meta-heuristic method that is the SA (Simulated Annealing) method.

Due to extensive aspects of the problem and elongation of solving time with exact methods such as LINGO, metaheuristic method is used to solve the problem instead of exact methods. It is important to mention that

In which is separation time between aircraft *l* and *j*, assuming that aircraft *l* is serviced earlier than aircraft *j*.

it is very important to make quick decisions for optimum use of runways. Sometimes this is not possible with exact methods and this is one of the reasons of using SA solution. This algorithm is mainly based on Pair Wise Interchange and includes the following stages.

**Neighborhood search method:** Unlike constructive algorithms, improvement heuristics start with an already built schedule and try to improve it by some given procedures. Their use is necessary since the constructive algorithms (especially some algorithms that are adapted from pure makespan heuristics and some dispatching rules such as the SPT and LPT rules) do not consider due dates (and therefore, they do not consider the minimization of the number of tardy jobs). In this research, some fast improvement heuristics will be investigated to improve the overall function value by dealing mainly with the due date criterion. The iterative algorithms described in the following and in section 5 are based on the pairwise interchange (PI) neighborhoods.

The PI neighborhood exchanges a pair of arbitrary jobs  $\pi_r$  and  $\pi_i$ , where  $1 \leq i, r \leq n$  and  $i \neq r$ . Such an operation swaps the jobs at positions  $r$  and  $i$ , which yields  $\pi = [\pi_1 \dots \pi_{r-1} \pi_i \pi_{r+1} \dots \pi_{i-1} \pi_r \pi_{i+1} \dots \pi_n]$ . For example, assume that the current solution is [4 9 8 7 3 1 6 2 5] and then randomly the couple of job positions to be exchanged is selected, e.g., positions 1 and 3. Thus, the new solution will be [8 9 4 7 3 1 6 2 5]. In the PI neighborhood, the current solution has  $n \times (n-1) / 2$  neighbors (Jungwattanakit *et al.*, 2007).

- Step 1 : Take all aircrafts at stage 1 (procedure stage) in one sequence
- Step 2 : Select two arbitrary aircrafts and exchange their positions
- Step 3 : Divide this sequence aircrafts to K sections
- Step 4 : Assign section 1 to procedure 1, section 2 to procedure 2, ... and section K to procedure K
- Step 5 : Take all aircrafts at stage 2 (runway stage) in one sequence
- Step 6 : Select two arbitrary aircrafts and exchange their positions
- Step 7 : Divide this sequence aircrafts to K section
- Step 8 : Assign section 1 to runway 1, section 2 to runway 2, ... and section to runway K

**Determination of an initial solution algorithm:** Since the flexible flow shop scheduling problem is NP-hard (this is already true for two stages, with at least one stage with multiple machines (Gupta, 1988)), algorithms for finding an

optimal solution in polynomial time are unlikely to exist. Thus, heuristic methods are studied to find approximate solutions. Most researchers develop existing heuristics for the classical flexible flow shop problem with identical machines by using a particular sequencing rule for the first stage. They follow the same scheme (Santos *et al.*, 1996).

According to Graham notation  $F2||L_{max}$  problem is the reduced form of this research problem which is known as a NP-hard problem which results that problem also is a NP-hard (Garey and Johnson, 1978).

Therefore, it is not possible to solve the problem using exact methods in logical time. Instead of exact methods, an innovative method is used to initial solution of this problem. Because the stage related to the runways is the main stage, aircraft is allocated to the runways and based on that, allocation of aircraft to procedures will be specified more.

**Major algorithm:** In order to allocate the aircraft to runways, the major problems become a virtual one in which it is assumed that there is only one stage and for each aircraft a virtual processing time is calculated. This process is as follows:

Step 1 : Virtual processing time of aircraft on aircraft is calculated from the following relationship:

$$P_{ij} + \min_{k \in \text{Runway}(i)} P'_{kj} = P_{ij}^* \quad (30)$$

Step 2 : Prioritize the aircraft based on WEDD algorithm and allocate them to runways according to virtual processing times (in this step, assume that procedure stage does not exist).

Step 3 : After allocation of aircraft to runways, do the time schedule in the major problem in backward form so as to obtain the time of starting landing operations of each aircraft on the relevant runway. (The manner of backward time schedule operations will be explained hereunder).

Step 4 : These times of landing start will be due date for procedures stage. Now based on these due dates for step 1, obtain allocation of aircraft to different procedures and operations finish time through WEDD algorithm.

Step 5 : Based on the obtained allocations in step 2 for runways stage and completion of operations related to procedure step, determine final time schedule of aircrafts according to the real processing time in the runways stage.

Step 6 : Finish the algorithm.

**Backward scheduling algorithm:** Do the following operations for each runway.

- Step 1 : Call the number of allocated tasks to the runway,  $q$ .
- Step 2 : Time of aircraft  $q$  so as to make the time of finishing landing operations equal to its delivery time ( $d_{(q)}$ ). In this case call  $St_q$  the time of starting landing. Also put  $u = q$ .
- Step 3 : Put  $u = u-1$ .
- Step 4 : If  $d_{(u)}$  is the time of delivery of  $u$  aircraft, time the  $u$  aircraft in such a way that the time of finishing landing operations becomes exactly as follows:

$$\text{Min}\{d_{(u)}, St_{(u+1)}\} \tag{31}$$

In this case name the time of starting landing  $St_{(u)}$ .  
 Step 5 : If  $u = 1$ , finish the algorithm. Otherwise proceed to

**WEDD algorithm:** The maximum job lateness and the maximum job tardiness are minimized by WEDD sequencing can be constructed as follows:

- Step 1 : Prioritize the aircraft based on the following sequence:  $\frac{d_{(1)}}{w_{(1)}} \leq \frac{d_{(2)}}{w_{(2)}} \leq \dots \leq \frac{d_{(n)}}{w_{(n)}}$

Which  $d_{(j)}$  and  $W_{(j)}$  are respectively the time of delivery and weight of aircraft with  $j$  priority. Also put  $u = 0$ .

- Step 2 : Put  $u = u-1$ .
- Step 3 : Allocated the aircraft with  $u$  priority to the runway and that can finish landing operations earlier than other runways. (Regarding the time of freeing of runways and aircraft ready time).
- Step 4 : if  $u = n$ , then finish the algorithm, otherwise proceed to step 2.

**IMPROVEMENT OF SIMULATED ANNEALING METHOD**

There are two ways in which SA may be combined with an alternative method; either using the alternative method to provide a good initial solution which SA attempts to improve, or by using SA to provide a good initial solution as a starting point for the alternative method. Johnson *et al.* (1987) provide some experimental results for the graph partitioning problem. They show that both quality of solution and running time may be improved by the use of a good starting solution. When a good initial solution is used, the initial temperature in the cooling schedule is reduced; otherwise the benefits of the

good initial solution will be lost. They also show that starting solutions which take advantage of the special structure of the problem instance being considered seem preferable to those obtained by general heuristics.

The second approach is exemplified by using SA as a way of obtaining a good initial solution for a branch and bound algorithm for integer programming algorithm.

**Iterative simulated annealing algorithm:** An SA algorithm is an iterative search method, in which an initial solution is repeatedly improved by making small local alterations until no such alteration yields a better solution. It was developed by Kirkpatrick *et al.* (1983). An SA algorithm simulates ideas and mechanisms found in the physical annealing of a solid. The concept comes from the field of material science in which a solid is first melted after heated in a high temperature and then it is slowly cooled so that it reaches a thermodynamic equilibrium.

In general, an SA algorithm is a stochastic optimization method for minimizing a function  $f$  over a discrete domain  $S$ . Starting from an initial solution  $s \in S$ , an SA algorithm generates a new solution  $s' \in S$  in the neighborhood of the initial solution  $s$  by using a suitable operator. Concerning the neighborhood, in this research, a PI neighborhood (i.e., two arbitrary jobs are selected and interchanged) was considered. The objective function value of the new solution is then compared to the objective function value  $f(s)$  of the initial solution (remember that the objective function value of the full schedule generated from the job sequence for the first stage is taken). The change in the objective function value,  $\delta = f(s') - f(s)$ , is calculated. If the objective function value decreases ( $\delta < 0$ ), the new solution is automatically accepted and it becomes the point from which the search will continue. If the objective function value increases ( $\delta \geq 0$ ), then a solution with a larger objective function value may also be accepted with a probability, usually determined by a function,  $\exp(-\delta/T)$ , where  $T \in \mathbb{R}$  is a control parameter of the SA algorithm, called the temperature. The role of the temperature  $T$  is significant in the operation of an SA algorithm. This temperature, which is simply a positive number, is periodically reduced every

Table 1: Time assignment of the example in two stages for test problems

AN	RT	CL	WT	DD	RWY1	RWY2	RWY3	PCR1	PCR2	PCR3
1	0	4	0.8	15	6	7	8	6	7	9
2	2	1	0.1	13	2	2	4	2	2	4
3	17	2	0.6	29	4	5	3	4	5	4
4	7	4	0.5	24	6	6	5	7	6	5
5	9	3	0.5	18	4	6	3	5	6	3
6	10	1	0.5	27	6	6	6	6	6	6
7	3	4	0.7	26	2	3	4	3	3	5
8	3	2	0.6	16	2	5	4	3	5	4
9	11	3	0.7	35	6	3	4	6	3	5
10	19	4	0.5	38	5	4	6	6	5	6

AN = Aircraft No., RT = Ready Time, CL = Class, WT = Weight, DD = Due Date, RWY = Runway and PCR = Procedure

Table 2: Results of test problems for LINGO and SA methods

SA results									
Coefficient	T = 0.1			T = 1			T = 2		
	MO	STD	DT (sec)	MO	STD	DT (sec)	MO	STD	DT (sec)
LINGO result									
<b>(Test Problem 1 (5 Aircrafts, 0 Procedure and 1 Runway))</b>									
Objective Function = 0, Duration Time = 13 sec									
0.75	0	0	2	0	0	3	0	0	5
0.8	0	0	4	0	0	6	0	0	7
0.85	0	0	7	0	0	9	0	0	9
0.9	0	0	11	0	0	12	0	0	14
0.95	0	0	21	0	0	23	0	0	27
LINGO result									
<b>(Test Problem 2 (5 Aircrafts, 0 Procedure and 3 Runways))</b>									
Objective Function = 0, Duration Time = 14 sec									
0.75	0	0	3	0	0	4	0	0	5
0.8	0	0	5	0	0	6	0	0	17
0.85	0	0	7	0	0	9	0	0	10
0.9	0	0	9	0	0	11	0	0	13
0.95	0	0	16	0	0	21	0	0	25
LINGO result									
<b>(Test Problem 3 (10 Aircrafts, 0 Procedure and 1 Runway))</b>									
Objective Function = 6.9, Duration Time = 35 sec									
0.75	6.9	0	7	6.9	0	9	6.9	0	11
0.8	6.9	0	10	6.9	0	12	6.9	0	15
0.85	6.9	0	12	6.9	0	18	6.9	0	21
0.9	6.9	0	20	6.9	0	31	6.9	0	32
0.95	6.9	0	42	6.9	0	63	6.9	0	66
LINGO result									
<b>(Test Problem 4 (10 Aircrafts, 1 Procedure and 3 Runways))</b>									
Objective Function = 23.1, Duration Time = 127 sec									
0.75	29.2	1.5	44	29.1	1.3	55	29.1	1.3	55
0.8	27.1	1.6	53	27.5	1.2	68	27.5	1.4	70
0.85	26.3	1.9	75	26.8	1.2	97	26.7	1.5	101
0.9	26.7	1.5	120	26.7	1.3	145	26.3	1.4	160
0.95	---	---	238	---	---	253	---	---	315
LINGO result									
<b>(Test Problem 5 (5 Aircrafts, 3 Procedures and 3 Runways))</b>									
Objective Function = 0, Duration Time = 24 sec									
0.75	0	0	6	0	0	8	0	0	11
0.8	0	0	8	0	0	11	0	0	15
0.85	0	0	11	0	0	14	0	0	18
0.9	0	0	17	0	0	21	0	0	26
0.95	0	0	34	0	0	34	0	0	55

MO: Mean of Objective, STD = Standard Deviation, DT = Duration Time

NT iterations, where NT denotes the epoch length, so that it moves gradually from a relatively high value to near zero as the algorithm progresses according to a function referred to as the cooling schedule (Jungwattanakit *et al.*, 2007).

**Validity of SA method:** Here for proving the validation of SA, several small test problems (10 aircraft, 3 procedures and 3 runways) according to Table 1 designs and then solve with both LINGO and SA method (Table 2).

It is noted that an optimal solution can be obtained by running commercial mathematical programming software, LINGO 8.0, with an Intel Pentium 4, 3.4 GHz, Core 2 Duo CPU with 2.00 GB of RAM.

**Computational results:** Solving the integrated model in macro-dimensional problems (increasing number of aircraft, procedure and runway), SA method is good; because, with increasing the problem dimension, duration time of LINGO increase and it is not applicable for air traffic controllers. Here three problem according Table 3 were considered.

Numerical results and Gantt chart values for these 3 problems, is showed in Table 4-9.

Throughout running the problems, it was found in coefficient 0.95, the duration time of results becomes too long.

It should be noted that in order to be used executively in practice, this is a decision aiding model not a decision making model. At the final stage, air traffic



**Table 3: Time assignment of three problems**

AN	RT	CL	WT	DD	RWY1	RWY2	RWY3	RWY4	PCR1	PCR2	PCR3	PCR4	PCR5	PCR6
1	0	4	0.8	15	6	7	8	4	6	7	9	10	8	7
2	2	1	0.1	13	2	2	4	5	2	2	4	3	9	9
3	17	2	0.6	29	4	5	3	3	4	5	4	4	8	8
4	7	4	0.5	24	6	6	5	4	7	6	5	2	8	8
5	9	3	0.5	18	4	6	3	4	5	6	3	5	4	10
6	10	1	0.5	27	6	6	6	3	6	6	6	5	10	7
7	3	4	0.7	26	2	3	4	3	3	3	5	5	9	6
8	3	2	0.6	16	2	5	4	5	3	5	4	8	11	3
9	11	3	0.7	35	6	3	4	3	6	3	5	8	12	4
10	19	4	0.5	38	5	4	6	4	6	5	6	10	5	6
11	20	1	0.8	18	2	6	8	6	7	7	10	11	4	4
12	20	1	0.7	19	4	7	8	4	2	7	2	10	5	5
13	20	3	0.7	21	3	7	5	5	2	2	3	8	4	9
14	21	2	0.7	22	3	6	6	4	3	5	5	6	6	10
15	23	3	0.3	23	5	4	7	3	7	3	4	6	7	11
16	25	4	0.5	25	6	3	3	4	5	3	6	6	12	8
17	25	4	0.6	26	3	5	4	4	7	4	6	7	9	4
18	25	1	0.3	26	4	4	4	5	2	6	6	8	8	10
19	25	2	0.4	26	5	4	5	3	3	5	7	11	3	8
20	25	4	0.6	26	5	4	4	6	8	6	8	10	5	4

**Table 4: Problem 1(15 aircraft, 3 procedure and 3 runways)**

Coefficient	T = 0.1			T = 1			T = 2		
	MO	STD	DT (sec)	MO	STD	DT (sec)	MO	STD	DT (sec)
0.75	98.9	3.9	32	98.7	3.8	39	97.7	4.8	41
0.8	94.2	3.8	39	88.6	3.7	48	89.7	3.2	53
0.85	87.4	3.7	52	85.6	3.1	68	84.6	3.1	70
0.9	85.1	4.1	62	83.5	2.1	96	84.4	2.2	108
0.95	---	---	---	---	---	---	---	---	---

MO = Mean of Objective, STD = Standard Deviation, DT = Duration Time

**Table 5: Gantt table of problem 1**

AN	1st stage			2nd stage		
	PCR No.	Start time	End time	RWY No.	Start time	End time
1	1	0	6	2	6	13
2	1	6	8	3	8	12
3	1	21	25	2	25	30
4	3	25	30	1	31	37
5	1	16	21	1	21	25
6	1	10	16	3	16	22
7	3	30	35	3	35	39
8	3	3	7	3	22	26
9	3	11	16	1	25	31
10	2	19	24	1	43	48
11	1	28	35	1	37	39
12	3	23	25	1	39	43
13	3	20	23	3	26	31
14	1	25	28	3	39	45
15	3	35	39	2	39	43

AN = Aircraft No, PCR No. = Procedure No., RWY No. = Runway No.  
Objective function = 90.8

controllers are responsible for control and direction of aircraft. The aircraft are classified based on the necessary separation among aircrafts. Time scheduling is entered to the program as delivery due times.

According to the Table 4-9, as one of the very remarkable advantages of this system we can refer to 3 and 10 runway case of the above aircraft. Because the aircraft 7 is the 3rd aircraft that enters the system, according to operating rule, the priority should be given

to the 3rd aircraft on the order of entry (First-Come-First-Serve) and according to wise logic of air traffic controllers; but as it is observed by solving this problem and implementing the program, this aircraft is served on the 15th min and by applying a little delay for it, in order to make the optimal use of runways system; because total delay of using the runways is minimized. This is the case that is known as Inserted Idleness in sequential references of operations and timing. Therefore, by considering them together and presenting an integrated model of management of allocation and operational programming of runways, appropriate measures with a more extended view to make the optimal and maximum use of capacity of airport air section are taken.

It should be noted that based on the results of this research, the SA method is known as the best solving method which provide the most optimal and quickest solution. Attention also should be paid, to the degree of relaxation and speed of the solving other models too.

**Suggestion for temperature reduction coefficient and initial temperature:** One of the other results of this research is determine the temperature reduction coefficient and initial temperature for SA method, according to Table 10-12.

**Table 6: Problem 2 (20 aircraft, 3 procedure and 3 runways)**

Coefficient	T = 0.1			T = 1			T = 2		
	MO	STD	DT (sec)	MO	STD	DT (sec)	MO	STD	DT (sec)
0.75	234.9	4.3	43	234.2	2.7	53	239.1	5.2	59
0.8	206.6	7.2	54	206.3	6.1	66	205.6	4.9	71
0.85	204.1	3.2	73	203.9	4.6	84	203.2	4.9	92
0.9	203.9	6.2	113	201.3	4.9	133	203.3	4.9	141
0.95	---	---	---	---	---	---	---	---	---

MO = Mean of Objective, STD = Standard Deviation, DT = Duration Time

**Table 7: Gantt table of problem 2**

AN	1st stage			2nd stage		
	PCR No.	Start time	End time	RWY No.	Start time	End time
1	2	0	7	1	12	18
2	1	2	4	1	10	12
3	2	33	38	1	38	42
4	3	51	56	1	57	63
5	3	8	12	2	12	18
6	2	10	16	3	16	22
7	3	3	8	1	8	10
8	2	28	33	2	50	55
9	3	12	17	1	18	24
10	3	19	25	2	42	46
11	3	36	46	3	46	54
12	3	25	27	2	35	42
13	3	27	30	1	54	57
14	3	46	51	1	51	54
15	1	27	34	2	46	50
16	2	25	28	2	28	31
17	3	30	36	3	36	40
18	1	25	27	2	31	35
19	3	56	62	1	63	68
20	1	34	42	3	42	46

AN = Aircraft No, PCR No. = Procedure No. and RWY No. = Runway No. Objective function = 200.6

**Table 8: Problem 3 (20 aircraft, 6 procedure and 4 runways)**

Coefficient	T = 0.1			T = 1			T = 2		
	MO	STD	DT (sec)	MO	STD	DT (sec)	MO	STD	DT (sec)
0.75	143.1	5.6	42	141.3	6.2	51	136.2	6.6	54
0.8	134.5	4.2	48	131.9	3.4	65	130.2	3.8	69
0.85	122.6	3.7	72	126.8	3.8	90	123.5	3.8	115
0.9	122.2	2.5	111	123.5	4.1	140	122.7	3.1	158
0.95	---	---	---	---	---	---	---	---	---

MO = Mean of Objective, STD = Standard Deviation, DT = Duration Time

**Table 9: Gantt table of problem 3**

AN	1st stage			2nd stage		
	PCR No.	Start time	End time	RWY No.	Start time	End time
1	2	0	7	1	12	18
2	1	2	4	1	10	12
3	2	28	33	1	33	37
4	4	7	9	3	9	14
5	3	9	12	2	12	18
6	2	10	16	3	16	22
7	3	3	8	1	8	10
8	5	3	14	4	14	19
9	3	12	17	1	18	24
10	6	19	25	4	50	54
11	4	20	31	3	31	39
12	6	25	30	2	31	38
13	4	31	39	4	39	44
14	5	21	25	1	37	40
15	1	27	34	4	47	50
16	2	25	28	2	18	21
17	3	25	31	3	39	43
18	1	25	27	2	27	31
19	6	30	38	4	44	47
20	5	25	30	3	43	47

AN = Aircraft No, PCR No. = Procedure No., RWY No. = Runway No. objective function = 125.7

Table 10: Problem 1(15 aircraft, 3 procedure and 3 runways)

TI	0.1				1.0				2.0				
CO	0.7	0.8	0.85	0.9	0.7	0.8	0.85	0.9	0.7	0.8	0.85	0.9	
MEO	98.862	94.27	87.32	85.09	98.675	88.46	85.64	83.53	97.725	89.66	84.57	84.43	
STD	3.8895	3.7915	3.7106	4.0429	3.7595	3.6317	3.1284	2.7183	4.8553	3.2153	3.0847	2.2579	
MIO	96.0	86.7	81.0	<b>79.1</b>	91.5	83.3	<b>81.0</b>	80.0	88.7	85.9	81.2	81.5	
MIS	79.1	79.1	79.1	79.1	79.1	79.1	79.1	79.1	79.1	79.1	79.1	79.1	
zR	5.08	4.00	2.22	1.48	5.21	2.58	2.09	1.63	3.84	3.28	1.77	2.36	
1-RC	1.0	1.0	0.9867	0.9305	0.1.0	0.9950	0.9816	0.9484	0.9999	0.9994	0.9616	0.9908	
RC	00.0	0.0	0.0132	<b>0.0694</b>	00.0	0.0049	<b>0.0183</b>	0.0515	6E-05	0.0005	0.0383	0.0091	
RAN					1					2			

TI = Initial Temperature, CO = Reduction Temperature Coefficient, MEO = Mean Objective, MIO = Min. Objective, MIS = Selected Min Objective, RC = Reliability Coefficient, RAN = RC Ranking

Table 11: Problem 2 (20 aircraft, 3 procedure and 3 runways)

TI	0.1				1.0				2.0				
CO	0.7	0.8	0.85	0.9	0.7	0.8	0.85	0.9	0.7	0.8	0.85	0.9	
MEO	234.9	206.56	204.09	203.71	234.16	206.31	203.9	201.35	239.02	205.59	203.27	203.29	
STD	4.3122	7.2762	3.7373	6.1794	2.6959	6.0894	4.6166	4.9706	5.2093	4.9521	4.9094	4.9760	
MIO	230.2	<b>194.0</b>	199	195.4	230.2	199.2	195.5	<b>193.8</b>	233.1	199.3	198	195.1	
MIS	193.8	193.8	193.8	193.8	193.8	193.8	193.8	193.8	193.8	193.8	193.8	193.8	
zR	9.53	1.75	2.75	1.60	15.00	2.05	2.19	1.52	8.68	2.38	1.93	1.91	
1-RC	1.0	0.9599	0.9970	0.945	1.0	0.9798	0.9857	0.9357	1.0	0.9913	0.9732	0.9719	
RC	0.0	0.0401	0.0030	<b>0.0548</b>	0.0	0.0202	0.0143	<b>0.0643</b>	0.0	0.0087	0.0268	0.0281	
RAN					2					1			

TI = Initial Temperature, CO = Reduction Temperature Coefficient, MEO = Mean Objective, MIO = Min. Objective, MIS = Selected Min Objective, RC = Reliability Coefficient, RAN = RC Ranking

Table 12: Problem 3 (20 aircraft, 6 procedure and 4 runways)

TI	0.1				1.0				2.0				
CO	0.7	0.8	0.85	0.9	0.7	0.8	0.85	0.9	0.7	0.8	0.85	0.9	
MEO	143.18	134.49	122.62	122.27	141.32	131.9	126.7	123.52	136.48	130.18	128	131.95	
STD	5.5675	4.1648	3.6929	2.5038	6.2480	3.4332	3.7989	4.1101	6.5751	3.8470	3.8346	3.1081	
MIO	134.5	127.6	<b>115.9</b>	116.4	135.3	129.7	119.5	<b>115.2</b>	125.8	128	125.8	125.7	
MIS	115.2	115.2	115.2	115.2	115.2	115.2	115.2	115.2	115.2	115.2	115.2	115.2	
zR	5.03	4.63	2.01	2.82	4.18	4.86	3.04	2.02	3.24	3.89	3.34	5.39	
1-RC	1.0	1.0	0.9777	0.9976	1.0	1.0	0.9988	0.9783	0.9994	0.9999	0.9995	1.0	
RC	0.0	0.0	<b>0.0222</b>	0.0024	0.0	0.0	0.0011	<b>0.0216</b>	0.0006	5E-05	0.0004	0.0	
RAN					1.0					2.0			

TI = Initial Temperature, CO = Reduction Temperature Coefficient, MEO = Mean Objective, MIO = Min. Objective, MIS = Selected Min Objective, RC = Reliability Coefficient, RAN = RC Ranking

According to Table 10-12, minimum objective and good reliability coefficient is shown with underlined numbers. As they show, best coefficient and initial temperature take place in 0.9 and 1.0, respectively.

### CONCLUSION

In this research, for the first time, the process of evolution of scheduling method which encompasses Integrated Model of Runway Assignment and Operations Planning for Airside Capacity Enhancement (ACE) is presented. In this model, 2 stages Flexible Flow Shop method was used.

Regarding the fact that air traffic controllers need decision making tools for assigning aircraft to runways and vice versa, certainly these expert and skilled persons have a limited time to select the best option for the manner of using the runway which may not always lead to the

most optimal option according to the aircraft control work load. This decision making process gets much more sophisticated so that an assistant decision maker appears to be unavoidable.

In this research, two solving method for integration of runway assignment and operations planning model were used. To solve these models, the exact methods were found suitable when the number of aircraft is small. However, for large airports with heavy traffic, the SA method can solve the problem in less time period. Throughout the research, it was found by increasing coefficient till 0.9, the accuracy of results becomes better. To overcome the complexity problem, the auxiliary virtual algorithm was used.

Advantages of SA method are acceptable accuracy in the short time that air traffic controllers can use this model as a decision-aiding and some cases as decision making tools.

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