A REVIEW OF AIRPORT RUNWAY OPTIMIZATION

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Chapter 1

Introduction

Airport capacity continues to be a limiting factor in the face of rising demand for more flights. Air traffic is expected to more than double in Europe and US, and perhaps triple in some regions, over the next 15 years. As a result, the technology and procedures used to manage these flows are struggling to keep pace and capacity is becoming a critical limitation. The current Air Traffic Management (ATM) systems, infrastructure and technology are not sophisticated enough and therefore cannot manage the air traffic and transportation system in an optimal way. Due to significant improvements which have already been achieved in enhancing en-route traffic capacity, the air traffic bottleneck is shifting from en-route segments to airport capacity (and hence runways and gates) (Soomer and Franx, 2008).

Air Traffic Control (ATC) in the busy terminal area is becoming one of the main challenges confronting air traffic controllers. Since building new airports or extending existing ones causes many serious economical, political, geographical and environmental problems, there is a great interest in improving and optimizing airport capacity. In recent years, several researchers have carried out studies in developing optimization models and algorithms to increase airport capacity.

One of the main factors which determines the runway throughput at the airports is the required separation between aircraft during landing and take off. The dependency on the leading and trailing aircraft type for aircraft separation make the sequencing and scheduling an important and non-trivial problem.

The Aircraft Landing Problem (ALP) and the Airport Take-Off Problems (ATP) seek to determine the sequence of aircraft landing on, or taking off from, the available runways at airports in order to optimize given objectives, subject to a variety of operational constraints. While optimally sequencing the landing and taking off of aircraft may increase the runway capacity in theory, it may not always be possible to implement these solutions in practice. For this reason, the challenge lies in putting theory into practice which can simultaneously handle the safety, efficiency, robustness, competitiveness, and environmental issues. This paper re-
views the literature on the airport runway optimization problem, most of which has appeared during the past three decades, and also identifies some key areas for future research.

Our study has investigated techniques and tools of Operational Research and Management Science (OR/MS) in solving the ALP and ATP. Some basic concepts of the ALP and ATP are explained in Chapter 2. Chapter 3 briefly represents general operational constraints, possible objective functions and some modelling techniques for solving the ALP and ATP. A review of the application of OR/MS techniques and tools in the ALP and ATP is introduced in Chapter 4. Finally, a conclusion together with some suggestions for further research is presented in Chapter 5.
Chapter 2

Basic Concepts

2.1 Introduction

An Air Traffic Management (ATM) system aims to assure safety and efficiency of air traffic flows by establishing a set of services. Three types of facilities control the aircraft between two airports. These are the airport traffic control tower, terminal airspace control centre and en-route control centre.

The airport traffic control tower is responsible for ground traffic control, take-off and landing control within about 5 Nautical Mile (nm) and 3000 ft Above Ground Level (AGL) from the airport. The following are the possible positions in the tower: clearance delivery, gate hold, ground control, ground plan, and runway control. The terminal airspace control centres, which are also called approach control airspace or Terminal Radar Approach Control (TRACON), handle departures and arrivals up to 40 nm and 10,000 ft from the airport. The en-route control airspace which is also named Air Route Traffic Control Centers (ARTCC) handle the traffic flow outside the terminal maneuvering area (see Figure 2.1) (de Neufville and Odoni, 2003).

The airspace is divided into a number of geographical regions (some very large and some quite small) known as sectors. A sector can be defined as a volume of airspace managed by a team of controllers. Generally, sectors which handle high-flying en-route traffic are much larger than the busy sectors which handle a large amount of climbing and descending traffic. Busy airspace, such as the London area in the UK, can be subdivided into super-low, low, high, and super-high sectors according to altitude. As a flight proceeds through the airspace, responsibility passes from one sector team to the next. There is a limitation on the number of aircraft that can fly in each sector at any given time, which depends on several factors such as safety, flight geometry, controllers’ workload, weather, surveillance equipment in use, and the training or experience of the air traffic controllers (Filar et al,
It appears that dividing the airspace into smaller and smaller sectors may help in dealing with the increasing traffic demand but it creates its own problems such as increasing the possibility of mistakes by pilots because of changing the radio frequencies more often and increasing the controllers’ workload because of greater need for co-ordination between sectors (de Neufville and Odoni, 2003; Duke, 2009).

### 2.2 Decision Problems

Generally, ALP/ATP consist of the *sequencing, scheduling, and runway assignment* decision problems. The sequencing process determines the sequence aircraft land or take-off from the set of feasible sequences, while the aim of scheduling is to assign Scheduled Landing Time (SLT)/Scheduled Take-Off Time (STT) to each aircraft in the sequence subject to maintaining the required degree of safety (Brinton, 1982; Ernst et al, 1999). When more than one runway is available for landing or take-off, each aircraft has to be assigned to a particular runway. During the peak periods, the demand for landing and take-off may reach or even exceed the runway capacity, which further complicates the decision problems (Bianco et al, 1997).

### 2.3 Dynamic and Static Models

The ALP and ATP models studied in the literature most commonly deal with *static* (off-line) case although some consider the *dynamic* (on-line or real-time) case. In the static version, the model is solved based on a given set of aircraft, where the complete information on these aircraft is assumed to be available. The solutions
may be revised over time as aircraft arrive and new information becomes available. However, there are different levels of uncertainties associated with the information about the aircraft, the operational environment (weather, runway situation, etc.), and taxiways. As time passes, this uncertainty is reduced. Consequently, in real situations, ALPs/ATPs should be solved in a dynamic environment.

2.4 Time Windows

A Scheduled Landing Time (SLT) is generated by air traffic controllers when an aircraft enters the Terminal Maneuvering Area (TMA). It must lie between the Earliest and the Latest Landing time of the aircraft, called the aircraft Time Window. The earliest landing time is the earliest possible time at which an aircraft can land on the runway given its current location, its maximum airspeed and the use of shortcuts. The latest landing time is the latest possible landing time subject to the maximum delay allowance, the slowest possible airspeed, and the fuel constraint.

A Calculated Time of Take-Off (CTOT) is assigned to some aircraft by the Central Flow Management Unit (CFMU) of EUROCONTROL in Brussels if they use congested routes or go to hub airports in Europe. The CTOT limits the time at which aircraft enter these congested areas to smooth the traffic in the airspace and at the airports (Atkin, 2008). Controllers can assign Scheduled Take-Off Time (STT) to each aircraft from five minutes before the CTOT to ten minutes after the CTOT. Therefore, the CTOT defines the time window for take-off of the aircraft.

The time window for an aircraft can be a disconnected set, which means an aircraft can land in any of the specified connected time intervals, although it makes the problem more complicated than the single-interval time window case (Balakrishnan and Chandran, 2006).

2.5 First-Come-First-Served (FCFS)

The simple way of sequencing and scheduling landing aircraft on a single runway is the First-Come-First-Served (FCFS) discipline. It assigns SLT to each aircraft based upon the order generated by the Estimated Landing Time (ELT) of the aircraft. A Trajectory Synthesizer calculates the ELT based on the planned arrival route, cruise speed (also known as the most economical speed or preferred speed), and the standard procedure descent profile. Controllers use it as a reference value in computing delays in the terminal area (Neuman and Erzberger, 1991). The FCFS order also follows the order of the aircraft which line up in a queue for take-off at the holding area. While the FCFS rule is fair in terms of Estimated Landing Time (ELT) or Estimated Take off Time (ETT) and makes the implemen-
tation of all the operational constraints straightforward, it does not necessarily match the preferred landing/take-off order and it does not consider other useful information (Carr et al., 2000). Moreover, it has been established that FCFS rarely provides the best sequence in terms of capacity, average delay or even average passenger delay (Capri and Ignaccolo, 2004).

2.6 Freeze Horizon

Scheduling of the landing and take-off of aircraft can be divided into two periods: the initial and final scheduling horizons. The first horizon for landing aircraft starts at the time the aircraft enter the TMA. The final scheduling horizon or freeze horizon is about two minutes before landing onto the runway (Neuman and Erzberger, 1991). A similar concept applies for the scheduling of aircraft take-off. The first horizon may start after the pushback time and the freeze horizon is two minutes before the take-off time. Generally, the freeze horizon begins by entering the aircraft into the holding area, but it varies based on the taxiway, holding area, and runway configuration.

2.7 Runway Capacity

Idris et al. (1998a,b) state that the runway is the main flow constraint in the airport system. Blumstein (1959) introduces the first important analytical model for estimating the capacity of an arrival runway. The runway capacity (maximum throughput) can be defined as the hourly rate of aircraft operations that are expected to be accommodated by a single or combination of runways. It is generally dependent on the runway occupancy time, mix of aircraft using the runway, availability of taxiways, aircraft type/performance, spacing between parallel runways, intersecting point of runways, mode of operation (segregated or mixed), performance of the ATM systems, weather condition (visibility, wind strength and direction), and noise restriction (Bazargan et al., 2002; de Neufville and Odoni, 2003). The airport capacity model presented by Newell (1979) shows that capacity can increase in mixed-mode. Since increasing the number of runways is often impractical, air traffic controllers aim to use methods and techniques to maximize the available runway throughput.

2.8 Runway Assignment

Airports can operate with different numbers and configurations of runways. These can be a single runway, one or pairs of parallel or intersecting runways, and their
Assigning runway to the landing/take-off aircraft is a tactical decision made by controllers. The runway assignment is typically dependent on the airport configuration, the direction of arriving aircraft (arrival feeder gate), and departure routes of the aircraft (Brinton, 1982), which is normally specified by the flight plan. While an aircraft approaches the runways, adjustments can be made to the flight plan by assigning the aircraft to an alternative runway, which is known as runway allocation, in order to balance both the landing/take-off on each runway and the controllers’ workload. Airline preferences such as parking gate location, taxi time from/to the gate, and controller preferences such as safety, shortest flight time, and low workload can lead a controller to assign a new runway to an aircraft (Isaacson et al, 1997).

2.9 Separation

The prime responsibility of the air traffic controllers is the safety of the flights. Standard vertical and horizontal separations which keep aircraft from becoming dangerously close comprise one of the main ATC safety considerations. The usual standard is set 1,000 ft as the minimum vertical distance between civilian aircraft operating in controlled airspace. The horizontal separations between aircraft vary depending on available ground facilities, the position of the aircraft, the type of aircraft, the airspeed of the aircraft, and other circumstances.

Vortices generated by the aircraft as a consequence of their lift are one of the reasons for the separations. A Wake Vortex (WV) is potentially hazardous because of the rolling moment it may impose on a following wake encountering aircraft. Generally, the WV separation required between consecutive aircraft depends on the airspeeds, landing/takeoff routes, and type of aircraft, and therefore it is sequence dependent. These vortices increase with aircraft size and weight, and heavier aircraft can tolerate more turbulent air. Therefore, when a heavy aircraft leads a lighter aircraft, the lighter aircraft must stay further back than when a heavy aircraft follows a heavy one, or even when a heavy aircraft follows a light one. Obviously, greater separation is required if a faster aircraft follows a slower aircraft than if a slower aircraft follows a faster aircraft.

As consequence of WVs, the International Civil Aviation Organization (ICAO) puts into force separation standards between the leader and the follower aircraft for approach, landing and takeoff to allow safe flight operations. The WV constraints govern the minimum permissible distance interval between aircraft lined up in sequence on the approach to land on the runway or on the queue to take off from the runway.

The simple ICAO’s standard international classification of aircraft into three weight categories (Heavy, Medium, and Light) and introducing distance separa-
tions in integer (or half integers) of nautical miles make air traffic controllers’ job simple at the expense of reducing the capacity (Tether and Metcalfe, 2003). During peak capacity operations, the WV is often a major concern. It effectively determines runway capacity and thus limits airport capacity in the terminal airspace. Such great asymmetries in the minimum required separation distribution, can be an opportunity to reduce the airborne delay by shifting aircraft positions in the landing sequence, but they also cause difficulty when solving an ALP or ATP.

The WV separation has to be considered between all pairs of aircraft, in other words it has to satisfy the triangle inequality, that is:

\[ S_{ik} \geq S_{ij} + S_{jk}, \quad \text{for all aircraft classes } i, j, k \quad (2.1) \]

where \( S_{ij} \) is the WV separation between aircraft \( i \) and \( j \) (Balakrishnan and Chandran, 2006). In multiple-runway situation, the WV separation depends upon the relative positions of the runways. Since, the scheduling algorithms deal with time instead of distance, the separation distances are generally converted into separation times using the fix landing speed of the aircraft type (Beasley et al, 2001).

Other factors that effect separation are the departure routes and speed groups of aircraft. Aircraft take-off along specified predefined departure route called Standard Instrument Departure (SID) routes. In addition to the WV separation, the SID separation has to be considered for two aircraft which follows the same SID route. Moreover, if two aircraft belong to different speed groups, then the separation may have to be modified depending on the two speed groups.

### 2.10 Holding

Controllers may make an aircraft wait before landing/take-off (holding) as a result of traffic congestion, poor visibility, weather conditions, occupancy of runway, or time slot losses. Holding an aircraft is complicated because of the restriction due to a predefined flight plan, congestion, capacity of the holding area and the dependency of the aircraft speed to its type, weather condition, the altitude.

Holding can be managed at stands or at holding points for departing aircraft. An aircraft can be held before landing by using Vector-for-Space (VFS), Holding Pattern (HP), detour, or speed control (see Figure 2.2). VFS and HP are the main holding procedures which are being used by the controllers to manage the waiting process in the terminal area (Artiouchine et al, 2008). VFS manoeuver consists of a deviation of the aircraft away from its original flight plan for a short time and HPs generate a constant prescribed delay for an aircraft. HPs near airports occurs when the aircraft is instructed to join a waiting loop which is called a holding stack as aircraft are stacked at different altitude levels above a feeder fix point (Bianco and Bielli, 1993). As the flights at the lower level are clear to leave the
hold, other flights are laddered down. Several holding patterns may exist in each terminal area and an aircraft can enter a holding pattern several times. Controllers can also use some techniques such as shortcut and speed up to allow aircraft to land before Estimated Landing Time (ELT)(Figure 2.2).

![Figure 2.2: Holding techniques]

### 2.11 Position Shifting

In general, reassigning an aircraft to a landing/take-off time far from its given place in the sequence is not feasible because of the operational constraints in practice. Dear (1976) introduces Constrained Position Shifting (CPS) for ALP to limit the extent of the scheduling revision. It defines a maximum number of positions an aircraft can shift from the FCFS order in a landing sequence, called Maximum Position Shifting (MPS). The CPS method respects the constraint of limited flexibility of controllers in moving aircraft from their initial positions in the FCFS order to new positions. Furthermore, when the MPS is small, it may retain an element of fairness among the aircraft by not deviating far from the FCFS sequence. Furthermore, from the modelling point of view, it reduces the size of the sequencing problem and search space. It has been shown that with a MPS of two or three, the most undesirable landing sequences, such as a heavy aircraft followed by a light aircraft with a high required separation distance, can be avoided and delays can be significantly reduced (de Neufville and Odoni, 2003). The MPS is defined by an integer $k$ defining the maximum allowable number of shifted positions from FCFS, and this environment is denoted by $k$-CPS.

As aircraft get closer to the runway, resequencing of the aircraft becomes increasingly inconvenient from the controllers’ point of view. Relative Position Shifting (RPS) takes this into account by defining the maximum number of shifts (either backward or forward) of the aircraft in the sequence relative to the position
that it occupies. The RPS can be defined by the air traffic controllers for any sub-
sequence of the landing/take-off sequence. Generally, the RPS value decreases
for the subsequences near the beginning of the sequence and can be set to zero in
the freeze horizon (Bianco et al, 1997).
Chapter 3

Problem Definition

3.1 Assumptions and Constraints

In the literature on airport runway optimization, different operational constraints are taken into account. In addition to the separation time, time windows and maximum position shift from the FCFS order, which have been discussed in the previous section, researchers consider precedence constraints and maximum delay. One aircraft may be given precedence over others due to overtaking constraints, airline preferences, or high priority flights (Balakrishnan and Chandran, 2006). Each aircraft has a maximum allowable airborne delay, which should be treated as a hard constraint. In addition, researchers consider the mode of use of the runway, which can either segregated mode or mixed mode. In segregated mode, the runway is solely used for either landing or take-off of the aircraft, while in mixed-mode, it can be used for both landing and take-off. Mixed-mode is usually more efficient than segregated mode since alternating landings and take-offs on the runway is effective in reducing or eliminating delays due to wake vortex constraints (Atkin et al, 2008).

3.2 Objectives

Air transportation has a number of different stakeholders, including ATC, airlines, airports, and government, who each have their own set of objectives. As a result, the formulation of the ALP and ATP may involve the simultaneous optimization of various and not necessarily aligned objectives, which inevitably leads to tradeoffs. The main objectives are as follows.

a) ATC aims to ensure safety and efficiency of the aircraft at the airport. The followings are desirable from ATC perspective (Idris et al, 1998a; Fahle et al,
2003; Lee and Balakrishnan, 2008):

- maximizing the runway throughput
- minimizing the approaching time of aircraft in the air
- minimizing the air traffic controllers’ workload
- maximizing the fairness among the aircraft
- minimizing the aircraft taxi-in/-out time
- minimizing the arrival/departure delay
- maximizing the appropriate balance between arrivals and departures.

b) The airline’s main objectives are:

- minimizing the operating costs (especially fuel costs)
- minimizing the engine run times before take-off
- maximizing the punctuality regarding the landing/take off time in published timetables
- minimizing total passenger delays
- maximizing the adherence to the airline priorities within their flights
- maximizing the connectivity between incoming and outgoing flights.

c) The airport priorities are:

- maximizing the punctuality relative to the operating schedule
- minimizing the need for gate changes due to delays.

d) The government preference is:

- Minimizing the environmental effects (noise and air pollution.)

In addition, for the airport operators, a small delay to the take-off can be beneficial as passengers can allocate more time shopping at the airport.
3.3 Modelling Techniques

The ALP and ATP can be modelled in a number of different ways. The next section provides more details of specific implementations and solution approaches from the literature. However, a number of core approaches are identified below.

Both the ALP and ATP can be formulated as a Mixed-Integer Programming (MIP) problems. Since the problem is NP-hard, the computation time grows exponentially with the number of aircraft, which it makes the approach unattractive for real-time implementation on practical size problems.

The ALP can be viewed as a machine scheduling problem with sequence-dependent processing times and setup times for optimizing objective functions such as makespan and tardiness by penalizing early and late jobs in terms of time windows. The following analogy illustrates the relationship between the ALP as a machine scheduling problem. Each job corresponds to a landing operation of the aircraft; each machine with capacity one represents a runway; the ready time (release time) of the job corresponds to the Estimated Landing Time (ELT) of the aircraft; the starting time of the job represents the Actual Landing Time (ALT) of the aircraft; the completion time of the job corresponds to the time the aircraft frees the runway; and the sequence-dependent processing time between jobs represents the separation between aircraft. There is a crucial difference between the ALP and common machine scheduling problem, which is the minimum required separations must be respected not only between immediate successive jobs (aircraft) but also between any pairs of jobs (Ernst et al, 1999).

The Travelling Salesman Problem (TSP) is one of the most intensively studied problems in computational mathematics. It is generally stated as finding the shortest route for a salesman who is required to visit \( n \) cities once and only once, starting and finishing at the same city of origin. The single-runway ALP can be represented as a time-dependent TSP where the costs of travelling between cities depends on their respective locations and their positions in the tour and by removing the constraint of returning to the starting city. Let each city corresponds to an aircraft; intercity distances represent the separation between aircraft; and the time windows for visiting each city be the landing time windows. The multiple-runway case may also be modelled as multiple-TSP.

Finally, it is natural to consider the ALP/ATP as a queueing system. Different classes of aircraft can be considered as customers of different types who are served by the runways that correspond to servers. The service time of each customer (aircraft) also corresponds to the separation time between the aircraft and its successive one. Different queueing models can be used to represent the ALP/ATP problem depending on the number of runways being used, the mode of operation at each runway (segregated or mixed), and the method of runway allocation by the controllers.
Chapter 4

Literature Review

4.1 Review of Aircraft Landing Problem

The research studies on the ALP are reviewed in this section. The subsections are organized according to the main methodology used in the study.

4.1.1 Dynamic Programming

Dynamic Programming (DP) is a general optimization technique for making sequential decisions. Almost all ALPs can be usefully modelled as DP problems because the models take into account future possible sequencing and scheduling decisions in assessing the current decision. Beginning with the early work of Psaraftis (1978), there have been several attempts to develop efficient dynamic programming algorithm for the ALP.

Psaraftis (1978) shows that ALP is closely related to the classical Travelling Salesman Problem (TSP). Based on the DP approach for solving the TSP, he develops three algorithms for the static case of ALP to examine two alternative objectives, the Last Landing Time (LLT), and the Total Passenger Delay (TPD) with respect to FCFS discipline. Implementation of the CPS concept makes the algorithm remarkable. It shows that CPS does not make the problem harder in terms of computational time for the single runway problem. The complexity of his exact polynomial algorithm is $O(n(n+1)^m)$, where $n$ is the number of aircraft and $m$ is the number of the aircraft classes (Balakrishnan and Chandran, 2006). The algorithms for solving the single runway-unconstrained case, single runway-constrained case, and two runway unconstrained case have been tested on various problem instances.

Based on his previous work, Psaraftis (1980) proposes a DP approach for sequencing jobs on a single machine to minimize the total processing time (Psaraftis,
This algorithm has been adapted for solving the ALP.

A study due to Bianco et al. (1999) shows that a certain production scheduling problem denoted as $1|r_j, \text{seq-dep}|\Sigma C_j$ with $n$ jobs is equivalent to the Cumulative Travelling Salesman Problem with Ready Times (CTSP-RT). A dynamic programming formulation and three lower bounds are proposed for solving the CTSP-RT. Since the problem is NP-hard, two heuristic algorithms have been developed which run in $O(n^2 \log n)$ and $O(n^4)$ time, respectively. Reformulation of the ALP on a single runway as a single machine scheduling problem with release dates and sequence-dependent processing times particularly makes it attractive. Not only the efficiency of the proposed algorithms have been evaluated using randomly generated test instances, but also they have been tested on two realistic ALP problem instances which include 30 and 44 commercial aircraft belonging to four categories. The aircraft are scheduled over a period lasting about 40 minutes, with total aircraft landing time and maximum and average landing delay being considered. As the CPS is not considered as a specific constraint, some aircraft can be delayed excessively.

Bayen et al. (2004) studies the ALP through a formulation as a single machine scheduling problem. It is mentioned that the difficulty of deriving efficient solutions to the problem of air traffic scheduling near airports is the minimization of the holding time generated by circling. A dynamic programming algorithm and linear programming algorithms with relaxation and rounding based are used in the main algorithm. The approximation algorithms alternatively approximate the sum of arrival times of all the aircraft (starting time of all jobs) and the arrival time of the last aircraft (makespan) with relative weightings of 5 and 3, respectively. As different classes of the aircraft are not considered, the required separation between landings is independent of the aircraft type.

More recently, Balakrishnan and Chandran (2006) present a dynamic programming-based approach for a fixed set of aircraft (the static case) in order to maximize the runway throughput (equivalently, minimizing the landing time of the last aircraft or makespan). The problem of scheduling aircraft landings in a CPS environment is considered, subject to various operational constraints imposed by arrival time windows, minimum aircraft separation requirements, and precedence relations. The problem is formulated as a modified shortest path problem on a network with $O(n(2k+1)^{2k+2})$ arcs, where $n$ is the number of aircraft and $k$ is the maximum position shifting (see Figure 4.1). In addition to a source node $s$ and a terminal node $t$, the network consists of $n$ stages, where each stage represents an aircraft position in the final sequence. A node at stage $p$ of the network corresponds to a subsequence of the aircraft of length $\min\{2k+1, n-p+1\}$. If a node at stage $p$ can be followed by a node at stage $p+1$, they are connected by a directed arc. The network shown in Figure 4.1 represents all the sequence combinations of possible aircraft assignments to each position. A pruned network, which is sig-
nificantly smaller than the original network, can be produced by removing nodes which are not part of a path from source to sink (shown in grey) and which violate the precedence constraints.

Let $T(i)$ denote the earliest time that the sequence of node $i$ can begin in a sequence stating at node $s$ and ending in node $i$. The minimum separation between the leading aircraft $i$ and the trailing aircraft $j$ is denoted by $d_{ij}$, and $P(j)$ represents the set of predecessor nodes of $j$. The earliest time that the sequence of node $i$ can begin is represented by $e(j)$, which is the earliest arrival time of the initial aircraft of node $i$, and $l(i)$ denotes the latest arrival time of the initial aircraft of node $i$. The shortest path length in the network from $s$ to $t$, which corresponds to the a sequence with the smallest makespan, can be computed by the following forward dynamic programming recursion.

$$T(j) = \max\{e(j), \min_{i \in P(j): T(i) \leq l(i)} (T(i) + d_{ij})\} \quad (4.1)$$

Note that the density of the pruned network is significantly smaller than the predicted complexity expression in practice. Since the basic network remains the same for the given number of aircraft and MPS, it can be stored and recalled when required. The computational experience of Balakrishnan and Chandran (2006) is described with an implementation of the algorithm on realistic data of the arrival flow at Denver International Airport. It shows that the algorithm runtime is fast for not more than 3 position shifting and at most 50 aircraft for each batch.
Chandran and Balakrishnan (2007) introduce a dynamic programming algorithm to compute the tradeoff curve between the robustness (reliability of a schedule) and throughput based on their earlier work (Balakrishnan and Chandran, 2006). Their proposed algorithm with a time complexity of $O(n(L/\varepsilon)^3)$, where $n$ is the number of aircraft, $L$ is the largest difference between the latest and the earliest landing time over all aircraft, and $\varepsilon$ is the desired output accuracy, is computationally efficient.

More recently, Lee and Balakrishnan (2008) have extended the previous framework proposed by Balakrishnan and Chandran (2006) and Chandran and Balakrishnan (2007) by presenting a dynamic programming algorithm for minimizing the total delay costs of an arrival schedule. Also, the problem of minimizing the fuel costs of the arrival schedule as the main operating cost for most airline, has been studied using the proposed algorithm by allowing the Earliest Landing Time to be less than the the Estimated Landing Time, which is known as Time Advance (TA). The study shows that up to 3 minutes of TA is advisable in most practical cases. By generating 1000 problem instances of 30-aircraft sequences using a Poisson distribution, the tradeoff between minimizing the average delay and maximizing the throughput as objectives, which are not necessarily aligned, has been investigated. It shows that the significant improvements in the average delay are achievable through decreasing the throughput so that it becomes relatively small.

Several polynomial-time dynamic programming algorithms for the ALP, but based on concepts for problems of scheduling jobs, are presented by Brentnall (2006) and Brentnall and Cheng (2008). Six sequencing algorithms which include three DPs, two FCFS rules, and a heuristic that represents a potential algorithm for an operational AMAN (Arrival Manager) systems are implemented. Moreover, four delay sharing strategies include all delay in hold, delay as late as possible, delay as early as possible, and delay evenly throughout the route strategies are implemented. By linking the algorithms and methods to a discrete-event simulation and using several statistical methods, the output from simulations based on Stockholm Arlanda airport model is analyzed.

### 4.1.2 Branch-and-Bound

The tree search approach based on the Implicit Enumeration (IE) scheduling algorithm has been developed for ALP and runway assignment optimization by Brinton (1982) at the foundation of Branch-and-Bound (BB). Static, dynamic, and depth limiting methods are used to reduce the amount of the tree branches which needs to be searched. A weighted combination of cost function terms is considered although the IE algorithm does not depend on the optimization criteria. The methodology is the foundation of the Traffic Management Advisor (TMA) tool of the Center TRACON Automation System (CTAS) developed at NASA Ames.
Research center. The implementation of runway and sequence optimization is discussed, however no detailed computational results have been shown.

Another branch-and-bound (BB) algorithm based upon a 0-1 mixed integer programming formulation is proposed in Abela et al (1993) to minimize the overall linear costs of speeding up or holding of all aircraft in the ALP for the single runway case. Furthermore, a Genetic Algorithm (GA) is presented as an approximate solution approach and it also provides the upper bounds on the optimal solution to the problem. The force feasible and squash heuristics operators are used to ensure that the schedule after crossover satisfies the minimum separation times and are not far out in time. The computational results for problem instances up to 20 aircraft are presented.

A specialized simplex method is proposed in Ernst et al (1999) to find the optimal landing schedule given a partial ordering of the aircraft. They develop a heuristic-based Problem Space Search (PSS) which consists of the simplex algorithm to compute the optimal landing time, a constructive based heuristic to generate a good sequence, and a GA to search the perturbation space. The heuristic algorithm and simplex method are used to obtain upper bound and lower bound for the branch-and-bound algorithm which minimizes the sum of delay by satisfying the separation criteria between all pairs of aircraft. Tightening intervals, upper-bound-based fixing, fixing based data, and interface procedures are used as pre-processing methods to improve the performance of the branch-and-bound algorithm. The extension of the algorithms are shown to take multiple runways into account. The OR-Library (Beasley, 1990) data sets used to evaluate the heuristic and exact algorithms involving up to 50 aircraft on both single-runway and multiple-runway.

In addition to give extensive literature overview on the ALP in Beasley et al (2000), they present optimal solution algorithms based upon Linear Programming (LP)-based tree search for both single- and multiple-runway. The model is based on an earlier MIP formulation by (Abela et al, 1993). Their objective is to minimize the total cost which defines as the deviation from the estimated landing time. Some additional constraints are proposed in order to reduce the zero-one space of the mixed integer formulation and strengthen the LP relaxations. The static ALP is solved optimally for the public data from OR-Library (Beasley, 1990) involving up to 50 aircraft and four runways.

### 4.1.3 Branch-and-Price

The multiple runways case of the ALP has been addressed by Wen (2005) and Wen et al (2005) to optimize the total deviation from the estimated landing time for each aircraft at the airport. It has been formulated as a set partitioning problem with side constraints on the number of runways. A branch-and-price exact
algorithm is developed and tested using the problem instances from OR-Library (Beasley, 1990) which include 50 aircraft and 4 runways. The experimental results show that the linear relaxation of the set partitioning model provides better lower bound than the linear relaxation of the mixed integer programming and all problems can be solved by generating less than 450 columns and exploring 12 branch nodes.

4.1.4 Heuristics

A heuristic algorithm for the dynamic ALP based on Constraint Position Shifting (CPS) concept is presented in Dear and Sherif (1989, 1991). The CPS technique is applied to both static and dynamic version of the problem. Computational results are presented for involving up to 500 aircraft and one runway.

4.1.5 Meta-heuristics

Genetic Algorithm

Since, Genetic Algorithms (GA) are global and parallel search techniques that use the concepts of the evolutionary theory and natural genetics, they are able to progress towards solutions for realistic optimization problems in real-time situations.

Generally, the order of each aircraft in an optimal landing queue is used to construct chromosomes and it can even include the assigned landing time of each aircraft (Beasley et al, 2001).

One of the first and the simplest application of the GA in minimizing the earliness/lateness of the ALP is investigated by Stevens (1995). Three minutes separation has been considered between the leading aircraft and trailing aircraft within the one hour scheduling horizon and an aircraft cannot be asked to land more than three minutes earlier than its optimal landing time. Three experiments have been performed on ten data sets involving up to 40 aircraft and two runways.

Based on early work done by Stevens (1995) on the permutation based approach, Ciesielski and Scerri (1997, 1998) compare two GA algorithms for real-time ALP dynamically in terms of percentage of valid solutions and best fitness by specifying a 30 seconds time slot and variable times between landings. The first algorithm builds the new schedule from the scratch and the second one seeds it from the population left at the end of the last problem by removing landed aircraft and inserting new arrival aircraft to scheduling horizon. The computational results are presented for two data sets including 28 aircraft in a 37 minutes period and 29 aircraft in a 38 minute period on two runways.
Cheng et al (1999) design four different genetic schemes for solving the multiple runway ALP. The minimum separation matrix is specified based on the aircraft types and aircraft are not allowed to be scheduled earlier than their corresponding Estimated Landing Times. The sum of all the delay squared is used as the fitness of the chromosome pair to prevent loading up one flight with a long delay. Two chromosomes are used in the first formulation to present the landing sequence and the runway assignment. In the second and third schemes, each chromosome addresses a priority list for the flights. In spite of the first three schemes which use GA approach, the last scheme is based on a Genetic Programming (GP) approach and chromosomes are defined as mathematical operations and functions. One instance involving 12 aircraft and three runways are used to evaluating the four strategies.

A Population Heuristic (PH) is developed by Beasley et al (2001) to improve the single runway utilization. The algorithm aims to minimize the squared deviations from estimated landing time in the presence of five separation criteria, since the aircraft are classified into five categories at London Heathrow airport, and the time window restriction for static ALP. The results are presented for a single problem instance from different data sets relating to landing based on observations during a busy period at London Heathrow airport.

Later, Hansen (2004) examines the efficiency and effectiveness of GA and GP methods in solving ALP based on the formulation developed by Cheng et al (1999). Applying four genetic search methods on four different test scenarios show that the GP method provides the best fitness value and the solutions can support the controllers in the real-time situations.

Regarding to the objective function, three different formulations are presented in Capri and Ignaccolo (2004) respect to minimizing the delays which depends on the aircraft class, maximizing the system capacity, and minimizing the sum of the landing times to solve the ALP. The static models which consist of the GA, the GA with maximum landing time constraint, Cheapest Insertion Heuristic (CIH) algorithm (Bianco et al, 1997), and FCFS algorithms have been compared using four test problem cases proposed by Bianco et al (1997). The performance of the dynamic model is evaluated by four test problem cases up to 30 aircraft which characterized by different arrival intervals, Relative Position Shifting (RPS) constraint, and maximum landing time.

The Receding Horizon Control (RHC)-based GA introduced by Hu and Chen (2005a), minimizes the airborne delay which is the deviation of Actual Landing Time (ALT) from Estimated Landing Time in a dynamic environment. The RHC also known as model predictive control, is an N-step-ahead online optimization strategy.

The mutation operator is adopted and no crossover operator is used because of the special structure of the chromosomes in Aircraft Landing Problems (ALPs).
The performance of the developed RHC-based GA algorithm is compared with algorithm introduced in Bianco et al (1997) and a conventional GA algorithm which are based on the Conventional Dynamic Optimization (CDO) using test problem instances from Bianco et al (1997). Moreover, the ALP is modelled using RHC concept and its performance is evaluated under different levels of uncertainties and congestion in Hu and Chen (2005b).

The comparison of the RHC with some other optimization strategies is presented in Figure 4.2 (Hu and Chen, 2005b). It shows the \textit{off-line} strategy optimizes ALP for the entire time horizon, the \textit{one-step-ahead adjustment} makes adjustment only for the current time interval, the \textit{conventional dynamic optimization} optimizes ALP over the horizon from the current time and at the beginning of each interval repeats the same procedure, and the \textit{RHC} optimizes the ALP over the receding horizon and repeats the same procedure at the beginning of each interval based on new information.

![Figure 4.2: Different Optimization Strategies](image)

Later, Hu and Paolo (2008) present a new construction of chromosome as 0-1-valued matrix based on neighbouring relationship between each pair of aircraft. The binary representation makes easier to adopt an efficient uniform crossover operator. The proposed binary-representation-based GA is compared with the permutation-representation-based GA introduced in (Hu and Chen, 2005a) for static and dynamic cases.

Moreover, Hu and Paolo (2009) design a GA with uniform crossover for the multi-runway ALP using the following relationship between aircraft to construct the chromosomes rather than order of the aircraft in the queues. Suggested method is compared with the GP method in Hansen (2004) and the extended version of the GA in Hu and Chen (2005a).

Two different population heuristics, Scatter Search and Bionomic Algorithm, are applied in Pinol and Beasley (2006) paper for the multiple-runway ALP. Two different objective functions, linear and non-linear, are considered. The objective uses a non-linear function is based on the difference between the actual (scheduled) landing time, \( x_i \), and the estimated (target) landing time, \( T_i \). The aim is to
maximize the overall aircraft contribution by considering penalty for landing after $T_i$ which is $-(x_i - T_i)^2$ and the gain for landing before $T_i$ which is $(x_i - T_i)^2$.

$$\text{Maximize } \sum_{i=1}^{n} D_i, \quad D_i = \begin{cases} -d^2 & \text{if } d \geq 0, \\ +d^2 & \text{Otherwise.} \end{cases} (4.2)$$

The second objective minimizes the cost that occurs for each aircraft which linearly dependent on deviation from the estimated landing time. If an aircraft, $i$, lands before the estimated landing time, the corresponding cost deviation is deduced from slope $g_i$ and if it happens after the estimated landing time, the cost is deduced from slope $h_i$. Eq.(4.3) displays the function which $\alpha_i$ and $\beta_i$ refer how soon or late an aircraft lands.

$$\text{Minimize } \sum_{i=1}^{n} (\alpha_i g_i + \beta_i h_i) \quad (4.3)$$

Computational results presented involving up to 500 aircraft and 5 runways.

**Ant Colony**

Ant Colony Optimization (ACO) as a constructive metaheuristic technique with biological foundation has been examined to solve Aircraft Landing Problem (ALP) by Randall (2002). Algorithm tries to minimize the difference between a estimated landing time and the actual landing time for each aircraft subject to a specified time window and the separation criteria. There are penalties associated with landing either later or earlier than a estimated landing time (Beasley et al., 2000). Six problem instances from Beasley (1990) has been used for experimental test and show that the quality of the solution is not as good as Beasley et al (2000).

**4.1.6 Other Methods**

**Queueing Theory**

The ALP is considered as a special queueing system with the incoming aircraft as customers of different types and separation time between the $n$th and the $n + 1$st aircraft as the service time of the $n$th customer in Bauerle et al (2007). The single runway problem is modelled as an M/SM/1 queueing system, where 'SM' stands for 'Semi-Markov'. The stability condition and average waiting time is also derived. Several routing heuristic strategies are studied and compared with respect to the average delay for assigning aircraft to two runways.
4.1.7 Comparison

Some research studies try to compromise different algorithms for solving the ALP. Fahle et al (2003) consider the simplest model of single runway ALP with time window and separation constraints in a static environment. They present four exact methods including a Mixed Integer Programming (MIP) model which uses continuous time, an Integer Programming (IP) formulation that deploys discrete time and they are both proposed by Beasley et al (2000), the other two exact methods consist of a Constraint Programming (CP) model, and a Satisfiability Problem (SAT) formulation. In addition to the exact methods, two local search heuristics, a Hill Climbing (HC) algorithm and a Simulated Annealing (SA) algorithm, are also developed. Six mentioned methods have been evaluated using three problem instances up to 123 aircraft in terms of quality, speed, and flexibility.

In another article, Beasley et al (2004) adopt the LP-based tree search (Beasley et al, 2000), a heuristic algorithm (Beasley et al, 2000), and a population heuristic (Beasley et al, 2001) to solve dynamically the ALP as a displacement problem. The computational results are presented for two sets of test problems involving up to 500 aircraft and five runways.

4.2 Review of Aircraft Take off Problem

It seems that researchers are more interested in ALP than ATP as most of the literature studies have focused on ALP and there are few studies on ATP.

The flow constraints and the dynamics of the airport systems are studied in Idris et al (1998b,a). They analyze the departure flow at Logan airport. It shows that the airport is a complex queuing system. As aircraft compete for limited resources such as gates, ramp, taxiways and runways queues are built on the surface of the airport. It is concluded that the runway system is the main flow constraint and cause delays.

4.2.1 Dynamic Programming

A dynamic programming algorithm is proposed for sequencing take-off aircraft at one of the simplified holding point at London Heathrow airport by Craig et al (2001). Some possible strategies for sequencing the take-off aircraft at stands are also considered in their research.

Based on the model which has been proposed in Balakrishnan and Chandran (2006) for ALP, they introduce a dynamic programming recursion for ATP in Balakrishnan and Chandran (2007). The approach is also extended for multiple-runway and active runway crossing for ATP.
4.2.2 Heuristics

A two-stage heuristic algorithm for solving the runway operation planning problem is introduced in Anagnostakis and Clarke (2002, 2003). The first stage aims to maximize the throughput by sequencing the departure class slots where ignores the downstream constraints. The second stage is formulated as an integer programming model to assign aircraft to class slots and to minimize the delay-based objective function by fulfilling the remaining constraints. The approach is completely explained in Anagnostakis’ thesis (Anagnostakis, 2004).

4.2.3 Meta-heuristic

The initial model of the simplified ATP at London Heathrow airport including the holding point structure is studied in Atkin et al (2004). Different search heuristic algorithm have been investigated and they have been concluded that Tabu search performs the best among the other search techniques. Later, the model is described in detail in Atkin et al (2006) and the effects of the different constraints on the scheduling the ATP are investigated.

In Atkin et al (2007), a hybrid approach which uses different search methodologies and a heuristic approach are proposed to solve the static version of the ATP. The following weighted multi-objective function (Eq.(4.4)) has been considered.

\[
\text{Minimize } \sum_{i=1}^{n} (W_{1}(d_{i} - h_{i}) + W_{2}(\max(0, c_{i} - a_{i}))^{2} + C(d_{i}, b_{i}, l_{i}, h_{i}) + P(c_{i}, a_{i}, v_{i}, s_{i})).
\]

(4.4)

where \(a_{i}\) represents the position of the aircraft \(i\) in the arrival order at the holding point, \(v_{i}\) displays the weight category of the aircraft \(i\), \(s_{i}\) represents the speed group of aircraft \(i\), \(h_{i}\) stands for the SID route of the aircraft \(i\), \(b_{i}\) shows the earliest time which aircraft \(i\) can take off, \(l_{i}\) represents the latest time which aircraft \(i\) can take off, \(c_{i}\) displays the position of the aircraft \(i\) in the take off order, \(d_{i}\) shows the take off time of the aircraft \(i\) in the schedule, and \(W\) represent the weight of the objective. The weighted multi-objective function includes the weighted sum of delay, reordering cost, CTOT cost, and the additional penalty cost to apply penalties to schedules which delay certain types of aircraft and aims to avoid penalising these aircraft.

The introduced model is evaluated using six time period data of the London Heathrow airport. The result shows that the availability of more information about the aircraft taxiing around the runway can reduce delays and improve the CTOT compliance.

Although Atkin et al (2007) evaluate the performance of the improved model is evaluated with imprecise information in Atkin et al (2008) by assuming that
there is complete information about the taxiing aircraft. The improvement includes the possibility of swapping between two identical or similar cost schedule over time, considering the taxiway congestion, and proving some guarantee of the value of the schedule. The extended work with more details is also presented in Atkin’s thesis (Atkin, 2008).

### 4.2.4 Constraint Satisfaction

A constraint satisfaction model is introduced for ATP in Leeuwen et al (2002). The ILOG solver and scheduler are used as tools to model and to solve the problem. The flights are mapped onto activities, the taxiways, runways, and exit points of an airport are modelled as resources, and different type of constraints such as take off order, timeslot, separation are listed as temporal or resource constraints in the ILOG environment. The result of the model for real data from Prague airport for up to 12 aircraft in a 50-minute time interval is also presented.

As the problem size gets larger, the model fails to find the solution in a reasonable time. Leeuwen and van Hanxleden Houwert (2002) introduce the constraint relation techniques to overcome the highly complex or conflicting situation in practice. The constraints are divided into different sets of soft constraints which can be relaxed and the hard constraints which are not allowed for relaxation. Conflicting additional controller-imposed constraints, timeslot constraints, and preferred runway constraints are considered as soft constraints.

### 4.2.5 Queuing Model

A simple queuing model of the departure system is proposed by Pujet et al (1999) and is evaluated using runway configuration and traffic data. The intention is to relieve the departure traffic congestion on the airport surface.

### 4.3 Review of Runway Scheduling Problem

There are couple of studies on airport runway optimization which analyze the landing and take-off operations at the same time.

#### 4.3.1 Dynamic Programming

Trivizas (1998) introduces a dynamic programming scheduling approach for solving the static runway scheduling problem optimally based on the Constraint Position Shifting (CPS) concept. The mixed-mode, segregated-mode, and multiple-runway are considered in his research study. The experimental results obtained
with real traffic data and airport configuration shows that even a reasonable value such as $MPS = 3$ can increase the capacity up to 20 percent.

### 4.3.2 Heuristic

A model for scheduling the landing and take off aircraft in the Terminal Manoeuvring Area (TMA) is introduced in Bianco et al (2006). The proposed deterministic jobshop scheduling model can represent several operational constraints and different runway configurations. It analyzes the runway, TMA, inbound and outbound paths, fixes and holdings as unique system. The solution method is based on a fast local search heuristic algorithm. The experimental results using real data of Milan-Malpensa and Rome-Fiumicino airports shows that the average delay may be reduced by more than 40% and the TMA capacity may increase up to 30% in comparison with the FCFS sequencing scenario.

### 4.3.3 Software

There are a number of software systems available to help controllers managing the traffic flow. Although, some of the crucial tasks of ATC and some aspect of scheduling are still performed manually.

**CTAS**

NASA Ames Research Center, in cooperation with the Federal Aviation Administration (FAA), has been developing the most extensive suite of software decision support tools (DSTs), known as the Center-TRACON Automation System (CTAS) as a set of tools to assist air traffic controllers in managing complex air traffic control flows which aim to improve the efficiency and the safety using real-time flight plan, track data for all aircraft of interest, and up-to-date weather information (Erzberger, 1992).

The main tools of CTAS are: Traffic Management Advisor (TMA) and Final Approach Spacing Tool (FAST). TMA is a time-based planning tool that assists controllers with sequencing and scheduling of arrival aircraft in balancing airport capacity. The most important advisors consist of estimated landing time, scheduled landing time, and delay values for each aircraft. The Dynamic Planner (DP) performs the main automation function of the TMA and generates the schedule landing aircraft. FAST give advice advisors to controllers in spacing aircraft on final approach. The main advisories are runway assignment and landing sequence for each aircraft.
AMAN

Arrival Manager (AMAN) proposed by EUROCONTROL Experimental Center (EEC) is a computerized DST which helps the controllers to sequence arrival flights. AMAN assigns each aircraft to a destination runway and generates the sequence of landing flights and provides the controller with the corresponding control actions to expedite the traffic efficiency using flight plans and radar updates information. The AMAN sequence calculation process is configured to have specific criteria (minimum total delay) applied for delay distribution in a fair and unbiased manner (EUROCONTROL, 2005).
Chapter 5

Discussion

5.1 Government Plans

Increasing air traffic over the next 15 years puts pressure on air navigation service providers around the world to improve safety levels, reduce delays and cut the costs, even though the current ATM systems are not be able to fulfil these future demands. This is the reason behind the implementation of the SESAR and NextGen air traffic management systems. SESAR (Single European Sky ATM Research) is a European air traffic control infrastructure modernization program which aims to eliminate the fragmented approach to European Air Traffic Management (EATM), to transform its system, to synchronize all stakeholders, and to federate resources (EUROCONTROL, 2009). The Next Generation Air Transportation System (NextGen) is the transformation of entire air transportation system which uses twenty first century technology to support the current and future demand for aviation services in the United States (FAA, 2009).

5.2 Key Results

After reviewing the research studies on ALP and ATP and observations of controllers’ works at London Gatwick airport and Stockholm Arlanda airport, we would like to highlight the following key results.

• Practical vs. Theoretical Models
  As it has been explained above, many theoretical models may show an increase on the capacity of a runway, but it may not be necessarily possible to implement them in real situations. The problem can occur because of ignoring some critical operational constraints in the modelling, relaxing some
of the hard constraints in obtaining a solution, or requiring unreasonable computational resources.

- **Quick and Good vs. Slow and Optimal Solutions**
  Effectiveness is one of the essential properties of a solution technique which can demonstrate the usability of the method in reality. In real situations, controllers are interested in algorithm which can quickly (in a matter of seconds) find a good solution (near-optimal) rather than an optimal solution achieved after a lengthy computation. Many algorithms that are proposed in the literature take far too long to be run by air traffic controllers in real time.

- **Defining the Objective Functions and Constraints**
  With different stake holders (airports, airlines, ATCs, and government), finding the correct optimization criterion is a difficult job. Moreover, careful attention needs to be paid to define constraints so that the algorithm produces solutions that can be potentially operationalized.

- **Robustness and Flexibility**
  There are different level of uncertainties associated with the information about the ATP/ALP, as typically happens in a dynamic environment. However, most studies consider a static rather than a more realistic dynamic environment. Therefore, resequencing and rescheduling of the landing and take-off of aircraft should be taken into account. The model should generate robust, flexible, and adaptable sequences that can accommodate sudden changes.

- **More Focus on the Decision Problem than the Control Problem**
  To the best of our knowledge, there are more research studies on the decision part of the ALP/ATP than control aspects. In other words, deriving the sequence and schedule for the landing/take-off of aircraft are more often investigated than determining how to land/takeoff in the assignment slot. This is one of the reasons that most of the theoretical research cannot be implemented in the real-world.

- **Increasing the Number of Separation Categories**
  Currently, ICAO classifies the aircraft into three categories. Since WV separation is one of the main factors which affects the runway throughput and hence delay, extending the aircraft classes may increase the runway capacity. On the other hand, it may increase the controllers’ workload which can be done by developing new decision support tools.
• **Integrated Model**
There are several models that solve problems involving individual components of airport operations relatively effectively. However, a major challenge is to form an integrated model. Possible types of integration include: integrating runway scheduling, ground movement controlling, and gate assignment; scheduling take-offs and landings at the same time which requires runways at several airports to be scheduled simultaneously.

• **Throughput, the Most Critical Objective**
Although, different objective functions such as delay, fuel cost, punctuality, etc have been considered in the literature studies, in real world the most important and sometimes the only objective which has been considered by the controllers in sequencing and scheduling of the landing and take off aircraft is the throughput. It could have happened because of the lack of updated information in advance, workload, and shortage of the decision support tools.

• **Availability of Information in Advance**
There is a great benefit to be gained if the precise information become available for controllers as early as possible. One aim of the Collaborative Decision Making (CDM) is to provide the information for all parties (airport, airlines, and ATC) in advance. It helps controllers to schedule landing and take-off flight with better perspective of the system in the future.

• **ATP as an Extension of ALP**
Some research studies on ALP discuss that their model and solution methods can be extended for ATP. We believe that these two problems are somehow completely different. ATP is also a more complicated problem than the ALP because of the level of uncertainty and type of the operational constraints; So the model which has been developed for ALP cannot be easily modified for ATP.

• **US vs. Europe**
Definitely, there are more research studies which have been done on ATP and ALP in the US than the Europe and unfortunately there is no collaboration between these two communities. On the other hand, the number of available runways per airport in the US is generally more than the Europe and it may change the types of problem modelling and operational constraints. We think research studies on ALP and ATP are noticeably of different type in the US and in the Europe and joint research project can be a good opportunity for both communities for further improvements.
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