DOKUZ EYLÜL UNIVERSITY
GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES

SINGLE AIRPORT GROUND HOLDING PROBLEM: AN APPLICATION IN ADNAN MENDERES AIRPORT

by

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October, 2011

İZMİR

SINGLE AIRPORT GROUND HOLDING PROBLEM: AN APPLICATION IN ADNAN MENDERES AIRPORT

A Thesis Submitted to the Graduate School of Natural and Applied Sciences of Dokuz Eylül University In Partial Fulfillment of the Requirements for The Degree of Master of Science in Industrial Engineering, Industrial Engineering Program

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M. Sc THESIS EXAMINATION RESULT FORM

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ABSTRACT

Traffic congestion is a critical problem in the air transportation systems. Congestion problem occurs whenever the capacity of airport runway systems and/or Air Traffic Control (ATC) sectors is exceeded over a period of time. It is mostly associated with peak traffic hours of the day or peak travel times in the year, as well as with periods of poor weather conditions when airport or en route sector service rates can be significantly reduced. In the absence of the long-term capacity improvements that can be obtained through the construction of additional runways or through advances in ATC technologies, traffic flow management (TFM) is the best available way to reduce the cost of delays.

Ground-holding ("gate-holding" or "ground-stopping") is typically imposed on aircraft flying to congested airports or scheduled to traverse congested airspace. It involves the action of delaying take-off beyond a flight's scheduled departure time. The initial approach of modeling ground holding problem is studied as “Single-Airport Ground Holding Problem (SAGHP)” which proposes solutions to the problem of deciding the optimal planning for an airport by taking into account the limitations with regard to the number of landing and take-off operations that can be carried out in a given time interval.

The aim of this study is to propose a mathematical model for a real-world SAGHP, which deal with the allocation of airport runway capacity and operational capacity of ATC services to expected demand so that total weighted tardiness of flights is minimized. The problem is formulated as an integer linear programming model based on the practical constraints through the analysis of air traffic control services in İzmir Adnan Menderes Airport. The proposed model is evaluated under different traffic scenarios (i.e., low, medium and high level of congestion). The performance criteria are considered as total weighted tardiness, total number of delayed flights and total tardiness due to arrival/departure flights. Computational experiments for the various data sets are carried out by using CPLEX problem solver and the results are discussed.

Keywords: air traffic flow management, single airport ground holding problem, integer programming

TEK MEYDANLI YERDE BEKLEME PROBLEMİ: ADNAN MENDERES HAVALİMANINDA BİR UYGULAMA

ÖZ

Hava trafiği sıkışıklığı hava taşımacılığında ciddi bir problem teşkil etmektedir. Sıkışıklık problemi belirli bir zaman periyodunda hava trafik kontrol sektör kapasiteleri ve/veya meydan kullanım kapasiteleri aşıldığında ortaya çıkmaktadır. Bu durum, havaalanı ya da hava sektörleri hizmet oranlarının önemli ölçüde azaldığı kötü hava koşullarında, günün en yoğun trafik saatlerinde ya da yılın en yoğun trafik zamanlarında gerçekleşmektedir. Ek pist yapımı ya da hava trafik kontrol teknolojilerindeki gelişmeler ile sağlanabilecek uzun dönem kapasite iyileştirmelerinin yanı sıra, gecikme maliyetlerini düşürmede yerde bekleme yaklaşımlarını da içeren hava trafik akış yönetimi en uygun yöntemdir.

Yerde bekleme yaklaşımları genel olarak yoğun meydanlara uçan uçaklara veya yoğun hava sahalarına planlanan uçuşlara uygulanmaktadır. Bu yaklaşım, bir uçuşun planlanan kalkış veya iniş zamanından sonrasına ertelenmesini içermektedir. Yerde bekleme probleminin ilk yaklaşımı, bir meydan için belirli zaman aralıkları içinde gerçekleştirilecek kalkış ve iniş sayısıyla ilgili kısıtlamaları dikkate alarak en uygun planlanmayı çözmeye çalışan, “Tek Meydanlı Yerde Bekleme Problemi” dir.

Bu çalışmanın amacı, uçuşların ağırlıklandırılmış toplam gecikmesini en küçüklemek amacıyla, meydan kapasitesinin ve hava trafik kontrol hizmetleri işletme kapasitesinin beklenen talebe tahsis edildiği bir gerçek hayat tek meydanlı yerde bekleme problemini matematiksel modelleme yaklaşımı ile çözmektir. Problem, İzmir Adnan Menderes Havalimanı hava trafik kontrol hizmetleri incelenip operasyonel kısıtlar göz önüne alınarak, doğrusal tam sayı programlama modeli olarak formüle edilmiştir. Önerilen model üç farklı trafik senaryosunda değerlendirilmektedir (düşük, orta ve yüksek seviye sıkışıklık). Performans ölçütü olarak, toplam ağırlıklandırılmış gecikme ve toplam geciken uçuş sayısı göz önünde bulundurulmaktadır. Farklı veri kümeleri için yaratılan problemler CPLEX paket programı kullanılarak çözülmüş ve sonuçlar tartışılmıştır.

Anahtar Sözcükler: hava trafik akış yönetimi, tek meydanlı yerde bekleme problemi, tamsayı programlama

CONTENTS

CHAPTER ONE
INTRODUCTION

1.1 Motivation of the Research

In recent years, the increasing demand for air transportation has led to greatly use of air traffic networks. An *air traffic network* is composed of airports, airways and sectors (i.e. subsets of the airspace). Each of these elements has its own limited capacity (Gilbo, 1993). The airport capacity, measured in terms of allowed movements (landings and takeoffs) for a given time period, is a quantity that can be estimated with reasonable accuracy. It is determined by the airport characteristics (i.e. location, number of runways, topology, etc.), safety requirements and weather conditions. The sector capacity, on the other hand, is described as the number of aircrafts that can simultaneously be controlled by the air traffic controllers of a sector in a given time interval (e.g. an hour) (Andreatta, Brunetta, & Guastalla, 1998).

The technology and procedures used for managing air transportation have advanced evenly over 60 years to handle increased traffic load and complexity in air traffic networks. However, incremental changes in technology and procedures are no longer sufficient to keep up with the growth in traffic. Traffic levels are growing at a rate of 4% to 6% each year in most developed economies and demand is projected to exceed capacity within a decade (International Civil Aviation Organization [ICAO], 2004). In the 2006 annual report of the U.S. Federal Aviation Administration Air Traffic Organization, it is noted that "using our current approach, air traffic controllers will not be able to handle traffic at 25 percent above today's levels. Air Traffic may increase to this level much by 2016 (Neal, Flach, Mooij, Lehmann, Stankovic, & Hasenbosch, 2011).

When air traffic demand exceeds the capacity of airport runway systems and/or of air traffic control (ATC) sectors over a period of time, congestion arises. It is mostly associated with peak traffic hours of the day or peak travel times in the year, as well as with periods of poor weather conditions when airport or en route sector service rates can be significantly reduced. Congestion leads to delays in departures and queues before landing. Delays cause significant costs in the forms of inconvenience to passengers and large losses to air companies. It can also deteriorate the airspace safety (Ball, Chen, Hoffman & Vossen, 2000).

In the European airspace including Turkey, many sectors are often congested. Additionally, the saturation point in terms of the capacity is occasionally reached in most of the airports during the operating periods. According to delay statistics reported by Eurocontrol, the average delay per departure from all causes increased by 40% to 14.8 minutes in 2010. The percentage of flights delayed by more than 15 minutes increased to 23% from 18%. In regard to arrivals, the average delay per arrival increased by 50% year on year to 15.7 minutes (Eurocontrol, 2011). On the other hand, the number of flights in Europe rose in 2010 to 9.49 million. Eurocontrol released its new long-term forecast of flights in Europe and state that average annual growth is likely to be between 1.6% and 3.9%, leading to between 13.1 and 20.9 million flights in 2030 (Eurocontrol, 2010).

Building new airports or additional runways would certainly increase the network capacity, but it requires high investment to implement, and its effects are only available in the long term. In the short term, on the other hand, the best way that can be achieved by the system is to limit the size and the impact of the delays produced by congestion, or, in other words, to control the air traffic flows in order to eliminate the demand exceeding the available capacity. This approach is known as *air traffic flow management (ATFM)* (Andreatta & Jacur, 1987).

ATFM aims to avoid congestion and delays. When delays must be imposed, the objective is to reduce their impact on airspace users as much as possible. The ATFM becomes a critical activity when demand is higher than the nominal capacity. It is important to recognize that the need for ATFM stems from the fact that nominal operating conditions are (increasingly) rare. The fundamental challenge for ATFM, therefore, arises when the system is disrupted. Fluctuating weather conditions, equipment outages, and demand surges might cause significant capacity-demand imbalances (Wu & Caves, 2002).

Because these disruptions are highly unpredictable, the resulting capacity-demand imbalances are needed to resolve in a dynamic fashion. However, instead of using local measures (e.g. holding aircraft in the airspace), ATFM attempts to balance the system and prevent local overloading by adjusting the flows of aircraft on a national or regional basis. This is further complicated by the fact that airlines' flight schedules are usually highly interconnected. The aircraft, crews, and passengers that compose the flight schedule might all follow different itineraries, thus creating a complex interaction between the airline's flight legs. Thus, delays of a single flight leg can propagate throughout the network and local disruptions might have a global impact. Furthermore, changes in traffic patterns over time, such as the recent growth in unscheduled air traffic, also complicate ATFM (Agustin, Alonso, Escudero & Pizarro, 2009).

1.2 Research Objectives and Methodology

The objective of ATFM is to match the capacity of the air traffic networks with the transportation demand, so as to ensure that aircraft can flow through the airspace *safely* and *efficiently*. Given the complexity of the system, as well as the large number of stakeholders involved, it is difficult to define an appropriate notion of efficiency. Traditionally, performance of the system has been measured in terms of schedule deviations. In fact, ATFM aims at minimization of delay between actual and scheduled operations. While this provides aggregate performance indicators that are valuable to the air traffic service provider, they do not necessarily reflect the extent of the service provided to users.

Ground-holding ("gate-holding" or "ground-stopping") is typically imposed on aircraft flying to congested airports or scheduled to traverse congested airspace. Ground holding is the action of delaying take-off beyond a flight's scheduled departure time. The objective is to minimize the total delay cost which is sum of airborne and ground delay costs, considering expected demand-capacity imbalances at destination airports by assigning ground delays to flights. The GHP can be classified into two sub-problems; the single airport ground holding problem (SAGHP) and the multi airport ground holding problem (MAGHP). The SAGHP is solved for one destination airport at a time, whereas a network of airports is considered in the MAGHP (Vossen, Hoffman & Mukherjee, 2009).

In this thesis, we considered a real-world SAGHP and developed a mathematical model to support tactical ATFM decisions related to ground delays. The model has been established on the practical constraints through the analysis of air traffic control services in Izmir Adnan Menderes Airport. The data used in this study is based on the real traffic statistics registered in the Turkish Air Traffic Control System. The objective of the model is the minimization of total weighted tardiness of arrival and departure flights subjected to pre-tactical limitations to avoid the overshoot of the airport capacity. The proposed model is applied to different traffic scenarios such as low, medium and high level of traffic congestion (i.e. March, May and July) in view of the scheduled flights to/from Adnan Menderes Airport in 2010. The problem is solved using CPLEX 12.1 (IBM, 2010) for a 4-hour time-period between 08:00 and 12:00 in which congestion is caused by insufficient capacity of the airport. The computational performance of the proposed model is tested under three scenarios with respect to the number of delayed flights and tardiness performance measures. The proposed model helps air traffic controllers working on an Air Traffic Control Center (ACC) for the efficient, safe and reliable management of air traffic flows by considering the current status of the airport and expected demand.

1.3 Organization of the Thesis

The remainder of the thesis is organized as follows. In Chapter two, to gain a more comprehensive understanding of this problem, various concepts related to Air Traffic Flow Management, i.e., relevant terminology, basic components of air traffic control services, air traffic control clearances, model classification and solution methods in literature are described.

In Chapter three, detailed information about Ground Holding Problem (GHP) is provided. To identify the current research issues, a comprehensive literature review on ground holding problem is conducted and a structural framework is proposed to review the applications. Using this structural framework, we focus on the SAGHP specifications of the published literature in chronological order.

In Chapter four, a case study derived from Adnan Menderes Airport in Turkey is introduced. The real-world problem is formulated as a linear programming model and various sets of computational experiments are carried out for the investigated SAGHP.

Finally, Chapter five gives the concluding remarks, represents the contributions and identifies future research directions.

CHAPTER TWO
AIR TRAFFIC FLOW MANAGEMENT

2.1 Overview of Air Traffic Control Services

The Procedures for Air Navigation Services and Air Traffic Control (PANS-ATC) was first prepared by the Air Traffic Control Committee of the International Conference on North Atlantic Route Service Organization (Dublin, 1946). Since then, further editions were issued periodically. In the fourteenth edition (2001), entitled Procedures for Air Navigation Services-Air Traffic Management (PANS-ATM), the provisions and procedures relating to safety management of air traffic services and to air traffic flow management are also included. The PANS-ATM are complementary to the Standards and Recommended Practices contained in Annex 2 (Rules of the Air) and in Annex 11 (Air Traffic Services). According to these standards, there is a common air traffic terminology to achieve the safety and performance requirements of air traffic control in all countries.

2.1.1 Basic Definitions

The relevant terminology of the air traffic control services is given below (ICAO Doc.4444, 2001).

Aerodrome. A defined area on land or water (including any buildings, installations and equipment) intended to be used either wholly or in part for the arrival, departure and surface movement of aircraft.

Aerodrome control service. Air traffic control service for aerodrome traffic.

Air-ground communication. Two-way communication between aircraft and stations or locations on the surface of the earth.

Air traffic. All aircraft in flight or operating on the manoeuvring area of an aerodrome.

Air traffic control service (ATCS). A service provided for the purpose of:

a) preventing collisions:

1) between aircraft, and

2) on the manoeuvring area between aircraft and obstructions, and

b) expediting and maintaining an orderly flow of air traffic.

Air traffic control unit. A generic term meaning variously, area control centre, approach control unit or aerodrome control tower.

Air traffic flow management (ATFM). A service established with the objective of contributing to a safe, orderly and expeditious flow of air traffic by ensuring that ATC capacity is utilized to the maximum extent possible, and that the traffic volume is compatible with the capacities declared by the appropriate ATS authority.

Air traffic service (ATS). A generic term meaning variously, flight information service, alerting service, air traffic advisory service, air traffic control service (area control service, approach control service or aerodrome control service).

Alternate aerodrome. An aerodrome to which an aircraft may proceed when it becomes either impossible or inadvisable to proceed to or to land at the aerodrome of intended landing. Alternate aerodromes include the following:

i. Take-off alternate. An alternate aerodrome at which an aircraft can land should this become necessary shortly after take-off and it is not possible to use the aerodrome of departure.

ii. En-route alternate. An aerodrome at which an aircraft would be able to land after experiencing an abnormal or emergency condition while en route.

iii. Destination alternate. An alternate aerodrome to which an aircraft may proceed should it become either impossible or inadvisable to land at the aerodrome of intended landing.

Approach control service. Air traffic control service for arriving or departing controlled flights.

Approach control unit. A unit established to provide air traffic control service to controlled flights arriving at, or departing from, one or more aerodromes.

Approach sequence. The order in which two or more aircraft are cleared to approach to land at the aerodrome.

Apron. A defined area, on a land aerodrome, intended to accommodate aircraft for purposes of loading or unloading passengers, mail or cargo, fuelling, parking or maintenance.

Area control centre (ACC). A unit established to provide air traffic control service to controlled flights in control areas under its jurisdiction.

Area control service. Air traffic control service for controlled flights in control areas.

Area navigation (RNAV). A method of navigation which permits aircraft operation on any desired flight path within the coverage of station-referenced navigation aids or within the limits of the capability of self-contained aids, or a combination of these.

ATS route. A specified route designed for channelling the flow of traffic as necessary for the provision of air traffic services.

Clearance limit. The point to which an aircraft is granted an air traffic control clearance.

Controlled airspace. An airspace of defined dimensions within which air traffic control service is provided in accordance with the airspace classification.

Controlled flight. Any flight which is subject to an air traffic control clearance.

Estimated off-block time. The estimated time at which the aircraft will commence movement associated with departure.

Estimated time of arrival. For IFR flights, the time at which it is estimated that the aircraft will arrive over that designated point, defined by reference to navigation aids, from which it is intended that an instrument approach procedure will be commenced, or, if no navigation aid is associated with the aerodrome, the time at which the aircraft will arrive over the aerodrome. For VFR flights, the time at which it is estimated that the aircraft will arrive over the aerodrome.

Expected approach time. The time at which ATC expects that an arriving aircraft, following a delay, will leave the holding point to complete its approach for a landing.

Final approach. That part of an instrument approach procedure which commences at the specified final approach fix or point, or where such a fix or point is not specified,

a) at the end of the last procedure turn, base turn or inbound turn of a racetrack procedure, if specified; or

b) at the point of interception of the last track specified in the approach procedure; and ends at a point in the vicinity of an aerodrome from which:

- a landing can be made; or
- a missed approach procedure is initiated.

Flight information centre. A unit established to provide flight information service and alerting service.

Flight information region (FIR). An airspace of defined dimensions within which flight information service and alerting service are provided.

Flight information service. A service provided for the purpose of giving advice and information useful for the safe and efficient conduct of flights.

Flight level. A surface of constant atmospheric pressure which is related to a specific pressure datum, 1013.2 hectopascals (hPa), and is separated from other such surfaces by specific pressure intervals.

A pressure type altimeter calibrated in accordance with the Standard Atmosphere:

- when set to a QNH altimeter setting, will indicate altitude;
- when set to QFE altimeter setting, will indicate height above the QFE reference datum;
- when set to a pressure of 1013.2 hPa, may be used to indicate flight levels.

The terms “height” and “altitude”, used in Note 1 above, indicate altimetric rather than geometric heights and altitudes.

Flight plan. Specified information provided to air traffic services units, relative to an intended flight or portion of a flight of an aircraft.

Flow control. Measures designed to adjust the flow of traffic into a given airspace, along a given route, or bound for a given aerodrome, so as to ensure the most effective utilization of the airspace.

Height. The vertical distance of a level, a point or an object considered as a point, measured from a specified datum.

Holding point. A specified location, identified by visual or other means, in the vicinity of which the position of an aircraft in flight is maintained in accordance with air traffic control clearances.

IFR flight. A flight conducted in accordance with the instrument flight rules.

Instrument meteorological conditions (IMC). Meteorological conditions expressed in terms of visibility, distance from cloud, and ceiling, less than the minima specified for visual meteorological conditions.

NOTAM. A notice distributed by means of telecommunication containing information concerning the establishment, condition or change in any aeronautical facility, service, procedure or hazard, the timely knowledge of which is essential to personnel concerned with flight operations.

Radar approach. An approach in which the final approach phase is executed under the direction of a radar controller.

Radar contact. The situation which exists when the radar position of a particular aircraft is seen and identified on a radar display.

Radar control. Term used to indicate that radar-derived information is employed directly in the provision of air traffic control service.

Radar service. Term used to indicate a service provided directly by means of a radio detection device (radar) which provides information on range, azimuth and/or elevation of objects.

Runway. A defined rectangular area on a land aerodrome prepared for the landing and take-off of aircraft.

Standard instrument arrival (STAR). A designated instrument flight rule (IFR) arrival route linking a significant point, normally on an ATS route, with a point from which a published instrument approach procedure can be commenced.

Standard instrument departure (SID). A designated instrument flight rule (IFR) departure route linking the aerodrome or a specified runway of the aerodrome with a specified significant point, normally on a designated ATS route, at which the en-route phase of a flight commences.

Taxiing. Movement of an aircraft on the surface of an aerodrome under its own power, excluding take-off and landing.

Taxiway. A defined path on a land aerodrome established for the taxiing of aircraft and intended to provide a link between one part of the aerodrome and another, including:

a) Aircraft stand taxilane: A portion of an apron designated as a taxiway and intended to provide access to aircraft stands only.

b) Apron taxiway: A portion of a taxiway system located on an apron and intended to provide a through taxi route across the apron.

c) Rapid exit taxiway: A taxiway connected to a runway at an acute angle and designed to allow landing aircrafts to turn off at higher speeds than are achieved on other exit taxiways thereby minimizing runway occupancy times.

Wake turbulence categories of aircraft. Wake turbulence separation minima shall be based on a grouping of aircraft types into three categories according to the maximum certificated take-off mass as follows:

- HEAVY (H) — all aircraft types of 136 000 kg or more;

- MEDIUM (M) — aircraft types less than 136 000 kg but more than 7 000 kg; and
- LIGHT (L) — aircraft types of 7 000 kg or less.

Helicopters should be kept well clear of light aircraft when hovering or while air taxiing.

2.1.2 Air Traffic Control Services

Air Traffic Control Services are implicated in three main services;

- Area Control Service,
- Approach Control Service,
- Aerodrome Control Service.

Area control service is provided by an area control centre (ACC); or by the unit providing approach control service in a control zone/ area of limited extent which is designated primarily for the provision of approach control service, when no ACC is established (ICAO Doc.4444, 2001). In Figure 2.1, we can see the Airspace Management Planning Chart which shows the control areas of Europe established by Eurocontrol.

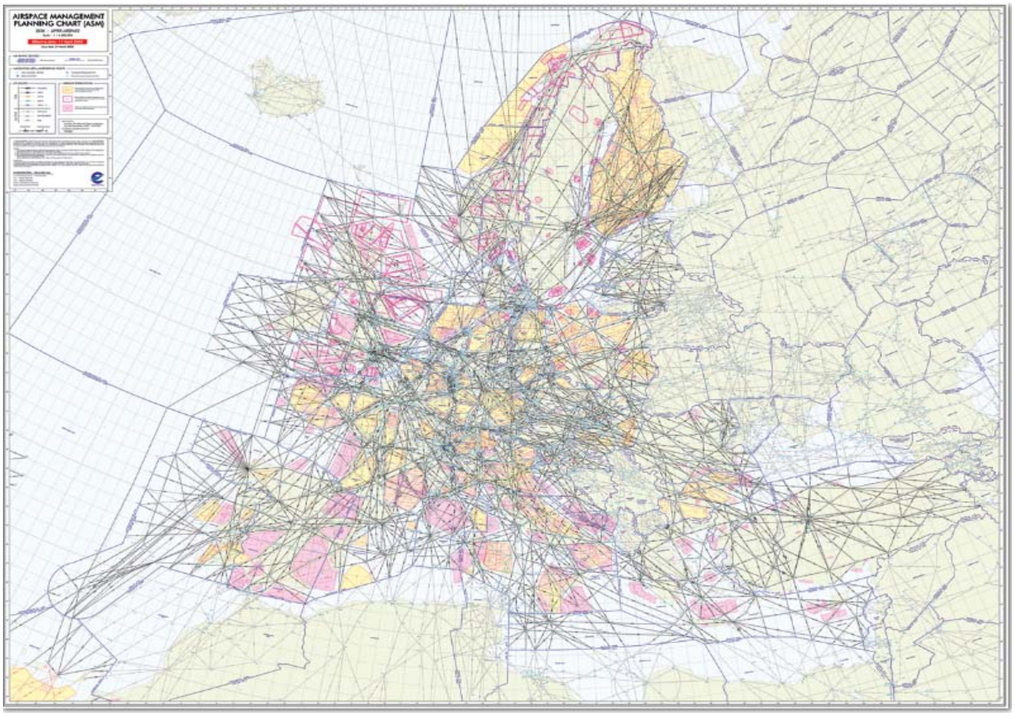

Figure 2.1 The airspace management planning chart

On the other hand, approach control service is provided by an aerodrome control tower or an ACC, when it is necessary to combine the responsibility of one unit under the functions of the approach control service and those of the aerodrome control service. It is also provided by an approach control unit, when it is necessary to establish a separate unit (ICAO Doc.4444, 2001). In Figure 2.2, we can see the Approach Control Terminal Area of Adnan Menderes Airport.

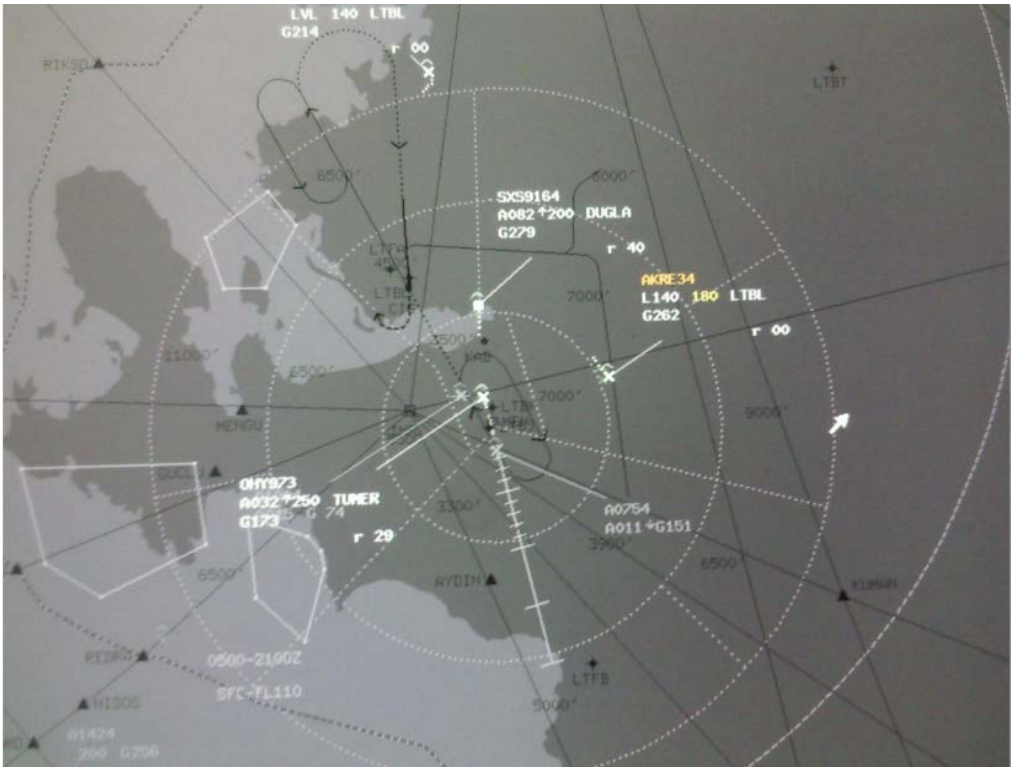

Figure 2.2 The approach control terminal area of Adnan Menderes Airport.

Note that, approach control service may be provided by a unit co-located with an ACC, or by a control sector within an ACC.

Finally, aerodrome control service is provided by an aerodrome control tower. In Figure 2.3, we can see the aerodrome control tower of Adnan Menderes Airport.

Figure 2.3 The aerodrome control tower of Adnan Menderes Airport.

2.1.3 Division of Responsibility for Control between Air Traffic Control Units

The appropriate ATS authority designates the area of responsibility for each air traffic control (ATC) unit and, when applicable, for individual control sectors within an ATC unit. If there is more than one ATC working position within a unit or sector, the duties and responsibilities of the individual working positions should be defined.

Except for flights which are provided aerodrome control service, the control of arriving and departing flights is divided between units providing aerodrome control service and units providing approach control service as follows (ICAO Doc.4444, 2001):

Arriving aircraft: Control of an arriving aircraft will be transferred from the unit providing approach control service to the unit providing aerodrome control service when the aircraft is in the vicinity of the aerodrome, and it is considered that approach and landing will be completed in visual reference to the ground, or has reached uninterrupted visual meteorological conditions. When the aircraft is at a prescribed point or level, it will also be transferred. Lastly, when the aircraft has landed, as specified in letters of agreement or ATS unit instructions, the transfer must be accomplished.

Departing aircraft: Control of a departing aircraft will be transferred from the unit providing aerodrome control service to the unit providing approach control service, when visual meteorological conditions prevail in the vicinity of the aerodrome; prior to the time the aircraft leaves the vicinity of the aerodrome. It will be transferred prior to the aircraft entering instrument meteorological conditions and when the aircraft is at a prescribed point or level. When instrument meteorological conditions prevail at the aerodrome; the aircraft will be transferred immediately after the aircraft is airborne.

When area control service and approach control service are not provided by the same air traffic control unit, responsibility for controlled flights rests with the unit providing area control service.

A unit providing approach control service, assume control of arriving aircraft, provided such aircraft have been released to it, upon arrival of the aircraft at a point, level or time agreed for transfer of control, and shall maintain control during approach to the aerodrome.

The responsibility for the control of an aircraft will be transferred from a unit providing area control service in a control area to the unit providing area control service in an adjacent control area at the time of crossing the common control area boundary as estimated by the ACC having control of the aircraft or at such other point, level or time as has been agreed between the two units.

The responsibility for the control of an aircraft shall be transferred from one control sector/position to another control sector/position within the same ATC unit at a point, level or time, as specified in local instructions.

2.1.4 Air Traffic Control Clearances

Clearances are issued solely for expediting and separating air traffic and are based on known traffic conditions which affect safety in aircraft operation. Such traffic conditions include not only aircraft in the air and on the maneuvering area over which control is being exercised, but also any vehicular traffic or other obstructions not permanently installed on the maneuvering area in use.

If an air traffic control clearance is not suitable to the pilot-in-command of an aircraft, the flight crew may request and, if practicable, obtain an amended clearance.

The issuance of air traffic control clearances by air traffic control units constitutes authority for an aircraft to proceed only in so far as known air traffic is concerned. ATC clearances do not constitute authority to violate any applicable regulations for promoting the safety of flight operations or for any other purpose; neither do clearances relieve a pilot-in-command of any responsibility whatsoever in connection with a possible violation of applicable rules and regulations.

ATC units shall issue such ATC clearances as are necessary to prevent collisions and to expedite and maintain an orderly flow of air traffic. ATC clearances must be issued early enough to ensure that they are transmitted to the aircraft in sufficient time for it to comply with them.

An ATC unit may request an adjacent ATC unit to clear aircraft to a specified point during a specified period. After the initial clearance has been issued to an aircraft at the point of departure, it will be the responsibility of the appropriate ATC unit to issue an amended clearance whenever necessary and to issue traffic information, if required.

When so requested by the flight crew, an aircraft shall be cleared for cruise climb whenever traffic conditions and coordination procedures permit. Such clearance shall be for cruise climb either above a specified level or between specified levels.

The route of flight shall be detailed in each clearance when deemed necessary. The phrase “cleared via flight planned route” may be used to describe any route or portion there of, provided the route or portion thereof is identical to that filed in the flight plan and sufficient routing details are given to definitely establish the aircraft on its route.

Subject to airspace constraints, ATC workload and traffic density, and provided coordination can be affected in a timely manner an aircraft should whenever possible be offered the most direct routing. (ICAO Doc.4444, 2001).

2.1.5 Separation Methods and Minima between Aircrafts

Separation methods between aircrafts can be classified into two parts;

(i) Vertical Separation,

(ii) Horizontal Separation.

Vertical Separation Application

Vertical separation is obtained by requiring aircraft using prescribed altimeter setting procedures to operate at different levels expressed in terms of flight levels or altitudes. The vertical separation minimum (VSM) shall be:

a) A nominal 300 m (1 000 ft) below FL 290 and a nominal 600 m (2 000 ft) at or above this level, except as provided for in b) below; and

b) Within designated airspace, subject to a regional air navigation agreement: a nominal 300 m (1 000 ft) below FL 410 or a higher level where so prescribed for use under specified conditions, and a nominal 600 m (2 000 ft) at or above this level.

Horizontal Separation Application

Lateral separation shall be applied so that the distance between those portions of the intended routes for which the aircraft are to be laterally separated is never less than an established distance to account for navigational inaccuracies plus a specified buffer. This buffer shall be determined by the appropriate authority and included in the lateral separation minima as an integral part thereof.

Lateral separation of aircraft is obtained by requiring operation on different routes or in different geographical locations as determined by visual observation, by the use of navigation aids or by the use of area navigation (RNAV) equipment.

Longitudinal separation must be applied so that the spacing between the estimated positions of the aircraft being separated is never less than a prescribed minimum. Longitudinal separation between aircraft following the same or diverging tracks may be maintained by application of speed control, including the Mach number technique. When applicable, use of the Mach number technique shall be prescribed on the basis of a regional air navigation agreement.

In applying a time- or distance-based longitudinal separation minimum between aircraft following the same track, care must be exercised to ensure that the separation minimum will not be infringed whenever the following aircraft is maintaining a higher air speed than the preceding aircraft. When aircraft are expected to reach minimum separation, speed control shall be applied to ensure that the required separation minimum is maintained.

Longitudinal separation may be established by requiring aircraft to depart at a specified time, to arrive over a geographical location at a specified time, or to hold over a geographical location until a specified time. Longitudinal separation between supersonic aircraft during the transonic acceleration and supersonic phases of flight should normally be established by appropriate timing of the start of transonic acceleration rather than by the imposition of speed restrictions in supersonic flight. (ICAO Doc.4444, 2001).

2.1.6 Use of Radar in the Air Traffic Control Service

The information presented on a radar display may be used to perform the following functions in the provision of air traffic control service (ICAO Doc.4444, 2001):

- Provide radar services as necessary in order to improve airspace utilization, reduce delays, provide for direct routings and more optimum flight profiles, as well as to enhance safety,

- Provide radar vectoring to departing aircraft for the purpose of facilitating an expeditious and efficient departure flow and expediting climb to cruising level,

- Provide radar vectoring to aircraft for the purpose of resolving potential conflicts,

- Provide radar vectoring to arriving aircraft for the purpose of establishing an expeditious and efficient approach sequence,

- Provide radar vectoring to assist pilots in their navigation, e.g. to or from a radio navigation aid, away from or around areas of adverse weather, etc,

- Provide separation and maintain normal traffic flow when an aircraft experiences communication failure within the area of the radar coverage,

- Maintain radar monitoring of air traffic,

- When it is applicable, maintain a watch on the progress of air traffic, in order to provide a non-radar controller with, improved position information regarding aircraft under control, supplementary information regarding other traffic, and Information regarding any significant deviations by aircraft from the terms of their respective air traffic control clearances, including their cleared routes as well as levels, when appropriate.

2.2 Classification of Air Traffic Flow Management Approaches

International Civil Aviation Organization (ICAO) has introduced the Global Air Navigation Operational Concept which represents a fundamental change in the operating paradigm for air navigation services (ICAO, 2005). The future operational concept includes the following elements (NICTA-National ICT Australia Submission, 2010):

- Changes to the organization and management of the air traffic networks which are designed to improve access and utilization,
- Dynamic and flexible management of capacity to meet demand and respond to uncontrollable events (e.g., weather conditions and emergencies),
- Synchronization of traffic flows to improve safety and efficiency,
- Implementation of risk-based conflict management,
- Seamless management of services across all phases of a flight.

Major system development programs are underway around the world to implement fundamental concepts within the Global Air Navigation Operational Concept. The Next Generation Air Transportation System (NextGen) program in the United States (Joint Planning and Development Office, 2007) and the Single European Sky ATM Research (SESAR) program in Europe (SESAR, 2007) are some examples of this concept (Neal et al., 2011).

In case of traffic congestion, policies adopted in North America and Europe are different. In North America, collaborative processes between the Air Traffic Command Control, System Command Center and Airline Operational Control Centers are implemented. These initiatives belong to a wider framework called Collaborative Decision Making. This concept has been explored by several authors (Ball & Hoffman, 2000; Panayiotou & Cassandras, 2001).

In Europe, there is a different structure; no such collaborative processes are implemented, since both en-route airspace and airports is highly congested. This is because of both the airway system, built up by a fixed track system connecting airports, and of the existing air navigation and air traffic control rules. Turkey is involved in Europe's air traffic control system. At the present time, the minimum safe separation between aircraft is assured only by means of altitude and/or longitudinal separations. This type of structure represents a bottle-neck for air traffic flow with the increase of flight volume. Though some measures have been taken to reduce traffic congestion, much more is needed before air traffic can once again flow safely and efficiently (Vranas, Bertsimas & Odoni, 1994).

Solution approaches concerning Air Traffic Flow Management Problem can be categorized according to the planning horizon such as long-term, mid-term and short-term solutions:

- Long-term approaches include building new airports and additional runways or advances in Air Traffic Control Technologies.
- Medium-term approaches focus on the ways that disperse traffic to less utilized airports or less congested periods through regulations, incentives, etc.
- Short-term solutions aim at minimizing the unavoidable delay costs under the current capacity and demand. Short-term solutions generally involve ground-holding policies with the main aim of safety and much more less holding costs.

In recent years, many mathematical and simulation models have been developed in order to reduce the amount of congestion and to examine the possibility of introducing auxiliary systems which supports air traffic management in a more comprehensive way. In most of the models, the objective is to minimize system-wide delay cost, which has two components-ground and airborne delays. In the literature, these optimization models are generally formulated as linear and/or integer programming models.

According to Bertsimas & Patterson (1998), the following modeling variations are considered in the literature:

i. Deterministic vs. stochastic models, which are distinguished by whether the capacities of the system (airports and sectors in the airspace) are assumed deterministic or probabilistic.

ii. Static vs. dynamic models, which are distinguished by whether or not the solutions are updated dynamically. In the static versions, the ground (and airborne) holds are decided once for all at the beginning of the day, whereas in the dynamic versions they are updated during the course of the day as better weather (and hence capacity) forecasts become available.

According to the type of problem they address, TFM approaches can be classified in three distinct classes: Ground Holding Problem (GHP), Generalized Tactical TFM Problem (GTFMP) and Traffic Flow Management Re-routing Problem (Guastalla, 1997). Other options beyond ground holding and re-distribution of air traffic flows, include: speed control of airborne aircraft; metering of air traffic (i.e., controlling the rate at which aircraft go past a given point in airspace); and airborne holding en route and, especially, near or inside terminal airspace.

2.2.1 Ground Holding Problem (GHP)

The ground holding problem has received great interest to many researchers for more than a decade. The objective of solving this problem is to minimize the sum of airborne and ground delay costs in the face of anticipated demand-capacity imbalances at destination airports (Mukherjee & Hansen, 2007).

Models in this class are of a tactical nature and attempt to assign ground holding delays to flights, with the objective of minimizing the cost of delays to aircraft operators, while satisfying existing capacity constraints at airports or en route. The GHP can be classified into two sub-problems: *Single-Airport Ground-Holding Problem (SAGHP)* and *Multi- Airport Ground-Holding Problem (MAGHP).* As their respective names suggest, the two problems consider, respectively, a single airport at a time (SAGHP) and an entire network of airports simultaneously (MAGHP). In the SAGHP, ground holding times are assigned to the flights travelling to some particular airport, where scheduled demand is expected to exceed available capacity during some period of time. In the MAGHP, delays are assumed to propagate in the network of airports, as aircraft perform consecutive flights, thus necessitating the examination of an entire set of airports simultaneously (Brunetta, Guastalla & Navazio, 1998).

The GHP can be further categorized into a "deterministic" version (deterministic *GHP)* and a probabilistic version (stochastic *GHP).* The stochastic version arises because the GHP must often be solved in the presence of considerable uncertainty. In other words, deciding how much ground-holding delay to assign to a flight is complicated by the fact that, it is often difficult to predict how much delay a flight will actually suffer in practice. The reason is that sector capacities and, especially, airport capacities are often highly variable and may change dramatically during the course of a day because of weather conditions or other uncertain events. Moreover, small changes in visibility or in the height of the cloud-cover may translate into large differences in airport capacity.

Generalized Tactical TFM Problem (GTFMP) is another version of the GHP. It considers the possibility of assigning airborne delays to flights, either at the arrival airport or in a sector. In addition to determining release times for aircraft (ground-holds), GTFMP also takes into consideration the possibility of assigning some airborne delays to flights at specific points on their route. These delays could be absorbed though airborne holding at these points or possibly by exercising speed control or metering of the traffic flow (Bertsimas & Odoni, 1997).

2.2.2 Traffic Flow Management Rerouting Problem (TFMRP)

In addition to ground holding, TFM has several other options in order to balance the traffic demand and capacity. The most common approach is the *redistribution of air traffic flows* over these networks of airways. The redistribution decisions can be effected through changes in the routing of flights and can be accomplished in the following two ways (Bertsimas & Patterson, 2000):

- *strategically,* (i.e., planning in advance the routes of scheduled flights in a *region* in a way that ensures a desirable distribution of traffic flows);

- *tactically,* (i.e., re-routing aircraft in real-time, possibly changing an aircraft's flight plan even after that aircraft is already airborne).

When the weather conditions are indigent, the capacities of some airports and sectors are forced to drop significantly or even to become zero. Aircrafts must then fly alternative routes if they were scheduled to pass through airspace regions of reduced capacity. Currently, these rerouting decisions are handled through the experience of the air traffic controllers and not through a formal optimization model (Matos, Chen & Ormerod, 2001).

In the United States, the Air Traffic Command Center (ATCC) initiates an iterative process with the Airline Operations Centers (AOC) to reschedule and reroute flights so that the delay costs caused by the weather conditions are kept to a minimum. The ATCC contacts each airline’s operation center concerning the necessity of rerouting. Then, a set of new flight path is determined to complete its scheduled flights under the new limited capacity scenario information. This collaborative decision making approach is based on two central principles as expressed on the website of the Federal Aviation Administration (FAA). First, better information will lead to better decision making and second, tools and procedures need to be in place to enable the ATCC and the National Air Space users to more easily respond to the changing conditions. The FAA further states that the attempt to minimize the effects of the reduced capacity requires the up-to-date information exchange between both the airline and FAA (Bertsimas & Patterson, 2000).

In Bertsimas & Patterson (1998), it was illustrated that MAGHP model can be extended to efficiently accommodate dynamic rerouting decisions. They presented two possible approaches: the path approach and the sector approach.

The path approach first defines Q_f as a set of possible routes that flight f may fly. In the formulation (TFMP), it is assumed that Q_f only contains one route, which they denoted as P_f. To make the formulation more manageable (but still large), they restricted the size of Q_f. They extended the TFMP variables in the following manner:

$$w_{ft}^{jr} = \begin{cases} 1 & \textit{if flight } f \textit{ arrives at sector } j \textit{ by time } t \textit{ along route } r, \\ 0 & \textit{otherwise} \end{cases}$$

$$w_{ft}^{j} = \sum_{r \in Q_f} w_{ft}^{jr}$$

Moreover, since the departure and arrival airports will remain the same for a given flight over all routes, P (f, 1) and P (f, N_f) will be independent from the particular route. Using the newly defined variables they modify the TFMP to include rerouting. The size of the resulting formulation will be at most a factor $\max_f \left|Q_f\right|$ larger than the TFMP formulation. This implies that it is able to handle problems with a relatively small number of alternative paths.

Then it is decided that the flight should be routed to which sector next. They defined N(f, j), the set of sectors that flight f can enter immediately after exiting sector j, as well as P(f, j), the set of sectors that flight f can enter immediately before entering sector j. The authors extended the TFMP variables in the following manner:

$$w_{ft}^{jj'} = \begin{cases} 1 & \textit{if flight } f \textit{ arrives at sector } j' \textit{ from sector } j \textit{ by time } t\ , \\ 0 & \textit{otherwise} \end{cases}$$

$$w_{ft}^{j} = \sum_{j' \in N(f,j)} w_{ft}^{j'j}$$

Thus, the departure and arrival airports will remain the same for a given flight over all routes. In this manner, P (f, 1) and P (f, N_f) will be independent of the particular choice of sectors.

CHAPTER THREE
GROUND HOLDING PROBLEM AND LITERATURE REVIEW

3.1 Brief Overview of Ground Holding

As stated earlier, traffic congestion is a critical problem in the most developed air transportation systems in the world. Congestion occurs whenever the capacity of air traffic network is exceeded over a period of time. In the absence of the long-term capacity improvements that can be obtained through the construction of additional runways or through advances in ATC, traffic flow management (TFM) is the best available way to reduce the cost of delays. On a day-to-day basis, TFM attempts to "match", dynamically, air traffic demand with the capacity of airports and airspace sectors of the ATC system. Ground holding, as a part of TFM, is a relatively recent phenomenon in air transportation industry. Fundamental stages of a flight are displayed in Figure 3.1.

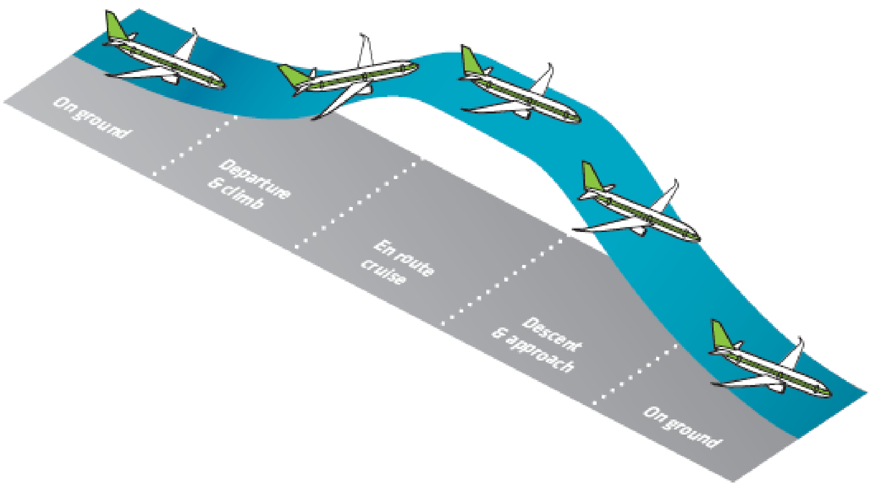

Figure 3.1 Stages of a flight

If delays were encountered, they were previously absorbed while the aircraft was airborne, typically by circling in the air ("stacking") near the airport of destination. However, widespread use of ground-holding began during the 1981 air traffic controllers' strike in the United States, as this was seen a way to reduce controller workload by limiting the number of aircraft which were airborne at any given time. When it was realized that ground-holding was also a fuel-saving practice, its use became an inevitable part of established TFM practice in air transportation systems.

Ground-holding ("gate-holding" or "ground-stopping") is the action of delaying take-off beyond a flight's scheduled departure time. It is typically imposed on aircraft flying to congested airports or scheduled to traverse congested airspace. The motivation for this policy is that, as long as a delay is unavoidable, it is safer and less costly for the flight to absorb this delay on the ground before take-off, rather than in the air.

3.2 Single Airport Ground Holding Problem (SAGHP)

The single airport ground holding problem deals with the optimal planning for an airport, taking into account the limitations with regard to the number of landing and take-off operations that can be carried out within the time units. Decisions are made on arrival slot allocation to various flights based on airport arrival capacity forecasts. The goal is to efficiently use the available capacity while absorbing necessary delays by ground holding of flights. If the forecast is accurate, then the ground delays will be such that the number of aircraft arriving at any time interval equals the airport “acceptance rate” (i.e., the maximum number of arrivals that the airport can accommodate) during that time. But in practice, forecasts are rarely accurate, because it is very difficult to predict the operating conditions of an airport several hours in advance.

Decisions made under uncertainty can cause airborne delays when the number of planned arrivals exceeds airport capacity during a time period. Unnecessary ground delays may result if the capacity forecast proves pessimistic. In practice, the Federal Aviation Administration (FAA) in USA mitigates the effect of capacity uncertainty by exempting long-distance flights (such as coast-to-coast flights) from a Ground Delay Problem (GDP) by limiting the scope of the problem to a geographical area surrounding the destination airport (Mukherjee & Hansen, 2007).

3.2.1 Mathematical Formulation

The SAGHP model assumes that the capacity of the given arrival airport, say *k*, is a deterministic function of time, known in advance with certainty. Besides this deterministic characteristic, an unlimited capacity in the departure airports and air-sectors is assumed, so no alternative routes are considered and the flight speed is not taken into consideration. Additionally, no continued flights are considered. The time horizon consists of *T* time periods, and an extra time period $T+1$, whose capacity is large enough to allow the arrival of any number of flights (e.g., a night period where any number of arrivals can be accommodated); it is the way to treat cancellation flights. No airlines preferences are considered on how to allocate the ground holding of the flights (Agustin, Alonso, Escudero & Pizarro, 2009).

The basic formulation of the SAGHP adapted from Agustin et al. (2009) is given below,

Notations

Sets

F : set of flights

T : set of time periods $\{1, ..., T\}$, where $T^+ = T \in \{T+1\}$.

Parameters

r_f: scheduled arrival to airport *k* for flight $f, f \in F$.

c^d_f : ground holding delay time unit cost of flight $f, f \in F$.

R_t : arrival capacity of airport k at time period $t,\ t \in T$ for the given scenario.

Decision Variables

x^t_f : 0-1 variable such that its value is 1 if flight *f* is planned to arrive to airport *k* at time period *t* and, otherwise, it is zero, $\forall f \in F, t \in T^+$.

Objective Function

The pure 0-1 model to obtain the planned arrivals of the flights at airport k to minimize the total ground holding delay cost is as follows:

$$\min \sum_{f \in F} \sum_{t \in T^+ | r_f \leq t} c_f^d x_f^t \qquad (3.1)$$

Constraints

$$\sum_{t \in T^+ | r_f \leq t} x_f^t = 1 \qquad \forall f \in F \qquad (3.2)$$

$$\sum_{f \in F} x_f^t \leq R_t \qquad \forall t \in T \qquad (3.3)$$

$$x_f^t \in \{0, 1\} \qquad \forall f \in F,\ t \in T^+ | r_f \leq t. \qquad (3.4)$$

The mathematical model given above is a typical Generalized Assignment Problem (GAP). Numerical problems can be solved by using standard GAP and Minimum Cost Flow algorithms.

3.2.2 Literature Review on the Single Airport Ground Holding Problem (SAGHP)

SAGHP was first systematically described by Odoni (1987). Odoni defined the ATFM problem domain, identified the major issues and suggested decision support needs. The author assumed a discrete time horizon, deterministic demand and a deterministic capacity. The deterministic SAGHP (both static and dynamic) was first formulated as a network flow problem by Terrab & Odoni, (1993). The stochastic SAGHP was formulated and solved as a stochastic programming problem by Richetta & Odoni (1993) (the static case) and Richetta & Odoni (1994) (the dynamic case). A review of optimization models for the SAGHP is given in Andreatta, Odoni & Richetta (1993).

This strategy has also been applied at the Boston Logan airport by Andreatta & Jacur (1987), Andreatta et al. (1993) and the Frankfurt airport by Platz & Brokof (1994). Other applications have been made by the Institute of Flight Guidance for several airports in Germany, whose results can be seen in Völkers & Bohme (1995).

Richetta & Odoni (1993) formulated the SAGHP as a stochastic linear programming model with a single stage. The main feature of the stochastic programming model is that it simplifies the structure of the control mechanism by making ground-hold decisions on groups of aircraft (i.e., on aircraft classified according to the cost class and schedule) rather than individual flights. Additional constraints, such as limiting the maximum acceptable ground-holds and airborne delays are also introduced. The advantage of their solution is that, even for the largest airports, problem instances result in linear programs that can be optimally solved. They present a set of algorithms and compare their performance to a deterministic solution and to the passive strategy of no-ground holds under different weather scenarios.

Milan (1997) considers assigning priorities for landings in an overloaded air traffic network which consists of departure airports, a single landing airport and a network of airways connecting the airports. The flights planned to be carried over the network represent the demand which should be met during a time period under given conditions. Landing airport capacity is the element of the network which causes congestion and potentially lengthy flight delays which spread over the network. Under such conditions the landing airport and the ATC network are considered to be overloaded. The model is based on a concept of deterministic priority queues which enables ATC to control and distribute the total delays and their costs to particular flights subject to given criteria. The various service rules such as FCFS (First come-first served) and PRD (Priority Discipline) which are synthesized on the basis of flight characteristics can be applied by ATC in a saturated network, where the landing airport is assumed to be a single congested element. The application of these rules under specific traffic conditions may produce a quite opposite effect on the total delays and costs imposed to the particular flight classes while they are being served in the ATC network. The particular service rule should therefore be chosen with caution. The model can be used for planning purposes. It will also support calculation of the total cost of aircraft delays under various conditions prevailing in the ATC network during a given time period, as well as sensitivity analysis of the cost of these delays depending on changes in various influencing factors.

Hoffmann & Ball (2000) explore various ways to add banking constraints to the SAGHP to enforce the temporal grouping of certain collections of flights known as banks. This study deals with a resource allocation problem in which each flight bound for an airport suffering reduced arrival capacity must be assigned to an arrival slot. The authors develop five basic models of the ground-holding problem with banking constraints. They show analytically that two of these models, XSS (the Double Sum Model) and XGF (the Ghost Flight Model), are equivalent in LP strength and that the banking constraints induce facets. The computational performance of the models is tested on both real and constructed data sets. By branching on marker variables employed in several of the models, they obtain dramatic savings in obtaining integer solutions. The computational results indicate that XGF is a powerful formulation which handles real-world instances of SAGHP.

Wang & Zhang (2005) introduce a new recursion event-driven model that considers different delay cost. The difference comes from the three different types of aircraft (Heavy, Medium and Light). When numbers of flights are higher, it is difficult to get the real-time solution. Discrete-event analyze method is used to solve the SAGHP. The concept of delay time equivalent quantity is presented to solve the combination optimization problem and a fast algorithm is given basing on it. They assume the destination airport is the only constraint source, when the capacity is determined and known. They transfer all airborne delay to ground delay by making the aircraft hold on the ground for a length time. The simulation results validate the feasibility of the proposed model and algorithm. As the model is event-driven, the system will be optimized according to new data for every landing event, the nature of the model is dynamic. Through importing the delay time equivalent quantity, the calculation is simplified. This method can also be extended for additional types of aircrafts.

Mukherjee & Hansen (2007) present a dynamic stochastic integer programming (IP) model for the SAGHP, in which ground delays assigned to flights can be revised during different decision stages, based on weather forecasts. The performance gain from their model is particularly significant in the following cases: (1) under stringent ground holding policy, (2) when an early ground delay program (GDP) cancellation is likely, and (3) for airports where the ratio between adverse and fair weather capacities is lower. The choice of ground delay cost component in the objective function strongly affects the allocation policy. When it is linear, the optimal solution involves releasing the long-haul flights at or near their scheduled departure times and using the short-haul flights to absorb delays if low-capacity scenarios eventuate. This policy resembles the current practice of exempting long-distance flights during ground delay programs. For certain convex ground delay cost functions, the spread of ground delay is more or less uniform across all categories of flights, which makes the overall delay assignment more equitable. Finally, they present a methodology that could enable intra-airline flight substitutions by airlines after the model has been executed and scenario-specific slots have been assigned to all flights, and hence to the airlines that operate them. This makes the model applicable under the collaborative decision making (CDM) paradigm by allowing airlines to perform cancellations and substitutions and hence re-optimize their internal delay cost functions.

Mukherjee, Hansen & Liu (2008) investigate the real-world applicability of scenario-based approaches to the single airport stochastic ground holding problem, including the static model of Ball (1999) and the dynamic Mukherjee-Hansen model (2007). Their results demonstrate the feasibility of applying these models to real-world airports. First, they find that capacity scenarios, which previous studies have assumed but not look for, exist and can be inferred from historical data. Second, they find that, for certain airports, the scenarios follow a tree structure has similar profiles during the early parts of the day and then branch out later on. The authors propose a heuristic for identifying the branching points. Next they show that the dynamic model, by anticipating and then using the new information that becomes available after a branching point, can reduce delay costs over 60% when compared to the static model in the idealized case when actual capacity profiles precisely follow the scenario profiles. The results come with two major caveats. Firstly, the applications are based on annualized scenario trees that are unlikely to match the situation on a particular day. The challenge of blending information about the general patterns followed by capacity profiles with information specific to a particular day to form a customized tree has yet to be addressed. The benefits of scenario-based air traffic management cannot be adequately assessed until a method for developing such customized trees has been developed.

Table 3.1 summarizes some of the reviewed models of SAGHP. The papers are ordered chronologically. For each selected model, the table illustrates the objective functions and solution approaches.

Tablo 3.1 Summary of the review on SAGHP

Author	Year	Problem Definition	Objective Function	Solution Approach
Richetta & Odoni	1993	Static GHP	Minimize total delay cost	Stochastic Linear Programming
Milan	1997	SAGHP	Minimize total delay cost	Deterministic Queuing System
Hoffmann & Ball	2000	SAGHP with banking constraints	Minimize total delay cost	LP Relaxation
Wang & Zhang	2005	SAGHP	Minimize delay cost	Discrete - event driven model
Mukherjee & Hansen	2007	SAGHP	Minimize expected total delay cost	Dynamic Stochastic IP model
Mukherjee et al.	2008	Stochastic SAGHP	Minimize total delay cost	Static & Dynamic Optimization

3.3 Multi Airport Ground Holding Problem (MAGHP)

The MAGHP considers the airspace network besides the airport capacity. In this methodology the field of work is extended and the inter-relationship which exists between different airports is included. The objective consists of finding a planning adapted to the limitations of the capacity imposed by the infrastructures available at each airport (Bertsimas & Patterson, 1998).

Figure 3.2 displays the sector boundaries of the National Airspace of Turkey.

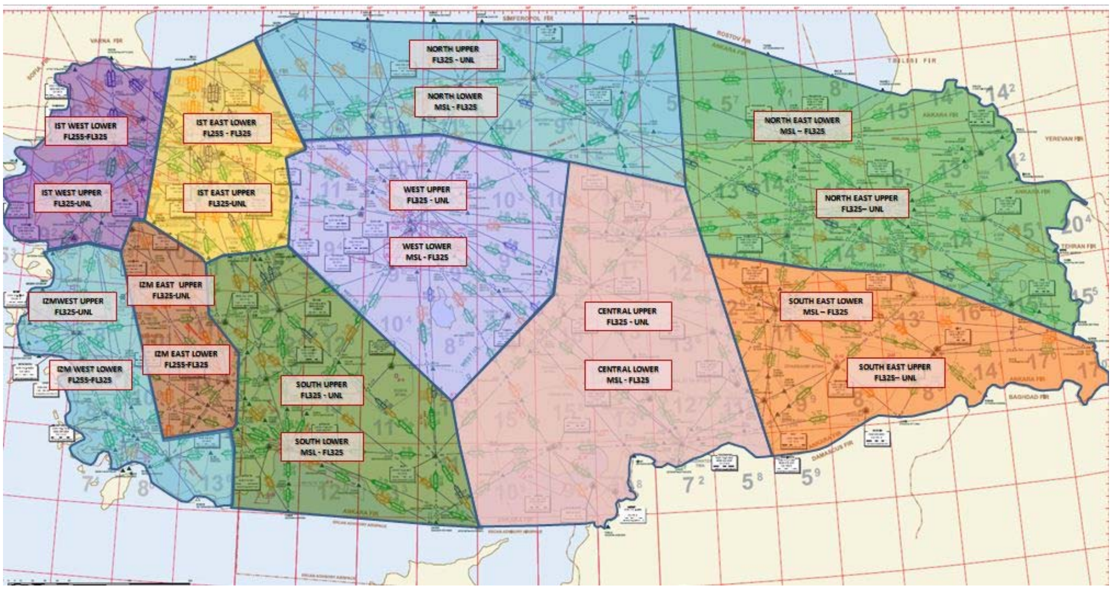

Figure 3.2 Sector boundaries of Turkey

Each flight passes through contiguous sectors while it is en route to its destination. There is a restriction on the number of airplanes that may fly within a sector at a given time. This number is dependent on the number of aircraft that an air traffic controller can manage at one time, the geographic location, and the weather conditions. We will refer to the restrictions on the number of aircraft in a given sector at a given time as the en route sector capacities.

The issue of congestion at these sectors is as critical as congestion in the terminal areas, since the cost of holding an airborne aircraft is not only dependent on the location of aircraft. Thus, airborne delay costs could further be reduced if we could determine the optimal time for a flight to traverse the capacitated sectors.

3.3.1 Mathematical Formulation

The MAGHP model assumes that the departure and arrival capacity of the airports are generally deterministic functions of the time, known in advance with certainty (Andreatta, Brunetta & Guastalla, 1997). Besides these characteristics, it is assumed that an unlimited capacity in the air sector. Therefore, no scheduled or alternative routes are considered and the flight speed is not taken into consideration. The upper bounds on the ground holding and air delay are unlimited and then it paves the way for considering even partially flight cancellations. Notice that a flight is continued e.g. if the related aircraft will also perform the continuation flight along the time horizon. It is also assumed that the *slack* time for a continued flight is known, such that if the flight arrives at its destination at most slack time periods late, then the departure of the continuation flights not affected; otherwise, the ground holding delay of the continuation flight is the total (ground holding plus air) delay of the continued flight minus the slack time, at least (Bertsimas & Patterson, 1998).

According to Bertsimas & Patterson (1998), basic notations and terms in relation to the simplest MAGHP are given as follows:

A set of flights $\boldsymbol{F} = \{1, \ldots, F\}$

A set of airports $\boldsymbol{K} = \{1, \ldots, K\}$

A set of time periods $\boldsymbol{T} = \{1, \ldots, T\}$

A set of pairs of flight that are continued $\boldsymbol{f} = \{(f', f): f'$ is continued by flight $f\}$

They refer to any particular time period t as the "time t." The input data of the problem is given as follows:

Notations

$\boldsymbol{N_f}$ = number of sectors in flight *f's* path,

$$\boldsymbol{P(f, i)} = \begin{cases} \text{the departure airport}, & \text{if } i = 1, \\ \text{the } (i-1)^{st} \text{ sector in flight } f\text{'s path}, & 1 < i < N_f, \\ \text{the arrival airport}, & \text{if } i = N_f \end{cases}$$

$\boldsymbol{P_f} = (\mathrm{P}(f, i) : 1 \leq i \leq N_f)$,

$\boldsymbol{D_k(t)}$ = departure capacity of airport k at time t,

$\boldsymbol{A_k(t)}$ = arrival capacity of airport k at time t,

$\boldsymbol{S_j(t)}$ = capacity of sector j at time t,

$\boldsymbol{d_f}$ = scheduled departure time of flight f,

$\boldsymbol{r_f}$ = scheduled arrival time of flight f,

$\boldsymbol{S_f}$ = turnaround time of an airplane after flight f,

$\boldsymbol{c_f^g}$ = cost of holding flight f on the ground for one unit of time,

$\boldsymbol{c_f^a}$ = cost of holding flight f in the air for one unit of time,

$\boldsymbol{I_{fj}}$ = number of time units that flight f must spend in sector j,

$\boldsymbol{T_f^j}$ = set of feasible times for flight f to arrive to sector j = $[\underline{T}_f^j, \overline{T}_f^j]$,

$\underline{\boldsymbol{T}}_f^j$ = first time period in the set T_f^j, and

$\overline{T}_f^j$ = last time period in the set T_f^j.

Note that by "flight", the authors mean a "flight leg" between two airports. Also, flights referred to as "continued" are those flights whose aircraft is scheduled to perform a later flight within a time interval of its scheduled arrival.

Decision Variables

$$w_{ft}^j = \begin{cases} 1 & if\ \ flight\ \ f\ \ arrives\ at\ \mathrm{sec}tor\ \ j\ by\ time\ t \\ 0 & otherwise \end{cases}$$

The w_{ft}^j is defined as 1 if flight f arrives at sector j by time t. This definition using *by* and not *at* is critical to the understanding of the formulation.

They also defined for each flight a list P_f including the departure airport, the pertinent sectors and the arrival airport, so that the variable w_{ft}^j will only be defined for those elements j in the list P_f. Moreover, they defined T_f^j as the set of feasible times for flight f to arrive to sector j, so that the variable w_{ft}^j will only be defined for those times within T_f^j. Thus, in the formulation whenever the variable w_{ft}^j is used, it is assumed that this is a feasible (f, j, t) combination. Furthermore, one variable per flight-sector pair can be eliminated from the formulation by setting $w^{j}_{f,\overline{T}^{j}_{f}} = 1$. Since flight f has to arrive at sector j by the last possible time in its time window, they simply set it equal to one as a parameter before solving the problem. To ensure the clarity of the model, consider the following example which depicts two flights traversing a set of sectors (see Figure 3.3).

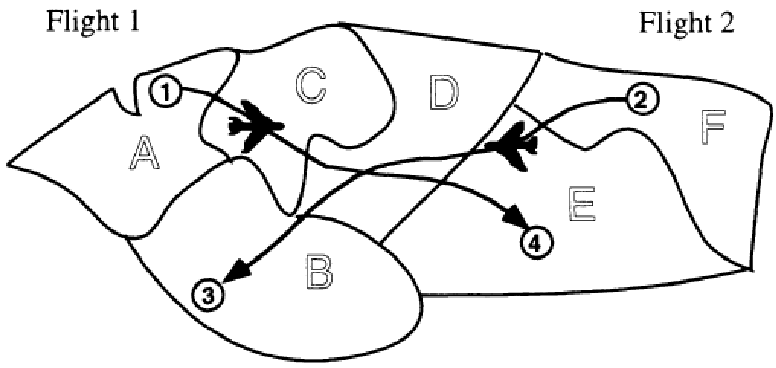

Figure 3.3 Two possible flight routes (Bertsimas & Patterson, 1998)

In this example, there are two flights, 1 and 2, each with the following associated data:

$P_1 = (1, A, C, D, E, 4)$ and

$P_2 = (2, F, E, D, B, 3)$.

If the current position of the aircraft to occur at time t is considered, then the variables for these flights at this time will be:

$$w^{1}_{1,t}\ , = 1,\ w^{A}_{1,t} = 1,\ w^{C}_{1,t} = 1,\ w^{D}_{1,t} = 0,\ w^{E}_{1,t} = 0,\ w^{4}_{1,t} = 0,\ \text{and}$$

$$w^{2}_{2,t} = 1,\ w^{F}_{2,t} = 1,\ w^{E}_{2,t} = 1,\ w^{D}_{2,t} = 0,\ w^{B}_{2,t} = 0,\ w^{3}_{2,t} = 0.$$

Having defined the variables w_{ft}^{j}, it is expressed that several quantities of interest as linear functions of these variables will be as follows:

1. The variable u_{ft}^{j} = 1 if flight *f* arrives at sector *j* at time *t* and 0 otherwise, can be expressed as follows:

$$u_{ft}^{j} = w_{ft}^{j} - w_{f,t-1}^{j} \text{ and vice versa, } w_{ft}^{j} = \sum_{t' \le t} u_{ft'}^{j}.$$

As expressed earlier, the variables w_{ft}^{j} are only defined in the time range T_f^j, so that $w_{f,(\underline{T}_f^j - 1)}^{j}$=0. Furthermore, the constraint that a flight must arrive at sector *j* at some time *t*, originally expressed by the restriction $\sum_{t \in T_f^j} u_{ft}^{j}$ = 1 can now be replaced by the simpler expression $w_{f,\bar{T}_f^j}^{j}$ = 1. As previously mentioned, this can be handled as a parameter before the problem is solved, thus eliminating many variables and constraints. This substitution is fundamental to the performance of this model.

2. Noticing that the first sector for every flight represents the departing airport, the total number of time units that flight *f* is held on the ground can be expressed as the actual departure time minus the scheduled departure time, i.e.,

$$g_f = \sum_{t \in T_j^k, k=P(f,1)} t u_{ft}^{k} - d_f = \sum_{t \in T_j^k, k=P(f,1)} t(w_{ft}^{k} - w_{f,t-1}^{k}) - d_f$$

3. Noticing that the last sector for every flight represents the destination airport, the total number of time units that flight *f* is held in the air can be expressed as the actual arrival time minus the scheduled arrival time minus the amount of time that the flight has been held on the ground, i.e.,

$$a_f = \sum_{t \in T_j^k, k=P(f,N_f)} t u_{ft}^{k} - r_f - g_f = \sum_{t \in T_j^k, k=P(f,N_f)} t(w_{ft}^{k} - w_{f,t-1}^{k}) - r_f - g_f$$

Objective Function

The MAGHP seeks to decide how much each flight is going to be held on the ground and in the air in order to minimize the total delay cost.

The objective of the formulation is to minimize total delay cost. Using the variables g_f and a_f for the amounts of ground and air delay respectively, as defined above, the objective function can be expressed simply as follows:

$$\text{Min} \sum_{f \in F} \left[c_f^g g_f - c_f^a a_f \right]$$

Substituting the expressions, the authors derived the formulations above for the variables w_{ft}^j, the following expression is obtained:

$$\text{Min}$$

$$\sum_{f \in F} \left[c_f^g \Big(\sum_{t \in T_j^k, k=P(f,1)} t(w_{ft}^k - w_{f,t-1}^k) - d_f \Big) - c_f^a \Big(\sum_{t \in T_j^k, k=P(f,N_f)} t(w_{ft}^k - w_{f,t-1}^k) - r_f - \Big(\sum_{t \in T_j^k, k=P(f,1)} t(w_{ft}^k -- w_{f,t-1}^k) - d_f \Big) \Big) \right]$$

Rearranging variables, the objective function is presented now along with the complete formulation.

$$IZ_{TFMP} = \text{Min}$$

$$\sum_{f \in F} \left[(c_f^g - c_f^a) \sum_{t \in T_j^k, k=P(f,1)} t(w_{ft}^k - w_{f,t-1}^k) + c_f^a \sum_{t \in T_j^k, k=P(f,N_f)} t(w_{ft}^k - w_{f,t-1}^k) + (c_f^a - c_f^g) d_f - c_f^a r_f \right] \tag{3.5}$$

Constraints

$$\sum_{f:P(f,1)=k} (w_{ft}^k - w_{f,t-1}^k) \leq D_k(t) \qquad \forall\, k \in K,\ t \in T, \tag{3.6}$$

$$\sum_{f:P(f,N_f)=k} (w_{ft}^k - w_{f,t-1}^k) \le A_k(t) \qquad \forall k \in K,\ t \in T, \tag{3.7}$$

$$\sum_{f:P(f,i)=j,P(f,i+1)=j',i<N_f} (w_{ft}^j - w_{ft}^{j'}) \le S_j(t) \qquad \forall j \in J,\ t \in T, \tag{3.8}$$

$$w_{f,t+l_{fj}}^{j'} - w_{ft}^{j} \le 0 \qquad \begin{cases} \forall f \in F, t \in T_f^j, j = P(f,i), \\ j' = P(f,i+1), i < N_f, \end{cases} \tag{3.9}$$

$$w_{f,t}^{k} - w_{f',t-s_f}^{k} \le 0 \qquad \begin{cases} \forall (f',f) \in L, t \in T_f^k, \\ k = P(f,1) = P(f',N_f), \end{cases} \tag{3.10}$$

$$w_{f,t}^{j} - w_{f,t-1}^{j} \ge 0 \qquad \forall f \in F, j \in P_f,\ t \in T_f^j \tag{3.11}$$

$$w_{ft}^{j} \in \{0,1\} \qquad \forall f \in F, j \in P_f,\ t \in T_f^j \tag{3.12}$$

The constraints (3.6), (3.7) and (3.8) take into account the capacities of various aspects of the system. The first constraint ensures that the number of flights which take off from airport *k* at time *t* will not exceed the departure capacity of airport *k* at time *t*.

The constraint (3.7) ensures that the number of flights which may arrive at airport *k* at time *t* will not exceed the arrival capacity of airport *k* at time *t*. In each case, the difference will be equal to one only when the first term is one and the second term is zero. Thus, the differences capture the time at which a flight uses a given airport.

The constraint (3.8) ensures that the sum of all flights which may feasibly be in sector *j* at time *t* will not exceed the capacity of sector *j* at time *t*. This difference gives the flights that are in sector *j* at time *t*, since the first term will be 1 if flight *f* has arrived in sector *j* by time *t* and the second term will be 1 if flight *f* has arrived at the next sector by time *t*. So, the only flights that will contribute a value of 1 to this sum are those flights that have arrived at *j* and have not yet departed from *j* by time *t*.

Constraints (3.9) and (3.10) represent connectivity between sectors. They stipulate that if a flight arrives at sector j' by time $t + l_{fj}$, then it must have arrived at sector j by time t where j and j' are contiguous sectors in flight *f's* path. In other words, a flight cannot enter the next sector on its path until it has spent l_{fj} time units (the minimum possible) traveling through sector j, the current sector in its path.

Constraints (3.11) represent connectivity between airports. They handle a case, in which a flight is continued, i.e., the flight's aircraft is scheduled to perform a later flight within some time interval. We will call the first flight *f'* and the following flight *f*. Constraints (3.11) state that if flight *f* departs from airport *k* by time *t*, then flight *f'* must have arrived at airport *k* by time $t - s_{f'}$. The turnaround time, $s_{f'}$, takes into account the time that is needed to clean, refuel, unload and load, and further prepare the aircraft *f* or the next flight. In other words, flight *f* cannot depart from airport *k*, until flight *f* 'has arrived and spent at least $s_{f'}$ time units at airport *k*.

Constraints (3.12) represent connectivity in time. Thus, if a flight has arrived by time *t*, then $w^j_{ft'}$, has to have a value of 1 for all later time periods, $t' \geq t$.

The major reason the authors used the variables w^j_{ft} , as opposed to the variables u^j_{ft} is that the former variables well capture the three types of connectivity in TFMP: connectivity between sectors, connectivity between airports, and connectivity in time. Of course, given that the two sets of variables are linearly related, the same constraints can be captured using the u^j_{ft} variables.

3.3.2 Literature Review on the Multi Airport Ground Holding Problem (MAGHP)

In one of the first studies which address the MAGHP, Vranas, Bertsimas & Odoni, 1994a present three general pure 0-1 integer programming formulations which also take into account the possibility of cancelling flights. The authors propose a heuristic algorithm which finds a feasible solution to the integer program by rounding the optimal solution of the LP relaxation. Finally, they give extensive computational results with the goal of obtaining qualitative insights on the behavior of the problem under various combinations of the input parameters. Implementation results demonstrate that the problem can be solved in reasonable computation times for networks with at least as many as 6 airports and 3000 flights. The formulations refer to static deterministic versions of the problem, but the authors claim that they can be easily extended to cover dynamic versions.

Bertsimas & Patterson (1998) build a model that takes into account the capacities of the National Airspace System (NAS) as well as the capacities at the airports. The authors show that the resulting formulation is rather strong as some of the proposed inequalities are facet defining for the convex hull of solutions. The model is extended to account for several variations of the basic problem, most notably, how to reroute flights and how to handle banks in the hub and spoke system. The authors present that by relaxing some of their constraints they obtain a previously addressed problem and that the LP relaxation bound of our formulation is at least as strong when compared to all others proposed in the literature for this problem. Large scale, realistic size problems with several thousand flights are considered in this study. An integer programming model is developed for the TFMP which is rather strong as some of the proposed inequalities are facet defining for the convex hull of solutions. The authors illustrate how their models can be adjusted to account for several variations in the problem's characteristics, most notably how to handle banks in the hub and spoke system and how to reroute flights. The computation times were reasonably small for large scale, realistic size problems involving thousands of flights. Short computational times and integrality properties are particularly important, since these models are intended to be used on-line and solved repeatedly during a day.

Navazio & Jacur (1998) consider a traffic situation with “multiple connections” or “banking,” i.e., the situation where some flights are assigned a set of “preceding” flights; no “successive” flight can start until all its preceding flights have landed. The problem consists of distributing delays to flights, so as to minimize the total delay cost, by respecting airport capacity, connections, and time constraints imposed by airlines. They construct an integer linear programming model and solve it to optimality with CPLEX. Because the computation time is too high (hours) for real-world instances, they propose an alternative heuristic algorithm, which shows a very low computation time (seconds) and acceptable errors when tested on 30 realistic instances with strongly diversified data. According to the authors, the heuristic algorithm they proposed appears to fit into the context of real air traffic control, both as a decision maker and as a human decision support, also when the problem instance had very large size.

Brunette, Guastalla & Navazio (1998) deal with the static MAGHP and introduce a new “library” of 32 test cases in which congestion is caused by insufficient capacity at arrival airports. They solve the instances of their library using an exact algorithm and two heuristic algorithms based on “priority rules”. First, the authors use the heuristic algorithm proposed by Andreatta, Brunetta & Guastalla, 1997 (ABG algorithm). Then, they introduce a new heuristic algorithm, where flight priority is computed as a cost function and not on the basis of a fixed table. Lastly, the authors described an exact algorithm based on a 0–1 linear programming formulation of the MAGHP, which is established upon the study presented in Bertsimas & S. Patterson, 1998. Implementation results are compared for the new algorithm with the ABG and BS algorithms by solving all instances of their library and present several remarks that should be made after the computational results.

Alonso, Escudero & Ortuna (2000) develop a model and a robust algorithmic framework for the ATFM problem under uncertainty in arrival and departure flights and airspace capacity due to weather conditions. For this purpose, they use the state-of-the-art 0-1 deterministic model based on the model presented by Bertsimas & Stock (1996). They present two versions of the stochastic model, depending upon the type of recourse policy to use. A multistage scenario analysis approach based on a simple and full recourse scheme is used. The air traffic scheduling can be implemented for a given set of initial time periods in the full recourse environment and the solution for the other periods does not need to be anticipated. They present a Fix-and-Relax approach to solve the large-scale 0-1 deterministic equivalent model.

Rossi & Smriglio (2001) investigate a set packing formulation of the ground holding problem and design a branch-and-cut algorithm to solve the problem in high congestion scenarios, i.e., when lack of capacity induces flights cancellation. The constraint generation is carried out by heuristically solving the separation problem association with a large class of rank inequalities. This procedure exploits the special structure of the ground holding problems intersection graphs. The computational results indicate that the proposed algorithms outperform other algorithms in which flight cancellation has been allowed.

Dell' Olmo & Lulli (2003) propose a new two-level hierarchical architecture for ATFM problems with corresponding mathematical models. The first level represents the air route network, and its solutions provide the air traffic flows on each arc of the network. This level interacts with the second one, which represents the single airway and its own air traffic flows. The latter model allows to assign the optimal air traffic route to each aircraft and to optimize the airway's capacity. Furthermore, for the airway optimization model they carry out a computational analysis, providing both exact and heuristic solutions, for problem instances based on the real data sets. Experimental results are obtained with the CPLEX solver exploiting the mixed integer mathematical formulation and with a proposed heuristic algorithm for problems of larger size, respectively. The heuristic solutions obtained are within a maximum gap of 13% from the LP relaxation.

Bertsimas, Lulli & Odoni (2008) present a new mathematical model for the ATFM problem. The key feature of the model is that it also includes rerouting decisions and they are formulated in a compact way. In fact, it does not require any additional variable, but it only introduces new constraints, which implements local routing conditions. They also present three classes of valid inequalities with the scope of strengthening the polyhedral structure of the underlying relaxation. A wide computational analysis on realistic instances demonstrated the viability of the proposed model. The authors solved realistic instances of the problem in short computational times (less than 15 minutes), which are consistent with the decision process inside the ATFM Central Unit. Their approach includes all the air traffic control decisions (ground holding, air holding, adjusting speed of aircraft and rerouting) combined with the attractive computational times, makes us optimistic that this approach may succeed in becoming the main air traffic control engine.

Summary of the reviewed literature considering MAGHP is depicted in Table 3.2.

Tablo 3.2 Summary of the review on MAGHP

Author	Year	Problem Definition	Objective Function	Solution Approach
Vranas, Bertsimas & Odoni	1994	Static MAGHP	Minimize total delay cost	0-1 Integer Programming
Bertsimas & Patterson	1998	Deterministic MAGHP	Minimize total delay cost	0-1 Integer Programming
Navazio & Jacur	1998	Static MAGHP	Minimize total delay cost	Integer Linear Programming
Brunetta et al.	1998	Static GHP	Minimize the overall delay costs	Heuristic Algorithm & 0-1 Linear Programming
Alonso et al.	2000	Stochastic TFMP	Minimize weighted sum of delay costs	Stochastic 0-1 Program based Fix-and-Relax Approach
Rossi & Smriglio	2001	GHP	Minimize cancellation & delay costs	Branch-and-cut algorithm
Dell'Olmo & Lulli	2003	TFMP	Minimize total delay of the set of aircrafts	Heuristic Algorithm
Bertsimas, Lulli & Odoni	2008	ATFMP	Minimize total delay cost	Integer Programming

CHAPTER FOUR
AN APPLICATION OF SAGHP

4.1 The Air Navigation Service Provider in Turkey

The Air Navigation Service Provider (ANSP) is an organization that separates aircraft on the ground or in flight in a dedicated block of airspace on behalf of a state or a number of states. ANSPs can be government departments, state owned companies, or privatized organizations. The majority of the world's ANSPs are united in the Civil Air Navigation Services Organization located at Amsterdam Schiphol Airport.

State Airports Administration (DHMI) is the responsible authority in Turkey for the provision of Air Traffic Services (ATS) within the entire territory of Turkey, including its territorial waters as well as the airspace over the high seas within Ankara and İstanbul Flight Information Regions (FIRs). In brief DHMI is the ANSP of Turkey.

The services are provided in accordance with the provisions contained in the following International Civil Aviation Organization (ICAO) documents:

Annex 2 - Rules of the Air
Annex 11 - Air Traffic Services
Doc.4444 - Procedures for Air Navigation services - Rules of the Air and Air Traffic Services (PANS- RAC)
DOC 8168 - Procedures for Air Navigation on services - Aircraft operations (PANS - OPS)
DOC. 7030 - Regional Supplementary Procedures

The authority, which has carried on its services under different names and status since 1933 with its facilities and equipment that constitute infrastructure of Turkish

Civil Aviation, has continued providing services as a state owned enterprise since 1984 within the framework of Law Decree numbered 233 and the Principle Statute.

General Directorate of State Airports Authority (DHMI) is a state economic enterprise (SEE), which has legal entity, autonomy over its activities, liability limited with its capital, is associated with Ministry of Transportation, and its services are accepted as privilege with latest legal regulation.

The DHMI's purpose and subject of activities that are defined by Principle Statute are as follows (DHMI, 2010):

1. Air transport required with civil aviation activities, management of airports, performing ground services at airports and air traffic control services, establishment and operation of air navigation systems and facilities and other related facilities and systems, and to maintain them at the level of modern aeronautics.

2. DHMI that has to perform its undertaken tasks according to international civil aviation rules and standards is in this sense a member of ICAO, which was launched according to Civil Aviation Agreement that entered into force to ensure safety of life and property at international aviation and to provide regular economic working and progress. Furthermore, it is a member of relevant international organizations, especially such as Eurocontrol and Airports Council International (ACI).

3. As part of air navigation and airport management services by DHMI, traffic of airplanes and passengers, which are offered service, has increased significantly in recent years. Especially, there has been significant progress at international flight airplane and passenger traffic of the international airports. Istanbul/Ataturk Airport and Antalya Airport are among the leading airports of Europe due to the increase in the international traffic.

4.2 The SAGHP in Adnan Menderes Airport

İzmir Adnan Menderes Airport is an international airport named after former Turkish prime minister Adnan Menderes. It is located in Gaziemir district of İzmir. Satellite image of the airport can be seen in Figure 4.1.

City	İzmir
Starting Date of Operation	1987
Aerodrome Status	Civil
ICAO Code	LTBJ
IATA	ADB
Traffic Type	Domestic / International
Passenger Capacity passenger/year	9000000
Geographical Coordinates	38°17`21"N, 27°09`18"E

Figure 4.1 Satellite Image of Adnan Menderes Airport

Adnan Menderes Aerodrome, which is built on a total area of 8,230,945 m^2, has two terminals with capacity of 9 million passenger / year on 136,199 m^2, which consists of 28,500 m^2 domestic flights terminal and 107,699 m^2 international flights terminal. The aerodrome has two composite runways that are 3,240×45 meters long.

International Flights Terminal, which was built by build-operate-transfer model and is operated by TAV (Tepe Akfen Vie), has the following features:

- 107,699 m² area,
- A capacity of 5 million passengers per year,
- 9 passenger bridges,
- 66 check-in counters on 5,354 m^2,
- 16 passport counters,
- 4 custom control benches,
- Parking garage with 2,311 vehicles capacity on 69,000 m² area, including 80 open bus parking.

Domestic Flights Terminal has the following features:

- 28,500 m² area,
- A capacity of 4 million passenger per year,
- 6 Passenger bridges,
- 38 Check-in counters,
- Parking garage with 1005 vehicles capacity on 30,967 m² areas.

The aircraft traffic statistics of Adnan Menderes Airport from year 2007 to year 2011 can be seen in Table 4.1. Figure 4.2 presents the graphical representations of the related statistics.

Table 4.1 Adnan Menderes Airport Aircraft Traffic Statistics

Year (months)	Domestic	% change	International	% change	Total	% change
2011 (April)*	16,074	↑13	3,874	↑21	19,948	↑14
2010 (all)	46,206	↑14.1	16,972	↑23.8	63,178	↑16.6
2009 (all)	40,492	↑6.5	13,705	↓2.1	54,197	↑4.2
2008 (all)	38,014	↑1	14,000	↓0.9	52,014	↑0.5
2007 (all)	37,647		14,127		51,774	

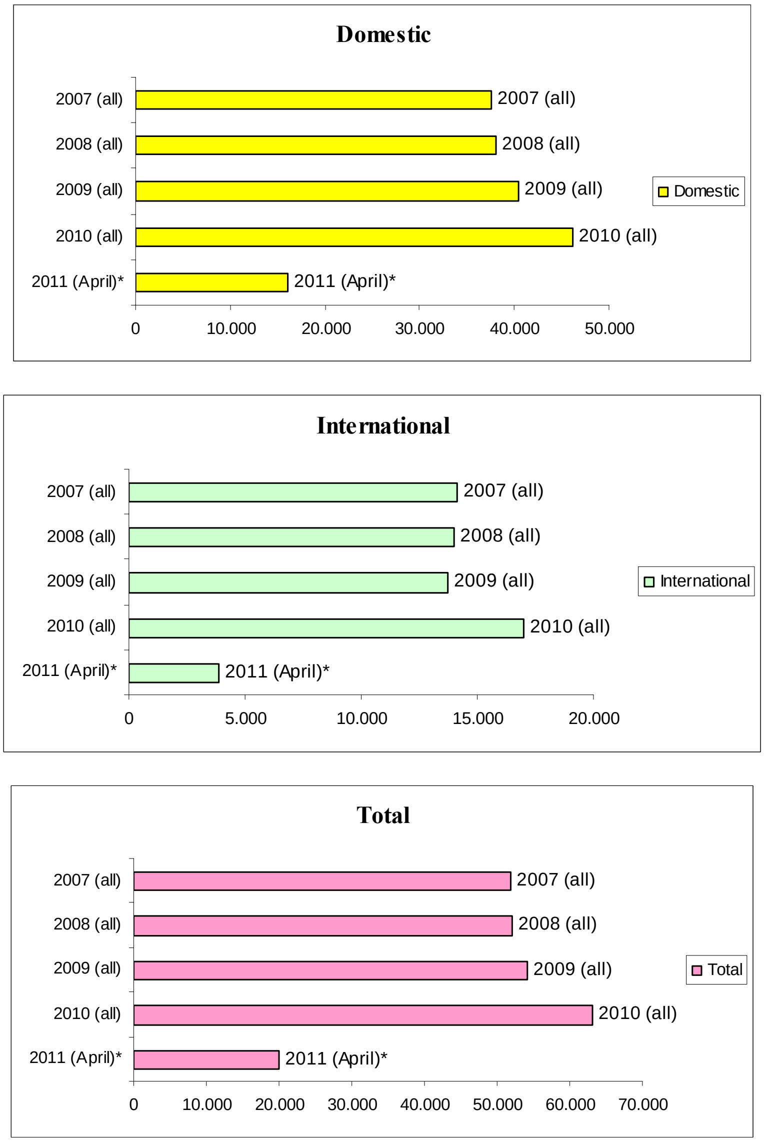

Figure 4.2 Aircraft Traffic Statistics

4.2.1 Problem Statement

In this research, we have considered the SAGHP of Adnan Menderes Airport and developed a mathematical model with the aim of minimizing total weighted tardiness. The proposed model has been established on the real constraints through the analysis of air traffic control services in İzmir Adnan Menderes Airport.

Basic components that will be used in our problem (e.g., runway, taxiway, tower and apron) are illustrated in Figure 4.3. Runway is a defined rectangular area on the land aerodrome prepared for the landing and take-off of the aircrafts. Aerodrome control service is provided by the tower. Apron is the area on the aerodrome that accomodates aircrafts for the purposes of loading or unloading passengers, mail or cargo, fuelling, parking or maintenance. Taxiway is the defined path on the aerodrome established for the taxiing of aircrafts and intended to provide a link between one part of the aerodrome and another.

Figure 4.3 Adnan Menderes Airport Aerial view

Both the arrival and departure flights use the same runway and for the safety issues, arrival flights have a priority on departure flights.

With respect to turbulence categories, aircrafts considered in the investigated problem can be categorized into three types: light (L), medium (M) and heavy (H).

Push-back and taxi times have critical importance for the investigated problem. Before a flight with a medium or heavy aircraft type takes off, a push-back vehicle compatible with the aircraft type of the flight pulls the plane and transfers it to the taxiway. A specified number of push-back vehicles are dedicated to each aircraft type. The length of time period a push-back is busy depends on the aircraft type, i.e., it takes four minutes, for the medium category aircrafts and eight minutes for heavy category aircrafts. Thereafter, the aircraft goes along the taxiway until it reaches the beginning of runway. This taxi time also differs with the aircraft type: six minutes for medium types and 12 minutes for heavy ones. In the final step, each aircraft completes its take-off within two minutes. We note that every two-minute time intervals are taken as a single period, since the length of all actions described above are in the multiples of two. Figure 4.4 and 4.5 illustrate the push-back, taxiing and take-off actions. When a medium category aircraft departs at time period t+5, it occupies time periods t+2, t+3 and t+4 for taxiing and it occupies time periods t and t+1 for push-back. When a heavy category aircraft departs at time period t+10, it occupies time periods from t+4 to t+9 for taxiing and it occupies time periods from t to t+3 for push-back. For each aircraft type, the total number of push-back vehicles used within each time interval should be in their available limits.

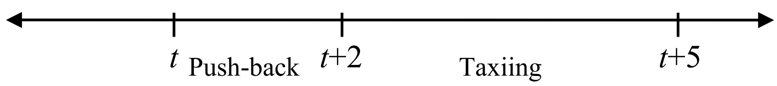

Figure 4.4 Time scale axis for medium category aircrafts

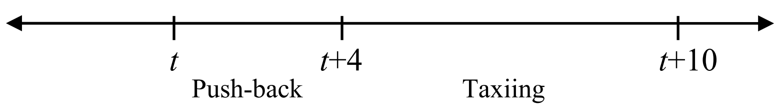

Figure 4.5 Time scale axis for heavy category aircrafts

In addition to push-back and taxiing times, cleaning actions on the runway should also be considered. After a heavy aircraft lands on the runway or departs from the runway, the runway must have been cleaned up for the succeeding flights, since the heavy aircrafts might drop some foreign objects on the runway which might cause serious problems for the succeeding flights. This cleaning procedure takes four minutes (e.g., two periods).

We finally note that the arrival flights are allowed to be landed, up to four periods before their planned (scheduled) arrival times, and departure flights are allowed to be taken off up to three periods before their planned departure times.

4.2.2 Basic Assumptions

There are some basic assumptions that will be taken into account when solving the problem:

- The capacity of the given airport, say *k*, is a deterministic function of time, known in advance with certainty.
- An unlimited capacity in air-sectors is assumed.
- No alternative routes are considered.
- Arrival and departure advances in the schedule are only possible within a specific tolerated time. Apart from this time no advances in the schedule are allowed.
- No continued flights are permitted.
- Preferences of airlines on how to allocate the ground holding of the flights are not taken into consideration.
- Arrivals and departures within a particular time are independent from each other.
- The capacities of the apron and the ground holding positions of the given arrival airport are sufficient within a particular time.

4.2.3 Proposed Mathematical Model

For convenience and readability, the parameters and the notations of the investigated SAGHP are presented below:

Notations

Sets:

F : set of flights ($F= A \cup D$)

A : set of arrival flights

D : set of departure flights

FT : set of aircraft types

Indices:

i,i' : flight indice, $i,i' = 1, ..., n$

t : time period index, $t = 1, ...,T, T+1$

a : aircraft type index

Parameters:

ctg_a : turbulence category of aircraft type a (Light: 1, Medium:2, Heavy:3)

$type_i$: aircraft type of flight i ($type\ i \in FT$)

due_i : planned arrival/departure time period of flight i

w_i : weight coefficient of flight i in the objective function

pb_a : number of pushback vehicles belonging to aircraft type a

Decision Variables

x_{it} : 0-1 variable, if arrival aircraft $(i \in A)$ arrives within time period t,1; otherwise 0.

y_{it} : 0-1 variable, if departure aircraft $(i \in D)$ departs within time period t,1; otherwise 0.

$tard_i$: number of periods that of arrival/departure flight i is delayed.

Objective Function

$$\min \sum_{i \in F} w_i tard_i \tag{4.1}$$

Constraints

$$\sum_{t=1}^{T+1} t x_{it} - due_i \le tard_i \qquad \forall i \in A \tag{4.2}$$

$$\sum_{t=1}^{T+1} t y_{it} - due_i \le tard_i \qquad \forall i \in D \tag{4.3}$$

$$\sum_{t=due_i-4}^{T+1} x_{it} = 1 \qquad \forall i \in A \tag{4.4}$$

$$\sum_{t=due_i-3}^{T+1} y_{it} = 1 \qquad \forall i \in D \tag{4.5}$$

$$\sum_{i \in A} x_{it} + \sum_{i' \in D} y_{i't} \le 1 - \sum_{s=1}^{2} \sum_{i \in A | ctg_{type_i} = 3} x_{i,t-s} - \sum_{s=1}^{2} \sum_{i' \in D | ctg_{type_{i'}} = 3} y_{i',t-s} \quad , \qquad t = 3,4,...T \tag{4.6}$$

$$\sum_{i \in A} x_{it} + \sum_{i' \in D} y_{i't} \le 1 - \sum_{i \in A | ctg_{type_i} = 3} x_{i,t-1} - \sum_{i' \in D | ctg_{type_{i'}} = 3} y_{i',t-1} \quad , \qquad t = 2 \tag{4.7}$$

$$\sum_{i \in A} x_{it} + \sum_{i' \in D} y_{i't} \le 1, \qquad t = 1 \tag{4.8}$$

$$\sum_{i \in D | type_i = a \& ctg_i = 2} \quad \sum_{s=t+4 | s \le T}^{t+5} y_{is} \le pb_a \ , \qquad t = 1,...,T\ , \quad \forall a \in FT \tag{4.9}$$

$$\sum_{i \in D | type_i = a \& ctg_i = 3} \quad \sum_{s=t+7 | s \le T}^{t+10} y_{is} \le pb_a \ , \qquad t = 1,...,T\ , \quad \forall a \in FT \tag{4.10}$$

$$x_{it} \in \{0,1\} \ , \qquad \forall i \in A \ , \qquad t = 1,...,T+1 \tag{4.11}$$

$$y_{it} \in \{0,1\} \ , \qquad \forall i \in D \ , \qquad t = 1,...,T+1 \qquad (4.12)$$

$$tard_i \geq 0 \, , \qquad \forall i \in F \qquad (4.13)$$

The objective function (4.1) specifies the minimization of total weighted tardiness of arrival and departure flights. Weight coefficient w_i is taken as 2 for arrivals and 1 for departures.

Constraints (4.2) and (4.3) calculate the number of tardy periods ($tard_i$) for the related arrival and departure flights, respectively.

Constraint (4.4) and (4.5) ensures that each flight should exactly be performed. Also, for arrival flights, four periods before the planned arrival times are allowed and for departure flights, three periods prior to the planned departure times are allowed. We also define a dummy period, T+1 so that the flights that cannot be scheduled in the specified time horizon can be assigned to this dummy period which has an unlimited capacity. Surely, this period will only be used when the flights cannot be assigned to the periods 1,…, T.

Constraints (4.6), (4.7) and (4.8) ensure that in any time period only one departure or arrival flight can be executed and if the cleaning and maintenance procedure is in progress due to the arrival/departure of a third category (heavy) flight, the runway is blocked along two time periods for both the departures and the arrivals.

Constraints (4.9) and (4.10) ensure that the total number of push-back vehicles used for particular time periods before the departure of flights with the second and third aircraft types should be in their existing limits.

Constraints (4.11), (4.12) and (4.13) are the integrality constraints.

4.2.4 Computational Results

In this section, first, the summary of the results obtained from the model will be given. Then, the computational results will be explained and interpreted in detail with illustrated tables and figures.

In this study, we have investigated a real-world SAGHP. We have applied three different scenarios in the view of Adnan Menderes Airport (i.e. March, May and July) and solved the problem using CPLEX 12.1. We considered 4 hours time-period between 08:00 and 12:00 (totally 120 periods). 107 types of aircraft were taken into consideration. For Scenario March, between 50 and 60 flights are taken into consideration, while it is between 70 and 80 for scenario May and between 100 and 120 for scenario July. We tested the computational performance of the model having regard to these three months. Some data sets are given in Appendix B.1, B.2 and B.3.

The computational results are summarized in Table 4.2.

Table 4.2 Computational Results

Scenarios	Test Problem Number	Number of Flights	Total Weighted Tardiness	Average Tardiness	Tardiness due to Arrival Flights (x2)	Tardiness due to Departure Flights (x1)	The Total Number of Flights Delayed	The Number of Arrival Flights Delayed	Departure Delayed Number of Flights	Number of Iterations (CPLEX)	CPU Time (sec.)
March	1	60	14	0.23	1	12	3	1	2	808	3.95
	2	60	10	0.17	4	2	5	3	2	332	4.29
	3	60	9	0.15	1	7	3	1	2	382	3.61
	4	60	38	0.63	12	14	6	2	4	647	3.43
	5	60	15	0.25	2	11	3	2	1	303	3.24
	6	55	0	0	0	0	0	0	0	207	2.68
	7	55	13	0.24	2	9	6	2	4	582	3.17
	8	52	11	0.21	1	9	6	1	5	567	2.93
	9	59	106	1.80	6	94	13	5	8	893	3.22
	10	56	5	0.09	0	5	2	0	2	585	3.12
May	1	75	27	0.36	3	21	6	2	4	970	3.55
	2	75	49	0.65	13	23	6	2	4	1352	3.50
	3	75	32	0.43	6	20	10	3	7	1277	3.83
	4	75	77	1.03	24	29	15	8	7	2709	4.35
	5	75	63	0.84	8	47	13	5	8	1833	4.09
	6	75	3	0.04	0	3	1	0	1	386	3.33
	7	72	24	0.33	0	24	4	0	4	827	3.34
	8	75	5	0.07	2	1	3	2	1	548	3.77
	9	75	14	0.19	3	8	5	3	2	578	3.24
	10	75	20	0.27	0	20	1	0	1	882	3.64
July	1	108	353	3.27	41	271	36	14	22	6327	7.38
	2	103	165	1.60	32	101	30	12	18	3725	5.19
	3	109	448	4.11	67	314	37	11	26	5528	6.61
	4	106	245	2.31	10	225	33	9	24	3904	6.05
	5	104	352	3.38	62	228	29	10	19	5734	6.95
	6	108	549	5.08	19	511	41	12	29	16084	12.09
	7	108	785	7.27	167	451	37	13	24	25514	15.25
	8	108	631	5.84	86	459	45	17	28	15708	11.48
	9	108	854	7.91	174	506	37	13	24	19494	12.34
	10	108	649	6.01	44	561	52	14	38	15833	11.17

Figures 4.6, 4.7 and 4.8 show the total weighted tardiness for March, May and July respectively. For example, in the sixth test problem of March Scenario, all of the flights has been performed on or before their planned time (due_i).

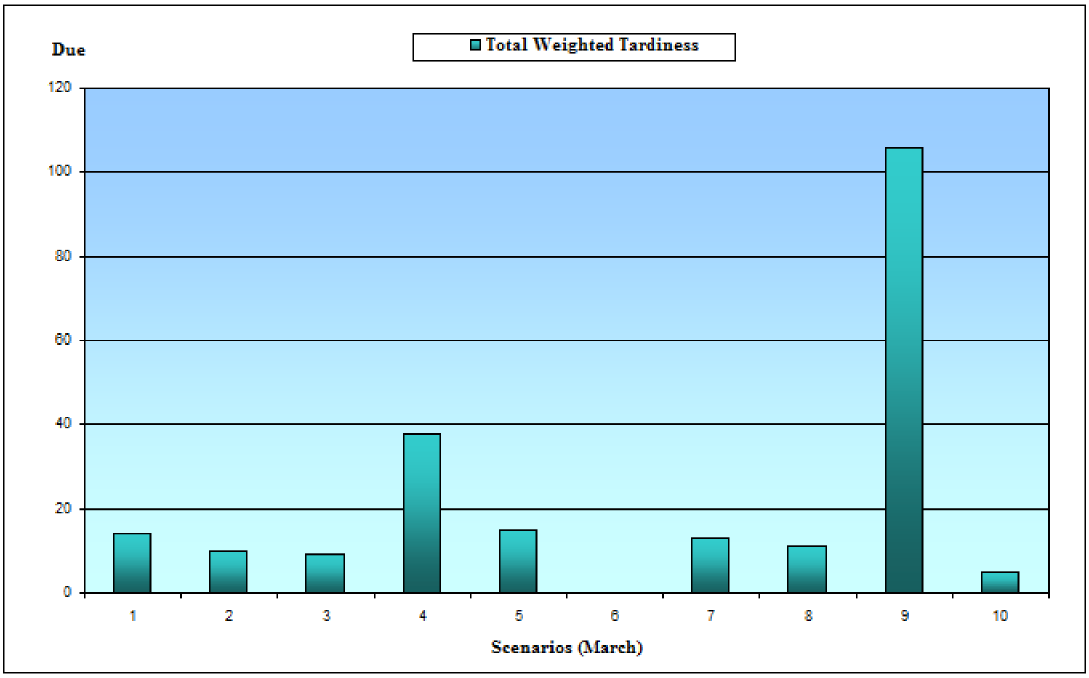

Figure 4.6 Total Weighted Tardiness (March)

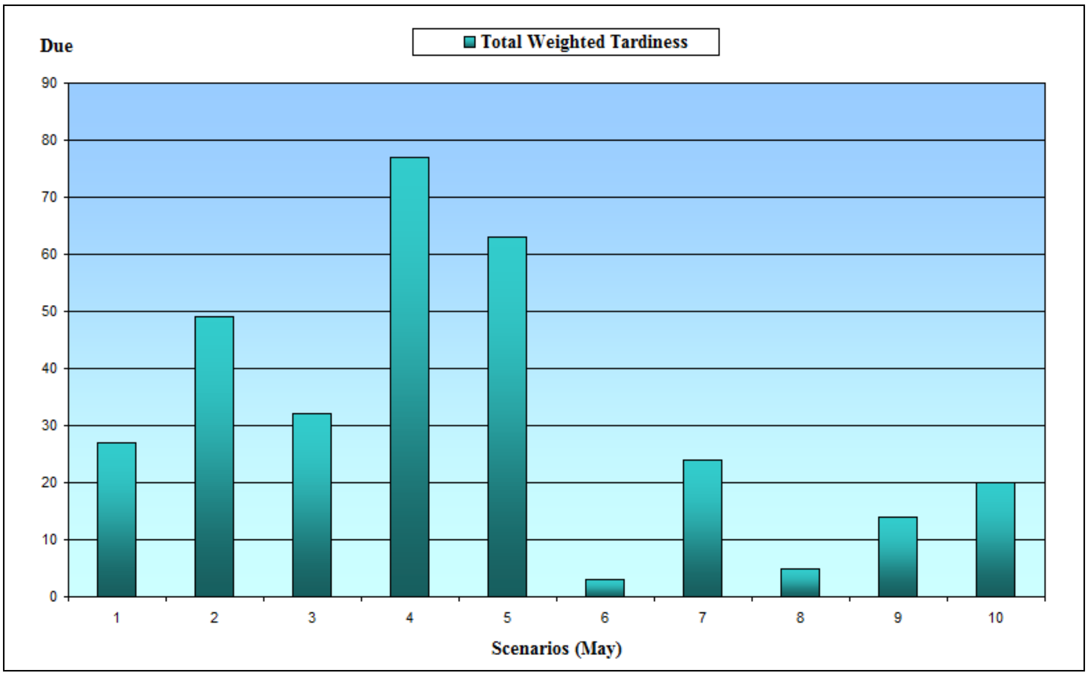

Figure 4.7 Total Weighted Tardiness (May)

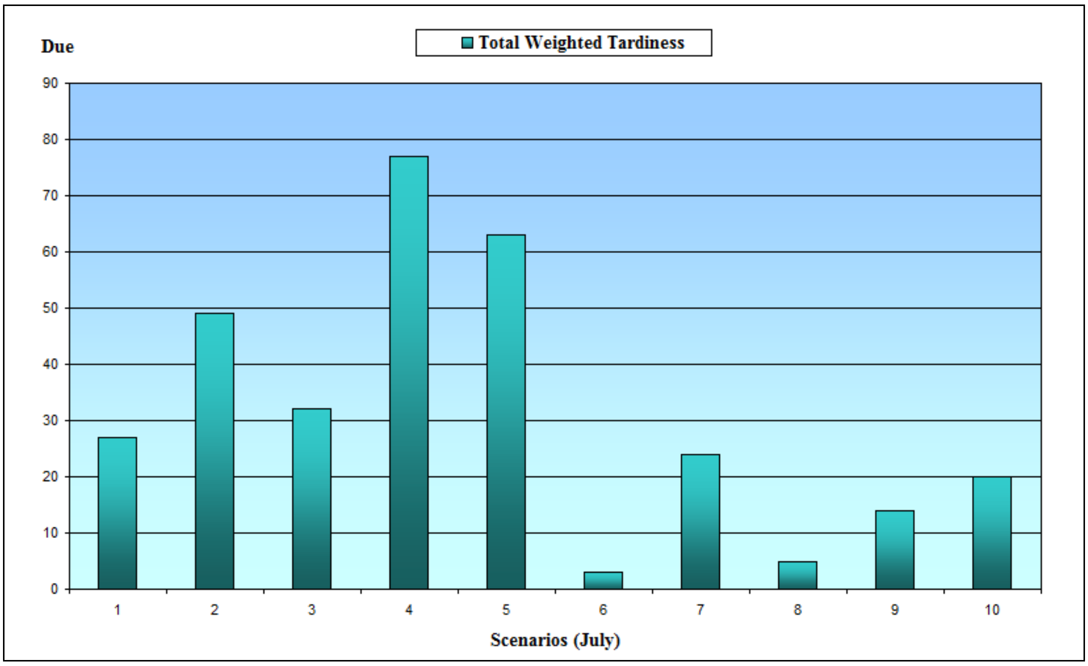

Figure 4.8 Total Weighted Tardiness (July)

Figure 4.9 shows the averages of total weighted tardiness with respect to each scenario. July has the biggest tardiness level, as expected.

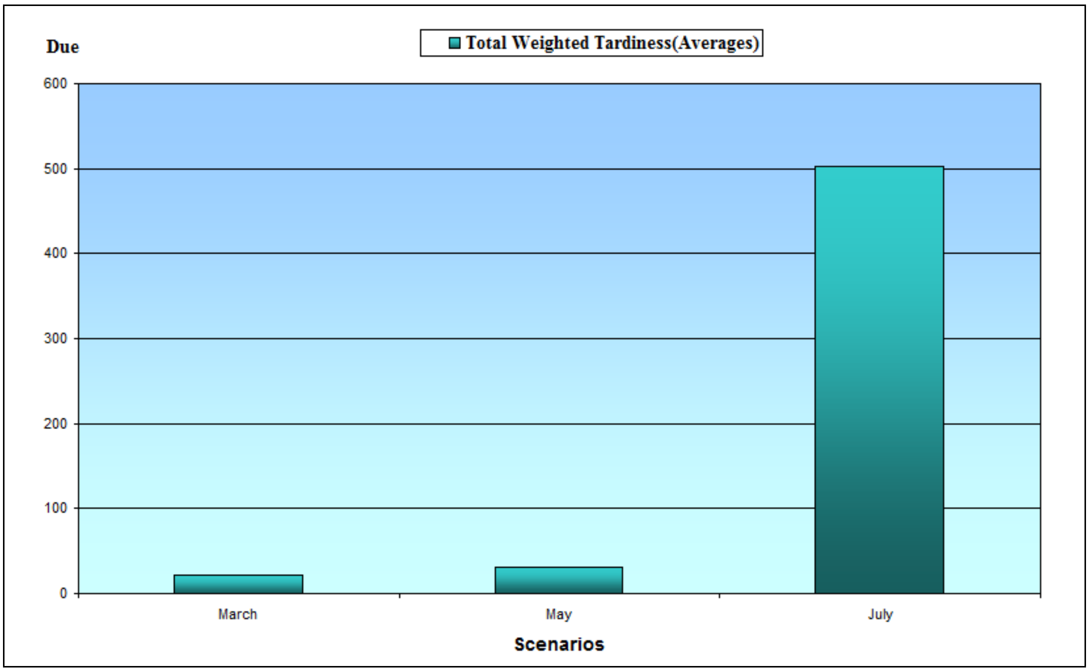

Figure 4.9 Averages of Total Weighted Tardiness

Figures 4.10, 4.11 and 4.12 show the numbers of delayed flights in relation to arrivals and departures for the scenarios March, May and July respectively. For example, in the sixth test problem of March Scenario, all of the flights has been performed on or before their planned time (*due*$_i$). It can be seen from the figures that delays on departures are much more than delays on arrivals due to the priority of arrival flights.

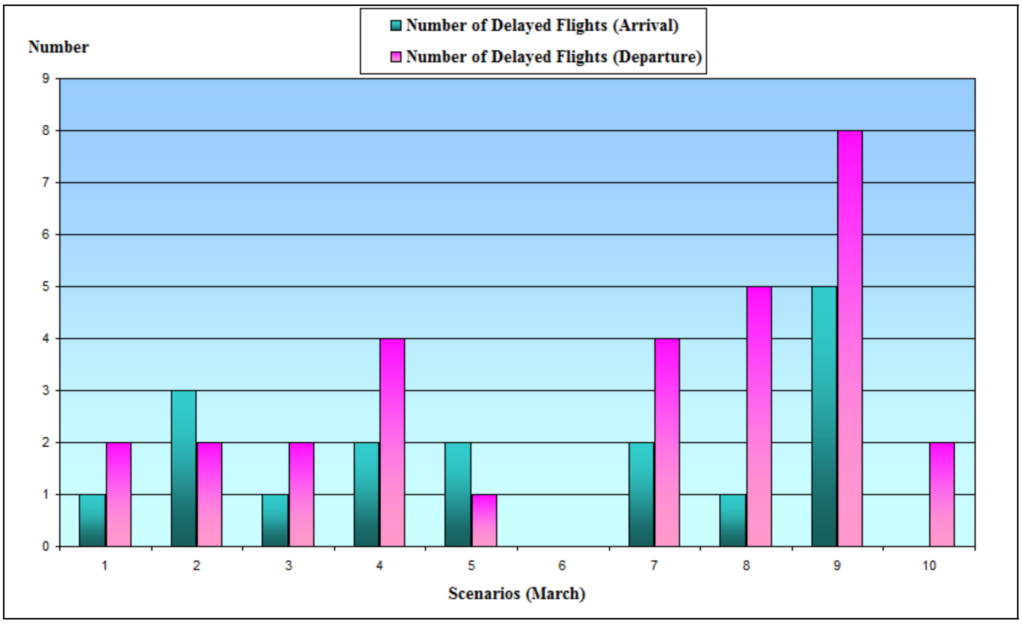

Figure 4.10 Numbers of Flights Delayed (March)

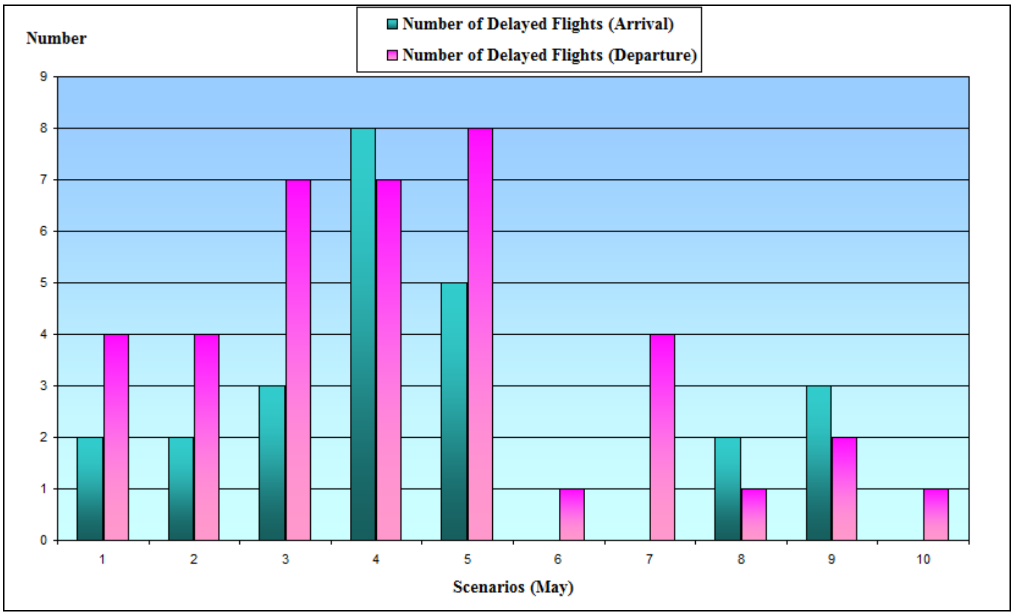

Figure 4.11 Numbers of Flights Delayed (May)

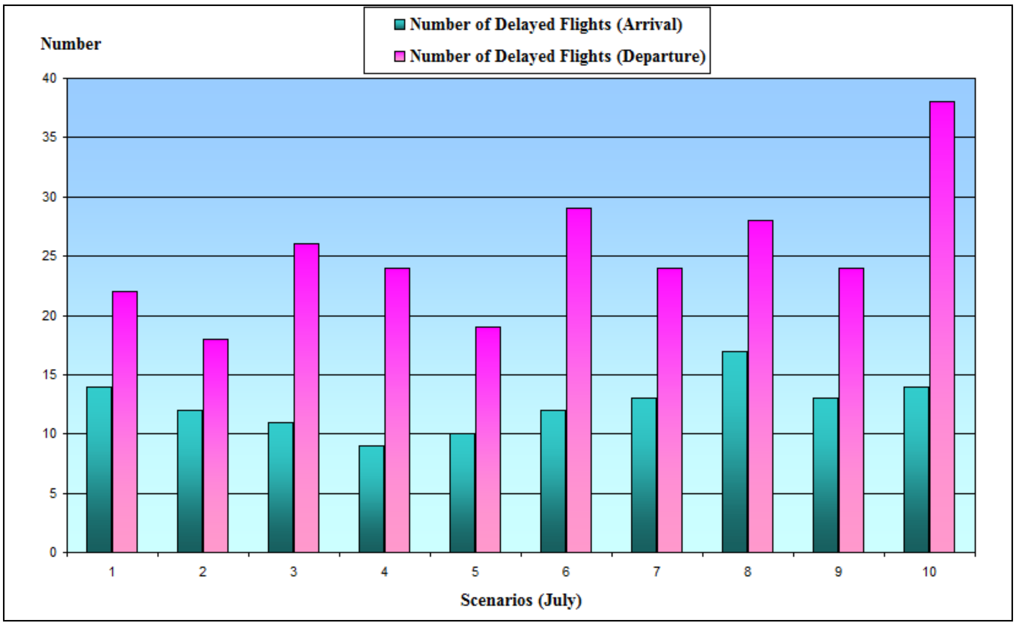

Figure 4.12 Numbers of Flights Delayed (July)

Figure 4.13 shows the average numbers of delayed flights having relation to each month. Again, as expected, the numbers of delayed flights reach its maximum in July.

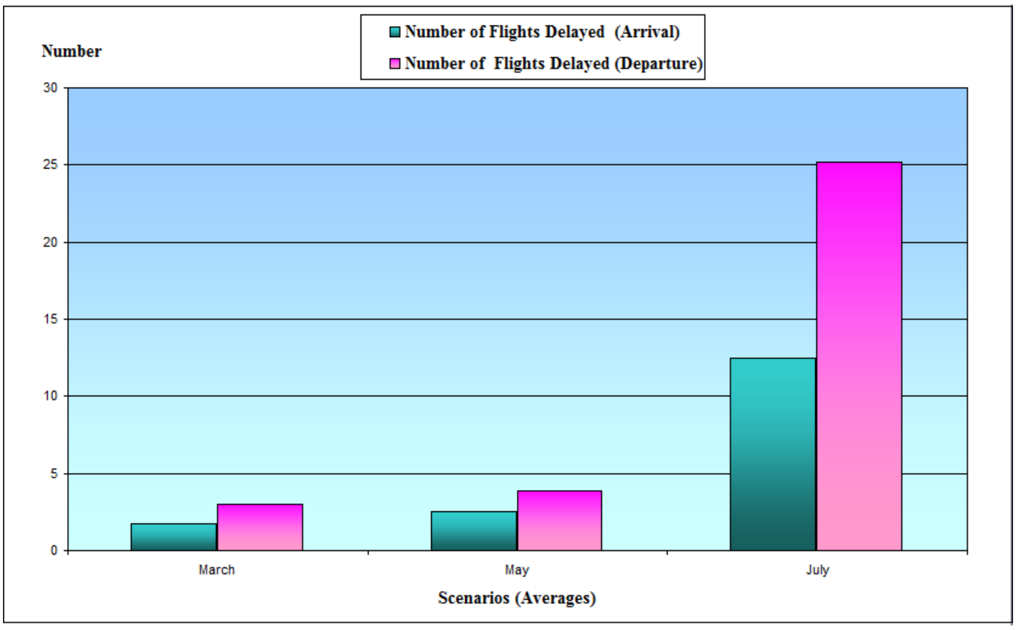

Figure 4.13 Averages of Number of Flights Delayed

Figures 4.14, 4.15 and 4.16 show the tardiness due to arrival and departure flights. For example, in the sixth test problem of March Scenario, all of the flights has been performed on or before their planned time (due_i). Scenario 9 has the biggest tardiness level.

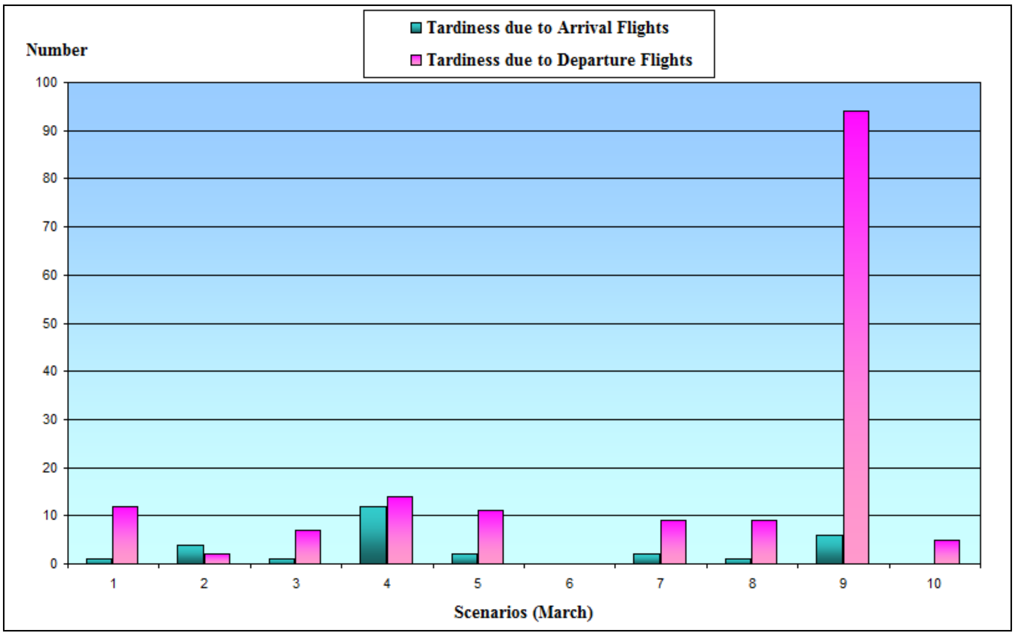

Figure 4.14 Tardiness due to Arrival and Departure Flights (March)

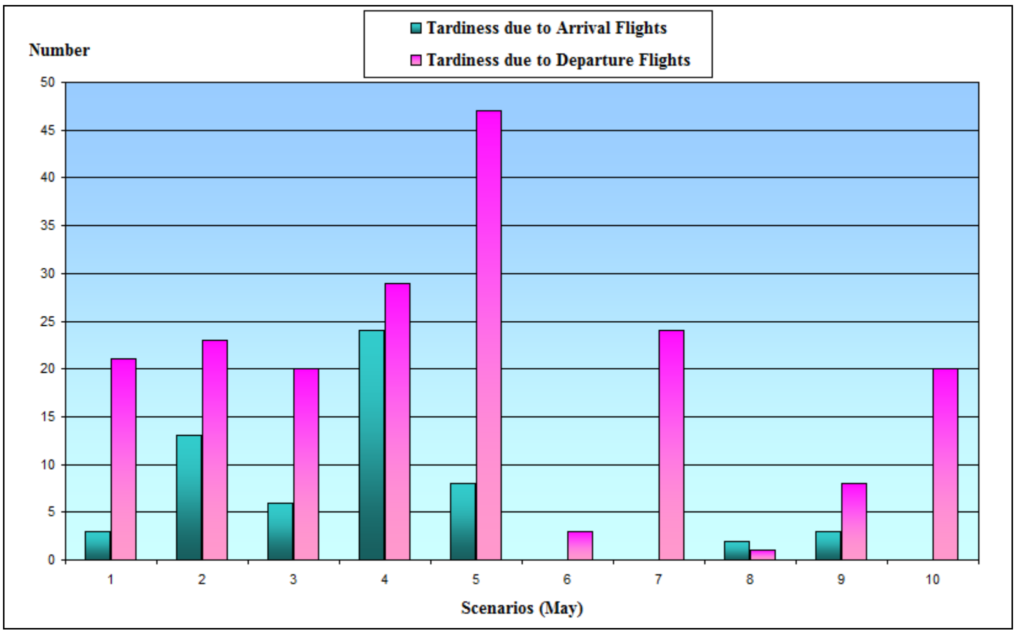

Figure 4.15 Tardiness due to Arrival and Departure Flights (May)

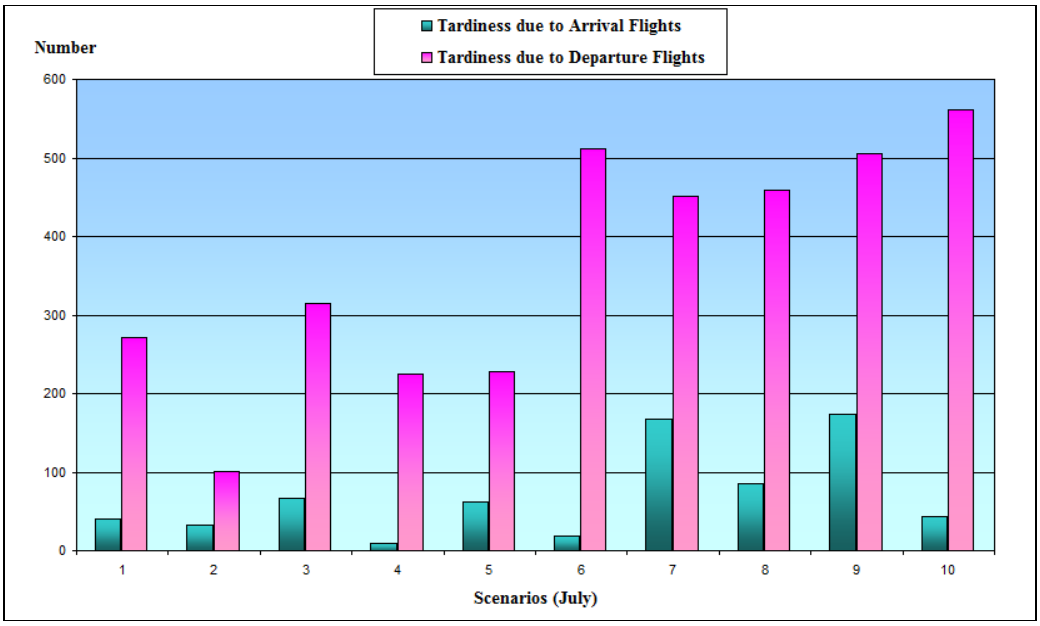

Figure 4.16 Tardiness due to Arrival and Departure Flights (July)

Figure 4.17 shows the average tardiness level due to arrival and departure flights. Among three scenarios, July has the biggest tardiness due to arrival and departures.

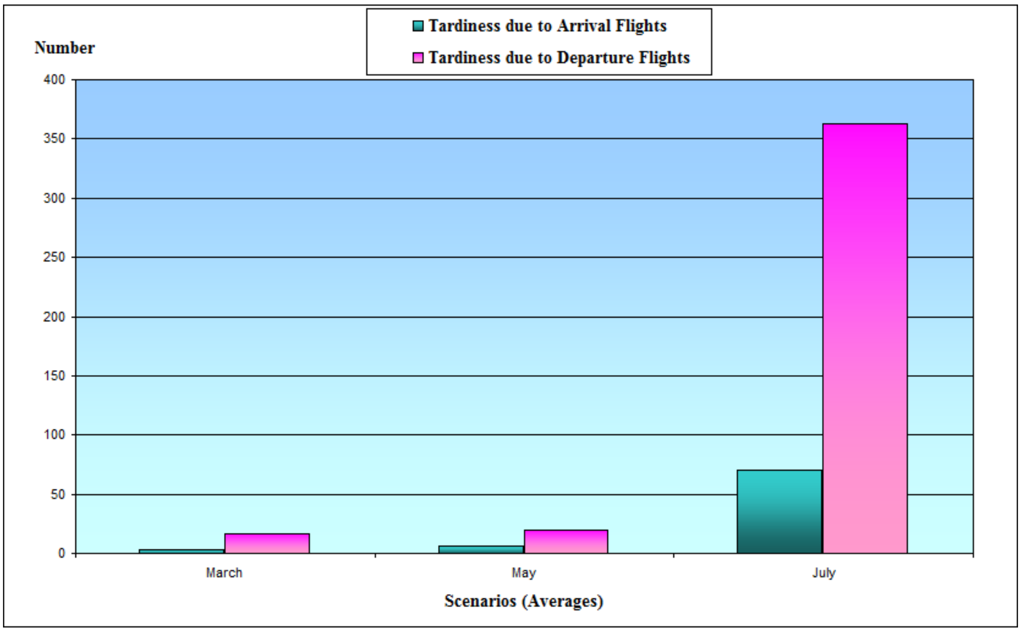

Figure 4.17 Averages of Tardiness due to Arrival and Departure Flights

We can observe from the computational results that the number of delayed flights reach its maximum level in July. It is an expected result since the traffic congestion gets its highest level in July. It is also observed that delays on departures are much more than delays on arrivals. This can be attributed to the fact that the weight coefficient of the arrival flights in the objective function is higher than the one of the departure flights. We mainly consider the investigated problem from the ATS provider's point of view. However, different criteria of ATS users (passengers or airline companies) can also be taken into account, and the problem can be extended to a multi objective one with additional criteria such as the sum of the weighted tardiness in terms of the aircraft types or airborne and ground delay costs.

Briefly, the results of the study indicate that weight coefficient of flights in the objective function, and operational constraints related to push-back and cleaning actions, have a large impact on the system performance. The proposed model above is generic and can be easily modified for different objective functions and ATC systems. For this purpose, additional requirements and operational constraints can be embedded into the proposed mathematical model. Thus, the model can be used as a decision support system to assist the real-time decision-making.

CHAPTER FIVE
CONCLUSION AND FUTURE RESEARCH

5.1 Summary and Concluding Remarks

The technology and procedures used for managing air traffic have advanced evenly over 60 years to handle increased traffic load and complexity. However, incremental changes to technology and procedures are no longer sufficient to keep up with the growth in traffic (Neal et al., 2011). When air traffic demand exceeds capacity, it produces *congestion*. Congestion leads to delays in departures and queues before landing and it causes discomfort to passengers and big losses to air companies. Many mathematical and simulation models have been developed in recent years, in order to reduce the amount of congestion. Ground-holding and redistribution of flows in the airspace are the two principal approaches used for TFM. The primary version of ground-holding policy considers a single airport and makes decisions about the ground-holds for this Single-Airport Problem (SAGHP). The SAGHP is a resource allocation problem in which each flight bound for an airport suffering reduced arrival capacity must be assigned to an arrival slot.

The main interest of this study was to propose a solution model for the real-world SAGHP of Adnan Menderes Airport. An integer programming (IP) model was developed and to evaluate the proposed IP model three different scenarios were generated (i.e., March, May, July).

Two performance measures; tardiness and number of delayed flights have been considered. Computational results have been obtained by using CPLEX 12.1. In the view of the computational results, it is clear that delays on departures are much more than delays on arrivals and the numbers of delayed flights reach its maximum in July.

5.2 Future Research Directions

The proposed model can be further extended focusing on the following topics:

- Multi-airport ground holding problem
- Emergency situations
- Re-routing of the aircrafts
- Calculation of total delay cost in relation to aircraft types, number of passengers, before and after connected flights etc.

In the future we plan to investigate extensions that will enable us to analyze networks of airports. Specifically, we need to address multiple destination flights and banks of flights in the hub-and-spoke system. In multiple destination flights a ground holding delay at any intermediate airport may generate additional costs in several downstream destination airports.

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APPENDIX A. 1 Table of Light Category Aircrafts

Aircraft type	Type No	Category	Category No	Total number of push-backs
A119	1	L	1	0
AS55	2	L	1	0
A504	3	L	1	0
B206	4	L	1	0
B412	5	L	1	0
BE20	6	L	1	0
BE32	7	L	1	0
C101	8	L	1	0
C172	9	L	1	0
C180	10	L	1	0
C206	11	L	1	0
C550	12	L	1	0
EAGL	13	L	1	0
F90	14	L	1	0
MF10	15	L	1	0
PA32	16	L	1	0
SF28	17	L	1	0
T67	18	L	1	0
T68	19	L	1	0
TB10	20	L	1	0
TB20	21	L	1	0
UH1	22	L	1	0
L70	23	L	1	0
KT1	24	L	1	0
RC3	25	L	1	0
T37	26	L	1	0
T38	27	L	1	0

APPENDIX A. 2 Table of Medium Category Aircrafts

Aircraft type	Type No	Category	Category No	Total number of push-backs	Aircraft type	Type No	Category	Category No	Total number of push-backs
H25B	28	M	2	1	A319	55	M	2	5
F4	29	M	2	1	A320	56	M	2	7
F27	30	M	2	1	A321	57	M	2	7
F50	31	M	2	1	AN12	58	M	2	1
F70	32	M	2	1	AN24	59	M	2	2
F100	33	M	2	1	AN26	60	M	2	1
FA90	34	M	2	1	AN30	61	M	2	1
LJ35	35	M	2	1	AN32	62	M	2	1
LJ60	36	M	2	1	AN72	63	M	2	1
MD80	37	M	2	3	AN74	64	M	2	1
MD83	38	M	2	1	AT72	65	M	2	1
MD87	39	M	2	1	B707	66	M	2	2
MD88	40	M	2	1	B733	67	M	2	1
MD90	41	M	2	3	B734	68	M	2	1
RJ70	42	M	2	1	B735	69	M	2	1
RJ100	43	M	2	1	B737	70	M	2	5
T154	44	M	2	3	B738	71	M	2	5
T134	45	M	2	2	B752	72	M	2	1
T204	46	M	2	2	B757	73	M	2	4
YK40	47	M	2	2	C130	74	M	2	1
YK42	48	M	2	2	DC8	75	M	2	2
C130	49	M	2	1	DC9	76	M	2	2
C560	50	M	2	1	E135	77	M	2	1
CL2P	51	M	2	1	FA10	78	M	2	1
CL60	52	M	2	1	GALX	79	M	2	1
CRJ7	53	M	2	1	GLF5	80	M	2	1
C56X	54	M	2	1					

APPENDIX A. 3 Table of Heavy Category Aircrafts

Aircraft type	Type No	Category	Category No	Total number of push-backs
A300	81	H	3	6
A306	82	H	3	1
A310	83	H	3	3
A330	84	H	3	3
A340	85	H	3	3
A342	86	H	3	1
A380	87	H	3	1
AN124	88	H	3	1
B703	89	H	3	1
B707	90	H	3	1
B742	91	H	3	1
B743	92	H	3	1
B747	93	H	3	1
B763	94	H	3	1
B767	95	H	3	4
B772	96	H	3	1
C5	97	H	3	1
C141	98	H	3	1
DC10	99	H	3	3
DC85	100	H	3	1
DC87	101	H	3	1
IL62	102	H	3	2
IL76	103	H	3	2
IL86	104	H	3	2
IL96	105	H	3	1
L101	106	H	3	1
MD11	107	H	3	3

APPENDIX B. 1 Data Sets of Scenario 6 and Scenario 9 for March

Scenario 6							
Period	**Flights**	**Type**	**Arrival/ Departure**	**Period**	**Flights**	**Type**	**Arrival/ Departure**
2	SXS9290	B738	1	51	OHY0052	MD88	1
4	KKK0020	A321	1	53	SXS9234	B738	2
5	THY209	B738	1	53	PGT0117	B738	2
6	THY2961	A320	2	53	THY2964	A330	2
8	PGT0116	B735	2	54	PGT2899	A319	2
8	THY232	B738	2	61	MATKP20	B412	1
9	HBVCJ	H25B	1	69	THY2337	B738	1
11	OHY0051	MD88	2	73	THY2342	A319	1
11	SXS9234	B738	2	75	PGT0123	A320	1
13	KKK0021	A321	2	77	SXS9122	B738	2
13	SXS9165	B738	2	78	MATKP04	B412	2
14	THY2336	A320	1	83	KKK4023	A321	1
15	KKK4022	B752	1	85	OHY0058	MD88	2
17	THY7007	B738	1	87	SXS9266	B737	1
18	THY234	A320	2	91	THY2341	A319	2
22	PGT2817	A319	2	95	PGT2136	A319	2
23	MATKP03	B412	1	100	SXS9120	B738	2
24	THY2965	A320	2	100	THY2310	B738	2
27	PGT0124	B738	2	100	PGT0114	B738	2
30	SXS9265	B738	1	111	KKK0025	B752	1
31	SXS9123	B738	2	112	THY239	B738	1
33	THY231	B738	1	117	OHY0053	MD88	2
35	THY2960	A320	1	118	SXS9235	B738	2
37	KKK0024	A321	2	118	PGT0115	B738	2
39	ESEN10	C130	1	118	THY2311	B738	2
41	ESEN07	C130	2	119	THY7017	B737	1
44	THY2309	B738	1	120	THY2343	B738	1
48	EM0065	C206	2				

APPENDIX B. 1 (Continued)

Scenario 9							
Period	**Flights**	**Type**	**Arrival/ Departure**	**Period**	**Flights**	**Type**	**Arrival/ Departure**
1	OHY0051	MD88	1	27	PGT0124	B738	1
2	SHY053	A321	1	29	THY2338	B738	1
2	SXS9234	B737	1	31	THY2965	B738	1
3	PGT0115	B738	1	32	SXS9122	B738	2
4	THY2961	A320	2	32	SXS9267	B738	2
5	THY3211	A321	1	33	KKK4023	A321	1
6	SXS9292	B737	1	38	SXS9167	B738	1
7	PGT2818	A319	1	41	THY2341	A320	1
8	THY7ED	B738	2	43	THY296	A320	2
8	SXS9165	B738	2	47	THY2309	B738	1
8	THY2337	B738	2	53	TCX2325	B767	2
8	PGT0123	B738	2	53	SXS9291	B738	2
9	THY2964	A320	1	59	PGT0027	B738	1
10	THY233	A320	2	63	OHY0053	MD88	2
11	SHY054	A321	1	66	THY2963	A320	1
12	CAI0455	B734	1	69	THY2311	B738	1
13	OHY0058	MD88	2	72	THY2312	A320	2
14	SXS9266	B737	1	77	KKK0021	B757	2
15	THY2960	A320	2	85	PGT0125	B738	1
16	PGT0114	B738	2	89	THY7EZ	A320	1
16	SXS9290	B738	2	91	KKK4022	B752	1
18	TCX2324	A321	1	93	PGT2817	A319	1
21	THY2310	A320	1	99	THY2336	A321	2
22	THY239	B738	2	105	SXS9123	B738	2
23	OHY0052	MD88	2	109	THY234	A321	1
24	PGT0116	B738	1	113	THY2966	A320	2
25	THY2962	A320	2	113	PGT2893	A319	2
25	PGT2819	A320	2	117	OHY0059	MD88	1
25	THY7EW	A320	2	120	SXS9265	B738	1
25	THY2340	A320	2				

APPENDIX B. 2 Data Sets of Scenario 4 and Scenario 5 for May

Scenario 4							
Period	**Flights**	**Type**	**Arrival/ Departure**	**Period**	**Flights**	**Type**	**Arrival/ Departure**
1	TCX0779L	B757	1	46	CFEMT	LJ35	2
1	TCX0255K	B752	1	49	TVF3813	B738	1
2	BAW2673	B734	2	53	KKK1031	A321	2
3	TCX0317L	B752	2	55	AEI0524	B738	1
3	URG0654	AN124	2	57	TRK2228	A321	1
3	TCX0255L	B752	2	59	SGX0422	B737	1
5	SXS0975	B738	2	61	PGT2141	A320	2
5	SXS0923	B738	2	62	SXS0973	B738	2
5	SXS0983	B738	2	63	KKK1030	A321	2
7	TRK2227	A321	1	67	AEI0525	B738	1
9	SXS0980	B738	1	68	SGX0423	B737	2
11	TWI0449	B734	1	70	SXS0970	B738	2
12	PGT0517	A320	2	71	TWI0450	B734	1
13	SXS0972	B738	1	72	DLH3370	A320	2
14	THY3695	B738	2	77	SXS0944	B738	2
15	SGX0421	B737	1	79	BRU8549	B733	1
17	DLH3373	A321	1	81	PGT3426	A320	1
19	PGT3417	A320	2	82	DLH3371	A320	2
20	CAI0418	B767	2	85	BRU8550	B733	2
21	BRU8495	B733	1	87	SXS0977	B738	1
23	BRU8496	B733	2	89	OHY4361	A321	1
24	BLF7035	MD90	1	92	PGT4807	A319	1
25	CAI0417	B737	1	94	HHI5642	B743	2
27	SAS7261	A321	2	95	HHI0562F	B737	2
27	OHY1491	A321	2	96	PGT5482	B738	2
28	THY5658	B738	1	99	SXS0959	B738	1
29	JTG0741	B733	2	101	SGX0424	B737	1
31	IRK7105	B733	2	103	FHY4574	A321	1
33	PGT2140	A320	1	105	PGT5481	B738	2
35	BLF7036	MD90	1	107	CAI0456	B734	1
36	SXS0976	B738	2	111	CAI0423	B734	2
36	TVF3812	B738	2	112	SGX0425	B737	1
36	SXS0981	B738	2	114	FHY4573	A321	1
36	THY5659	B738	2	116	CAI0455	B734	2
36	SXS0958	B738	2	117	PGT0399	A319	2
39	IRK7106	MD90	1	118	TCARC	LJ60	2
41	SAS7262	A321	1	119	SXS0971	B738	1
43	JTG0742	B733	1				

Scenario 5							
Period	**Flights**	**Type**	**Arrival/ Departure**	**Period**	**Flights**	**Type**	**Arrival/ Departure**
1	DLH3372	A321	1	59	TCX0201L	B752	1
1	XLF0823	B738	2	62	DLH3371	A320	1
1	SXS0922	B738	2	64	SXS0944	B738	1
1	SXS0945	B738	2	69	PGT0961	A320	2
3	PGT0328	A319	1	71	SXS0977	B738	2
5	TWI0632	B734	1	72	N818RF	GLF5	1
6	OHY0698	A321	1	73	RSJ9682	T134	1
7	GWI8926	A319	2	77	SXS0978	B738	2
7	GWI2938	A319	2	78	PGT2144	A320	2
9	URG0653	AN124	1	81	SXS0959	B738	1
10	GWI8927	A319	2	82	BRU8553	T154	1
10	GWI2939	A319	2	85	TWI0736	B734	1
11	OHY0365	A321	1	87	BRU8554	T154	2
13	URG0654	AN124	2	89	PGT2140	A319	2
14	SXS0983	B738	2	91	SXS0971	B738	1
14	SXS0923	B738	2	92	SXS0982	B738	1
14	SXS0960	B738	2	94	PGT2145	A320	2
17	TCARC	LJ60	1	96	SXS0974	B738	2
19	PGT0297	A320	1	97	PGT0962	A320	1
21	DLH3373	A321	1	98	DLH3377	A321	1
23	SGX0390	B737	1	101	TRA0273	B738	2
25	PGT0805	A319	2	103	SXS0922	B738	2
26	SXS0976	B738	1	104	SXS0945	B738	2
27	SXS0958	B738	2	106	IRM5008	A310	1
29	OHY0366	A321	2	107	PGT0516	A320	2
31	KKK1031	A321	2	107	THY3694	B738	2
32	NFA0023P	LJ35	2	108	PGT2141	A319	1
34	TGZ1601	CRJ7	1	109	TRA0274	B738	1
36	PGT0806	A319	1	110	IRM5007	A310	1
39	SXS0961	B738	1	111	TCX0779K	B767	2
41	SXS0979	B738	1	114	GWI0934	A319	1
43	KKK1030	A321	1	115	THY3EV	A310	1
47	NFA0023	LJ35	2	116	TCX0317K	B752	2
49	TCX0201K	B752	1	116	GWI0935	A319	2
50	DLH3370	A320	2	118	BAW2672	B734	1
51	SXS0970	B738	1	119	OHY1492	A321	1
55	SGX0391	B737	2	120	TWI0735	B734	2
57	PGT0298	A320	2				

APPENDIX B. 3 Data Sets of Scenario 2 and Scenario 10 for July

Scenario 2							
Period	**Flights**	**Type**	**Arrival/ Departure**	**Period**	**Flights**	**Type**	**Arrival/ Departure**
1	PGT5764	B738	1	35	BER2884	B738	2
1	BRU8554	T154	1	35	SXS0959	B738	2
2	TWI0469	B734	1	35	CAI0044	B738	2
3	N818RF	GLF5	2	35	THY5336	B738	2
3	PGT5763	B738	2	35	BER2885	B703	2
3	CAI0756	B734	2	35	TCLAB	B412	2
4	FHY7573	A321	1	39	SXS0910	B738	1
5	SXS0976	B738	1	40	CAI0755	B734	1
6	TOM0452	A321	2	42	SXS0982	B738	2
7	CAI0043	B734	1	42	SXS0971	B738	2
8	SXS0958	B738	1	44	TCARC	LJ60	1
9	TCARB	RC3	1	46	DLH3372	A320	1
10	KKK1031	A321	1	49	TRA0435	B738	1
12	AYY0111	LJ35	2	51	PGT3728	A320	1
12	TOM0453	A321	2	53	SXS0922	B738	2
14	PGT3724	A320	1	53	SXS0911	B738	2
15	KKK1030	A321	2	53	TRA0436	B738	2
16	SXS0973	B738	1	55	TOM0716	A320	1
17	AYY0112	LJ35	2	56	SXS0945	B738	1
17	SXS0935	B738	2	57	OHY0262	A321	1
18	FHY0559	A320	1	60	FHY0560	A320	2
19	OHY0272	A321	1	60	SXS0938	B737	2
21	DLH3372	A320	1	64	TOM0717	A320	1
22	PGT2140	A319	2	66	URG0653	AN26	2
23	PGT3727	A320	1	67	GWI0934	A319	1
24	SXS0970	B738	2	69	THY1838	B738	1
26	OHY2748	A321	1	71	PGT1815	A319	1
27	SXS0944	B738	1	73	OHY0802	A319	2
28	DLH3371	A320	2	73	GWI0935	A319	2
29	OHY0261	A321	1	73	THY1839	A319	2
30	OHY0801	A321	2	73	URG0654	AN26	2
31	SXS0977	B738	1	73	PGT2142	A319	2
32	NJE708N	C550	1	73	PGT1816	A319	2
33	PGT2141	A319	1	73	SXS0983	B738	2
34	NJE709N	C550	1	73	FHY0601	A320	2

Scenario 2			
Period	**Flights**	**Type**	**Arrival/ Departure**
77	SXS0923	B738	1
81	SXS0972	B738	2
83	SXS0939	B737	1
85	SVA9333	A306	1
89	THY5177	A321	1
90	DLH3373	A320	1
91	BRU8495	B733	1
95	ENT7701	B734	1
97	BRU8496	B733	2
97	SVA2333	A306	2
99	ENT7702	B734	1
101	SXS0975	B738	1
103	TCAEU	LJ60	1
104	PGT0805	A320	1
105	SXS0958	B738	2
105	SXS0979	B737	2
106	PGT0806	A320	1
107	SXS0973	B738	2
107	THY64R	A342	2
107	SXS912	B738	2
109	THY38C	A320	1
110	SXS919	B738	2
110	THY35V	B738	2
110	THY35Z	B738	2
112	KKK0021	A321	1
113	OHY0051	MD88	2
115	PGT0114	B737	1
116	TCARC	LJ60	2
117	SXS924	B738	1
118	THY5HR	A320	2
118	THY6DE	A320	2
118	MNB0311	A320	2
120	FHY0602	A320	2

Scenario 10							
Period	**Flights**	**Type**	**Arrival/ Departure**	**Period**	**Flights**	**Type**	**Arrival/ Departure**
1	PGT3727	A320	1	28	FHY0601	A320	1
1	GFTSL	CL60	1	29	SXS0924	B738	2
2	SXS0943	B738	2	29	SXS0983	B738	2
2	SXS0970	B738	2	29	SXS0972	B738	2
3	TCLAD	C56X	1	31	TCEUA	LJ60	1
4	OHY0261	A321	2	32	SHY055	A321	1
4	OHY0801	A321	2	33	PGT2140	A320	1
5	PGT2141	A319	1	35	BRU8495	B733	1
6	SXS0977	B738	2	36	ENT7701	B734	1
7	FXR0018A	RJ70	1	37	TUAF35	C5	1
8	BER2884	A320	2	38	BRU8496	B733	2
8	BER2885	A320	2	38	GMI6282	B733	2
9	CAI0044	B737	1	38	ENT7702	B733	2
10	SXS0957	B738	2	40	PGT2142	A320	1
10	SXS0971	B738	2	41	GMI6283	B733	1
11	PGT3728	A320	1	43	SXS0976	B738	2
12	TCLAD	C56X	2	44	PGT0805	A320	1
13	CAI0755	B737	1	46	SXS0958	B738	1
14	SXS0938	B738	2	47	KKK1031	A321	1
14	SXS0982	B738	2	49	SXS0979	B738	1
14	SXS0921	B738	2	51	TUAF36	C5	2
14	SXS0945	B738	2	51	TCEUA	LJ60	2
16	FHY0560	A320	1	51	KKK1030	A321	2
17	OHY0262	A321	1	51	SXS0973	B738	2
18	TOM0716	A320	1	53	PGT0806	A320	1
20	TRA0435	B738	2	55	SHY053	A321	2
21	TOM0717	A320	1	55	FHY0602	A320	2
22	TCARC	H25B	1	55	DLH3370	A321	2
23	TRA0436	B738	1	55	TCARB	C172	2
2	GWI0933	A319	2	57	ABR0415J	B733	1
24	OHY0802	A321	2	59	SXS0944	B738	1
24	THY1838	B738	2	61	DLH3371	A321	1
26	GWI0936	A319	1	63	ABR0416J	B733	2
27	THY1839	B738	2	64	SHY054	A321	1
27	SXS0939	B738	2	65	SXS0978	B738	2
27	TCARC	H25B	2	65	PGT0541	B737	2

Scenario 10			
Period	**Flights**	**Type**	**Arrival/ Departure**
65	SXS0959	B738	2
67	BAW2670	A319	1
70	FHY1574	A321	1
73	5YRIS	DC10	1
77	BAW2671	A319	2
77	OHY0396	A319	2
77	FHY1573	A319	2
77	DLH3372	A319	2
80	SHY056	B738	1
83	TCHJR	B412	2
83	SXS0974	B738	2
85	MNB0101	A300	1
88	SXS0922	B738	2
88	SXS0946	B738	2
90	THY1546	A320	1
93	URG0653	IL86	1
94	PGT0542	B737	2
97	GWI0934	A319	1
99	THY1604	B738	1
101	GWI0935	A319	1
103	THY1603	B738	1
105	THY1547	A320	2
107	OHY0395	A321	1
108	URG0654	IL86	2
108	SXS0975	B738	2
108	MATKP34	B412	2
108	SXS0923	B738	2
108	SXS0980	B738	2
108	SHY057	B738	2
110	PGT0297	A320	1
112	OHY2261	A321	1
114	TWI0449	B734	1
116	DLH3373	A320	2
117	RWZ9717	T204	1
119	OHY0181	A320	2
119	RWZ9718	T204	2