ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL OF SCIENCE
ENGINEERING AND TECHNOLOGY

ANALYSIS OF GENERATED DELAYS DUE TO AIR TRAFFIC CONTROL DECISIONS IN AIR TRAFFIC MANAGEMENT

M.Sc. THESIS

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İSTANBUL TEKNİK ÜNİVERSİTESİ ★ FEN BİLİMLERİ ENSTİTÜSÜ

HAVA TRAFİK KONTROLÜNDE KONTROLÖR KARARLARI NEDENİ İLE OLUŞAN GECİKMELERİN ANALİZİ

YÜKSEK LİSANS TEZİ

Utku EREN
(514111010)

Disiplinler Arası Programlar Anabilim Dalı

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Tez Danışmanı: Assoc. Prof. Dr. Gökhan İNALHAN

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Utku EREN, a M.Sc. student of ITU Graduate School of Science Engineering and Technology 514111010 successfully defended the thesis entitled **“ANALYSIS OF GENERATED DELAYS DUE TO AIR TRAFFIC CONTROL DECISIONS IN AIR TRAFFIC MANAGEMENT”**, which he/she prepared after fulfilling the requirements specified in the associated legislations, before the jury whose signatures are below.

Thesis Advisor :	**Assoc. Prof. Dr. Gökhan İNALHAN** Istanbul Technical University	....
Jury Members :	**Prof. Dr. İbrahim ÖZKOL** Istanbul Technical University	....
	Assoc. Prof. Dr. Mehmet Turan SÖYLEMEZ Istanbul Technical University	....

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FOREWORD

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August 2013 Utku EREN
(Astronautical & Electronics Engineer)

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ABBREVIATIONS

ACC : Area Control Center
ANSP : Air Navigation Service Provider
AOBT : Actual Off-Block Time
ASM : Airspace Management Planning Charts
ATC : Air Traffic Control
ATCO : Air Traffic Control Officer
ATFM : Air Traffic Flow Management
ATM : Air Traffic Management
ATS : Air Traffic Service
ATFCM : Air Traffic Flow and Capacity Management
AUA : Air Traffic Control Unit Airspace
CFMU : Central Flow Management Unit
COBT : Calculated Off-Block Time
CPR : Correlated Position Report
CTFM : Current Tactical Flight Model
CTOT : Calculated Take-Off Time
DDR : Demand Data Repository
ECAC : European Civil Aviation Conference
EOBT : Estimated Off-Block Time
ETA : Estimated Time of Arrival
ETFMS : Enhanced Tactical Flow Management System
EUACA : European Airport Coordinators Association
FIR : Flight Information Region
FPL : Filed Flight Plan
FTFM : Filed Tactical Flight Model
IBT : In-Block Time
IFPS : Integrated Initial Flight Plan Processing System
IOBT : Initial Off-Block Time
LOBT : Last Off-Block Time
NEVAC : Network Estimation and Visualization of ACC Capacity
OBT : Off-Block Time
RTFM : Regulated Tactical Flight Model
SAAM : System for Airspace Analysis at Macroscopic Level
SESAR : Single European Sky ATM Research
SRS : Schedule Reference Service
STAR : Standard Terminal Arrival Route
TMA : Terminal Maneuvering Area

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ANALYSIS OF GENERATED DELAYS DUE TO AIR TRAFFIC CONTROL DECISIONS IN AIR TRAFFIC MANAGEMENT

SUMMARY

With its intrinsic complexity, rapidly growing demand and almost saturated infrastructures, Air Transport Management is one of the most challenging fields of the near future. To be able to respond the need, there are many conducted researches and initiatives as Single European Sky ATM Research (SESAR) programme in Europe and its US counterpart NextGen. Resilience2050.eu is one of the projects carried out in Europe with the purpose of analyzing the current air traffic system's deficiencies in terms of resilience ability. Aimed to design disruption and perturbation adaptive ATM concepts of future beyond SESAR within the boundaries of safety, this research project analyzes the current system dynamics focusing on the propagation of unexpected and undesired events through the whole ATM system which underlies the theme of this thesis.

Macro analysis of the European Air Traffic Network system play a key role in pinpointing the elements and events that drive the system which are crucial for a resilient structure. Specifically the air transportation network across the airports, airspaces, subspaces and its segmentation define the structure of the flow network. In addition, scheduled flights, their densities across this network, and corresponding flight patterns define the nature of the flow across the network. The analyses provide an insight about the transportation network system's dynamics and serve to the construction of more accurate models which will enable the application of optimization problems into real world conditions. Accordingly, they form an essential part for the purpose of building a resilient structure and have an utter importance to construct reliable and robust air traffic management and control infrastructures.

The analyses in this project have been conducted with two types of data as ALL_FT+ trajectory data and DDR capacity data. Each file of the trajectory data gives the all flights' trajectories with point and airspace profiles over European Air Traffic Network whereas DDR capacity data provides the declared capacities for different entities of air transportation system such as airports, airspaces etc. Among from various flight models and radar data in ALL_FT+ structure, Planned and Actual Data have been extracted with some assumptions. The planned data structure represents the prior determined trajectory that is intended to be flown whereas the actual data is the actual flown trajectory. Since the ALL_FT+ data has a complex structure with many flaws, series of fixing and filtering algorithms have been developed to preclude the wrong computations which may conclude with false deductions.

The three parameters that create the infrastructure of analyses are capacity, traffic and delays. As it was mentioned, capacity values are obtained via DDR capacity data and the traffic and delays are extracted from ALL_FT+ data. The first leg of the analyses is to construct the network graph of the European Airspace where each

node in the graph may represent either airspaces or airports. This graph does not only depict the interactions between airspaces or airports, but also provide a framework to work on with traffic data. Each branch (edge) of the graph stands for reciprocal traffic flows between the related nodes. The complete connectivity graph is generated by the ALL_FT+ data itself thanks to continuous airspace profiles of each flight of the data and the airport indications in the point profiles. The benefits of the connectivity graph of the network model is tested and illustrated over France area in terms of airspaces, and the interactions are presented with findings. The analysis is conducted bidirectional in each branches of the graph and the time interval of the whole analysis has been chosen as a week to see daily patterns and their variations based on flight plans of each day. Additionally, the findings that obtained through the traffic flow graphs regarding the magnitude of sectors also have been confirmed via monitoring the number aircrafts per hour in each sector.

As a third parameter of the analyses, delays and their propagation across the network graph have been investigated. Delay is not only a solid merit of quality of service but also a key element which defines resilience in the Air Traffic Network. Individual delays for each phases that all flights experience have been calculated with seeking the differences between planned and actual data's elapsed times for each phase where the possible reasons for these differences may be unexpected events such as bad weather conditions or strikes. Aggregating these individual delays in terms of airspaces yields the delay distributions of airspaces over the European airspace network. Moreover classifying these delays in hourly intervals will depict the propagation of delays, and an example of this approach has been conducted over London area.

As a secondary approach, instead of using airspace centered analyses, network of airports have been investigated which shifts the focus to the propagation of delays between airport pairs. The approach introduces the examination of airport delays into analyses, hence the delays of Actual Off-Block Times and Taxi phases have been calculated and status of airports are monitored in terms of arrival/departure traffics and declared capacities. Incorporating the airports into the analyses provided the push-back delays and their evolutions through each flight's path which resulted with a complete track of delays. The efficiency of this approach has been tested in Munich International Airport Network with 11 edges.

The analyses have been conducted in different perspectives and results of each are given with comments. The events, conditions and procedures that drive the air transportation network system have been identified to get deeper understanding and the comparisons of potential modelling techniques for European Air Transportation Network have been presented holistically.

HAVA TRAFİK KONTROLÜNDE KONTROLÖR KARARLARI NEDENİ İLE OLUŞAN GECİKMELERİN ANALİZİ

ÖZET

Oldukça karmaşık yapısı, kendisine duyulan talebin hızlı artışı ve hızla tükenmekte olan altyapı kapasiteleri ile Havayolu Taşımacılığı Yönetimi yakın geleceğin en zorlu alanlarından biri halini almıştır. Bu alanda oluşan ihtiyacı karşılayabilmek amacı ile çok uluslu araştırmalar gerçekleştirilmekte ve gerek Avrupa'da (SESAR) gerekse Amerika Birleşik Devletlerinde (NextGen) çeşitli toplu girişim hareketlerinde bulunulmaktadır. Bu amaçla, Avrupa Birliği bünyesinde gerçekleştirilen projelerden biri olan Resilience2050.eu mevcut durumdaki hava trafik sisteminde bulunan ve sistemin beklenmedik olaylara direncini ciddi derecede etkileyen eksiklileri belirlemeyi hedef edinmiştir. Nihai amacı güvenlik sınırları çerçevesinde, aksaklıklara ve istenmedik karışıklıklara dayanıklı, geleceğin Hava Trafik Yönetimi konseptlerini geliştirmek olan bu projenin temelinde mevcut sistemin dinamiklerini ve beklenmeyen/istenmeyen olayların sistem içerisinde nasıl bir etki yaratarak devam ettiklerini inceleyen analizler bulunmaktadır. Bahsi geçen analizler bu tezin odak noktasını oluşturmaktadır.

Mevcut sistemin daha kararlı, oluşabilecek beklenmedik etkilere karşı daha dayanıklı ve verimli hale getirilme amacını taşıyan süreçte, Avrupa Hava Trafiği Ağı'nın makro analizi, hava trafik sistemlerinin alt bileşenlerinin ve sistemin davranışlarını oluşturan olayların belirlenmesinde çok büyük bir önem taşımaktadır. Hava taşımacılığı ağındaki havalimanları, havaalanları ve bu alanların segmentleri, bu ağı oluşturan temel elemanlar olarak nitelendirilirken, uçuş planları ve bu uçuşların ağ elemanları arasındaki yoğunluklarının oluşturduğu kalıplar ise trafik akışının karakteristiğini meydana getirmektedir. Bu bağlamda trafik ağı sisteminin dinamiklerini inceleyen makro analizler, bu sistemi daha yüksek doğrulukla temsil edebilecek modellerin oluşturulması için bir adım olmakta ve sistemi daha verimli kılmak amacı ile uygulanabilecek optimizasyon problemlerini gerçek sistem karateristikleri ile buluşturan bir köprü görevi görmektedir. Bu nedenlerden dolayı geleceğin daha güvenilir ve dayanıklı Hava Trafik Yönetimi ve Kontrol altsistemlerinin oluşturulmasında, makro analizler oldukça temel ve önemli bir yer tutmaktadır.

Bu proje kapsamında yürütülen makro analizlerde ALL_FT+ ve DDR Capacity olmak üzere iki farklı data yapısı kullanılmıştır. Temel olarak ALL_FT+ verileri uçağın rotalarını verirken, DDR Capacity verisi trafik ağının elemanları olan havalimanları ve havaalanlarına ilişkin altyapıların belirlenen kapasitelerini içermektedir. ALL_FT+ verileri günlük olarak dosyalanırken, her uçuş için 7 adet uçuş modeli ve bir adet radar ölçümleri veri alt grubu içermesi planlanmıştır ancak bu 8 adet veri alt grubu her uçuş için mevcut değildir. Ayrıca tüm bu 8 grup için de nokta bazlı ve havaalanı bazlı olmak üzere iki farklı data profili bulunmakta ve bu iki profil aynı veriye iki farklı bakış açısı kazandırmaktadır. Nokta bazlı profilde uçuşun rotası noktalar dizisi olarak ifade edilir iken, havaalanı bazlı profilde uçuşun rotası, içerisinden geçtiği hava alanlarının giriş ve çıkış noktaları olarak ifade edilmektedir. Dahası, tüm bu 8 grubun dışında

her uçuş verisinin başına eklenmiş ve yaklaşık 70 veri alanından oluşan bir ortak veri alanı bulunmakta ve bu alan, uçağın park alanından ilk harekete geçmesi planlanan ve geçtiği zamanlar, kalkış ve iniş havalimanları, uçuş numarası, uçuşun iptal olup olmadığı ve uçuşa dair bazı prosedür mesajları gibi bazı önemli bilgiler içermektedir. DDR capacity verisi ise yaklaşık olarak bir aylık veriler halinde depolanmış ve Avrupa Hava Sahası içerisinde bulunan havalimanlarının saatlik iniş/kalkış kapasitelerini ve kontrol havaalanlarının saatlik uçak barındırma kapasitelerini içermektedir.

ALL_FT+ datasının içerdiği aynı uçuşa ait bu 8 adet veri alt grubu içerisinden tezin temasını oluşturacak analizleri gerçekleştirmek amacı ile 3 adet veri grubu seçilmiştir. Birinci alt veri grubu (FTFM) planlanan uçuş datasını, ikinci alt grup (CTFM) planlanan uçuş datası ile radar verilerinin füzyonundan oluşan uçuş modelini, üçüncü alt grup (CPF-REF) ise radar verilerini içermektedir. Bu bağlamda birinci grup "Planlanan Uçuş Verisi" olarak atanırken mevcut olması durumunda üçüncü grup "Gerçek Uçuş Verisi" olarak kullanılmaktadır. Üçüncü grubun data içerisinde bulunmaması durumunda ise ikinci grup olan CTFM verisi gerçek uçuş verisi olarak kabul edilmektedir. Birçok geniş çaplı veri yapılarında olduğu gibi ALL_FT+ verisi de bazı hatalı veriler içermektedir. Bu hatalı verilerin olduğu gibi kullanılması özellikle gecikme analizlerinde oldukça yanlış sonuçlar vermektedir. Bu nedenle bir takım filtremele ve düzenleme algoritmaları yazılmış ve analizlerden önce veriler bu algoritmalardan geçirilerek yanlış çıkarımlara neden olabilecek sonuçların giderilmesi sağlanmıştır.

Kapasite, trafik ve gecikme parametreleri, bu çalışmada yapılan analizlerin alt yapısını oluşturmaktadır. Bu parametrelerin yalnız veya birbirleri ile birlikte incelenmeleri sonucu sistem davranışlarına dair bir takım sonuçlar elde edilmektedir. Daha önce de bahsedildiği gibi, parametrelerden biri olan kapasite DDR Capacity verisinin işlenmesi ile doğrudan elde edilmektedir. Trafik ve gecikme değerleri ise ALL_FT+ datası üzerinden hesaplanmaktadır. İlk işlem olarak, Avrupa havasahası üzerinde düğüm noktaları havalimanlarını ya da havaalanlarını temsil eden bağlantı grafı oluşturulmuştur. Veri yapısı içerisinde havasahaları çeşitli boyutlarda temsil edilmektedir. Bu bölgelerden en çok kullanılanları boyutlarına göre büyükten küçüğe "Uçuş Bilgi Bölgesi (FIR)", "Hava Trafik Kontrolü Birim Havaalanı (AUA)" ve "Temel Havaalanı (ES)" olarak sıralanabilir. Bu çoklu temsil, analizin istenilen düzeyde ve detayda gerçekleştirilebilmesine olanak tanımaktadır.

Avrupa havasahasının bağlantı grafı, havaalanları ya da havalimanları arasındaki bağlantıları göstermekle birlikte daha sonraki analizlerin yürütülmesi için bir ortam da oluşturmaktadır. Bu bağlamda düğümler arasındaki her bağlantı çift yönlü trafik akışlarını temsil etmektedir. Bağlantı graflarının tamamı, datadaki uçuşların havaalanı bazlı profillerinin birbirini kesintisiz takip etmesi özelliğinden faydalanılarak, data üzerinde koşan algoritmalar ile üretilmiştir. Ayrıca verinin tüm uçuşlar için daha önce de bahsedildiği üzere kalkış ve iniş havalimanlarını içermesi, havalimanları ağından oluşan grafların oluşturulmasını mümkün kılmıştır. Bağlantı grafının sağladığı fayda Fransa havasahası üzerinde oluşturulan bir havaalanları ağ modeli üzerinde test edilmiş ve hava alanlarının birbirleri ile etkileşiminin sonuçları sunulmuştur. Bu analiz ağ üzerindeki tüm bağlantılar için çift yönlü akışlarla gerçekleştirilmiş ve analizin zaman aralığı bir hafta olarak seçilmiştir. Bir haftalık datanın aynı anda işlenerek kullanılması, günlük karakteristik trafik akışlarının benzerliğini ve haftasonunda uçuş planlarına bağlı olarak yaşanan değişimleri göstermektedir. Bu karakteristik davranışın nasıl modellenebileceği hakkında da yorumlarda bulunulmuştur. Ek olarak, analiz sonucunda trafik akış grafı üzerinde sektör olarak adlandırılan havaalanlarının büyüklükleri ile ilgili varılan sonuçlar her sektördeki saatlik uçak sayısı verileri ile karşılaştırılarak doğrulanmıştır.

Üçüncü ve son parametre olan gecikme değerleri, hizmet kalitesinin en önemli ölçütlerinden biri olmakla birlikte, hava trafik ağının beklenmeyen ve/veya istenmeyen değişikliklere ne kadar dayanıklı olduğunun en temel göstergesidir. Bu bağlamda gecikmeler ve bu gecikmelerin sistemde nasıl dağıldığına dair analizler yapılmıştır. İlk olarak data içerisinde bulunan tüm uçuşların, uçuşun her fazı için yaşadıkları gecikme değerleri planlanan ve gerçekleşen uçuş dataları arasında yaşanan farklar ile hesaplanmıştır. Tüm uçuşların tüm havaalanlarında yaşadığı gecikmeler hesaplandıktan sonra bu gecikmeler ilgili havaalanı başlığı altında tekrar organize edilerek, havaalanlarının gecikme üretme karakteristiği çıkarılmıştır. Bu işlemin bir günlük veri üzerinde gerçekleştirilmesi üzerine, o gün için Avrupa havasahası ağı üzerinde problemli bölgelerin görüntülenmesi sağlanmıştır. Benzer işlemin saatlik olarak sınıflandırılması bir gün içerisinde gecikme karakteristiklerinin saatlik olarak nasıl değiştiği sonucunu vermektedir. Dolayısı ile hava trafik ağı sisteminde herhangi bir noktada oluşan aşırı gecikme üretimi sorununun sistem içerisinde bir sonraki saatte ne gibi bir etki yarattığı incelenebilmektedir. Bu durum Londra Havasahası üzerinde örneklendirilmiş ve sonuçlar ilgili bölümde verilmiştir.

Havaalanı bazlı analizlerin gerçekleştirilmesi sonucu, hava trafiği dinamiğini modelleme amacına hizmet edecek daha farklı yaklaşımların denenmesi yoluna gidilmiştir. Burada amaç sistem içerisinde gerçekleşen olayları en iyi şekilde temsil edebilecek ve olayların yarattığı etkinin yayılımını neden sonuç ilişkisi içerisinde daha net gösterebilecek modelleri oluşturma metodolojisini araştırmaktır. Bu nedenle ikinci bir yaklaşım olarak, havaalanı bazlı analizler kullanmak yerine, havalimanlarının ağından oluşan ve gecikmelerin yayılımını havalimanı ağı üzerinde inceleyen analizler gerçekleştirilmiştir. Burada bağlantı graflarının düğümleri havalimanlarını temsil ederken gecikmeler havalimanı çiftleri arasında incelenmiştir. Bu nedenle, ilk etapta havalimanı analizleri gerçekleştirilmiştir. Uçağın ilk hareket ettiği zaman olarak tanımlanan "Gerçek Hareket Zamanı"nda yaşanan gecikmeler ve uçağın taksi süresince yaşadığı gecikmeler de analiz edilmiş ve bu analizlerin sonucunda elde edilen bulgular havalimanına inen ve havalimanından kalkan uçakların saatlik sayıları ve ilgili havalimanı için ilan edilen kapasite değerleri ile birlikte değerlendirilmiştir. Havalimanlarının durumunun da modelleme süreci içerisine katılması ile hesaplanan yeni gecikme değerleri sistemde gerçekleşen olaylar hakkında daha fazla bilgi verirken uçuşun tüm fazlarında gerçekleşen gecikmelerin ve bu gecikmelerin ne nedenle oluştuğu hakkında da varsayımlarda bulunma fırsatı tanımaktadır. Ayrıca bu sayede gecikmeler uçuşun başlangıcından sonuna kadar tamamen izlenebilmektedir. İkinci yaklaşım Munich Uluslararası Havalimanını merkezinde bulunduran ve diğer 11 havalimanına bağlanan bir ağ üzerinde sınanmış ve sonuçlar ilgili bölümde sunulmuştur.

Bu çalışmada Avrupa Havasahası üzerinde gerçekleşen uçuşların ve yer operasyonlarının oluşturduğu sistemin modellenmesine ön ayak olacak analizler gerçekleştirilmiş ve modelleme için önerilerde bulunulmuştur. Analizler temel olarak iki farklı bakış açısı ile gerçekleştirilmiş ve iki yaklaşımın da avantaj ve dezavantajları belirtilmiştir. Hava Trafik sistemini süren ve etkileyen olaylar analizlerde görülen sonuçlar ile bağdaştırılmış ve bu sonuçların bir bütün olarak değerlendirilmesi ile modelleme yöntemi hakkında önerilerde bulunulmuştur.

1. INTRODUCTION

In 2010 Global Air Transport deals with 2.4 billion passengers, 43 million tonnes of cargo, 32 million jobs, just 1 accident for every 1.4 million flights, %2 of global carbon emissions and $545 billion in revenue [8]. With its coverage over the whole world, it provides connections between various regions where each region has peculiar characteristics and procedures. Notwithstanding the differences between regions, any event that concludes with a significant effect in any of these regions may have concrete impact on other. This worldwide transport phenomena with its entities such as aircrafts, airports and airspaces as well as its regional infrastructures and their independencies, is an extremely complex and active system. This current dynamic air traffic system consistently enlarges with the growing demand. In fact, various analyses and forecasts assume that the growth of air traffic will be approximately 5% per year where the financial crisis, epidemics etc. usually show only a temporary impact [9].

The ability to recover quickly from any disruption or unexpected event is a crucial and difficult to attain feature in complex sociotechnical systems such as Air Traffic System where large number of interacting human operators and technical systems, functioning over various regions under different organizations and procedures, have to manage air traffic system with certain safety and efficiency even in the case of uncertainty and disturbances. Although procedures and regulations tend to specify working processes in ATM to a considerable extent, the flexibility and system oversight of human operators are essential for efficient and safe operations in normal and more rare conditions [10]. Hence, the role of human operators in resilient ATM structure is vital, and construction of more automated and adaptive ATM structure of future is contingent upon good comprehension of the current human-invoked resilience. Even though the roles and responsibilities of humans will change with the advancement of current system towards to more automated ATM, intelligence, perception and flexibility of human operators will be the fundamental source for resilience of ATM system in the foreseeable future.

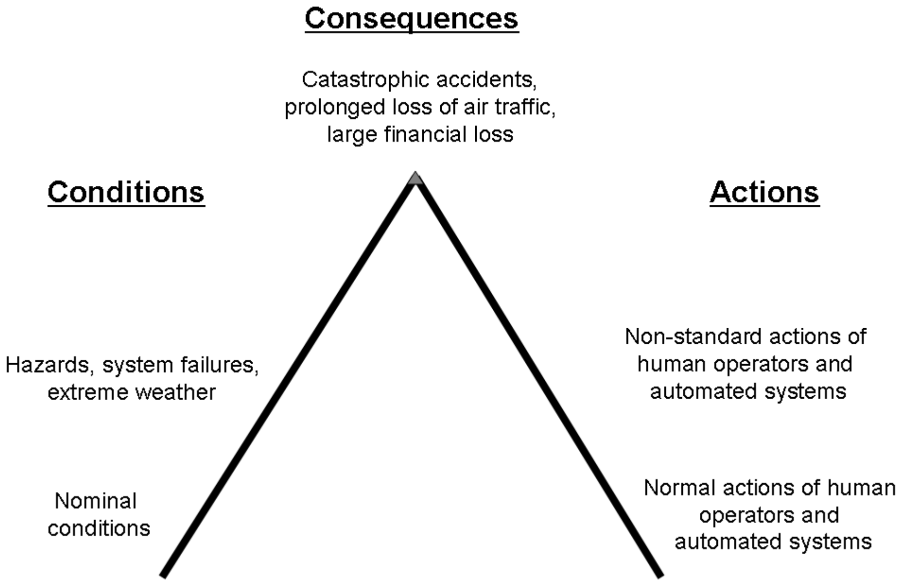


Figure 1.1: Air Transportation Resilience Pyramid [1].

1.1 The Context in ATM Modelling Research

Since the 1950s, various analytical and simulation models have been developed in order to represent the dynamical behavior of the air traffic system where the simulation environments are differentiated in level of detail and scope [11]. The level of detail can be categorized in two different perspectives as macroscopic and microscopic view. Macroscopic level analyses consider the traffic flows among specified entities as airports or airspaces whereas microscopic level deals with individual elements as aircrafts or passengers. The scope of a simulation environment is a metric for the area that simulation covers in terms of airspaces or airports which are to be modelled. Additional to individual aircrafts, ground elements or airport procedures, as well as the terminal characteristics shaped by passengers are also included to analyses over the last decade [11]. Depending on the scope and the perspective, models can be driven by either deterministic or stochastic processes.

Discrete-Event Simulation Model (SIMMOD) [12], ATC Fast Time Simulator and Air Traffic Optimizer (AirTOp) [13] and Total Airspace and Airport Modeler (TAAM) [14] can be given as simulation environment examples to microscopic level of detail. These simulation environments covers various areas of airport and airspaces such as runways, taxiways, apron or en-route airspace. Fast time simulation runs of these tools can provide answers to many questions with in the ATM context. These tools are mainly employed in order to evaluate new proposed operating procedures of the airport under investigation. The assessments can be made via performance indexes as capacity and delays. However, in order to be able to investigate stability and resilience, further research on these issues must be conducted. Multi-agent dynamic risk modelling (DRM) is a method that is part of the Traffic Organization and Perturbation AnalyZer (TOPAZ) safety risk methodology for the evaluation of accident risks in ATM [15]. The method uses Monte Carlo simulations in combination with bias and uncertainty evaluations to obtain quantitative accident risk probabilities and insight into the key contributions to the accident risk [16]. For the unexpected conditions, events and performance variances of humans and technical systems, Multi-agent DRM includes stochastic dynamic models which procures one of the resilience metrics in ATM by considering variety of stochastic disturbances at the level of accident risk.

1.2 Purpose of Thesis

ATM system is a composition of different elements and their interactions. The existence of these various elements may be in different scales and perspectives as spatial or temporal. Therefore, the elements of the ATM is categorized in layers where each one has a significant role in whole system dynamics. These layers can be named as: airport, airspace and weather layers. The elements constituting each layer are in interaction with each other as well as the elements of different layers affect each other which is the main source of the system's complexity. For instance, congestion (over capacity usage) in arrival airport's TMA airspace may be a reason for the ground holding procedure in an airport far from the arrival airport. Furthermore, the congestion at that arrival airport may be caused by a bad weather conditions that took place a long time ago over a different region which decreased the airspace capacity of related region. So the relations between elements are far beyond time and spatial distance parameters.

In order to quantify the resilience of the system, identify the system response in case of any disruption or perturbation via possible propagation of disruption across different elements of system, several analyses must be conducted. Working with data will make the utilization of data mining techniques obligatory and graph theory seems as a useful tool which has a proven usability when analyzing systems for which models or metrics do not exists, as is the case in the propagation of perturbations in the ATM systems.

In the light of these interactions between elements, any attempt for mandating resilience should consider this multi-layered nature. In this thesis, with the capability of available data, airport and airspace layers will be defined through data itself which is extracted from the real system, and their temporal and spatial variability will be investigated in event-oriented aspect. Each layer and their elements' connectivity are modelled as a network represented by a connectivity graph where each element affects the dynamics of the network system in a specific way. Additionally, this thesis seeks the propagation of any perturbation that occurred in an element. This propagation may occur in both, elements of the same layer or elements of different layers. For instance, the delay caused by bad weather conditions in any airspace may change the original route of the flight which results in more delays in neighboring airspaces. Similarly, congestion in arrival TMA airspace may cause a delay which is generated by departure airport's ground holding procedure. Therefore, the interactions of elements in the same layer as well as elements belong to different layers are taken into consideration in this thesis.

Structure of the thesis is as follows; second chapter gives an information about the source and the structure of the data that will be the backbone of the analyses, third chapter describes the delay types and calculations of them, fourth chapter presents the statistics about the quality of the data and processing procedures utilized in this thesis. Fifth chapter gives the final formulations and presents the generated connectivity graphs with elaborating their benefits whereas the sixth chapter includes the analyses and results in their development order. Seventh chapter is about an exclusive work on TMA regions which is carried out with a different and more detailed data, and finally eighth chapter gives holistic conclusions of overall thesis.

2. DATA SOURCES & DESCRIPTIONS

In this chapter, the Flight Data that is used in the entire thesis will be explained with its details and the source of the data will be given. Description of all technical words in the related part of the data will be elaborated.

2.1 Demand Data Repository (DDR) Project

EUROCONTROL deploys series of European-wide air traffic management (ATM) programs and projects, involving a range of ATM players. The main objective of all programs and projects is to construct a single European sky that will deliver the ATM performance required for the twenty-first century and beyond [17].

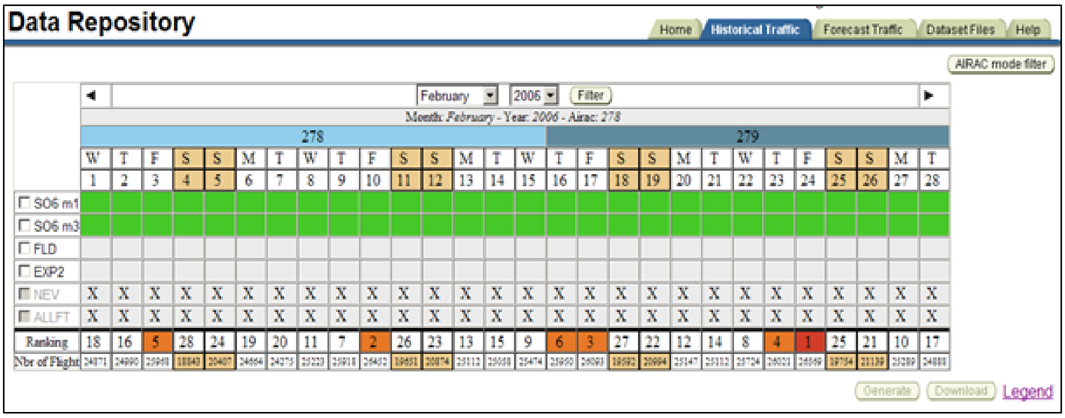
Demand Data Repository is one of these projects that aims to provide European airspace planners and airspace users with data that will depict straight picture of past and future European air traffic demand for the purpose of meeting the planning and monitoring needs. Its mission is to procure better prediction of European air traffic demand which will facilitate efficient operations planning. Besides being a tool for anticipating the forthcoming conditions, DDR provides a refined analysis of past demand in order to enable post-operations analysis and identify best practices for future operations [18].

In the strategic phase of the organization of Air traffic flow and capacity management (ATFCM), resources are mainly managed at the Air Navigation Service Provider (ANSP) level which is established with the purpose of managing flight traffic on behalf of a company, region or country. In the pre-tactical phase the airspace resource is managed at the national level [19]. In this regard, DDR is available to be utilized by a wide range of users. ANSP's and the Network Managers can employ it for operational planning purposes, seasonal preparation and planning of special events. ANSP's also use it for pre-tactical refinements to ATFCM and improving the planning of Air Traffic Control Officer (ATCO) rosters. Additionally, aircraft operators can take advantage of DDR project for flight planning purposes and any other actors involved in airspace management may use it for the collaborative pre-tactical planning of Airspace Management Planning Charts (ASM) [18]. DDR project currently consists of two phases as DDR1 and DDR2.

2.1.1 DDR Phase 1

DDR Phase 1 project pave the way for the first implementation of the repository. This version is currently available in operations to ANSP's and Aircraft Operators within European Civil Aviation Conference (ECAC). Owing to its user-friendly web interface, users can select and download demand data, according to their own specifications and multiple formats are available to that the DDR can be used with the existing EUROCONTROL tools and also with the users' own tools cite [20]. DDR project supplies historical traffic, future traffic and filtered traffic data.

Past traffic demand samples are available for any days, for all Europe, from January 2006 and user can navigate by date to download past traffic trajectories (flight plan and updated flight plan). As it is shown in figure 2.1 green cells in the calendar means the corresponding file has already been generated and is available for download, otherwise a double click on the cell will launch the generation from the database. Thanks to the high compression data transfer from the DDR to local computer is quick and multiple days can be downloaded in one shot [21].



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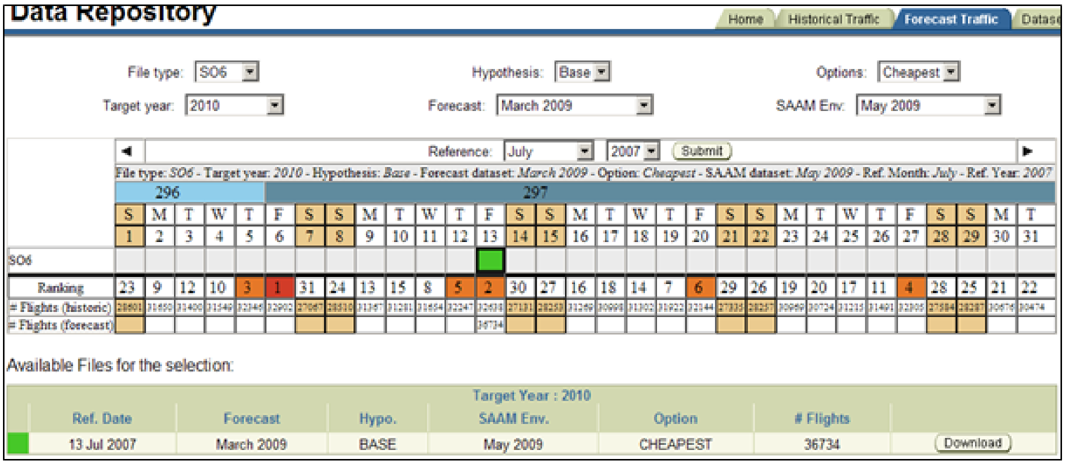
Ranking	18	16	5	28	24	19	20	11	7	2	26	23	13	15	9	6	3	27	22	12	14	8	4	1	25	21	10	17
Nbr of Flight	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

Figure 2.1: DDR Historical Traffic Panel [2].

In figure 2.2 Forecast traffic page which is used for generating and downloading future traffic trajectories with dataset selection and options is given. Forecast and Airspace datasets are two types of datasets used by the DDR for the generation of future traffic demand and new 4D trajectories. These datasets are also updated regular



File type: SO6 | Hypothesis: Base | Options: Cheapest

Target year: 2010 | Forecast: March 2009 | SAAM Env: May 2009

Reference: July | 2007 | Submit

File type: *SO6* - Target year: *2010* - Hypothesis: *Base* - Forecast dataset: *March 2009* - Option: *Cheapest* - SAAM dataset: *May 2009* - Ref. Month: *July* - Ref. Year: *2007*

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# Flights (historic)	28601	31650	31400	31549	32345	32902	27067	28510	31367	31281	31654	32247	32638	27131	28253	31269	30998	31302	31922	32144	27335	28257	30969	30724	31215	31491	32205	27584	28287	30676	30474
# Flights (forecast)													36734																		

Available Files for the selection:

Target Year : 2010

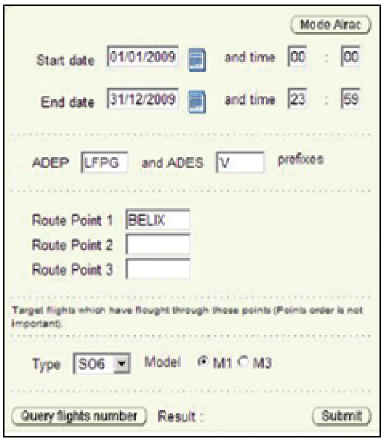
	Ref. Date	Forecast	Hypo.	SAAM Env.	Option	# Flights	
🟩	13 Jul 2007	March 2009	BASE	May 2009	CHEAPEST	36734	Download

Figure 2.2: DDR Forecast Traffic Panel [2].

basis by EUROCONTROL. Forecast dataset contains information on traffic statistics and forecast under the name of STATFOR. Besides providing statistics and forecasts on air traffic in Europe, STATFOR monitors and analyses the evolution of the Air Transport Industry. It supplies the information of the number of yearly/monthly flights in Europe, the air traffic growth forecast for a given state in a specific year and the traffic statistics per market segment for Europe [22]. Similarly, Airspace dataset contains future airspace design projects such as changes to the Air Traffic Service (ATS) route network, implementation of free route airspace and flight level constraints [21].

The available data in Forecast traffic page are future traffic samples with current traffic distribution (flight plan/flight plan enhanced with radar data), future traffic samples with new routings calculated on future environment and past traffic samples with new routings calculated on future environment. Also on the generation of new routings, shortest path (minimum route length), cheapest path (minimum cost taking into account route length and route charges) and optimal path (minimum cost taking into account route length, route charges and delays/overloads) options are available in DDR [21].

As it is illustrated in figure 2.3, the DDR allow users to obtain the traffic data over a long period of time based on some preferred criteria as origin, destination and route points. Any of those demands is applicable to Flight Plan (Model 1) or Flight Plan Enhanced with Radar Data (Model 3). The traffic data file in the form of traffic demand, 4D trajectories or flow demand can be generated and the number of flights



Start date 01/01/2009 and time 00 : 00
End date 31/12/2009 and time 23 : 59
ADEP LFPG and ADES V prefixes
Route Point 1 BELIX
Route Point 2
Route Point 3
Target flights which have flought through those points (Points order is not important).
Type SO6 Model ● M1 ○ M3
Result :

Figure 2.3: Data Extraction Panel based on criteria [2].

can be counted and displayed on the web page. All downloaded data files are formed as ASCII files and they can be used in either personal applications or in external tools for assessment, statistics and analysis. For instance, there are tools as SAAM (System for Airspace Analysis at Macroscopic level) and NEVAC (Network Estimation and Visualization of ACC Capacity) which can directly read DDR data files [21].

2.1.2 DDR Phase 2

Phase 2 of the Demand Data Repository project, which is an advanced version of DDR, developed on the DDR1 functionalities and provides improved demand forecasts that takes flight intensions into account via airport slot and airline schedule data that covers from the strategic planning phase right up to the pre-tactical phase. Forecasts are available for the whole European airspace and flight intension data are generally extends to 6 to 9 months before the day of operations. Moreover, these data are subsequently updated and refined up until the day before the operation. Phase 2 is currently available only in pilot mode with specific access conditions and is expected to become fully operational during the course of 2013 [18].

DDR2 acquires these flight intentions data from many sources. Daily feed of over 160 coordinated airports' slots are provided from The European Airport Coordinators Association (EUACA). Weekly file of consolidated airline schedules are obtained from Innovata which is the official source for the Schedule Reference Service where the Airline flight schedules database known as SRS Data. Daily feed of flight planning information for business jets are elicited by organizations such as Avinode. Also, individual airline schedule data and airport plans from non EUACA airports such as Istanbul etc. are collected and consolidated. In general, each predicted flight in a flight intentions source shall be described at least with the following information: departing and destination airports, estimated off block time (EOBT), estimated time of arrival (ETA), aircraft operator, aircraft type, type of flight and date of last information update [23].

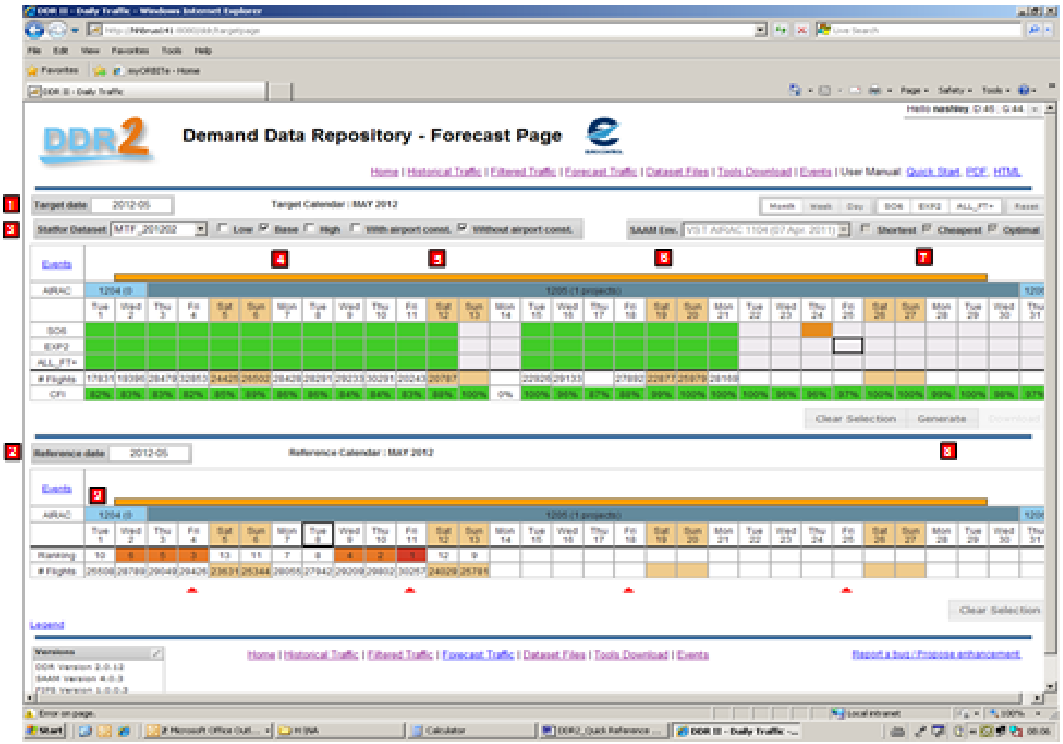


Figure 2.4: Screen shot of DDR2 Forecast Page [3].

The probable reasons to use DDR2 application is to generate or download historical 4D Trajectory SAAM/NEVAC traffic files (built on EUROCONTROL NM data) and forecasted 4D Trajectory traffic files (built on SAAM Environment dataset files, Flight intention and STATFOR/FIPS dataset files). Environment and Forecast (STATFOR) Dataset and software tools as NEST, SAAM and NEVAC also may be a reason to use DDR2 application [24].

2.1.3 Data File Formats

There are several data file formats in DDR project available to download and all files are highly compressed with 7za tool. While **SO6 m1** file format provides 4D flight trajectories last filled flight plan for SAAM tool, **SO6 m3** file gives same properties that are updated with radar data. Basically these two file formats present the demand with routings. Another file format is **FLD** which is an abbreviation for Flow Demand and this format gives the number of flights per city pairs. **EXP2** file format is consolidated to provide traffic demand with flight information and has no trajectory information. Finally, **ALL_FT** file format elicits the demand with routings and intersected sectors [2].

There are also “**.cfg**”, “**.capacity**” and “**.runway**” files extensions. “**.cfg**” extension stands for configuration and file includes configurations of Air Traffic Control Unit Airspaces (AUA) which gives the sub airspaces of AUA’s, whether they are divided into more sub airspaces or merged to form superior AUA’s with higher volume. “.capacity” file gives the hourly basis capacity declarations of related Air Traffic Control Unit Airspaces, points of Standard Terminal Arrival Route (STAR) and Airports’ Departure/Arrival movements. Finally “**.runway**” file includes hourly basis runway configurations for each European airport.

2.2 Data Description

Two different data sets that have been utilized in this project are ALL_FT and CAPACITY files.

1. ALL_FT+ records from 1st of March to 30th of November, 2011
2. DDR data spans from the 1st of January to the 31st of December, 2011

Consequently, capacity information is merged with flight routes and crossed sectors. CFG file is also employed to take advantage of sectorization process and have an insight on Air Traffic Control Unit Airspaces. ALL_FT data includes some properties about arrival and departure airports, rerouting parameters and many procedural status indicators etc. However the main data that has been processed in this project is the advanced and enriched version of ALL_FT data which is called **ALL_FT+** data.

2.2.1 ALL_FT+ Data

The ALL_FT+ data set is managed by the PRISME (Pan-European Repository of Information Supporting the Management of European Air Traffic Management Master Plan) group which offers an integrated set of data to develop and maintain an integrated ATM datawarehouse [25]. This data set encodes various types of information for individual flights occurred in European Airspace including those intercontinental flights that overfly European Airspace and it starts from the 1st of March, 2011, up to the 30th of November, 2011.

Data set structure has a total of 143 fields and 46 of these fields contain numerical parameters, 18 fields represent numerical values related to time, 12 fields are Boolean and 32 fields are composed of grouped parameters. Each field is distinguished from one another by the symbol ";" and those 32 compound fields are segmented internally via the symbol ":". Furthermore, these compound fields can contain several sequences separated by an empty space except for the compound fields that contain only one sequence. It is also important to note that these compound fields with multiple sequences (the ones that are separated by an empty space) have an indicator that is placed into the previous field of related compound field and gives the number of recorded sequences.

Besides having parameters of ALL_FT data, ALL_FT+ also includes several trajectories of interest for the analysis of horizontal flight efficiency [26]:

1. **FTFM** Filed Tactical Flight Model, corresponding to the last filed flight plan
2. **RTFM** Regulated Tactical Flight Model
3. **CTFM** Current Tactical Flight Model
4. **CPF** Correlated Positions reports for a Flight, that is, airspace profiles following as much as possible the actual flown trajectory based on radar positions.
5. **CPG_GEN** Correlated Position profiles generated by the Central Flow Management Unit (CFMU) path generation tool.
    - SCR: Shortest Constrained Route, The Integrated Initial Flight Plan Processing System (IFPS) of the EUROCONTROL CFMU compliant route. Available Conditional Routes (CDR) open and Route Availability Document (RAD) compliant
    - SRR: Shortest RAD Restrictions applied Route. All CDRs open
    - SUR: Shortest Unconstrained Route. No RAD applied, all CDRs open
    - DCT: Direct route. Any portion outside the FPM_AREA (Flight Path Monitoring Area) is “frozen”, that is, not generated by the tool.

In the ALL_FT+ dataset one can find information about the exact point that the aircraft change its plans in a flight regarding the planned information (FTFM), regulated one (RTFM) and the one prior to flying (CTFM). Moreover the ALL_FT+ dataset contains CPF-REF field which gives the data of exact points the flight went through.

All flight models have flight level profiles, point profiles and airspace profiles and all these profiles are compound attributes. Flight level profiles depict the vertical description of the flight route where the data consists of centesimal of barometric measurement, cruise speed and start distance which indicates the distance over the trajectory measured from the Aerodrome/Airport of departure.

Table 2.1 gives the full description of point profile data line whereas table 2.2 elaborates airspace profile line with examples. Both point and airspace profiles have incident number data which indicates the number of profile point/airspace data lines. The number of lines stands for how much data sampled through the entire trajectory

Table 2.1: Descriptions for each field of Point Profiles.

#	Field	Type	Size	Comment
1	TimeOver	HHMMSS	6	Time at the related point
2	Point	char	dynamic	Name-codes for the current point
3	Route	char	dynamic	Name-codes for the next point
4	FlightLevel	num	1-3	flight level, e.g. FL230
5	PointType	char	1	values A, D, G, N, S, V or W
6	GeoPointID	ggmmsso	7	g: grades m: minutes s: seconds o: orientation Latitude N/S and Longitude E/W
7	RelDist	num	1-4	Measured in kilometers, e.g. 106
8	IsVisible	char	1	Y or N

of the related flight. Consequently, trajectory of a flight can only be represented with incident number of data point via point profile data.

Airspace profile is a different perspective for flight trajectory and it illustrates the trajectory via crossed airspaces' entry and exit points. This profile also provides the same data in different scales, that is to say, airspaces are defined in NAS, FIR, AUA and ES levels respectively. National Airspaces are the biggest volumes and has the highest coverage followed by Flight Information Regions and Air Traffic Control Unit Airspaces. Therefore, the same trajectory is provided for each of these airspace types which let one to have the same data in different scales.

Table 2.2: Descriptions for each field of Airspace Profiles.

#	Field	Type	Size	Comment
1	EntryTime	HHMMSS	6	Entry time to airspace
2	AirspaceID	char	dynamic	Airspace ICAO codes
3	ExitTime	HHMMSS	6	Exit time to airspace
4	AirspaceType	char	2-4	Airspace type; NAS = National Airspace, FIR = Flight Information Region, AUA = ATC Unit Airspace, ES = Elementary Airspace
5	GeoPointofEntry	ggmmsso	7	e.g. 385642N
6	GeoPointofExit	ggmmsso	7	e.g. 772724W
7	EntryFlightLevel	num	1-3	Entry flight level, e.g. FL380
8	ExitFlightLevel	num	1-3	Exit flight level, e.g. FL240
9	EntryDistance	num	1-4	Measured in kilometers, e.g. 106
10	ExitDistance	num	1-4	Measured in kilometers, e.g. 106

2.2.2 Tactical Flight Models

There are three tactical models in use as FTFM, RTFM and CTFM. Filed Tactical Flight Model (FTFM) is a mathematical model containing a point and airspace volume profile created in Enhanced Tactical Flow Management System (ETFMS) for a flight when Flight plan details, and any subsequent changes, are received from Central Flow Management Unit (CFMU) [27]. It is the initial profile as it reflects the status of the demand before activation of the regulation plan and computed with the latest flight plan version sent by each AO to the CFMU/IFPS [28]. FTFM includes all filed flight plan, therefore it even gives the data of cancelled flights.

Regulated Tactical Flight Model (RTFM) is the version of FTFM which Air Traffic Flow and Capacity Management (ATFCM) measures have been applied to the flight. It is also called calculated profile [29]. Profile reflects the status of the demand after activation of the regulation plan and is computed with the latest ATFM slot Calculated Take-Off Time (CTOT) issued to the airline operator, by the ground regulation system. RTFM profiles are not strictly reflecting the traffic load situation that is output from the regulation process, after activation and/or update of the regulation, but is rather an approximate of the latest regulated planned demand situation [30].

Current Tactical Flight Model (CTFM) is a mathematical model for a flight which has been activated (also called Actual Profile) [31]. This model is computed with Radar Data sent by Area Control Centers to CFMU/ETFMS, so it can be deemed as a fused version of FTFM with real data.

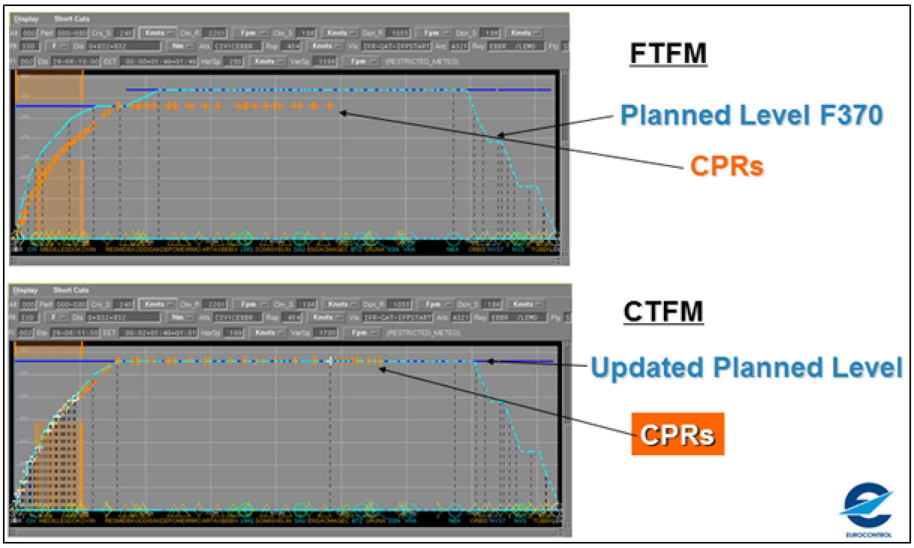


Figure 2.5: Flight Level Update during the Take-Off Process [4].

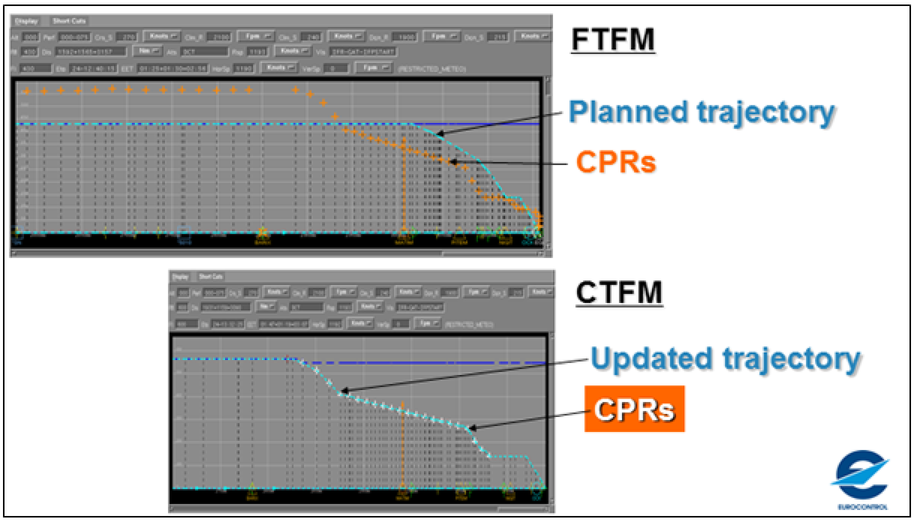


Figure 2.6: Flight Level Update during the Landing Process [4].

The process of CTFM calculation is illustrated in figure 2.5 and 2.6. As it can be seen from the figure, FTFM flight level profile which is plotted with blue lines is updated with CPR data which is given with orange lines. Therefore, CTFM becomes the result of the fusion of FTFM and CPR data and is updated from FTFM profile.

2.2.3 Correlated Position Report

Correlated Position reports (CPR) are based on radar position data and they represent the actual flow trajectory as much as possible. Position reports are Surveillance Data collected from area control centers and they are mainly extracted from messages/data that received during the flight. Contents of the data are aircraft's actual geographic position and altitude which is enriched with the flight plan information such as Call Sign, Estimated Off-Block Time etc. for correlation purposes. The frequency of the data is normally, data per minute provided by Air Navigation Service Providers (ANSPs) [4].

The purpose of the CPR is to provide 4D trajectory of the flight to CFMU when airborne and the message is received and processed by ETFMS in order to update flight data and get more accurate prediction of the sector counts. It is also used for statistical purposes as detecting flights that never took place or multiple flight plans for one flight [32].

2.2.4 Comparisons of Flight Models

Each flight data type has its own characteristics and point of views. Comparing these different trajectory profiles for the same flight provides Indication on the effects of different factors [26]:

Investigating Shortest Unconstrained Route (SUR) and Direct route (DCT) together provides a measure of the effects of route design, as it compares the shortest theoretical course with the best one available using the route network. Also comparison of SUR with shortest conditional route (SCR) yields a criterion for the effects of route availability since it analyses the differences between the route potentially available on the route network and the one that could actually be filed.

Route preferences/utilizations of the Aircraft Operators can be obtained from the FTFM versus SCR comparison, because it emphasizes the difference of the actually filed route and the best that could have been filed. Finally and most importantly, comparison of CPF and FTFM provides a measure of the effects of air traffic control decisions since it compares the actual flown trajectory to the one that was filed. For that reason, as it will be explained later, these two data type will be used in the calculation process of the delay.

2.2.5 DDR Capacity Data

As a secondary data, ".capacity" file is utilized to have the information of hourly basis declared capacity of airspaces as well as airports. Each ".capacity" file contains the data of around 30 days and each day's data consists of group of data lines. Data lines are separated with empty space character and a single line in the file has 9 fields which are explained in table 2.3.

In summary, each line of the data contains the capacity for an impartible (elementary) or collapsed (merged) sector with time windows of declarations. Also note that for Airspace, Point or Traffic Volume entities there exists only global category of declared capacities, whereas Aerodromes or Set of Aerodromes may have declared capacities in all three categories (global, arrival and departure).

Table 2.3: Description of a line structure of DDR capacity file with examples.

#	Field	Type	Size	Comment
1	Date	DD/MM/YYYY	10	Date of declaration
2	AirspaceID	char	dynamic	Airspace ICAO codes
3	TimeWindowBegin	HH:MM	5	Beginning time of declaration, e.g. 23:59
4	TimeWindowEnd	HH:MM	5	End time of declaration, e.g. 23:59
5	DeclaredSectorCapacity	num	2-3	0 till 999. 999 means infinite capacity
6	Separator	char	1	e.g. ;_;
7	ENVEntityTypes	char	2	AS = Airspace, PT = Point, AD = Aerodrome, AZ = Set of Aerodromes, TV = Traffic Volume
8	Category	char	1	G = global, A = arrival, D = departure
9	Database	char	1	Type of database extraction

In this chapter, two types of data that has been utilized for the theme of this thesis are explained in details with examples and their source is referred. Next chapter will present the delay types that will be analyzed in this project and give further information for some parameters regarding the calculation of these delay types.

3. DESCRIPTION & CALCULATION OF DELAYS

In this chapter, the delay types calculated in this project are expressed in detail and the data fields regarding the calculation process are explained. The delay types are defined through flight process and generated/absorbed delays across the European airspace network are categorized under three major phases: delay at departure airport, delay at each sector that flight crosses and delay at arrival network.

3.1 Phases of A Flight

Flights are the basic unit of air transport and are defined by various features. In spatial scope, a flight is composed of 3 phases as departure airport, arrival airport and route with level [5]. In time perspective, a flight is defined by its specific time points and intervals. Off-Block Time (OBT) is the time aircraft starts its movement i.e. the time that flight starts. Departure Taxi Duration is the time interval that aircraft spends in airport until it will take-off which takes us to the time point called Take-Off Time.

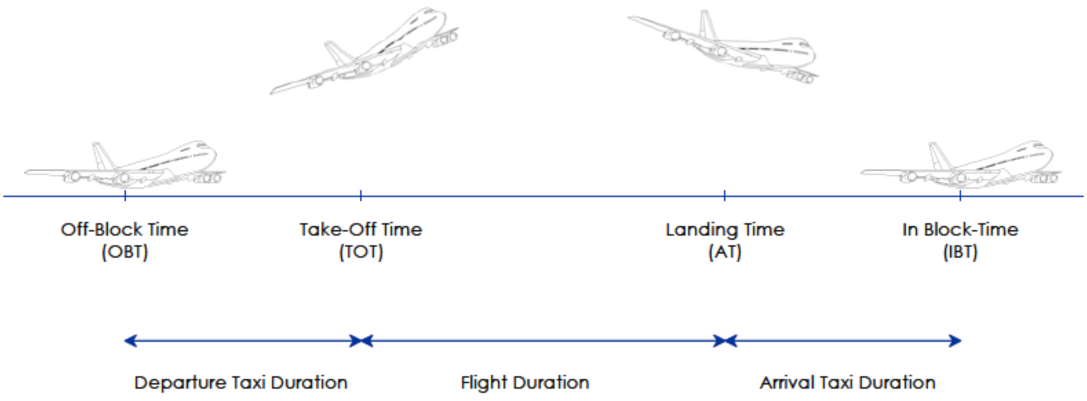


Figure 3.1: Phases of a Flight [5].

Take-Off Time is the time when the aircraft released into the air and lost its physical connection with the departure airport. After that point on an interval called flight duration begins. In this interval aircraft crosses many air sectors which starts with departure Terminal Maneuvering Area (TMA) and ends with arrival TMA. At the end of the arrival TMA phase aircraft lands at the time called Landing Time. Upon landing, aircraft gets into Arrival Taxi Duration phase which directs the aircraft to its gate. Finally, as the aircraft reaches the gate, it stops and the time for this point is called as In Block Time (IBT) which ends the flight [5].

3.2 Description of The Data Fields Regarding The Phases of A Flight

As it mentioned in the previous chapter, there are point and airspace profiles for various flight model/radar data. Although there are no certain statement of fact about it, the first point of the point profile or the entry point of the first airspace of airspace profile is considered as the Take-Off Time for a flight. After an extensive processing of the data, a supportive fact for this statement may be the flight levels of the first points. The first flight level field of the both point and airspace profiles takes variety of values and these values are measured with respect to height above sea level (%1 of meters above sea level).

Drawing a comparison between the first flight levels and the altitude of the departure airport, one will see that they are exactly the same. The same situation are also true for the arrival airport. Therefore, the first points of point profiles or the entry points of the first airspaces of airspace profiles are assumed to be the Take-Off Times whereas the last points of the point profiles or the exit points of the last airspaces of airspace profiles are assumed as Landing Times of a flight. This assumption paves the way for the calculation of the flight duration. Moreover, it is possible to calculate durations of each crossed sectors since airspace profiles have the each sectors entry and exit times. This opportunity provides a better description of the flight duration.

Besides point and airspace profiles the data has the parameters below;

Actual Off-Block Time (AOBT): This is the actual date and time the aircraft has vacated the parking position via pushed back or on its own power [33].

Initial Off-Block Time (IOBT): This is the estimation of AOBT that is given in the initial Filed Flight Plan (FPL) and updated by flight plan associated messages. It is also the reference time used for accessing the flight plan in the database and is the only off-block time known by the concerned air traffic service units [34].

Calculated Off-Block Time (COBT): This is Calculated Take-Off Time (CTOT) minus taxi time where CTOT is the time provided by the Central Flow Management Unit (CFMU), taking into account the European Civil Aviation Conference (ECAC), ATC flow situation, that an aircraft has been calculated to take off. The CTOT, also known as ATFM slot [35] [36].

Estimated Off-Block Time (EOBT): It is defined as the estimated time at which the aircraft will commence movement associated with departure [37]. It is also known as the Last Estimated Off-Block Time and Date [38].

Last Off-Block Time (LOBT): This is the estimation corresponds to the inbound and outbound flow at a given airport based on the last flight plan [5].

Given the Off-Block Times above, there are two types of Off-Block Times to utilize in this project: EOBT and AOBT. These values provide the information of departure taxi duration. Unfortunately, there are no In Block Time (IBT) field defined in the data, hence there is no way for extracting any information about the Arrival Taxi Duration from the data.

3.3 Types and Calculations of Delays

Based on the all phases of a flight the delay profile for each flight can be categorized in three major phases:

1. Delay generation at departure airport
    - Delay up to push-back phase
    - Delay at taxi to take-off
    - Delay at take-off to Terminal Maneuvering Area
2. Delay generation at sectors
    - Delay at en-route
3. Delay generation at arrival airport
    - Delay at Terminal Maneuvering Area entrance to landing
    - Delay at taxi to gate

Delays generated from the departure airport generally caused by ground holding procedures which is applied to keep aircraft ground instead of air in order to save fuel. These type of delays dependent on the configuration changes at the airport. Strikes and weather conditions may also be a source for these delays. Disturbance events as weather are also reasons for the re-routings which may result with delays generated at sectors. These sector delays are highly dependent on ATC operational procedures and approaches. Finally, delay generations at arrival airports are caused by congestion which is the excessive number of arrivals at the same time i.e. over arrival capacity usage.

Utilization of the data enables to determine all time parameters regarding the flight except the In Block Time which makes the calculation of Arrival Taxi Duration impossible. Therefore all delay types given above will be calculated with the exception of Delay at Taxi to Gate.

As it was mention in the previous section, data includes eight types of flight data (models/radar data). One of those flight models is Filed Tactical Flight Model which represents the planned flight. These plans are updated until the last day that flight occur. Because of that reason any deviation from that plan during the flight will be the induction of unexpected events took place during the flight. There are also CTFM and CPF data which represent the actual flown route as mentioned earlier.

Seeking the differences between different profiles will give a measure of variations between those profiles. Calculating each time intervals as it is given in figure 3.1 for each data profile and comparing them with each other will yield the derivations between the time intervals. Consequently, to calculate delays associated with those intervals, one has to assess PLANNED and ACTUAL data sets for a given flight where EOBT will be used as planned Off-Block Time whereas AOBT is the actual one. Determination of planned and actual data sets will be the interest of the next chapter.

Next chapter will give an insight for the quality of the data and its processing procedures to overcome the difficulties associated the utilization process in order to shape the data for calculation of the delays explained in this chapter. It will also provide solid samples from the data regarding those issues.

4. DATA QUALITY AND PROCESSING

After delivering the source and the description of the data, quality and the coverage of it, drawbacks and the adversities of processing will be explained and assumptions made in this process will be given with examples in this chapter.

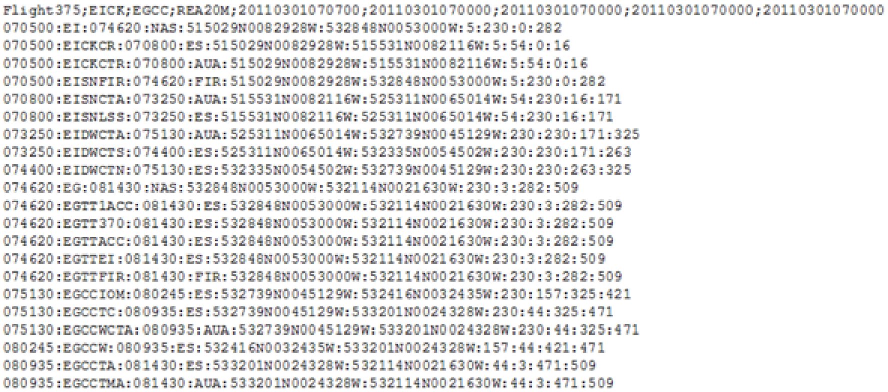
4.1 Data Processing

As it was mentioned in the previous section, each flight in ALL_FT+ data has 143 fields which contains 32 compound data set. With that being said, one should notice that whole fields of AL_FT+ data may not be filled in each flight as it is presented in "Data Quality" section with statistics. Therefore, first approach is to question the existence of the specific parts in the data and sort it out in order to create a new core structure.

4.1.1 Creating an Elementary Data Structure

ALL_FT+ data is provided in daily basis i.e. there is a unique file for each date and it is processed day by day. Basically, a file can be considered in 9 categories: 8 group of fields where each group is assigned to a different flight model or radar data (FTFM,...,CPF) and the first group that includes common parameters for the other 8 groups with many other information about related flight. Since the first group with 72 fields is the same for all other 8 groups, the data is separated into 8 different parts/files where each part contains the parameters of a flight model/radar data. Also note that, each flight model/radar data is consists of point and airspace profiles.

After 8 group of fields are sorted and filed for both point and airspace profiles, some required parameters from the first common group are selected and aggregated in a line which is pinned at the very beginning of each part for the further calculations. An example of RTFM part for airspace profiles is illustrated in the figure 4.1, and the ingredients of the fixed first line is given in table 4.1.



```
Flight375;EICK;EGCC;REA20M;20110301070700;20110301070000;20110301070000;20110301070000;20110301070000
070500:EI:074620:NAS:515029N0082928W:532848N0053000W:5:230:0:282
070500:EICKCR:070800:ES:515029N0082928W:515531N0082116W:5:54:0:16
070500:EICKCTR:070800:AUA:515029N0082928W:515531N0082116W:5:54:0:16
070500:EISNFIR:074620:FIR:515029N0082928W:532848N0053000W:5:230:0:282
070800:EISNCTA:073250:AUA:515531N0082116W:525311N0065014W:54:230:16:171
070800:EISNLSS:073250:ES:515531N0082116W:525311N0065014W:54:230:16:171
073250:EIDWCTA:075130:AUA:525311N0065014W:532739N0045129W:230:230:171:325
073250:EIDWCTS:074400:ES:525311N0065014W:532335N0054502W:230:230:171:263
074400:EIDWCTN:075130:ES:532335N0054502W:532739N0045129W:230:230:263:325
074620:EG:081430:NAS:532848N0053000W:532114N0021630W:230:3:282:509
074620:EGTT1ACC:081430:ES:532848N0053000W:532114N0021630W:230:3:282:509
074620:EGTT370:081430:ES:532848N0053000W:532114N0021630W:230:3:282:509
074620:EGTTACC:081430:ES:532848N0053000W:532114N0021630W:230:3:282:509
074620:EGTTEI:081430:ES:532848N0053000W:532114N0021630W:230:3:282:509
074620:EGTTFIR:081430:FIR:532848N0053000W:532114N0021630W:230:3:282:509
075130:EGCCIOM:080245:ES:532739N0045129W:532416N0032435W:230:157:325:421
075130:EGCCTC:080935:ES:532739N0045129W:533201N0024328W:230:44:325:471
075130:EGCCWCTA:080935:AUA:532739N0045129W:533201N0024328W:230:44:325:471
080245:EGCCW:080935:ES:532416N0032435W:533201N0024328W:157:44:421:471
080935:EGCCTA:081430:ES:533201N0024328W:532114N0021630W:44:3:471:509
080935:EGCCTMA:081430:AUA:533201N0024328W:532114N0021630W:44:3:471:509
```

Figure 4.1: Example for Airspace Profile data set of RTFM Part.

Explanations of the Off-Block Times and their role in calculations was the interest of the previous chapter. By using the sorting procedure, useful portion of the data for the theme of this thesis is assembled in a more elementary data structure.

4.1.2 Determination of Planned and Actual Data

After the creation of new data structure, there are eight distinguished data sets with solitary flight profiles. As it was explained in the previous chapter, the objective of the whole study is to sense the variations between planned and actual cases. In order to do so one has to fetch the necessary part from the data. In this case, appropriate flight profiles must be declared as planned and actual data.

It has been acknowledged from the previous definitions that FTFM corresponds to the last filed flight plan, therefore it is accepted as “Planned Flight Data”. When it comes to the determination of the actual fight data, a critical circumstance arises. Given the statistics in “Data Quality” section, one can easily realize that around %20 of the radar

Table 4.1: Field Descriptions of fixed first line of New Elementary Structure.

Field	Descripton	Example
1	Flight counter of a day, which is assigned by the algorithm	Flight375
2	Four letter ICAO code for departure airport	EICK
3	Four letter ICAO code for arrival airport	EGCC
4	Call signs (flight identification or flight ID)	REA20M
5	Actual Off-Block Time (AOBT)	20110301070700
6	Initial Off-Block Time (IOBT)	20110301070000
7	Calculated Off-Block Time (COBT)	20110301070000
8	Estimated Off-Block Time (EOBT)	20110301070000
9	Last Off-Block Time (LOBT)	20110301070000

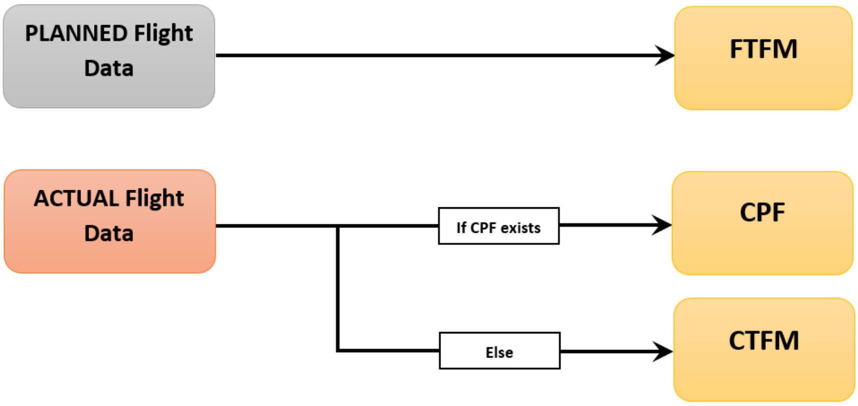


Figure 4.2: Determination Procedure of Planned and Actual Flight Profiles.

data (CPF) is missing. The first thing that might come to mind is the idea that those flights are cancelled. However, if that would have been the case, there would have been no flights arrived to LTBA Istanbul Ataturk Airport which is one of the most hectic airports in Europe. Moreover there is a specific field (field #20) that indicates whether the flight is cancelled (if field #20 is ‘CA’ then the flight is cancelled). The number of CA fields in a day is also completely coherent with number of missing CTFM profiles in that day.

Recall from the previous definitions that Current Tactical Flight Model (CTFM) is the fused version of FTFM with CPF data, hence it is obviously a wiser choice to use CTFM as “Actual Flight Data” in the absence of CPF data, rather than declaring the flight cancelled and not using at all. Figure 4.2 depicts the determination procedure in this manner. In spite of the fact that this procedure makes more sense, one should also be aware of that there are cases which FTFM and CTFM is the same, that is to say, CTFM is not fused with CPF data at all. It does not mean the flight is cancelled, though. It simply indicates that the flight route is not in radar coverage. In order to detect these situations Actual Flight Data set is labeled with its data source which denotes if the actual data belongs the CPF or CTFM profile.

Employing this determination procedure results with two sets of data for a same flight where each set has both point and airspace profiles with additional parameters such as Off-Block Times. Figure 4.3 simply depicts the outcome of the procedure for both point and airspaces. In figure red lines represents the planned data whereas white lines are the actual flown data and the markers are the entry and exit points of the FIR level

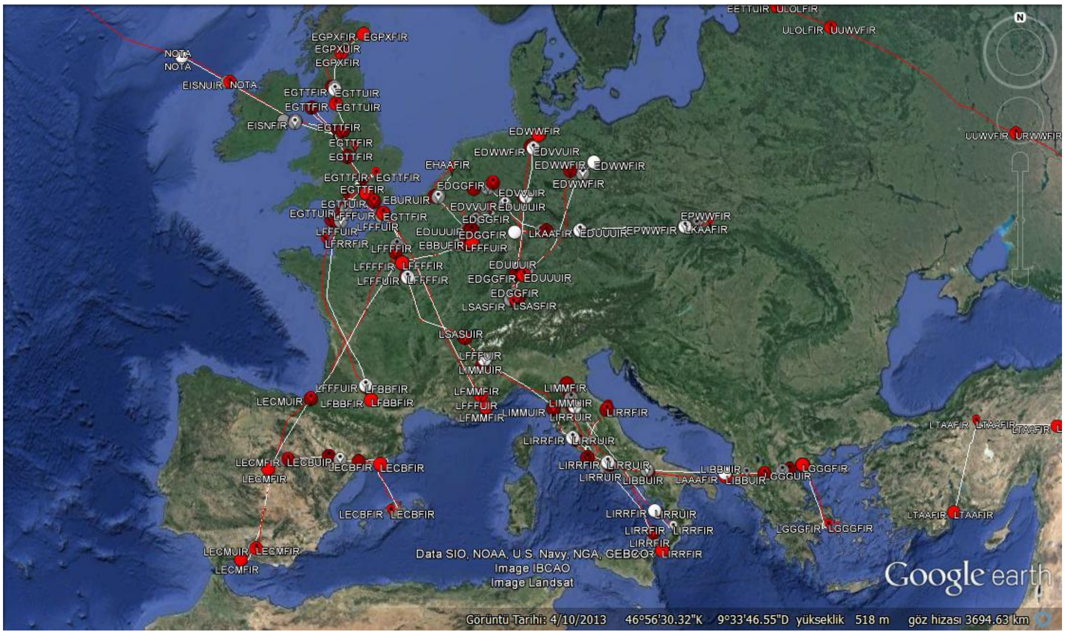


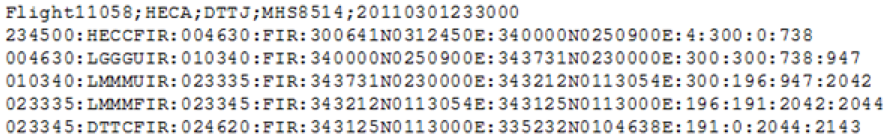
Figure 4.3: Planned/Actual flight data determination procedure for 25 flights.

airspaces. As it can be seen from the deviations between red and white lines, the procedure enables to compare the plans of the flight with the actual flown data which will be the keystone of the calculations that will take place in the next chapter.

4.1.3 Fixing the Day Flips

As it was mentioned before, data records are happen to be daily basis. The fact that each file/day recorded individually causes clocks to be independent from each other for each day. Accordingly, for the flights happened in the midnight, clock resets and starts from the beginning of the new day which causes discontinuities in the time records. An example of this case is given in figure 4.4.

In figure 4.4, the delay flip occurs at first FIR region and clock restarts for the new day. These kind of discontinuities bring about abnormal results in delay calculation process and they must be fixed. For this process two more parameters: EOBT and AOBT are employed to have the exact date of the time aircraft starts its movement. The day flips have been detected in the clocks of point or airspace profile sequences. Huge amount



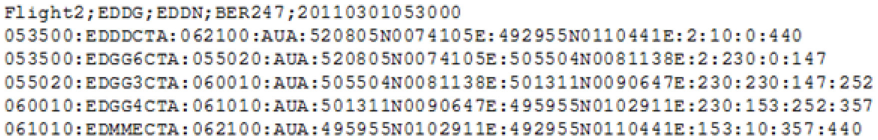
```
Flight11058;HECA;DTTJ;MHS8514;20110301233000
234500:HECCFIR:004630:FIR:300641N0312450E:340000N0250900E:4:300:0:738
004630:LGGGUIR:010340:FIR:340000N0250900E:343731N0230000E:300:300:738:947
010340:LMMMUIR:023335:FIR:343731N0230000E:343212N0113054E:300:196:947:2042
023335:LMMMFIR:023345:FIR:343212N0113054E:343125N0113000E:196:191:2042:2044
023345:DTTCFIR:024620:FIR:343125N0113000E:335232N0104638E:191:0:2044:2143
```

Figure 4.4: A day flip example in FTFM's point profile from March 1st, 2011.

of decrease in the clock (such as 80k seconds) alerts for the day flip and upon detection of this case, EOBT and AOBT values are questioned to recognize if the flip belongs the day before or the day after. Depending on the case, 86400 seconds (a day in terms of seconds) added to the points after the detection occurs or subtracted from the points before the detection point. The day flip case observed in 2362 planned data flights and 2369 actual data flights for March 1, 2011.

4.1.4 Processing ATC Unit Airspaces

Just like the scope differences of FIR, AUA and ES airspace types, ATC Unit Airspaces (AUAs) have their own levels. These levels are determined based on the staffing status of air traffic control centers or congestion of the related area. This different scopes are called as configurations of AUAs and stored in the airspace configuration file called CFG file. An example of this situation is given in figure 4.5.



```
Flight2;EDDG;EDDN;BER247;20110301053000
053500:EDDDCTA:062100:AUA:520805N0074105E:492955N0110441E:2:10:0:440
053500:EDGG6CTA:055020:AUA:520805N0074105E:505504N0081138E:2:230:0:147
055020:EDGG3CTA:060010:AUA:505504N0081138E:501311N0090647E:230:230:147:252
060010:EDGG4CTA:061010:AUA:501311N0090647E:495955N0102911E:230:153:252:357
061010:EDMMECTA:062100:AUA:495955N0102911E:492955N0110441E:153:10:357:440
```

Figure 4.5: An example of AUA hierarchy.

As it is illustrated in the data sample above, EDDDCTA encapsules the all other airspaces, in other words all airspaces are the sub airspaces of EDDDCTA. Because of that reason, only for ATC unit airspaces, the bigger airspace takes the first place in the data sequence. This situation can bring complexity into delay calculation process. Therefore, these airspaces must be eliminated and the only connected sub set of airspaces must be preserved for the calculation of delays.

4.2 Data Quality

This section mainly focuses on the quality of ALL_FT+ data. Since each day's data is filed separately i.e. there is a record file for each day, the unit data size is chosen as a day. What it means is that each day is analyzed separately and data is merged when is needed. The existence of eight different flight profile data in ALL_FT+ structure was mentioned in the previous section. In order to investigate each flight profile in detail, a data file which belongs to March 1st of 2011 is processed and each flight profile's existence in whole day is illustrated in figure 4.6.

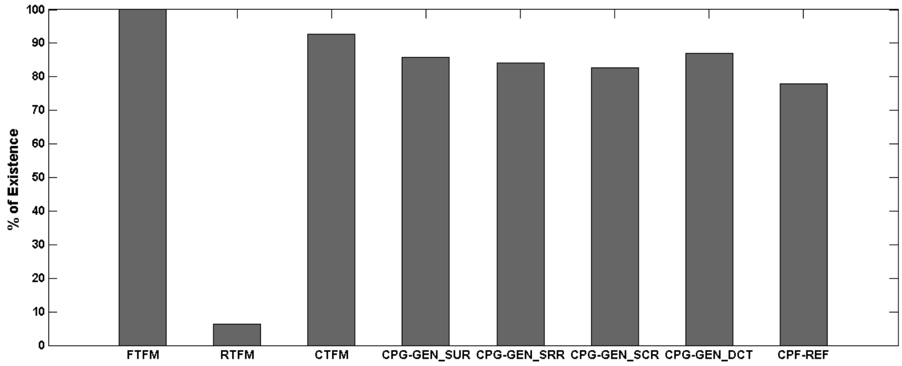


Figure 4.6: Each profile's existence in the whole data set for March 1st, 2011.

The availability of each profile in an arbitrary day can be seen from the figure 4.6. Note that FTFM profile does always exist for a planned flight and as it will be explained in the next section the difference between FTFM and CTFM existences equals to cancelled flights. Furthermore, the fact that the delays caused by ATC operations can be observed from the differences between FTFM and CPF-REF profiles is mentioned in previous chapters and for the reasons that were explained in the previous section, only three types of flight profiles (FTFM, CTFM, CPF-REF) will be utilized for the rest of the project, therefore in further quality analyses only these three flight models will be under investigation. The existence ratios of the FTFM, CTFM and CPF-REF profiles for seven days are given in the figure 4.7.

Figure 4.7 shows that for each day the existence ratios of these three profiles are almost the same. The fact that the ratio of CPF-REF does not change compared to FTFM profile is because the same flights is out of the range of radars all the time. As it

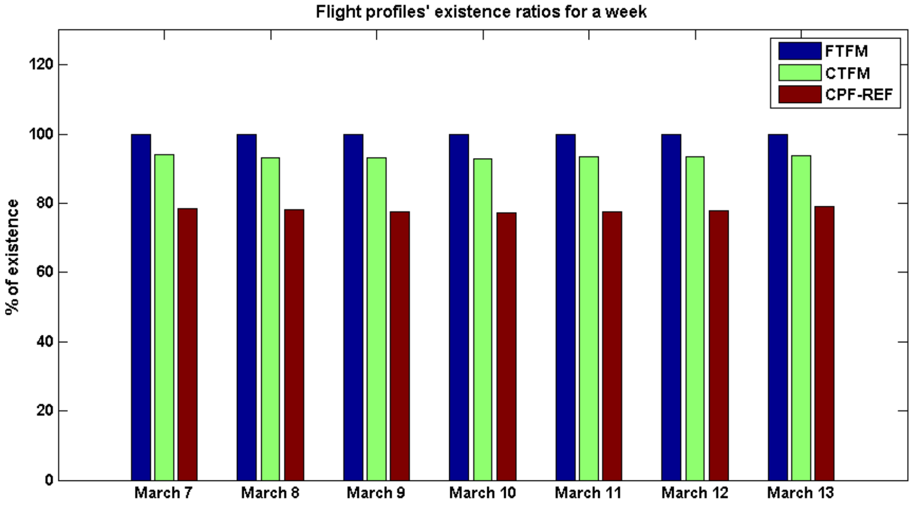


Figure 4.7: Flight profiles (FTFM, CTFM, CPF-REF) existence ratios for a week.

is indicated in the data processing section, the difference between FTFM and CTFM gives the cancelled flights, therefore, after the determination of the Planned and Actual profiles, around %93 of the total data will be utilized.

4.2.1 Off-Block Time Statistics

Besides Planned and Actual profiles, Off-Block Times are also extracted from the data, and their existence and equality statistics are also investigated. Out of 29661 utilized flights (%92.67 of the total data) for March 1, 2011:

- Existence of AOBT, IOBT, EOBT and LOBT is **%100** (for 29661 flights)
- Existence of COBT is **%6.62** (for 1954 flights)
- Equality of IOBT and EOBT is **%97.87** (for 29030 flights)
- Equality of EOBT and LOBT is **%99.09** (for 29391 flights)
- Equality of IOBT, EOBT and LOBT is **%97.87** (for 29030 flights)

This statistics has also a key role in the verification of the definition of Off-Block Times. As it has been already known, AOBT is the actual off block time and it is directly assigned to Actual profiles. However, the statistics showed that EOBT is the last updated Off-Block Time and it is almost same with the Last Off-Block Time.

4.2.2 Data Flaws

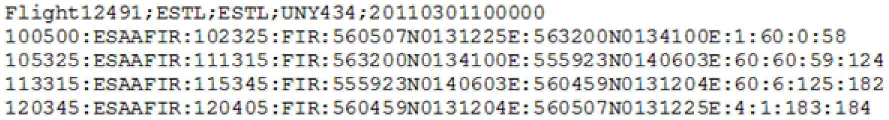
Using the Planned and Actual profiles as they are, gives meaningless results for delay calculations because of various flaws in the data. During the calculation process 4 major flaws are detected and they are named as:

- The Same Consecutive Airspaces Problem
- Not Connected Consecutive Airspaces Problem
- Airspaces with Zero Elapsed Time Problem
- Inconsistent Planned and Actual Profiles Problem

Each of these problems are explained in details with examples from the data and their proposed solutions for this project is provided as follows.

4.2.2.1 The same consecutive airspaces problem

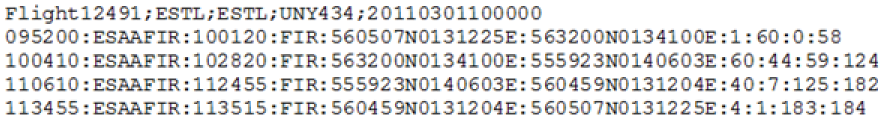
In the airspace profile sections of both Planned and Actual data, the same airspaces exist consecutively. An example of this situation is given below.



```
Flight12491;ESTL;ESTL;UNY434;20110301100000
100500:ESAAFIR:102325:FIR:560507N0131225E:563200N0134100E:1:60:0:58
105325:ESAAFIR:111315:FIR:563200N0134100E:555923N0140603E:60:60:59:124
113315:ESAAFIR:115345:FIR:555923N0140603E:560459N0131204E:60:6:125:182
120345:ESAAFIR:120405:FIR:560459N0131204E:560507N0131225E:4:1:183:184
```

Figure 4.8: An example for same consecutive airspace problem for planned profile.

The airspace profile in FIR level of Flight12491 for planned data is given in figure 4.8. The example clearly shows that, even if there is a geographic coordinate connection between the lines, the exit times of each line are not equal to the entry times of the next line. Despite the fact that aircraft follows a continuous route, there are time gaps between the lines. The actual data of the same flight is also given in figure 4.9:



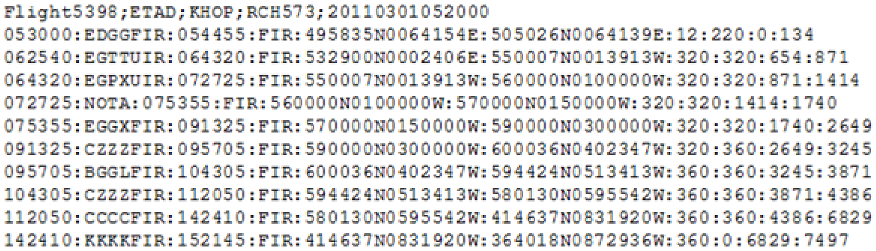
```
Flight12491;ESTL;ESTL;UNY434;20110301100000
095200:ESAAFIR:100120:FIR:560507N0131225E:563200N0134100E:1:60:0:58
100410:ESAAFIR:102820:FIR:563200N0134100E:555923N0140603E:60:44:59:124
110610:ESAAFIR:112455:FIR:555923N0140603E:560459N0131204E:40:7:125:182
113455:ESAAFIR:113515:FIR:560459N0131204E:560507N0131225E:4:1:183:184
```

Figure 4.9: An example for same consecutive airspace problem for actual profile.

The actual airspace profiles also suffer from the same problem. For this problem, the same sectors are reduced to one and entry exit times of this single airspace is taken as the entry time of the first line and the exit time of the last time. There are 161 this type of cases for planned data and 1395 cases for the actual data in March 1, 2011.

4.2.2.2 Not connected consecutive airspaces problem

This problem is similar to the same consecutive airspace problem, except it occurs in different airspaces. An example of this situation is given below.



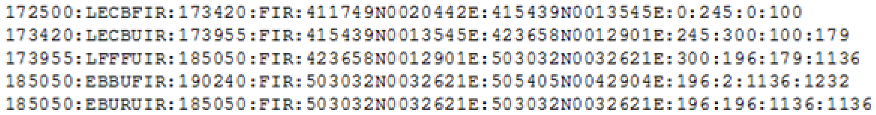
```
Flight5398;ETAD;KHOP;RCH573;20110301052000
053000:EDGGFIR:054455:FIR:495835N0064154E:505026N0064139E:12:220:0:134
062540:EGTTUIR:064320:FIR:532900N0002406E:550007N0013913W:320:320:654:871
064320:EGPXUIR:072725:FIR:550007N0013913W:560000N0100000W:320:320:871:1414
072725:NOTA:075355:FIR:560000N0100000W:570000N0150000W:320:320:1414:1740
075355:EGGXFIR:091325:FIR:570000N0150000W:590000N0300000W:320:320:1740:2649
091325:CZZZFIR:095705:FIR:590000N0300000W:600036N0402347W:320:360:2649:3245
095705:BGGLFIR:104305:FIR:600036N0402347W:594424N0513413W:360:360:3245:3871
104305:CZZZFIR:112050:FIR:594424N0513413W:580130N0595542W:360:360:3871:4386
112050:CCCCFIR:142410:FIR:580130N0595542W:414637N0831920W:360:360:4386:6829
142410:KKKKFIR:152145:FIR:414637N0831920W:364018N0872936W:360:0:6829:7497
```

Figure 4.10: An example for not connected consecutive airspaces for planned profile.

In figure 4.10 a huge time gap between EDGGFIR and EGTTUIR airspaces this gap also shows itself in geographic entry exit coordinates and flight levels. There are 97 cases like this one in planned profile and 1442 cases in actual profiles for March 1, 2011 data. For this problem, in order to maintain the connectivity of the airspaces the mean of the first airspaces exit and second airspaces entry times is calculated and the mean is assigned to entry and exit times. The same procedure is also utilized for both coordinates and flight levels.

4.2.2.3 Airspaces with zero elapsed time problem

In some cases, there are airspaces with zero elapsed time (entry and exit times are the same) in the airspace sequences. An example of this situation is illustrated in figure 4.11.



```
Flight7879;LEBL;EBBR;VLG8992;20110301171000
172500:LECBFIR:173420:FIR:411749N0020442E:415439N0013545E:0:245:0:100
173420:LECBUIR:173955:FIR:415439N0013545E:423658N0012901E:245:300:100:179
173955:LFFFUIR:185050:FIR:423658N0012901E:503032N0032621E:300:196:179:1136
185050:EBBUFIR:190240:FIR:503032N0032621E:505405N0042904E:196:2:1136:1232
185050:EBURUIR:185050:FIR:503032N0032621E:503032N0032621E:196:196:1136:1136
```

Figure 4.11: An example of Airspaces with Zero Elapsed Time for planned data.

In the last line of the figure 4.11, EBURUIR airspace has the same entry and exit times. The situation is same for the coordinates and the flight levels. This type of error not only alters the connectivity of airspace sequences but also creates singularities in the delay density calculations (delay density is the delay generated for a unit elapsed time in regarding airspace). This type of cases are filtered and removed from the airspace sequences to handle the singularities and maintain the connectivity. There are 107 such cases in the planned data and 43 in the actual data.

4.2.2.4 Inconsistent planned and actual profiles problem

The calculations of delay generations involve the processing of each airspace in airspace profiles of both planned and actual data. During these calculations extreme results appeared in delay generations which orientated the focus of the study to further examination of planned and actual data. After an extensive assessment, the planned and actual data separated into five different categories based on their airspaces. These categories for March 1, 2011 are presented with the number of flights they contain as follows. Out of 29661 flights:

1. Airspace sequences of Planned and Actual data are exactly the same (18769 flights)
2. Only the first and the last airspaces of Planned and Actual data are the same (5661 flights)
3. Only the first airspaces of Planned and Actual data are the same (2804 flights)
4. Only the last airspaces of Planned and Actual data are the same (2187 flights)
5. Neither the first nor the last airspaces of Planned and Actual data are the same (240 flights)

The first category is the easiest one to calculate sector delays because planned and actual data are perfectly matched. Since the second category involves changes in the plan and the flight occurred via different path, delay generations of each sector are calculated with some assumptions. At this point, delays for different airspaces (airspaces that belongs to a different path and the airspaces that the separation from the original course begins and ends) calculated holistically and the total delay is shared between those different airspaces with the proportion of their elapsed times over the total elapsed time. This assumption for the delay calculation necessitates the time connectivity of the consecutive airspaces for a correct partition of the total delay.

The first and the second categories can be interpreted as domestic flights over the European Airspace. On the other hand, most of the third category can be classified as

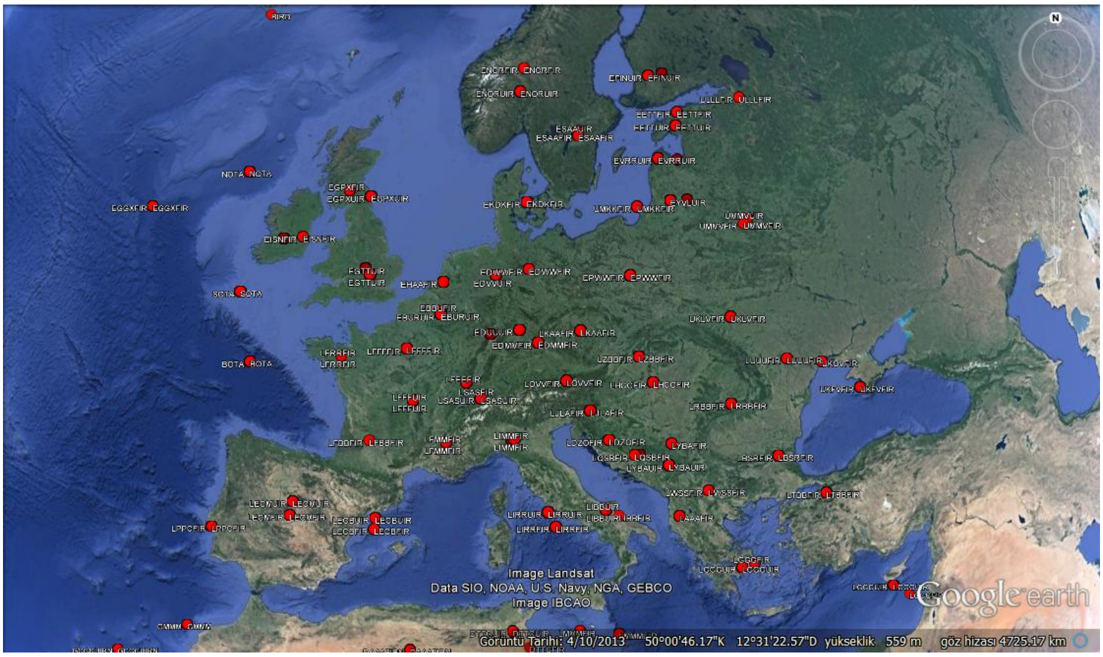
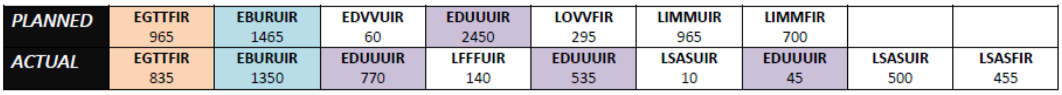


Figure 4.12: The Airspaces in FIR level that belong to the flawed data for Inconsistent Planned and Actual Profiles Problem.

the flights start from somewhere in the European airspace and end at another continent. Similarly the most of the flights in the fourth category can be interpreted as the flight coming from another continent to Europe. Since CPF-REF data has no coverage outside the European airspace, the incomplete actual data in these flights make sense. The same logic applies for the fifth category which can be explained as transit flights.

However the last three categories has also many flights with flawed data. In order to see if these flawed data are peculiar to some region, airspaces of those flights are plotted as it is given in figure 4.12. The figure clearly shows that the problem is related to the data itself rather than any region over European airspace. Utilization of these three categories in delay calculations result with incorrect solutions. Because of that reason they are not included into delay calculation process, but they are processed in traffic calculations since the aircrafts exist in the actual data. Consequently, for the delay calculations around %75 of the total data is utilized whereas the traffic calculations have been carried out with %90 of the data.



PLANNED	EGTTFIR 965	EBURUIR 1465	EDVVUIR 60	EDUUUIR 2450	LOVVFIR 295	LIMMUIR 965	LIMMFIR 700		
ACTUAL	EGTTFIR 835	EBURUIR 1350	EDUUUIR 770	LFFFUIR 140	EDUUUIR 535	LSASUIR 10	EDUUUIR 45	LSASUIR 500	LSASFIR 455

Figure 4.13: An example of category three, flawed data.

Figure 4.13 demonstrates the category three flawed data. Same colors indicated the common airspaces and the times elapsed in each sector for both planned and actual data is presented just below the airspace name. As it can be seen from the figure, both planned and actual data has same first airspaces, however, after the second airspace separation begins and flight ends in different airspaces.

Also note that, both LIMMFIR and LSASFIR are the FIR regions of European airspace. Therefore, it is a crystal-clear fact that, this category three data is actually a flawed data and using these kind of flights with flawed data will eventually add wrong results to the delay generation data pool.

5. FORMULATIONS AND CONNECTIVITY GRAPHS

So far, required descriptions and background is presented in order to process the data and calculate the possible delay. Necessary assumptions and several fixing algorithms have been employed to shape the data as well as improving the quality of it for the rest of the project. As a consequence eight different flight model is reduced to its simple forms as Planned and Actual data. In this chapter deviations between these two profile which are called delays will be investigated in all phases of all flights. First, the formulations for each phase will be given and then all calculated delays will be aggragated to charactarize airports or air sectors' behaviours in a daily or weekly scale.

5.1 Delay Formulations

Based on the data, the delays that are available to be calculated were presented in the earlier sections. Thanks to the planned and actual data structures delays are calculated for the all feasible phases of a flight with given formulas below:

Table 5.1: Delay calculations in each phase of a flight.

Delay generation at deperture airport	
Delay up to push-back phase	AOBT – EOBT
Delay at taxi to take-off	[ACT.AS(1,1) - AOBT] – ... [PLN.AS(1,1) - EOBT]
Delay at take-off to TMA exit	[ACT.AS(1,2) - ACT.AS(1,1)] – ... [PLN.AS(1,2) - PLN.AS(1,1)]
Delay generation at sectors	
Delay at en-route	[ACT.AS(end,1) - ACT.AS(1,2)] – ... [PLN.AS(end,2) - PLN.AS(1,2)]
Delay generation at arrival airport	
Delay at TMA entrance to touch-down	[ACT.AS(end,2) - ACT.AS(end,1)] – ... [PLN.AS(end,2) - PLN.AS(end,1)]

First delay may occur before the aircraft commence its movement which means aircraft departs from the gate later than its expected and this delay is calculated as difference between Off-Block Times. The second delay is called taxi delay and it is calculated as substracting planned taxi time from actual taxi time. Delays of the remaining phases of a flight calculated in the same fashion: substracting the planned duration of related phase from tha actual duration.

ACT in equations stands for Actual data where as PLN is for Planned and ACT.AS represents the actual airspace profiles. ACT.AS is a (nx2) dimensional matrix where each line is an air sector with 2 columns representing entry and exit times of that sector respectively. For instance ACT.AS(1,1) means the Take Off Time because it is the entry time of the first airspace. Similarly ACT.AS(end,2) is the Landing Time which is the exit time of the last airpace.

It is important to note that, in order to investigate the delays at arrival/departure TMAs, the airspace profile of the data must be processed in Air Traffic Control Unit Airspace (AUA) scale. AUA scale is the only scale that includes the airports' Terminal Manuevering Area. Furthermore, as it was mentioned in the previous chapter, processing the AUAs requires specific attention to CPG file which includes the configurations of each AUA. In other words, the first AUA in the data might not be a TMA of airport, instead it represents a larger area which subsumes the TMA. In such cases different procedures must be employed to select the TMA from airspace profiles.

5.2 Delay Propagation Model Approach

The three essential delay generators/absorbers were named in previous chapters as departure/arrival airports and enroute. Structuring these three entities in a sink and source model in traffic generation perspective is the sole purpose of the delay propagation model approach. Model asserts that traffic is generated by sources (deparure airports) and in conjunction with this traffic there is a delay generation/absorbtion. As the aircraft flies through air sectors on it destination path, this delay created in the source propagates and as soon as aircraft reaches its destination airport i.e. its traffic sink there is reflection of this delay. This reflection gives an insight about the sectors on the path. Analysing whole flights in this perpective will bring out

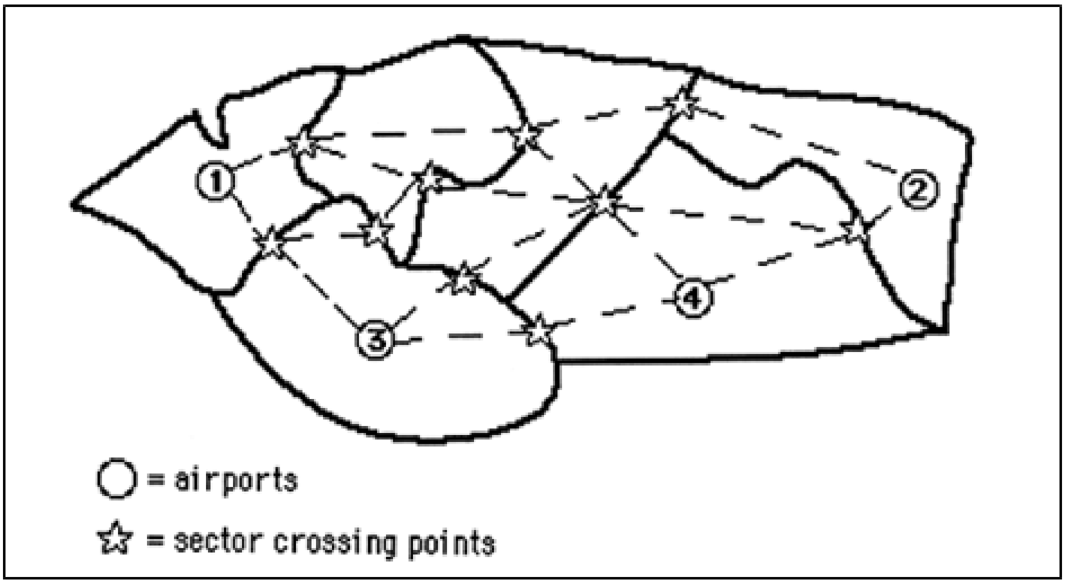


Figure 5.1: Network representation of airspace system [6].

the sectors and airports with problems and will demonstrate interaction of sectors with the dissemination of delays via sectors' connectivity graphs.

Delay propagation model approach has a perfect harmony with the data where each airport is a sink/source of the node based system and generates both traffic and delay. As it is illustrated in figure 5.1, throughout each flight, sectors are the delay generators or consumers of the system. Model undertakes the analysis in two perspective, on the one hand it investigates the airports and their TMAs, on the other hand it seeks the interactions of en-route airspaces in any scale, however, to be able to probe the status of TMAs one has to process the data in AUA level as it is mention earlier.

Another benefit of this approach is that it takes inbound or outbound traffic into account which provides a different prospect to analysis. Using the delay outcome alone will give an insight about the sectors' or airports' status but merging this information with traffic feed of related entity may supply reason for the delay resulting in better understanding of the events occured. For instance, consider an airport which generates great deal of delay as a sink while its traffic absorbtion is quite low, this situation increases the possibility of bad weather around the airport. On the contrary, if the traffic absorbtion would have been high above its usual rate, it would enhances the possibility of congestion i.e. over arrival capacity usage. This brief example shows that gathering more data will ensure better understanding of what is really going on. For that purpose capacity data for those entities will also be exerted.

5.3 Creating The Connectivity Graphs

Delay Propagation Model transforms individual flight routes into aggragated flows of aircrafts in specified time intervals. Although particular informations regarding each flight is sacrificed, collective characteristics of the system is contained with network representation whereas complexity of the system is boiled down to its essentials. In order to construct the network, one has to determine the entities that will present the nodes and the connectivity between those entities which is also called edges. Based on the data, this model can be structured around two different aspects: connectivity of airports or connectivity of airspaces.

Seeking the interactions between airspaces or airports requires the information of dependency to each other. In order to question the degree of dependence, the connectivity graph of the related entity must be acquired first. The structure of the data introduces an opportunity to auto generate these graphs via data itself without imposing any computational burden. Continuous flight segments enable to create connectivity and traffic flow graphs by determining connected airspaces within the flight trajectory data. For every types of airspace entities (i.e. NAS, FIR, AUA, ES etc.), directed flow graphs have been generated through ALL_FT+ data at every level and graphs are given in figure 5.2.

As it can be seen from figure 5.3, the same procedure is applied for airport entities and their connectivity graph is generated directy from the ALL_FT+ data according to each flight's departure and arrival airports. The crucial benefit of airport connectivity graph is provision of detailed analysis on highly congested routes where the graph gives the interactions of sinks and sources.

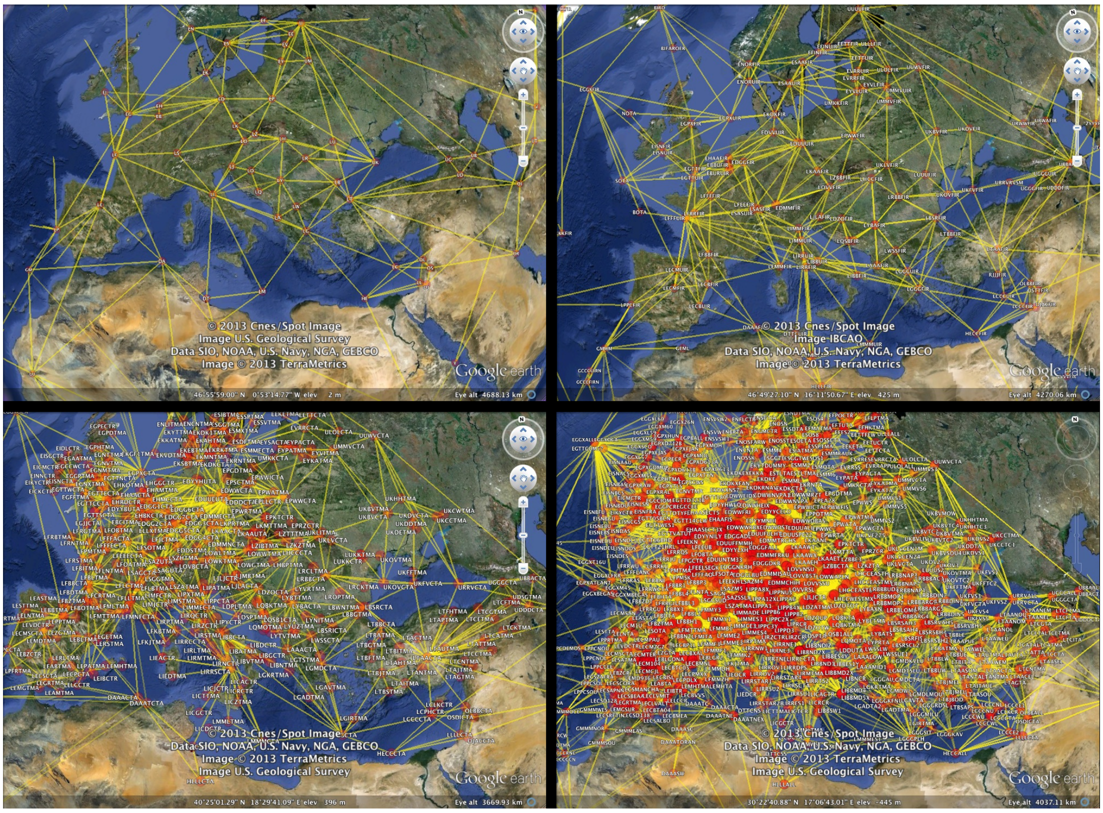


Figure 5.2: Starting from the top left corner moving clockwise European Airspaces' Connectivity Graphs in National (NA), Flight Information Region (FIR), Elementary Airspace (ES) and ATC Unit Airspace (AUA) scales.

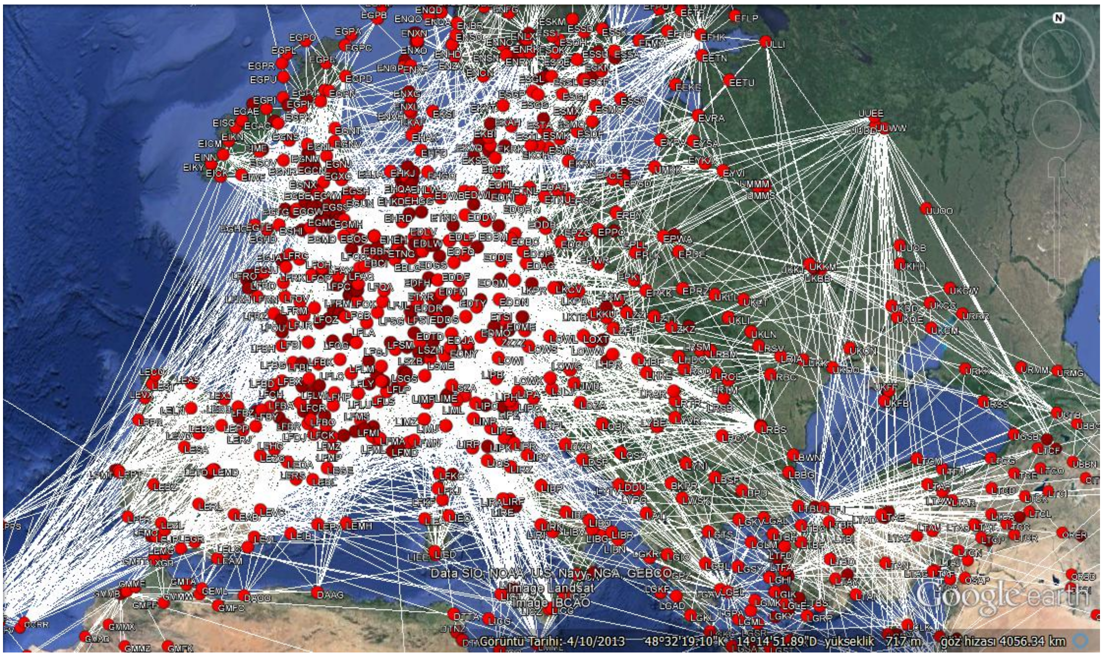


Figure 5.3: Connectivity graph of all Airports in Europe.

5.4 Traffic Analysis Over France with Connectivity Graph

Processing the data in FIR level results with 155 airspaces where minority of these airspaces do not belong the European Airspace because of the flights started or ended in different continents. All traffic flows between sectors and instantaneous number of aircraft values for all sectors are calculated with 15 minutes time resolution. Since the whole network system is huge to be illustrated in here, LFFFFIR is selected and its connectivities are illustrated. Originally, LFFFFIR has 11 connected airspaces as LFFFUIR, LFFFFIR, LFEEFIR, LFMMFIR, LFBBFIR, EBBUFIR, LFRRFIR, EGTTFIR, EGTTUIR, EBURUIR, EDGGFIR and EGPXUIR. Also it has a loop which represents the flights started and ended in itself. However, as it is presented in figure 5.4, the most interacted airspaces are chosen for the analysis.

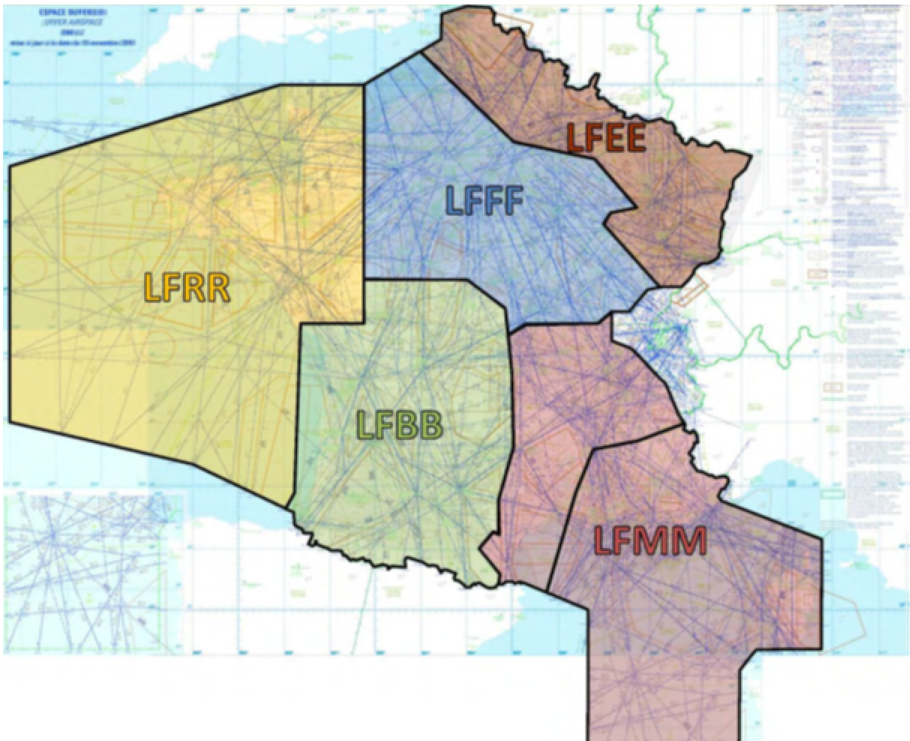


Figure 5.4: Connectivities of the airspaces over France [7].

In addition to those, there is also LFFFUIR which covers the high altitude area over these airspaces. The system of five edges and one loop with 6 nodes is analyzed and traffic flows and number of flights each sector contains are plotted with 15 minute resolution for 7 seven days which starts with 03/07/2011 Monday and ends with 03/13/2011 Sunday. Results of traffic flows are given in figure 5.5 and 5.6.

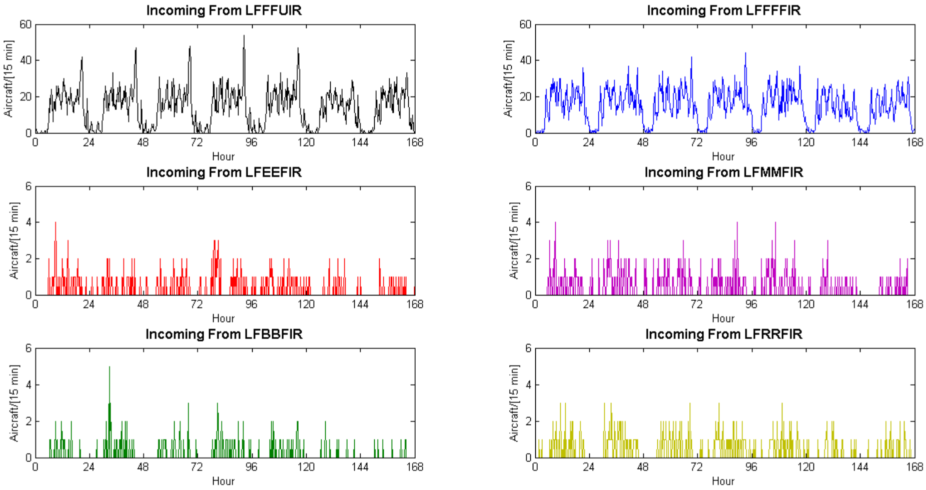


Figure 5.5: Incoming traffics to LFFFFIR from Neighbor Airspaces.

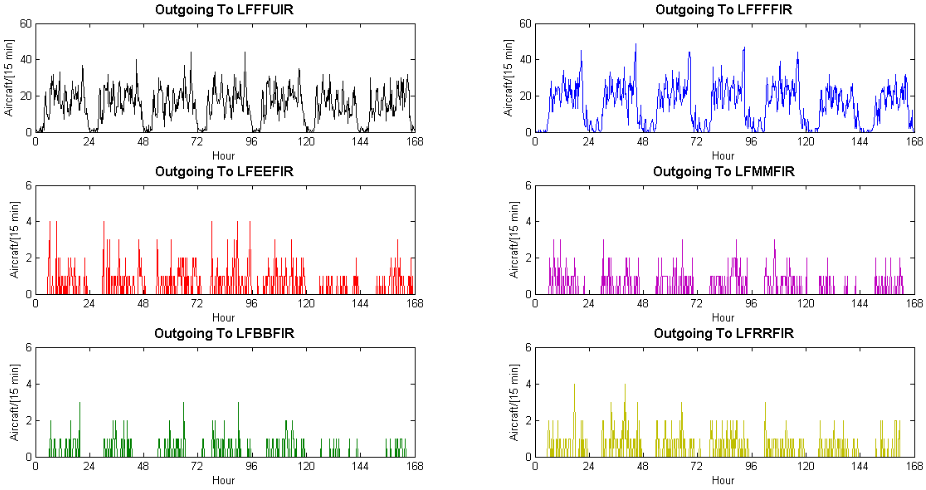


Figure 5.6: Outgoing traffics from LFFFFIR to Neighbor Airspaces.

Figure 5.5 and 5.6 are plotted for LFFFFIR which puts LFFFFIR at the center of the network. Incoming From LFFFFIR stands for the traffic generated by LFFFFIR whereas Outgoing To LFFFFIR shows the absorbed traffic by LFFFFIR. Examining LFFFFIR and LFFFUIR interaction carefully draws the conclusion that almost all the traffic flow from LFFFUIR is absorbed by LFFFFIR (check the similarity of Incoming from LFFFUIR and Outgoing to LFFFFIR). Similarly high portion of the traffic generated by LFFFFIR is transfered to the LFFFUIR (check the similariy of Incoming from LFFFFIR and Outgoing to LFFFUIR). The difference of the flow between these pairs are shared between other neighbor airspaces with some proportions.

In other words, the generated traffic from LFFFFIR is transferred to the high altitude airspace LFFFUIR to reach other nonconnected airspaces (long range flights). Considerably small portion of this generated flow is directed to neighbor airspaces and these flights can be called as domestic flights. The same situation also happens for the absorbed traffic where almost all of the incoming traffic from LFFFUIR is absorbed by LFFFFIR. This deduction also means that LFFFUIR has the highest traffic because of the fact that the interaction between LFFFFIR and LFFFUIR dominates the other neighbor airspaces. This inferent can be validated via figure 5.7.

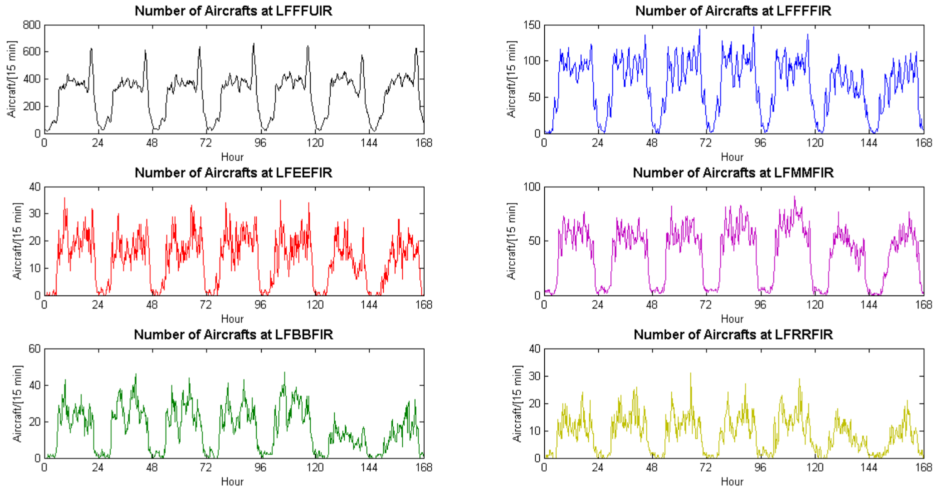


Figure 5.7: Instantaneous Number of Aircrafts in 15 minutes periods for airspaces.

Figure 5.7 points out that LFFFUIR is the most hectic airspace in this network. It can also be inferred that LFFFUIR is one of the main arteries of European Airspace network which transfers many flights across the Europe to various destinations and this thesis can be proved by the connectivity graph of the LFFFUIR airspace which includes 26 edges.

Also note that, all plots can be represented with one deterministic, almost periodic curve plus stochastic series. Identifying the deterministic curve and the stochastic processes' parameters will yield the representative model of the system. It is important to note that each day of the week must be investigated seperately (especially the weekends that have considerably different flight plans) and seasonal changes have to be included into modelling process.

6. RESULTS OF ANALYSES

In light of the foregoing, a set of analysis have been conducted. Results are sorted according to their development order and can be classified in two main perspectives as airspace centered delays and airport centered delays.

6.1 Sector Delays for Each Flight

The first task was to calculate the delays that are generated in each sector fight crosses. For that purpose, TMA and enroute delays are investigated. Enroute phases of flights are divided into preferred airspace types and delays are calculated for each airspace as the difference between actual and planned elapsed time in the related sector. Examples of results for this analysis in FIR level is given in figure 6.1.

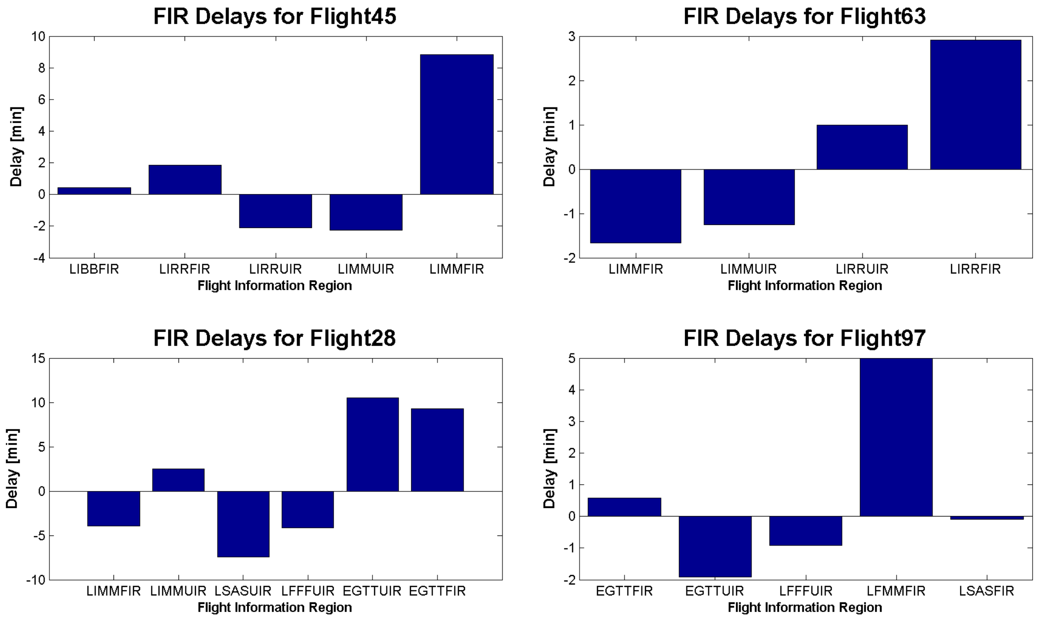


Figure 6.1: Delays generated in each crossed FIR for four flights.

Figure 6.1 indicates the effects of each crossed sector to the flight for four flights. In this analysis, delays generated by airport operations are not included with the purpose of investigating only delays generated in the air. Additionally, TMA delays are not distinguished from en route sectors which means the first and the last sectors given for each flight contain the departure and arrival TMAs respectively. This fact can be observed from the last sectors where the highest delay is generated usually (in the TMA of an arrival airport). The flight titled 45 is a great example for the case where the last sector generated more than 8 minutes delay for the flight. In flight 28 the last two FIR generates high amount of delay which may be caused by bad weather covers both sectors. Finally, flight 97 has the highest delay generation at the sector before the last one. This result may be caused by early ATC operations to regulate the arrivals to destination airport which concluded with neat TMA duration.

6.2 Delays on Airspace Network

Aggregating the results of sector delays for a whole day's flights and processing them in sectors' perspective yields the delay characteristics of each sector in FIR level. This approach provides the daily depiction of European airspace which marks the regions with high delays. The outcome of this approach is given with connectivity graph over Europe in figure 6.2.

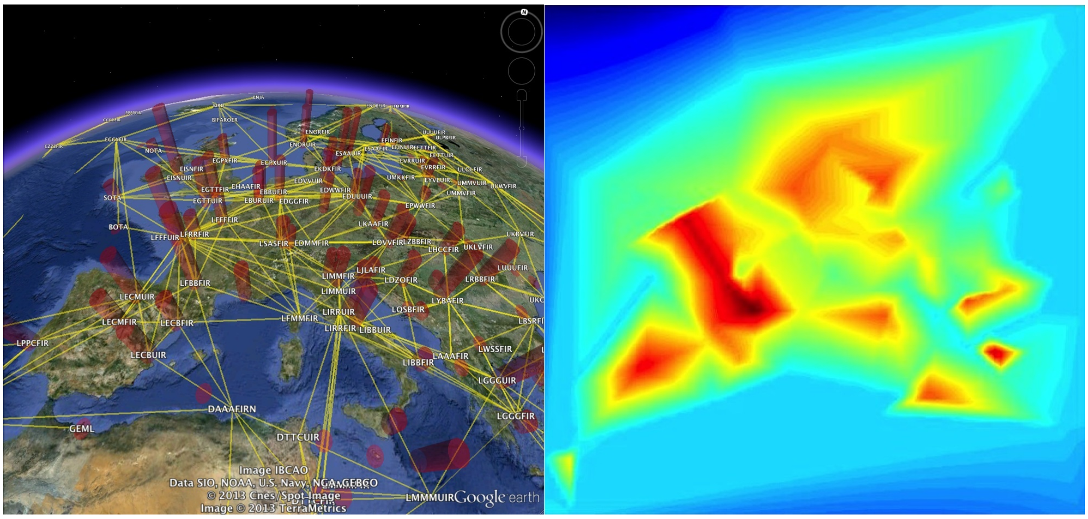


Figure 6.2: Total delays generated by each FIR level sector over Europe with connectivity graph.

Figure 6.2 illustrates the total delay generation for a whole day and it gives an insight about congested regions of European airspace. In light of this information, candidate regions for further analysis are selected. As an extension of this work, time unit has been decreased to 15 minutes and 7 days' data is processed simultaneously. Furthermore, traffic flows between FIR sectors are incorporated into analysis with the

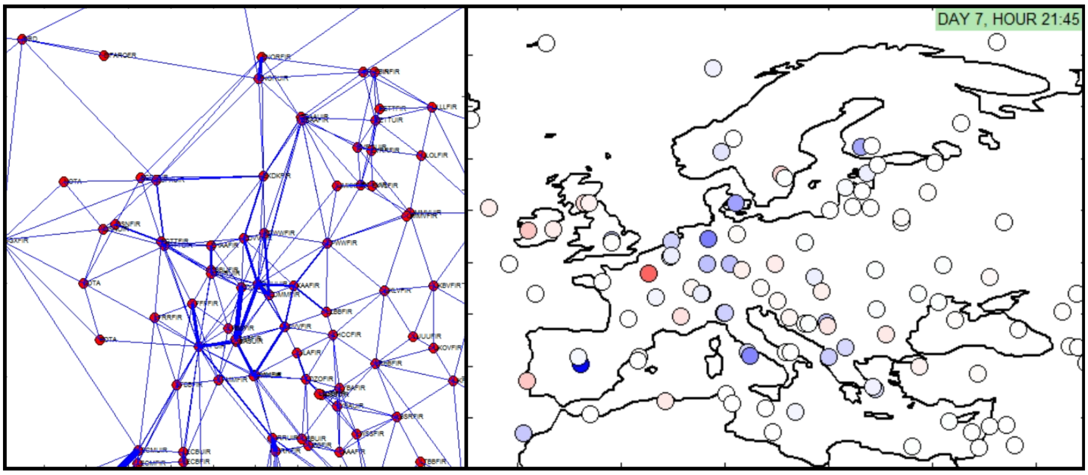


Figure 6.3: Traffic and Delay changes in 15 minutes time intervals over European Airspace.

intention of anticipating any probable correlation between delay and traffic. In order to reduce complexity traffic and delay changes are monitored in two different screens.

Figure 6.3 gives screenshots from animated traffic and delay data of 7 days. At left, traffic flow between related sectors are illustrated where the thickness of the line corresponds to density of the traffic flow. At right, delay generation of each sector is given with colors where the tone of the color gives an insight for the delay generation. The red tones stands for the delay generations and blue tones corresponds to absorption of the delay. The darker the color gets, the more delay the sector generates or absorbs. The most obvious result of these animations is the active weekends where delay generation and absorption changes gets more apparent.

Creating an animation with 15 minutes intervals may make it harder to detect the regions with congestion because it spreads the daily aggregated delays over a day, however, it gives another insight regarding the propagation of the delay in time which is the main focus of the next analysis.

6.3 Propagation of Airspace Delays

In order to monitor propagations of the delays over a selected area, instead of creating an animation, whole delay generation/absorption data logged and visualized daily on bar graphs with their connectivity and traffic flows. Since the all system is too complex to be illustrated in here, a congested are is selected with the help of the information obtained from previous analyses.

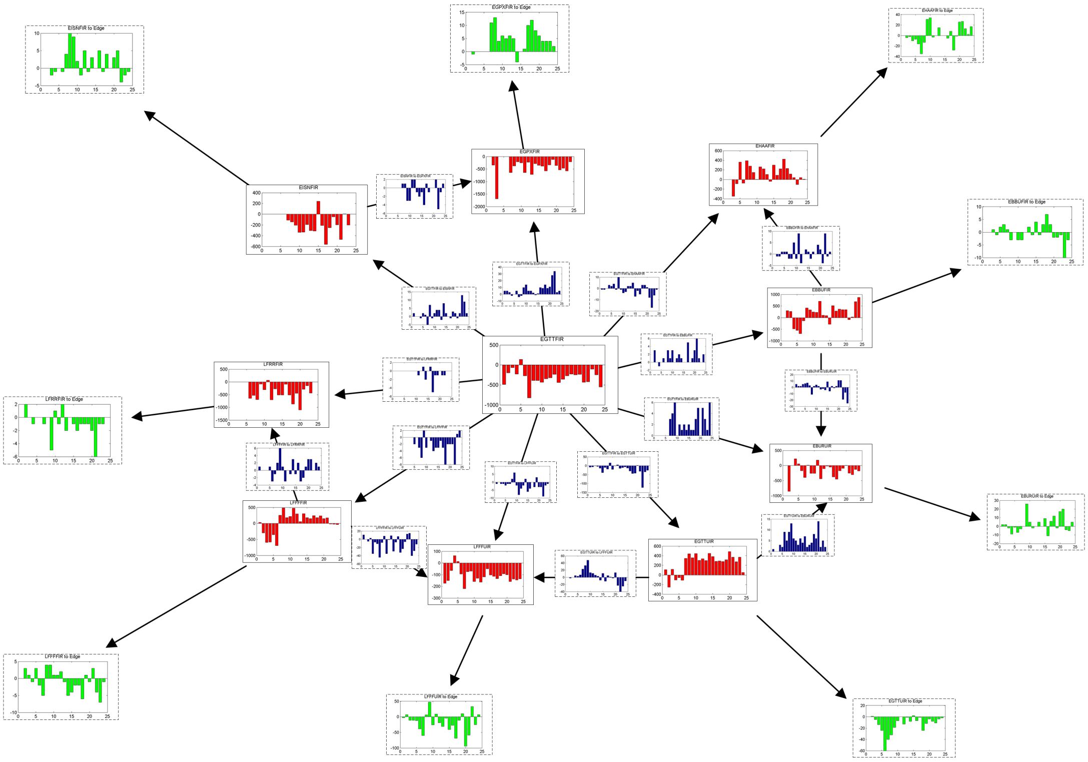


Figure 6.4: Hourly delay generations/absorptions for a whole day in EGTTFIR centered network.

As it is illustrated in figure 6.4, EGTTFIR centered network system has been constructed with hourly basis traffic flows and delay generations for a day. For this analysis traffic flows between sectors are the total flows which are calculated as outward minus inward traffic and the arrows represent the preselected directions. Therefore, if the traffic flow is negative, the total flow direction is inward (in to the sector) and vice versa. The green bars represent the traffic entering to/exiting from the system according to their sign.

According to graph, EGTTFIR (sector in the center) and LFFFUIR (sector below the EGTTFIR) sectors have similar delay generation characteristics. Both sectors absorb delay from the system for almost whole day. However, around 4 a.m. delay absorption in LFFFUIR decreasing and minor delay generation is observed. This delay generation propagated and appeared in EGTTFIR at 5 a.m. Despite this obvious result, it is hard to detect the all relations from this approach and requires further analysis. Moreover, the aggregation of all delays for each sector reduces the details of delay sources. For instance, if the reason for the delay generation is bad weather conditions over the sector, then all flights crossing that airspace will be affected. However, if the reason is ATC operations to regulate overflow arrival traffic to a specific airport, then this delay is generated by that airport not that airspace. Using this approach makes the detection of such cases impossible and might cause wrong deductions.

6.4 Airport Analyses

Drawing correct conclusions about the events took place and reasons for that events requires more perspective i.e. more parameters to be investigated. As it is mentioned in the previous analysis, using only airspaces for delay generation/absorption examination might result with wrong inferences. Since airports are the sinks/sources of the network system, they have to be included into analyses. For this purposes, first airports' arrival and departure characteristics are explored. Number of Departure and Arrivals per hour is provided with declared capacity values and airports' planned and actual departure taxi times are presented with taxi delays observed through the Day. In order to see the patterns and events (pattern changes) selected airports' status are given for seven days.

As it can be seen from figure 6.5 declared or planned taxi time for the Heathrow airport is fixed to 20 minutes and actual taxi times are slightly higher than planned taxi times. Hence the taxi delays throughout the week vary between 0 and 5 minutes. Airport's declared arrival capacity follows a pattern through the week and does not change even if arrival traffic exceeds the declared capacity almost every day of the week. Similarly, declared departure capacity is a straight line although there are severe over capacity departure rates per hour.

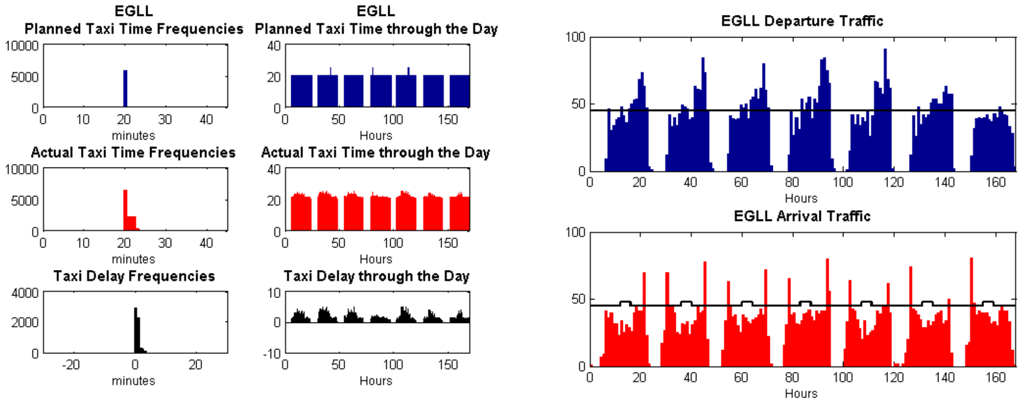


Figure 6.5: London Heathrow Airport's Status.

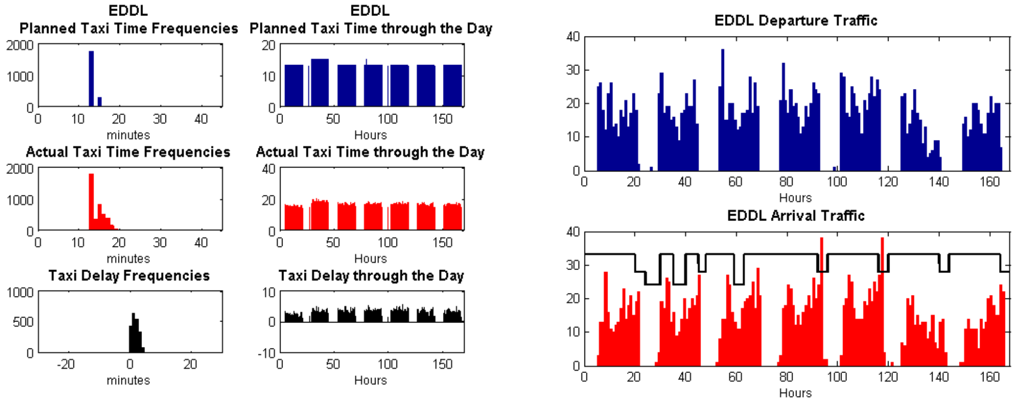


Figure 6.6: Düsseldorf International Airport's Status.

The declared departure capacity for Düsseldorf International Airport is 999 which means infinite capacity. That is why there are no capacity lines in figure 6.6 for departure traffic. In arrival side, an obvious pattern deterioration in Tuesday takes the attention. There is also different planned taxi times in contrast to usual planned taxi times which is 13 minutes in Tuesday. These two particular behaviors may be related to each other. Also note that, even if declared arrival capacity has a different pattern in Tuesday, the arrival traffic has the same pattern with weekdays. The reason for this situation may be the internal operations of the airport and capacity may be not related to incoming traffic at all. Other than that, taxi delay values vary between 0 and 5 minutes throughout the whole week.

Unlike the other airports mentioned in this section, Frankfurt Airport have more precise planned taxi times which can be seen from the planned taxi frequencies in figure 6.7. As EDDL, this airport has no declared departure capacity and its declared arrival

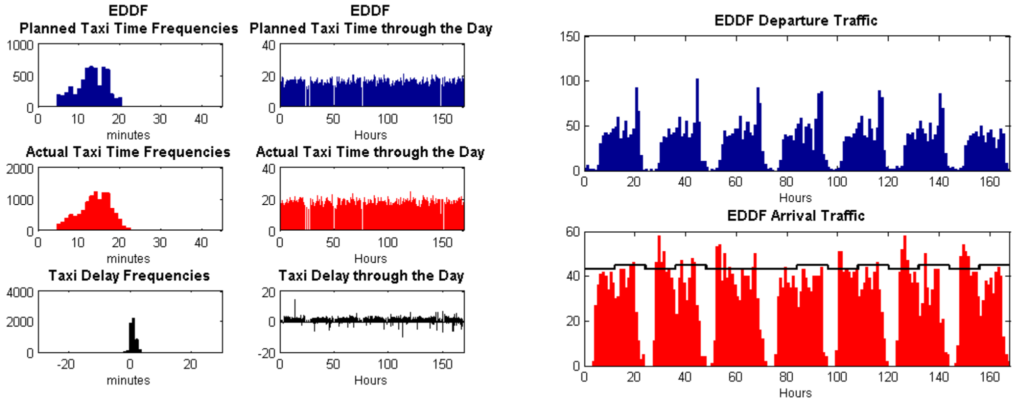


Figure 6.7: Frankfurt Airport's Status.

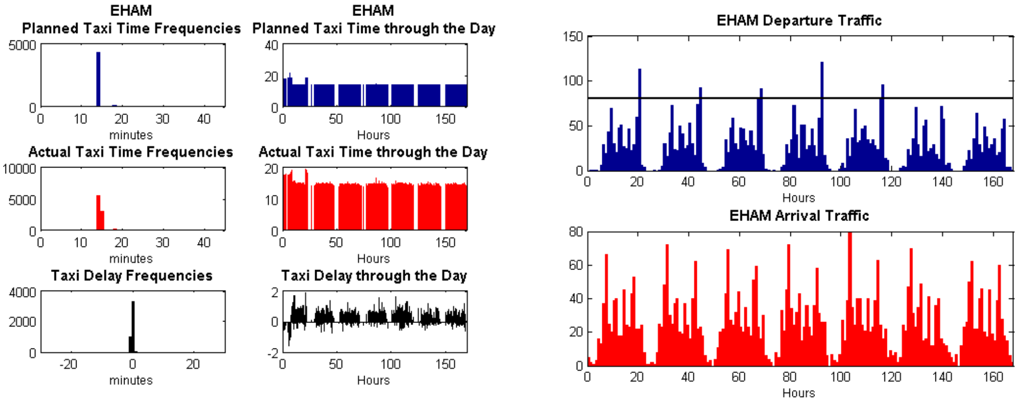


Figure 6.8: Amsterdam Schiphol International Airport's Status.

capacity follows a pattern with slight alterations. The salient property of this airport is the existence of negative taxi delay values.

As it is presented in figure 6.8, Schiphol airport's planned taxi times are mostly 15 minutes and its peculiar property is the capacity of the airport. The declared arrival capacity is infinite and the arrival traffic rate arises up to 80 arrivals per hour whereas the departure traffic rate can go beyond 100 departures per hour. The reason for this ability to support huge amount of movements is that airport is one of the biggest airports in Europe with its four runways.

Unfortunately Istanbul Atatürk Airport has no complete CPF-REF data profile which may be caused by being out of the coverage of radars. CPF-REF profiles for the all flights heading to LTBA or coming from LTBA has uncompleted data. In other words, for the flight departed from LTBA, data starts with airport location and after a huge gap data continues from somewhere in the route of the flight. Similarly, for the flights

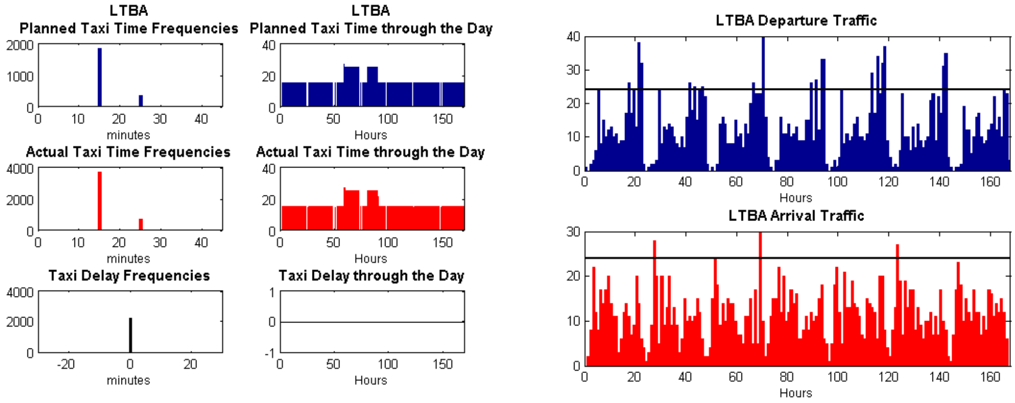


Figure 6.9: İstanbul Atatürk Airport's Status.

arriving to LTBA, data stops on somewhere on the route and after a huge gap flight arrives to airport all of a sudden. Because there is no radar data for the departure process, planned and actual taxi times becomes exactly the same which results in zero taxi delays as it can be seen from figure 6.9.

Status of examined airports show that more data regarding the airports is required in order to understand the events and the procedures applied. However, using the airports in the delay propagation analyses will be an effective way to observe the delays' evolution and will give more information about the potential reasons of delays.

6.5 Delays on Airport Network

After airports are analyzed individually, delay propagation is investigated over the airport connectivity graph. For this purpose, EDDM - Munich Airport centered graph has been constructed. Originally, according to connectivity graph, there are 77 airports connected to EDDM, but in order to focus on more representative data, 11 airports are utilized which have more than 20 reciprocal flights between EDDM in a day. The bidirectional EDDM network graph is depicted with its edges in figure 6.10.

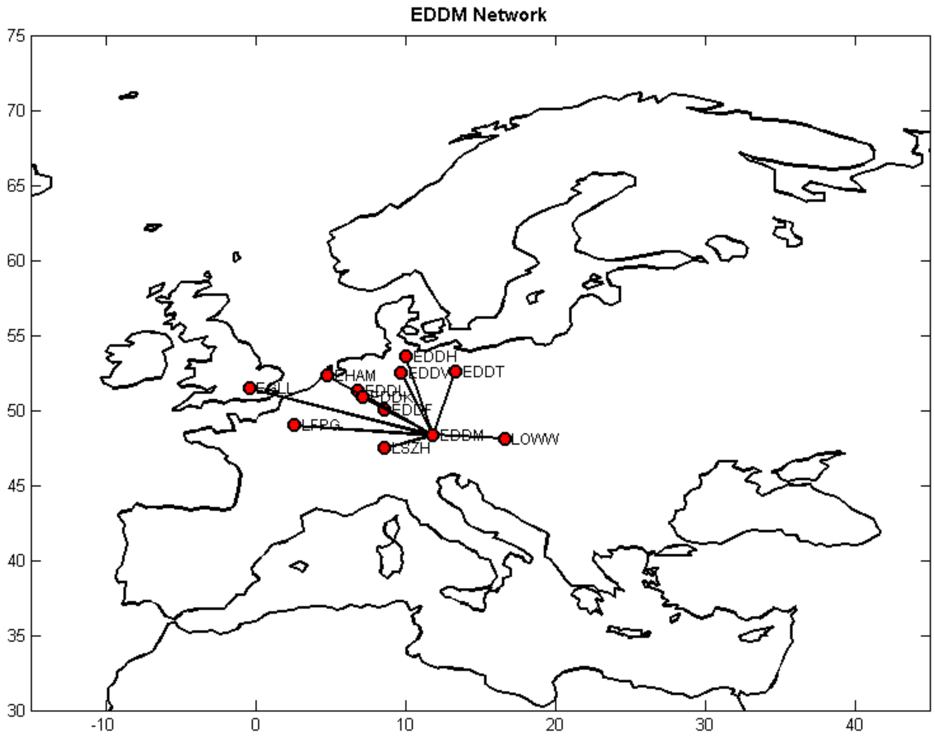


Figure 6.10: The bidirectional EDDM network graph with 11 edges.

Each airport's status is monitored with the all inward and outward flights and these calculated parameters are assumed to be the characteristics of the related airport. Edges (branches of the graph) represent the flights between two airports. Therefore, delays on the edges are only represented by the data of flights between related airport pairs. All delays on an edge are monitored for each flight with daily data which provides an information about propagation of the delays in each phase of a flight between an airport pair. This approach gives a more detailed answer to the question of which routes suffer more from delays and why. In other words, being able to distinguish the reasons of generated delays results with better understanding of the overall system. An example of this situation is given in the following results.

6.5.1 The First Example: Reciprocal interaction of Munich Airport (EDDM) & Vienna International Airport (LOWW)

For these examples compact figure groups are combined to monitor the whole flight process. The quadruplet figures given on the left side of figure 6.11 give the status of departure airport (EDDM). Push-back, Taxi and Departure TMA delays are calculated with all flights departed from EDDM. Also EDDM departure traffic is given with declared departure capacities (red line). The two figures in the middle, monitors the all flights from EDDM to LOWW-Vienna International Airport where the figure at the top stands for departure process and the bottom figure is the arrival process. Each bar in these figures is the instantaneous delays at that moment and the difference between them gives the delay generated between those points. These two are the key figures which indicate the delay propagation between the airport pair. Based on the detailed representation, one can diagnose the problem and source of the delay with higher accuracy. The last two figures on the right, gives the status of arrival airport (in this case LOWW) in terms of Arrival TMA delays and Arrival Traffic respectively. Since these figures are meant to be the characteristics of the airport, they are calculated with the all inward traffic data. The arrival capacity data is also given in the arrival traffic figure (if available) with a red plot.

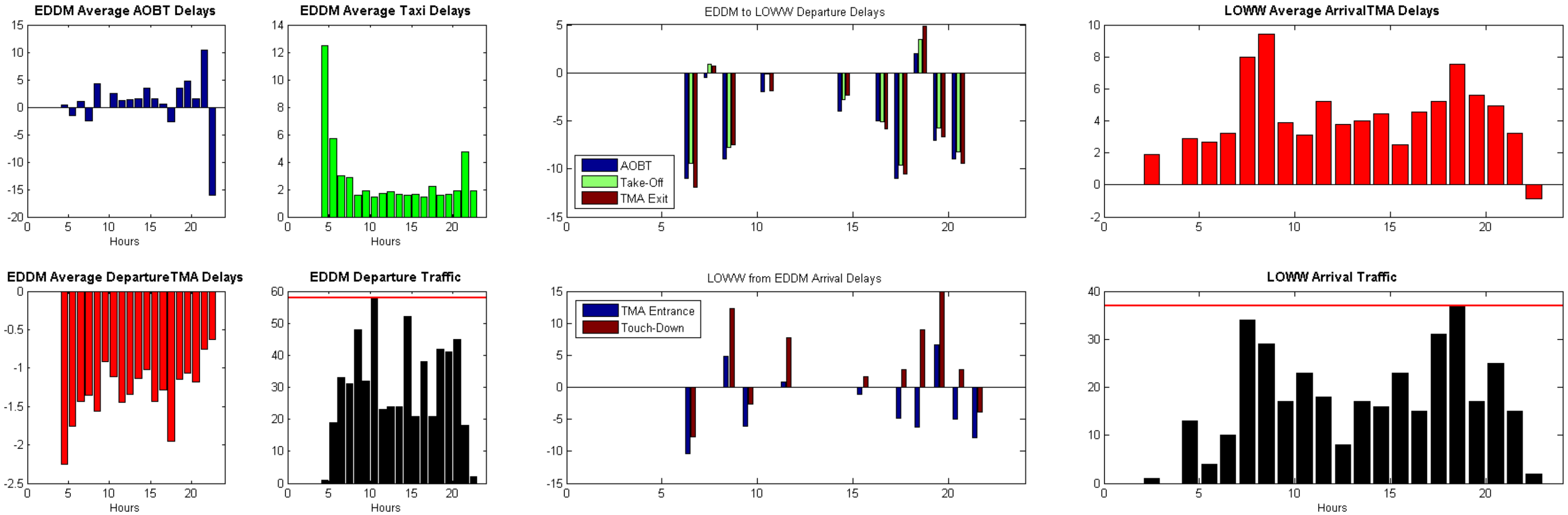


Figure 6.11: EDDM and LOWW airports’ status and monitored flights from EDDM to LOWW.

Figure 6.11 gives the full monitoring of the airport pair's status and the route between them. Even though Push-back delays of the EDDM airport have positive values most of the day, flights of the airport pair have negative push-back delays consistently which might be interpreted as an effort to compensate the arrival TMA delays of destination airport. Taxi delays of the departure airport is always positive, so, each flight of the airport pair experiences modest taxi delays at the take-off with one exception. Around 4 am the average taxi delays are observed as more than 12 minutes, however, the departure traffic at the same time interval reveals that there is a single flight which experienced 12 minutes delay during that interval. Hence, this specific result cannot be treated as the system characteristics in that time interval. Departure TMA delays are always negative which means almost all flights absorb a little delay in this phase. The propagation figures indicate a healthy route status which has delay generation around zero (the difference between Arrival TMA Entrance and Departure TMA Exit points). However, as it appears, arrival TMA is generating the most of the delays and the delay generation is completely coherent with the incoming traffic density (note the similarity of the characteristics of the arrival TMA delays and arrival traffic flows). Also these graphs give an insight for the most congested periods of arrival airport in a day.

The same airport pair is also investigated in the opposite traffic direction where LOWW is departure and EDDM is arrival airport. Since the departure airport is not in the center of this sub network, planned and actual taxi times with frequencies and taxi delays are also provided in figure 6.12. The first thing that is to be noted in the figure is the overflow traffic in the departure airport. There are four excessive departure traffic periods in 24 hours which have no any certain effect on push-back or taxi delays. Although there is a slight rise in both push-back and taxi delays with the over departure capacity usage between 7 and 8 pm, this event is not a sufficient evidence to draw a quick conclusion about the correlation between push-back, taxi delays and departure traffic. The inoperative attribute of departure capacities over delays are more like a supportive hypothesis for the inference that capacities are declared less than the actual capacity of the airports.

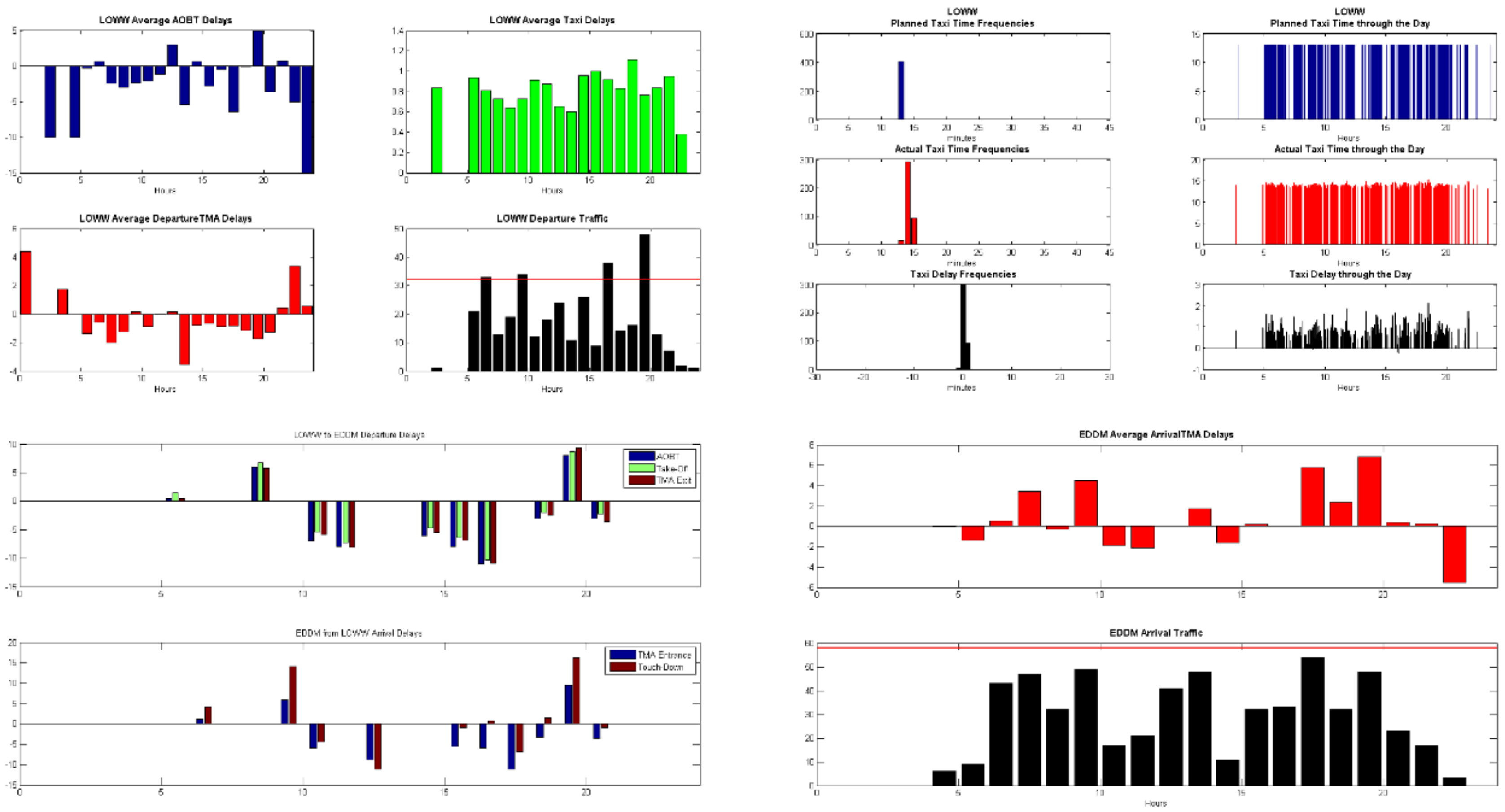


Figure 6.12: EDDM and LOWW airports' status and monitored flights from LOWW to EDDM.

Merging the monitored individual flights' information between the airports for both direction gives a solid reflection about the airspaces' status between the airports. As it can be seen from the delay generations of en-route airspaces (the difference between Arrival TMA Entrance and Departure TMA Exit points) for both direction, there is no any significant event that resources any delay generation in the airspaces. Additionally, individual flights reveals the dominancy of arrival TMA delays as expected and the delay generations in TMA region is consistent with EDDM arrival TMA delay characteristics which is given in red bars at the bottom right corner. It is also crucial to note the relation between arrival TMA delays and arrival traffic where the characteristics of them are similar with minor differences.

6.5.2 The Second Example: Reciprocal interaction of Munich International Airport (EDDM) & Frankfurt International Airport (EDDF)

Originally all airport pairs in the network are monitored with the same procedure, however, it is not practical to present all output in here. Nevertheless, it is a crystal-clear fact that, investigating more airport pairs will enlarge the comprehension of the events of the overall system which will increase the ability to perceive the air traffic dynamics. Therefore, in order to observe more detail with a different viewpoint, unlike the previous example, a domestic (in terms of centered airport EDDM) airport EDDF is investigated. The results for departures from EDDM to EDDF is given in figure 6.13.

This example poses different effects on action. For instance, although the arrival TMA delays are negligible or negative during the least congested hour intervals, arrival TMA delays have not a direct dependency based on their patterns which indicates the different events' consequences. Moreover, there is a certain raise in push-back delays between 3 and 8 pm, even though there are no any significant changes in AOBT delay characteristics (which is called push-back delay) in that time interval. This circumstance proves that these delays are not related to departure airport and peculiar to this airport pair which may be originated a ground holding precaution to a bad weather at en-route airspaces and/or predicted congestion at the arrival airport.

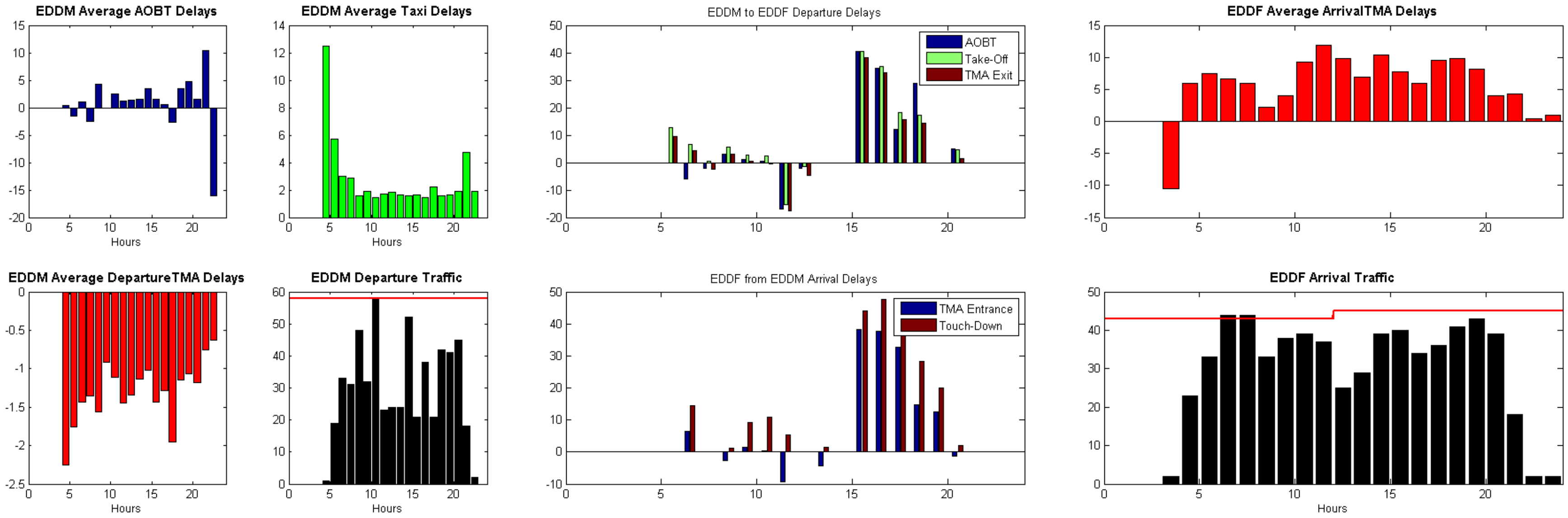


Figure 6.13: EDDM and EDDF airports' status and monitored flights from EDDM to EDDF.

In order to make more certain inferences about the reason of this abnormal push-back delays, the same airport pair is investigated in the opposite flow direction and the results are presented in figure 6.14. The figure clearly emphasizes the similar push-back delays in the same interval at opposite flow direction which indicates that the same ground holding procedure is also applied in EDDF, although there are no dramatic variations in AOBT delay characteristics of departure airport or departure traffic flow. As a result, one can diagnose that these salient raises in push-back delays for both direction of the flow is caused by the ground holding procedures which are probably employed to compensate the effects of bad weather conditions at en-route airspaces. However, utilizing other types of data sources as weather forecasts is imperative to be completely sure about what really happened. As it can be seen from figure 6.14, the second outcome of this analysis is that almost all flights from EDDF to EDDM have negative arrival TMA delays even in the most congested hours of EDDM. The same situation occurs in the flights departed from EDDK, EDDL and EDDT airports. This outcome may be a consequence of some priority or separation procedure of EDDM airport for some domestic flights.

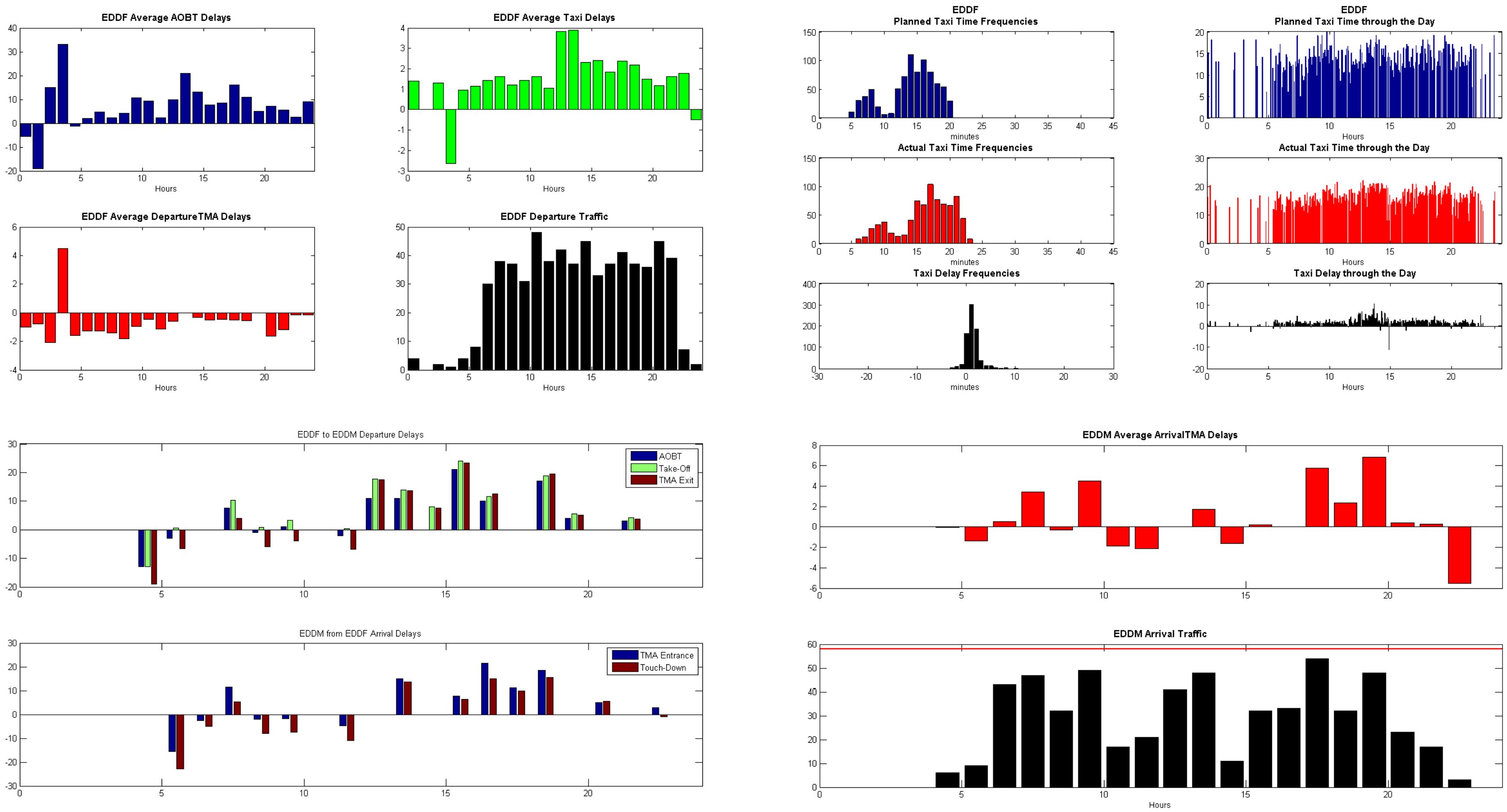


Figure 6.14: EDDM and EDDF airports' status and monitored flights from EDDF to EDDM.

7. EXCLUSIVE ANALYSIS OF TMA AT İSTANBUL ATATÜRK AIRPORT

In the previous section a delay propagation model across the network is identified. As identified, the operations in airports (both at arrival and departure) play a considerable part in flight delays. Since İstanbul Atatürk Airport is out of range in CPF-REF data as it mentioned in the previous section, in this section the focus has been shifted to demonstrate the structure in which the delay is realized at the arrival airport by using further detailed data obtained from DHMI (General Directorate of State Airports Authority) regarding LTBA. Specifically, it has been shown how the terminal operations and the flight densities affect both the pattern and also the stochastic nature of the delays observed at the terminal phase.

The delays generated in TMA (Terminal Control Area/Terminal Manoeuvring Area) are described and İstanbul Atatürk Airport is illustrated for four days with an supplementary data file called “Eurocontrol Category 062 System Track Data”. Cat062 is a file of ASTERIX which stands for All Purpose STructured Eurocontrol SuRveillance Information EXchange system.

7.1 Data Processing

Category 062 is a system track data which means its collected by the transmission of one type of message, i.e. target reports and flight plan data. Therefore, data source identifier and service identification presents in every record. The data have a block structure and each block is separated by a unique line of characters. Some of these data blocks are not useful and the flight IDs are not present for all blocks. Each block has a track number which is assigned to each tracked object. Figure 7.1 presents the demonstration of raw data.

The first task is to sort the data file according to track-numbers. There are 4096 different track-numbers and they are not peculiar to each flight, that is to say, each track-number is circulated among flights through time. Furthermore, for the arrival TMA analysis, arrival flights and departure flights are isolated from each other. In

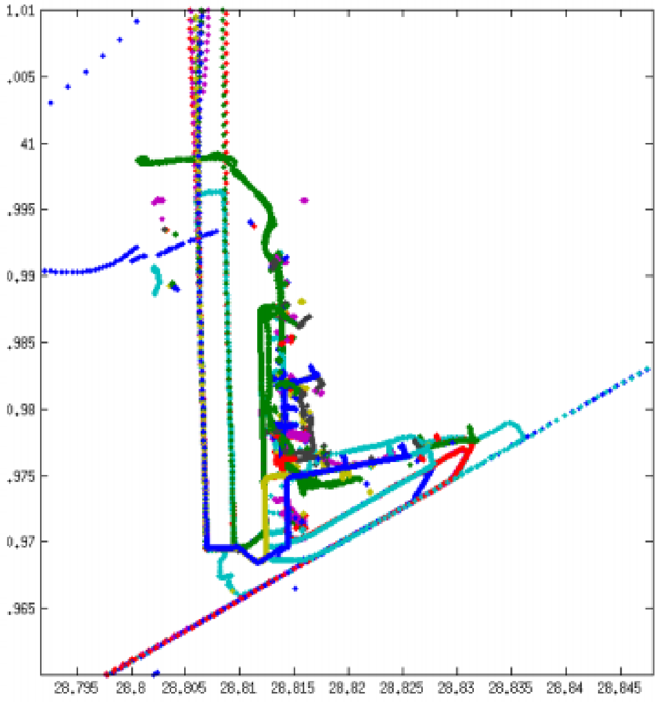


Figure 7.1: Raw data demonstration at İstanbul Atatürk International Airport.

figure 7.2, all flights with the same track number and the same flights after the utilization of separation algorithm is plotted. Note that each seperated flight has a different line color.

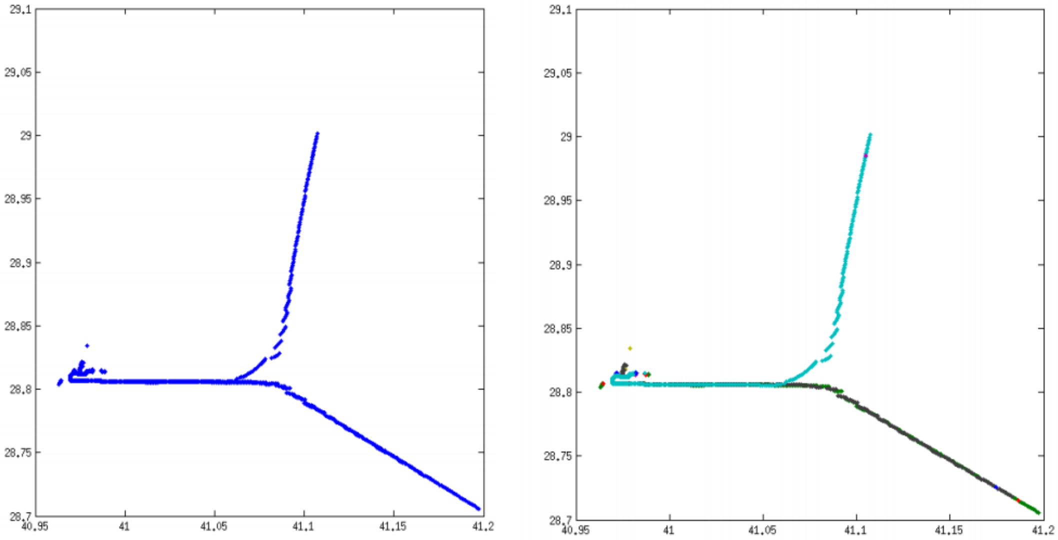


Figure 7.2: All arrival flights titled by Track Number 473 (at left), Seperated Flights with Track number 473 (at right).

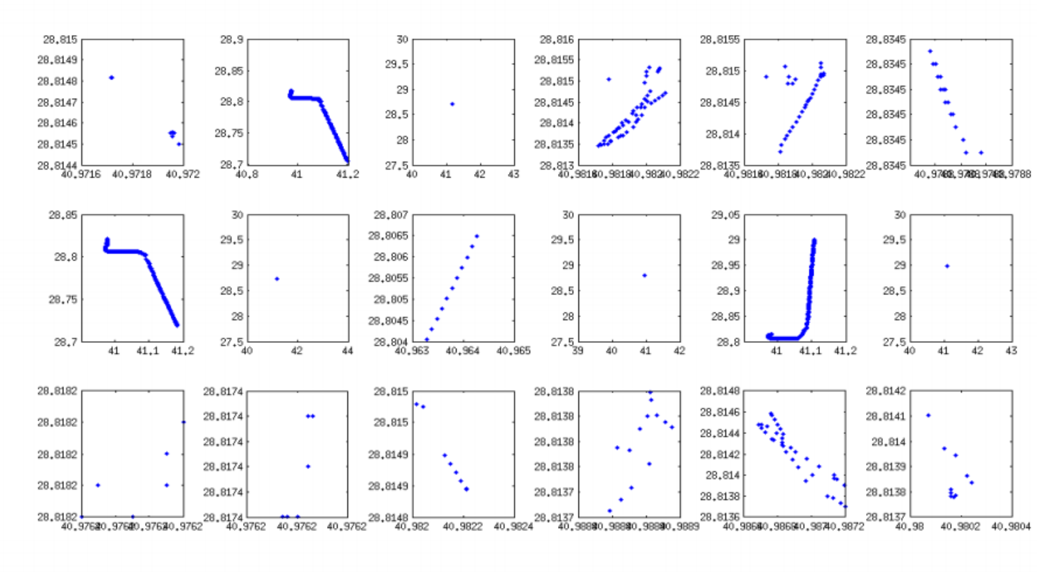


Figure 7.3: All flights with track number 473 in different frames.

As can be seen from figure 7.2, data is a raw radar track data, that is to say, it is not a preprocessed or high quality data. For that reason, it includes all planes that are in action at the airport. In the example above, there are 18 different flight data with track number 473. However most of these flights do not represent an arrival, hence they are useless. The proper arrivals need to be distinguished in order to obtain high quality for the sake of the analyses. All flights with track number 473 are plotted separately to emphasise the quality of it. Results in figure 7.3 show that there are only 3 useful flights out of 18 flights. Also note that most of the flight data does not even posess an action.

After the data mining process, useless data groups are eliminated and high quality data with only arrival flights are obtained and plotted in the figure 7.4. As can be seen from the figure there are 7 different entrance gates to TMA region of LTBA. In order to obtain more accurate results these 7 gates must be investigated separately. For that purpose, all flights are categorized by their entrance gates and 7 different category of flights plotted as follows. From that point on TMA delay calculation procedure is employed and its methodology is given in the next section.

Each category of flights presented with different colors and the high resolution of the data gives an opportunity to recognize the turn around (one of the green flights) and arrival ordering "U" patterns which results in extra delays. Also note that, aircrafts

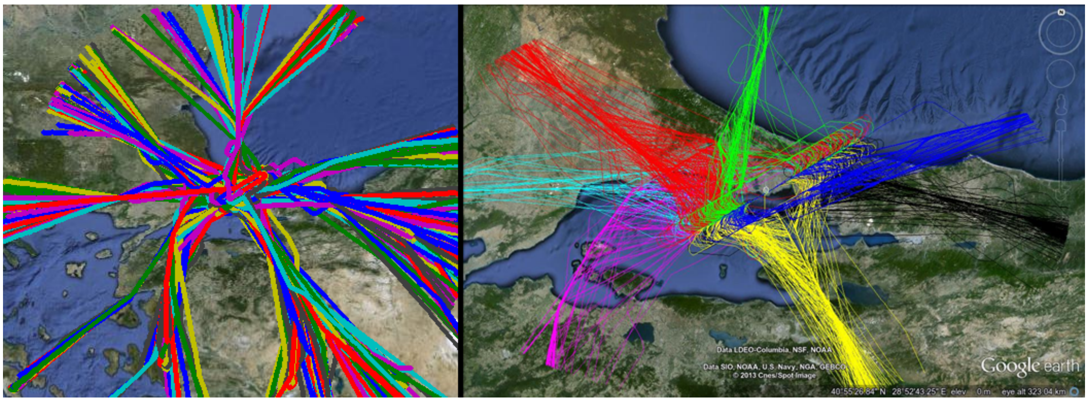


Figure 7.4: Refined high quality data for all flights (at left), Categorized high quality data for seven different TMA entry gates (at right).

landed in three different directions through the analysis which clearly reveals the runway configuration changes of the airport.

7.2 Delay Calculation Methodology

Since there are no actual and planned data for this analysis, a different delay calculation methodology which utilizes only actual data is employed to calculate TMA delays. After the categorization of all flights, the same methodology is applied for each category.

1. Calculate the time elapsed in the TMA region via Landing Time minus Entrance to TMA Time
2. For each approaching direction (each category), minimum time spent in TMA is determined. This time is assumed as the best possible landing scenario which is also assumed to have zero delay.
3. The delays generated in TMA is calculated as difference between all flights' elapsed times in TMA and elapsed time of the best possible landing scenario.

Remember that the procedure is applied for all categories separately which yields seven different best possible landing scenario from each entry to TMA direction. In order to represent the Terminal Control Area which is generally designed in a circular configuration centered on the geographic coordinates of the airport, an ellipse is chosen and the enter time to that ellipse is stored along with touch down time. The figure above demonstrates the actions that took place in the TMA ellipse which are mainly the U turn patterns to regulate arrivals in the congested times.

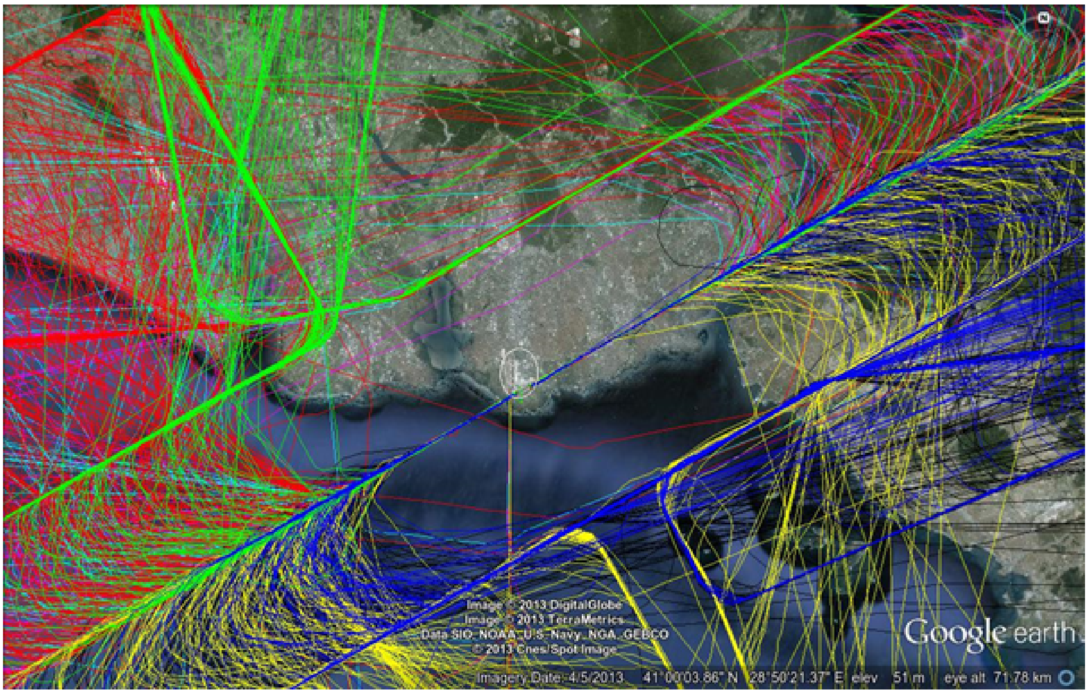


Figure 7.5: All arrivals from 7 different TMA entry gates and the U turn patterns which are the main sources of TMA delays.

7.3 Results

The final refined data includes 1492 arrivals. These 1492 arrivals are sorted with their approach directions and for each direction, minimum approaching time is selected and subtracted from every approaching time in related approach direction. This final value represents the delay that is generated in TMA. The data record starts from 12:00 p.m. of 22 March and ends at 9:00 a.m. of 25 March. Accordingly, the generated delay histograms are not complete for 22 and 25 march but the data includes the whole weekend.

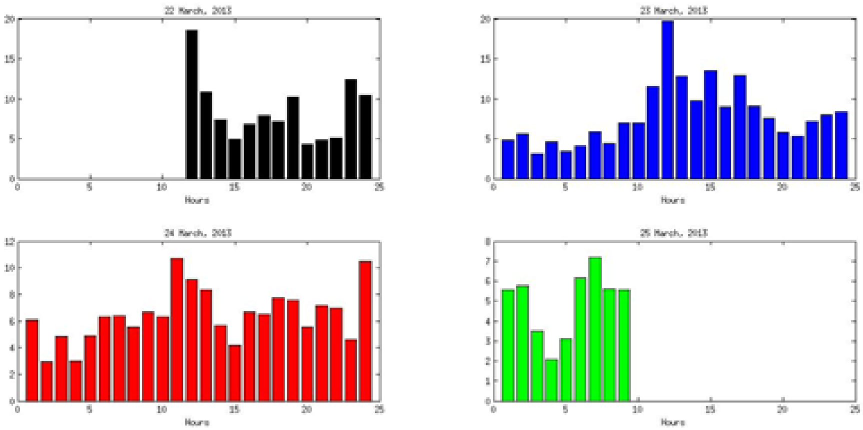


Figure 7.6: Average Delays per Arrival for each hour in the Data.

As a first approach average delays per arrival have been plotted for each hour and the results have been presented in figure 7.6. Based on the three day data the most congested hour in the LTBA is generally around 12:00 pm. For fridays and saturdays the average delay per arrival can reach up to 20 minutes. In other words, each flight that arrives around 12:00 pm has around 20 minutes arrival TMA delay. This value decreases in sundays to 10 minutes. However on sundays at 12:00 am another congestion occurs which shows itself with 10 minutes arrival TMA delays per flight on average. This congestion also occurs on friday nights. According to results saturday is the day when the most severe TMA delays occur. From the histograms, a threshold for average delays per arrival can be determined to detect the congested periods (hours) of a day. In this regard, individual arrival delays are grouped in intervals in order to analyse the distributions of delays and a new set of histograms is constructed for both whole days and congested periods of the day.

As a threshold, 7 minutes is selected which means any hour that has more than 7 minutes average delay per arrival is considered as congested. Furthermore to be able to compare the whole day and the congested periods, delay distribution histograms are normalized as it has been presented in figure 7.7. The results can be interpreted as delay density distributions which has a mean value with other values around it. The mean value is close to the peak of the distribution and as the TMA delays increases, the distribution shifts to right and vice versa. The results of delay density distributions show the exact same characteristics and the mean of distributions are different from each other where the congested periods have more average delay values than the entire days' data. As the threshold increases, the distribution again shifts to right. However

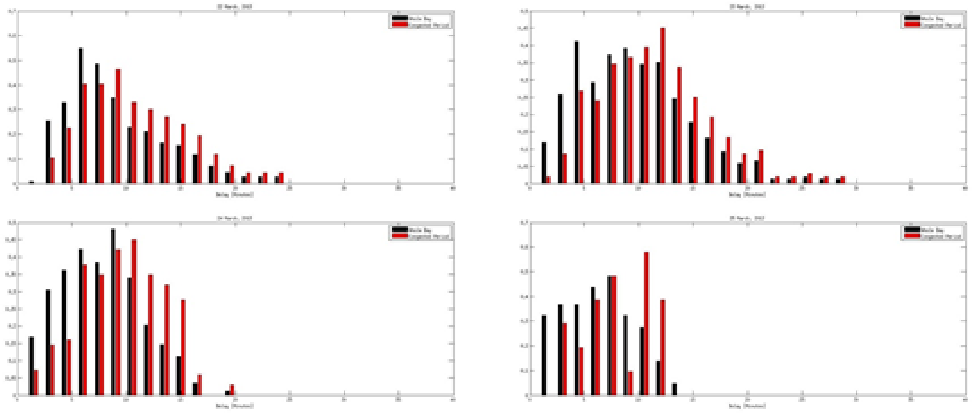


Figure 7.7: Delay density distributions for each day data.

increasing the threshold decreases the number data that represents the congested hours which results in alterations in density distribution.

The overall results of the TMA analysis emphasize the importance of these regions. Delays generated in TMA regions may exceed 20 minutes which may be the biggest delay generation in the whole flight for some flights. For that reason, analysis of these regions must be conducted separately for the sake of the whole analyses. Moreover these delays must be isolated from the delays generated in en-route airspaces, since they are highly dependent on the status of the arrival airport rather than the airspace itself.

8. CONCLUSIONS AND RECOMMENDATIONS

Macro level representation of air traffic and transportation phenomena over the European Air Traffic Network is of capital importance for pinpointing the elements and events that drive the system. Macro Analyses not only demonstrate the dynamics of air traffic network coupled with observation but also provide an insight for the system behavior under extreme conditions. The analyses pave the way for application of transportation optimization problems into real world conditions. Therefore they play a significant role in network planning & design and they occupy an important place to construct reliable and robust air traffic management and control infrastructures.

8.1 Data Understanding

Within the scope of the European Air Traffic Network's Macro analysis, ALL_FT+ and DDR data structures and their crucial features have been completely revealed after extensive research. ALL_FT+ data has been employed to extract the information of daily flight routes and their crossed airspace profiles whereas DDR capacity data has utilized to observe the capacity declarations for ATC unit airspaces and arrival/departure flow rates of airports. Since the ultimate goal of the analyses is to observe the dynamics of delay propagation, FTFM, CTFM and CPF-REF data profiles have been extracted from eight different data structures of ALL_FT+ data. Two different profiles of each flight model: point profile and airspace profile, have been processed and analyzed simultaneously. Besides extracting these three models, auxiliary parameters as departure, arrival airports and Off-Block Times also have been sorted out in the contemplation of clarifying all phases of each flight. The attempt of using Off-Block Times also provided an insight about airports' status and delays generated by ground procedures in macro analyses which is also a subsidiary information for micro analyses.

8.2 European Air Traffic Model

The first leg of the analyses was to constitute the network graph of the European Airspace which would allow us to realize the traffic flow pathways. In addition, development of the connectivity graph of airspace sectors in any level would give a framework to work on any desired level of detail. Continuous airspace profiles of each flight enabled the construction of connectivity with traffic flow graphs and directed flow graphs have been generated for every types of airspace entities directly from ALL_FT+ data. In order to observe the traffic interactions between nodes of the graph, the network model has been tested over France, where each node of the graph is selected as FIRs. Analysis has been conducted for a week to see daily patterns and their variations based on the flight plans for each day. Two directions of each pathway have been investigated separately and the relations of each FIR sector and the degree of their relation have been pointed out clearly. The model presented the full description of the general situation regarding the traffic flow over the selected area, and the findings that were obtained through the traffic flow graphs regarding the magnitude of sectors also have been confirmed via monitoring the number aircrafts per hour in each sector.

8.3 Delay Propagation Model Approach

After the investigation regarding the connectivity of airspaces and their reciprocal traffic flows, delay propagation analyses have been conducted. In light of the phases that each fight experiences, delay descriptions for each phase have been presented. According to the data detail and capabilities, the following delays have been calculated: a) Delay up to push-back phase, b) Delay at taxi to take-off, c) Delay at take-off to TMA exit, d) Delay at en-route, e) Delay at TMA entrance to touch-down. Delay calculation procedure involves planned and actual flight data which are determined from FTFM, CTFM and CPF-REF profiles. FTFM profile has been utilized as planned profile whereas CPF-REF employed as actual data. Because there is a significant amount of data loss in CPF-REF profile, CTFM profile is utilized in the absence of CPF-REF. Using planned and actual data as they are, causes preposterous results for delay calculations. Hence, fixing and filtering algorithms must be employed to preclude the wrong computations which may result in false deductions. The examples of these cases and their existence ratios have been presented with their performed solutions.

When the fixing and debugging process of crippled data is accomplished, individual delays of each flight have been calculated with subtracting the actual elapsed times of each flight's phases from the planned ones. This action seeks the differences between planned and actual profiles which are caused by unexpected events such as bad weather conditions or strikes. Cumulative evaluation of all flights' crossed en-route airspaces from each airspace perspective resulted with the delay distributions of airspaces over the European airspace network. This analysis brought out the congested areas of the European airspace, and visualization of hourly delay distributions of each airspace gave an insight about the propagation of delays. An example of this approach has been conducted over the London area. Results showed the traces of delay propagations between highly coupled airspaces with same delay generation characteristics. Nevertheless, it appeared that using only airspace delay generations/absorptions is not enough to observe the dependencies of airspaces to each other, because the ability to extract an information about the source of the delay has been sacrificed.

In order to have another perspective to increase the capability of the model, network of airports have been investigated instead of using airspace centered analyses. In this approach focus has been shifted to the propagation of delays between airport pairs. Therefore, examination of airport delays became more of an issue. Because of that reason, push-back delays and taxi delays have been calculated and statuses of airports are monitored in terms of arrival/departure traffics and declared capacities. Although capacity values seemed to have no relation with traffic values, some pattern alterations have been observed in a single week's data. This analysis also showed the push-back delays and their evolutions through each flight's path which provided a complete track of delays.

8.4 Terminal Maneuvering Area Analysis

Numerous analyses revealed that most of the delay generations occur in the TMA regions of the airports (especially the arrival TMAs). For the purpose of obtaining more comprehensive information about the arrival TMA region, an analysis regarding LTBA-Istanbul Ataturk Airport is conducted for four days with a supplementary data. Arrival TMA delays have been calculated as the subtraction of minimum elapsed time at TMA from every other flights' elapsed times. Results showed a strong relation between congested traffic and delays. In the congested hours of the airport, the mean of delay distribution shifts to right and gets bigger values than usual. This analysis is also important to insulate the TMA delays from the en-route airspace delays because TMA delays are the result of congested airports rather than airspace itself.

8.5 Final Inferences

Holistically, as the most of the delays in the air generated by arrival TMA regions, airport analyses elucidated that most of the delays at airports happened at push-back phase which is known as the ground holding procedure. Push-back delays have many potential reasons such as bad weather conditions, strikes or predicted congestion at destination airports, whereas the variations in taxi delays or declared nominal taxi times are more likely related with airport procedures as runway configurations. Hence, to get deeper understanding about the events that took place in the airport and to be able to make more certain inferences about the reasons of push-back or taxi delays, further analyses with different type of data are mandatory. Additionally, numerous multi-day airport analyses revealed that there are daily, periodic departure capacity overflows in certain airports, which have no noticeable effect on departure delays. The reason of these circumstances may lay in the process of capacity declarations where the capacities are declared less than the actual capacity of the airports. These situations are highly dependent to airport procedures and, therefore monitoring the status of airports in terms of the events took place or alterations in the declared capacity requires more information (data) i.e. more perspective to carry out full scale evaluations.

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CURRICULUM VITAE

Name Surname: Utku EREN

Place and Date of Birth: Bursa, Mayıs 1989

Adress: Controls and Avionics Laboratory
Istanbul Technical University, Faculty of Aeronautics and Astronautics,
Room: 312B, Maslak Istanbul, TURKEY

E-Mail: utkueren89@gmail.com

B.Sc.: Istanbul Technical University, Faculty of Aeronautics and Astronautics
Astronautical Engineering, 2011

B.Sc.: Istanbul Technical University, Faculty of Electrical and Electronics Engineering
Electronics Engineering, 2012

M.Sc.: Istanbul Technical University,
Graduate School of Science Engineering and Technology,
Defense Technologies Programme, 2013

Professional Experience and Rewards:

TUBITAK Research Fellowship	*2011 – present*
Faculty of Aeronautics and Astronautics Best Student Award	*Summer 2011*
Astronautical Engineering Best Student Award	*Summer 2011*
Turkish Education Foundation(TEV) Fellowship	
• *Best Student in Faculty Award*	*Summer 2011*
• *Best Student in Program Award* for each year	*2007 – 2011*

List of Publications and Patents:

▪ Baskaya E., **Eren U.** and Inalhan G., "Design and Development of a Reliable ADCS and Indigenous Bus Architecture for Nanosatellites : ITUpSAT II", 63rd *International Astronautical Congress*, Naples, ITALY, October 1-5, 2012

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