DEPARTMENT OF AVIATION TECHNOLOGY

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ARRIVAL MANAGER (AMAN) AND ITS IMPLEMENTATION STUDY IN VILNIUS INTERNATIONAL AIRPORT

Bachelor‘s degree final work

Air Traffic Controller study programme, state code 601H41002

Aerospace Engineering

Vilnius, 2015

DEPARTMENT OF AVIATION TECHNOLOGY

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<u>Overview</u>

The aim of this thesis is to study in detail the working principle of AMAN, its components involved, develop a trajectory prediction simulator using BADA 3.6 and compare the initial flight plan predicted time with that of TP simulator. Due to the increasing traffic demands in major European airports, those airports are implementing it to assist the controllers and decrease their workload. AMAN is used to balance the flow of inbound aircraft and capacity of airport by proving sequence of aircrafts approaching the runway and it also helps controllers in the sequencing and merging process which reduces the workload of the controllers. In this thesis special attention is given to Baltic FAB and in particular study of AMAN and its implementation is done for Vilnius International Airport.

The objective of thesis is to develop a trajectory prediction simulator because all AMAN's are based on prediction of aircrafts arrival time and is also the most important part of the AMAN. In order to develop this simulator software like MATLAB and NEST are used. However all the aircraft performance data for descent phase of aircrafts are obtained using the BADA 3.6.

The arrival time calculated by the trajectory prediction simulator is quite similar to that of initial flight plan arrival time. Better result in the prediction of arrival time is obtained using the trajectory prediction simulator. Nevertheless, we need to take into account that some assumptions were made in the development of the simulator and the results obtained are not hundred percent realistic.

On the other hand, it is seen that the traffic growth is getting higher and higher every year in Vilnius International Airport. But, it is operating far below the potential physical capacity of the airport and provided with higher number of flights to and from this airport, it can handle the traffic without any major problems. In long run if the air traffic goes on increasing in the same rate then there will be the need of AMAN implementation in Vilnius Airport to assist controllers and maintain the security level marked by the SESARJU.

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List of Abbreviations

AMAN	Arrival Manager
ATC	Air Traffic Control
ATCO	Air Traffic Controller
ATM	Air Traffic Management
ATSUs	Air Traffic Services Unit
BADA	Base of Aircraft Data
CAS	Calibrated Air Speed
CFMU	Central Flow Management Unit
CRCO	Central Route Charges Office
CST	Calculated Start-up Time
CTA	Controlled Time of Arrival
FAB	Functional Airspace Block
FDPS	Flight Data Processing System
FIR	Flight Information Region
FL	Flight Level
IFR	Instrumental Flight Rules
MTOT	Managed Take-Off Time
NEST	Network Strategic Tool
ODE	Ordinary Differential Equations
ODZ	Origin/ Destination Zone
OLDI	Online Data Interchange
RDPS	Radar Data Processing System
RWY	Runway
SESAR	Single European Sky Air Traffic Management Research
SES	Single European Sky
STAR	Standard Terminal Arrival Route
STATFOR	Statistical Forecasting service
TAS	True Air Speed
TMA	Terminal Maneuvering Area
TRACON	Terminal Radar Approach Control
VFR	Visual Flight Rules

Glossary of symbols

A list of symbols used in the equations throughout this document is given along with a description. However, in some places the engineering units typically associated with the symbol are also given.

Symbol	**Description**	**Units**
a	Speed of Sound	[m/s]
d	distance	[Nautical Miles]
D	Drag force	[Newton]
f	fuel flow	[Kg/min]
g	gravitational acceleration	[m/s^2]
$\frac{dh}{dt}$	rate of climb or descent	[m/s] or [ft/min]
h	altitude above sea level	[m] or [ft]
κ	isentropic expansion coefficient	
L	Lift force	[Newton]
m	Aircraft mass	[ton] or [Kg]
M	Mach	
P	Actual Pressure	[Pa]
P_0	Pressure at Sea level	[Pa]
Q	Lateral Force	[Newton]
R	Real gas constant for air	$[m^2/Ks^2]$
S	Reference wing surface area	$[m^2]$
T	Thrust	[N] and [Kelvin]
V	Speed	[m/s] or [knots]
ΔT	Temperature difference	[Kelvin]
W	Weight	[N]
Θ	Temperature	[Kelvin]
η	Thrust specific fuel flow	[kg/min/kN]
ρ	Air density	[kg/m^3]

Introduction

Air traffic management is getting complex everyday with the increasing number of air traffic in the European Airspace and all around the world. According to [2], by 2030 the air traffic will double in Europe and there is the need of new technologies and new methods to manage and accommodate this increasing traffic.

As traffic grows steadily, airport congestion and environmental impacts become a mounting problem and already a limiting factor at some airports. Many of the international hubs and major airports are operating at their maximum throughput for longer and longer periods of the day. Some have already reached their operating limits as prescribed by physical as well as political and environmental constraints. This situation is expected to become more wide spread and future traffic distribution patterns are likely to generate congestion at airports that currently do not experience capacity problems. [4]

European Airports are being the bottle-neck for the increasing number of delays. The runway operations are limited due to certain safety restrictions like: wake turbulence separation minima, adverse climate condition, runway incursion etc. In order to overcome these problems, different new ATM automation are being developed to assist the controllers and to reduce the controllers workload. Among those automation tools, AMAN is one of the metering tools that are being used in some of the busiest airports in the European Airspace and its use is growing continuously.

The aim of this thesis is to study in detail the working principle of AMAN, its components involved, develop a trajectory prediction simulator using BADA 3.6 and compare the initial flight plan predicted time with that of TP simulator. One of the other objectives is to study in particular the traffic situation in Vilnius airport and see the possibility of AMAN implementation in Vilnius International airport in near future.

The thesis is structured in 6 chapters, the first chapter deals with general introduction and background of SESAR, actual traffic situation and traffic forecast for Baltic FAB. The second and third chapter deal with explaining in details about working principle of current AMAN and extended AMAN respectively. In chapter four, it is explained about the construction and working principle of the trajectory prediction simulator and the analysis of the results obtained. Finally, the fifth chapter deals with the particular study of air traffic in Vilnius Airport, Runway capacity assessment of the airport and see the possibility of AMAN implementation in this airport.

Chapter 1 : Single European Sky ATM Research (SESAR)

The Single European Sky (SES) initiative aims to achieve "more sustainable and performing aviation" in Europe. SESAR, the Single European Sky ATM Research program, aims to develop the new generation air traffic management system capable of ensuring the safety and efficiency of air transport throughout the ECAC area in the timeframe to 2030.

SESAR addresses the full range of ATM stakeholders, including civil and military ANS providers, civil and military airport operators as well as civil and military airspace users. SES objectives cannot be achieved without the contribution of the validated SESAR technological solutions. The SESAR program is the technological pillar of the Single European Sky initiative. [26]

1 . 1 SESAR Joint Undertaking

European ATM is an extremely complicated process. Europe does not have a single ATM framework whereby air navigation is managed at a European level. Europe also has some of the busiest skies in the world with as many as 33,000 flights a day. The SES is an ambitious initiative launched by the European Commission in 2004 to reform the architecture of European ATM. It proposes a legislative approach to meet future capacity and safety needs at a European rather than local level. [27]

The key objectives of the SES are:

- To restructure European airspace as a function of air traffic flows
- To create additional Capacity
- To increase the overall efficiency of the air traffic management system.

In order to fulfill these objectives, the European Commission set high-level goals for the SES in 2012 to be met by 2020 and beyond:

- Enable a 3-fold increase in capacity which will also reduce delays both on the ground and in the air
- Improve safety by a factor of 10
- Enable a 10 % reduction in the effects flights have on the environment
- Provide ATM services to the airspace users at a cost of at least 50% less

Figure 1. 1. SESAR Performance Targets

1 .1. 1 Current Air Traffic Analysis

The number of people using the air transportation is on continues rise each day throughout the world because of its security, safety, time effective and comfort. Due to these reason the air traffic demand is growing in the alarming rate. European airspace, being one of the busiest skies in the world; is also in continues growth in the number of flights and passengers. Apart from the increasing number of passengers, the numbers of flights flying to and from European Airspace is also on rapid growth. The numbers of flights are increasing every month and the traffic complexity is getting higher and higher in European sky.

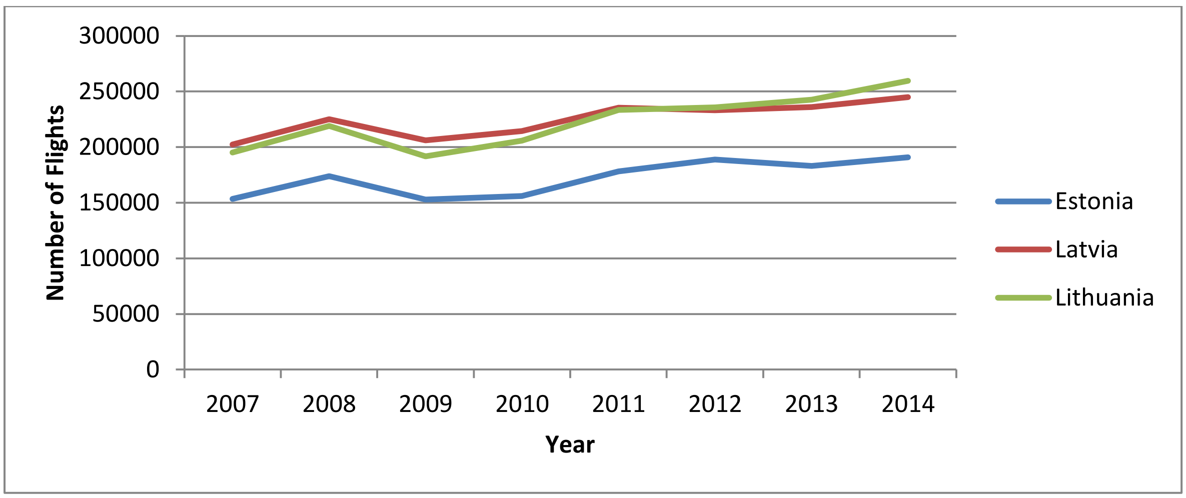


Figure 1. 2. Number of flights in Baltic Airspace [34]

Figure (1.2) illustrates us that the number of aircrafts flying in Baltic airspace is on continues growth. It can be clearly seen the effect of economic crisis between 2008 and 2009. However, from 2009 the number of flights is on rise and it is forecasted that the traffic growth will last longer with the same growth rate. It can be observed that the number of flights flying over Lithuanian airspace is increasing at higher rate than in Latvian and Estonian airspace. This growth in the number of flights in Baltic Airspace will imply the significant contribution on the increment in the number of flights in European sky.

In this section a brief study is done on the number of passengers in the major airports of the European airspace. Apart from that a particular study on the number of passengers in Vilnius, Kaunas, Riga and Tallinn airport is done.

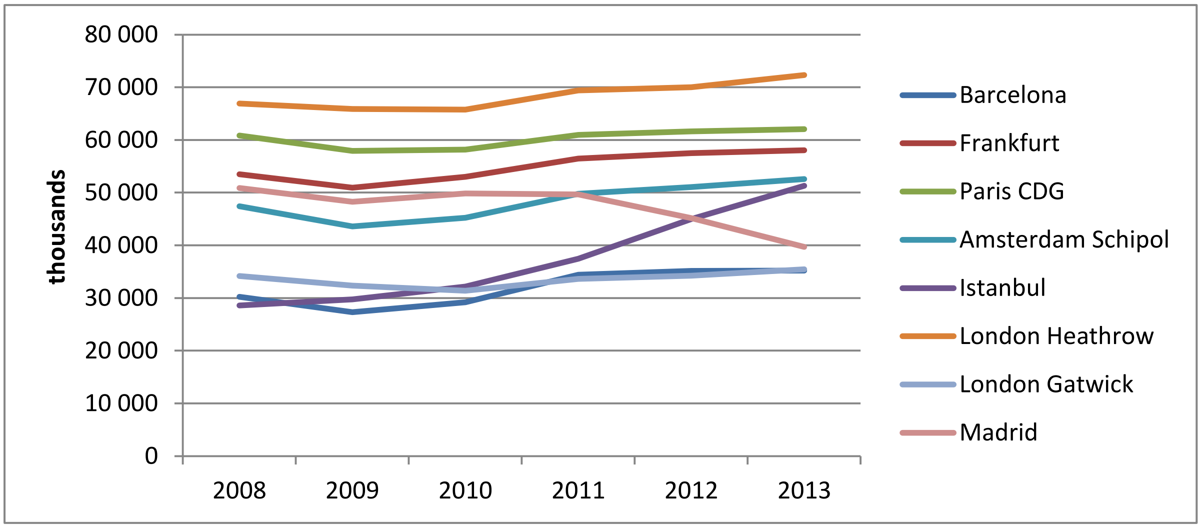


Figure 1. 3. Number of Passengers in Major European Airports [30]

We can see in figure (1.3) that the number is growing higher and higher every year. All these airports are getting higher number of passengers each year except Madrid-Barajas airport. However, the traffic growth in Turkish Airspace is growing in alarming rate. Each year the number of passengers flying from Istanbul airport is growing in millions and special consideration must be given to this airspace in order to maintain the safety and security requirements.

Table 1.1. Number of Passenger in Baltic Airports [30]

Airport/Year	2008	2009	2010	2011	2012	2013
Vilnius	2046088	1308632	1373859	1712467	2208098	2666865
Kaunas	410000	456698	809752	872618	829827	695509
Riga	3691000	4066854	4663472	5106926	4767764	4794019
Tallinn	1812000	1346236	1384831	1913172	2206290	1958801

As in other European airports the numbers of passenger in Baltic airports is also on growth. However, there is some dramatic decrease in the numbers between 2012 and 2013 in Tallinn airport.

1 .1. 2 Traffic Forecast in European Airspace

In this section we will analyze the traffic situation in European Airspace from 2007- 2014 and then the traffic forecast till 2020 is presented.

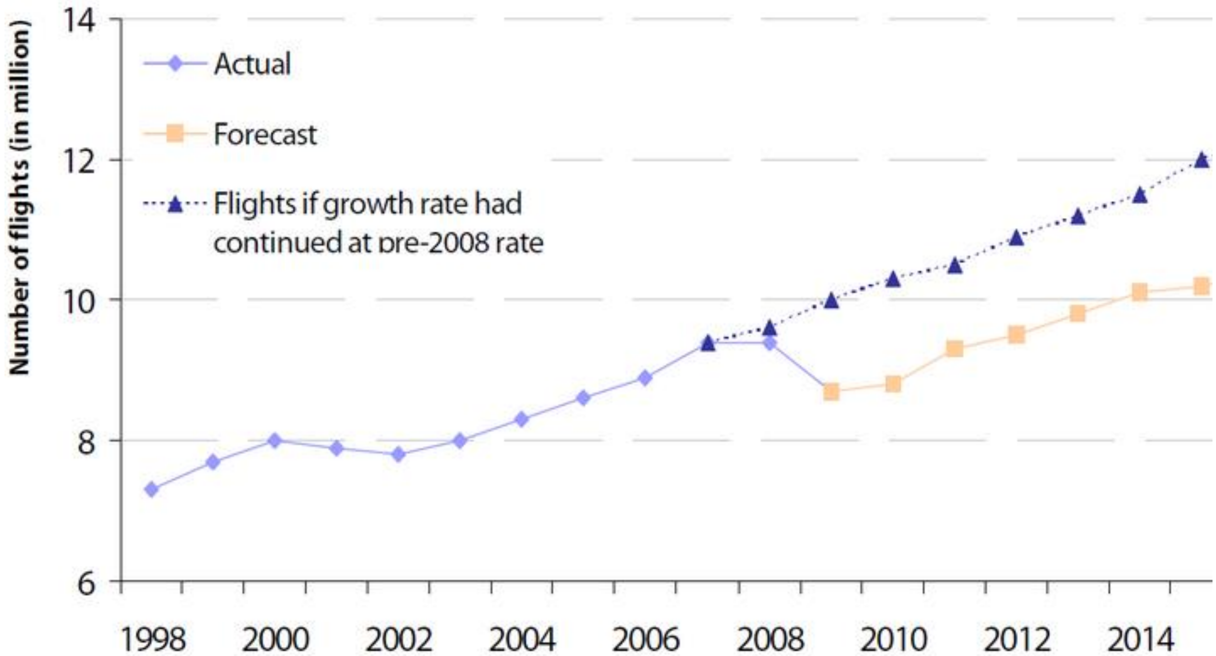


Figure 1. 4. Trend in the number of flights in European airspace [28]

The number of flights in the European Airspace has been in continues rise from 1998 till now. However there was a slight decline in the number of flights from the year 2008 due to the economic crisis. As we can see in the above figure, the air traffic is going to increase drastically in near future.

Even if the traffic growth rates in the medium term are expected to remain below the pre-2009 long term trends [29], there is still some potential for further growth of air traffic in Europe. However the demand will not be homogeneous and the traffic growth will not be uniform. Each market segment will be different, long-haul different from short-haul, and each part of Europe different from the other.

Looking 20 or more years ahead, it is more robust to consider not just a single forecast, but a range of potential scenarios for how air transport in Europe, and the factors influencing it, might develop. In [30] four different scenarios have been used to explore the future of the aviation and the risks that lie ahead [29]

- ***Scenario A: Global Growth (Technological Growth)***
  Strong economic growth in an increasingly globalized world, with technology used successfully to mitigate the effects of sustainability challenges such as the environment or resources availability
- ***Scenario C: Regulated Growth***
  Regulated growth deals with moderate economic growth with regulation reconciling the environmental, social and economic demands to address the growing global sustainability. This scenario has been constructed as the 'most likely' of the four, most closely following the current trends.
- ***Scenario C': Happy Localism***
  This scenario is introduced to investigate an alternative path for the future. With European economies being more and more fragile, increasing pressure on costs, stricter environmental constraints, air travel in Europe would adapt to new global environment but taking an inwards perspective.
- ***Scenario D: Fragmenting World***
  A world of increasing tensions between regions with more security threats, higher fuel prices, reduced trade, transport integration and knock-on are the effects of weaker economies.

In the 'most-likely' scenario of the forecast, there will be 14.4 million IFR movements in Europe in 2035, 1.5 times more than in 2012. The growth will average at 1.8 % annually but it will be faster in the early years, stronger in Eastern Europe and faster for traffic to and from Europe than from intra-European flights. Turkey will be the largest generator of extra flights in Europe, and will also see the biggest number of additional departing flights in its airspace. Two of the other scenarios forecast substantially different traffic volumes: 17.3 and 11.2 million flights, respectively.

Table 1. 2. Forecast of IFR traffic in Europe using different scenarios [29]

	IFR Mvts (Millions) 2035	**Traffic Multiple 2035/2012**	**Average Annual Growth 2035/2012**	**Extra Flights/day (thousands)**
A:Global Growth	17.3	1.8	2.6%	21
C:Regulated Growth	14.4	1.5	1.8%	13
C':Happy Localism	13.8	1.4	1.6%	12
D:Fragmenting world	11.2	1.2	0.7%	5

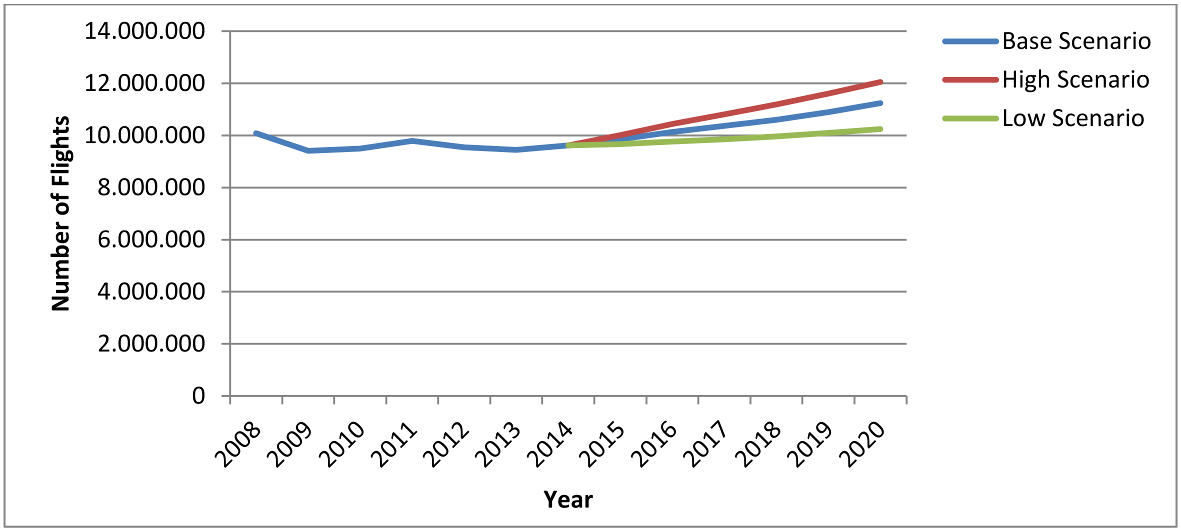


Figure 1. 5. Forecast for the number of flights over ESR08[1] Airspace [34]

EUROCONTROL'S impressive medium term forecast of flight numbers in Europe, covering 44 markets for the period 2012 to 2020, sees an average growth rate of 2.3 % per annum under its base case. It contains a number of key points concerning recent trends and the outlook for European airlines. EUROCONTROL sees the weak traffic environment of 2012 continuing in 2013, with another year of falling flight numbers and winter season especially weak. However, it forecasts a recovery in 2014 and that Turkey will lead the superior growth of Eastern countries both in 2013 and through to 2019. Airport capacity constraints and competition from high speed rail are forecast to cut 1.6 % from the total of flights in 2019 [15] [34].

1 .1. 3 Traffic Forecast in Baltic FAB

In this section we will study the forecast of growth of number of flights in the Lithuanian, Latvian and Estonian airspace. It can be observed from the figures (1.6, 1.7, and 1.8) that the rate of growth of number of flights in Baltic FAB is much higher than that in European FAB. This implies that the traffic complexity will rise over time in Baltic airspace. According to [35] Baltic FAB is expected to have the highest annual growth rate (3.5 %) over the next seven years.

From the figures (1.6, 1.7 and 1.8) we can notice that the rate of growth of number of flights over Lithuanian airspace is higher than other two countries. Lithuania is expected to have a growth rate of about 5.75% for next six years and Latvia and Estonia are expected to have growth of 1.3% and 5.6% respectively [35].

[1] ESR08 (Eurocontrol Statistical Reference Area), Represents the whole of Europe

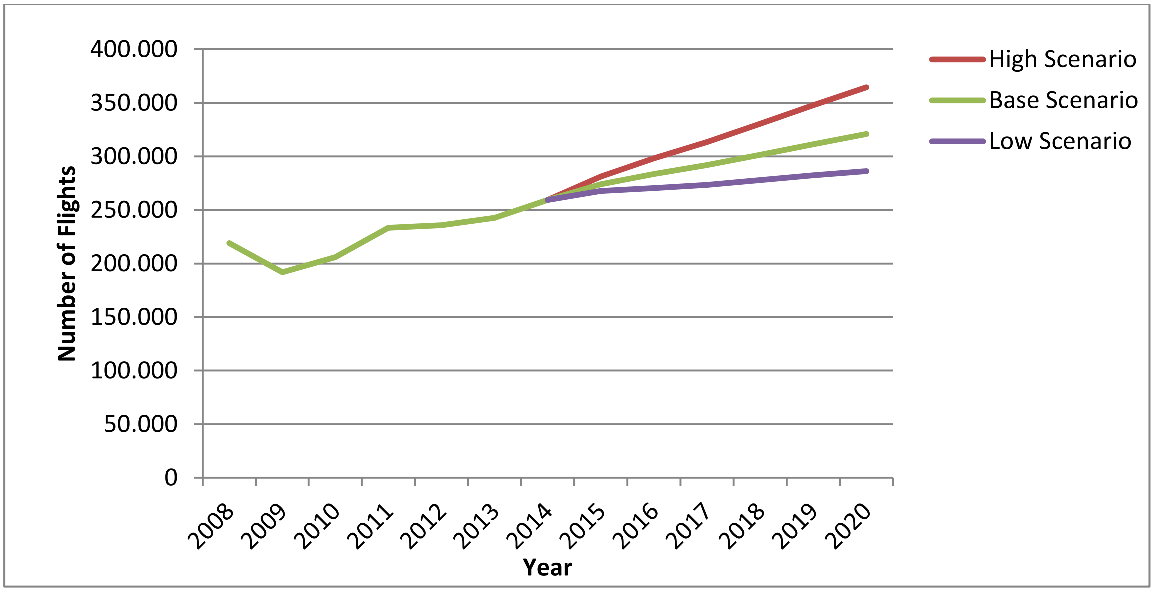


Figure 1. 6. Current flights and forecast for Lithuanian Airspace

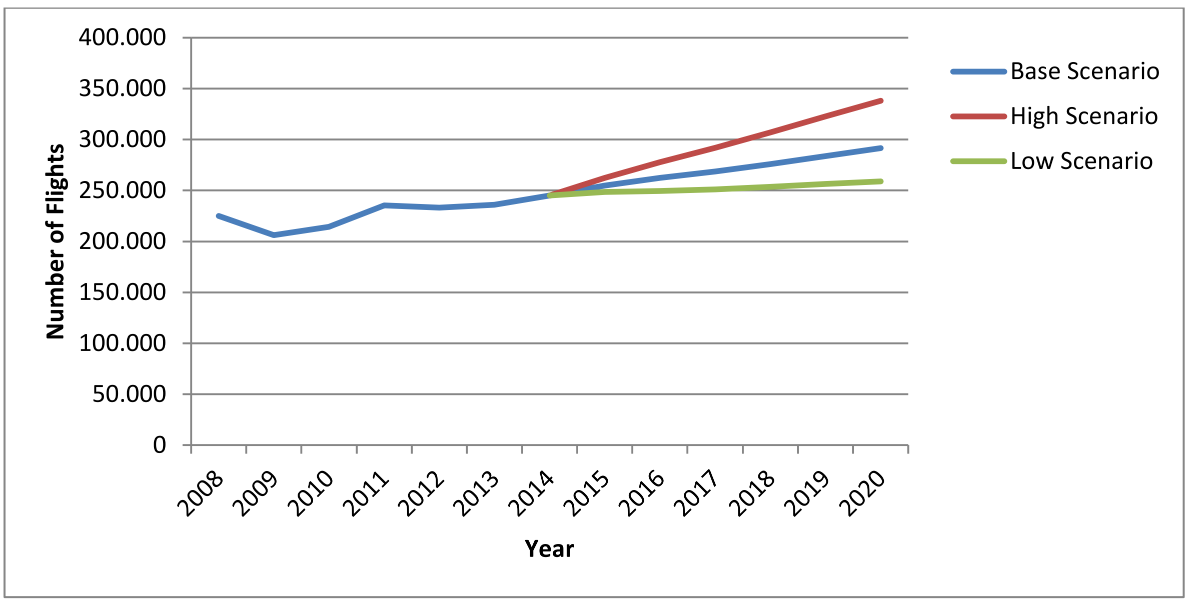


Figure 1. 7. Current flights and forecast for Latvian Airspace

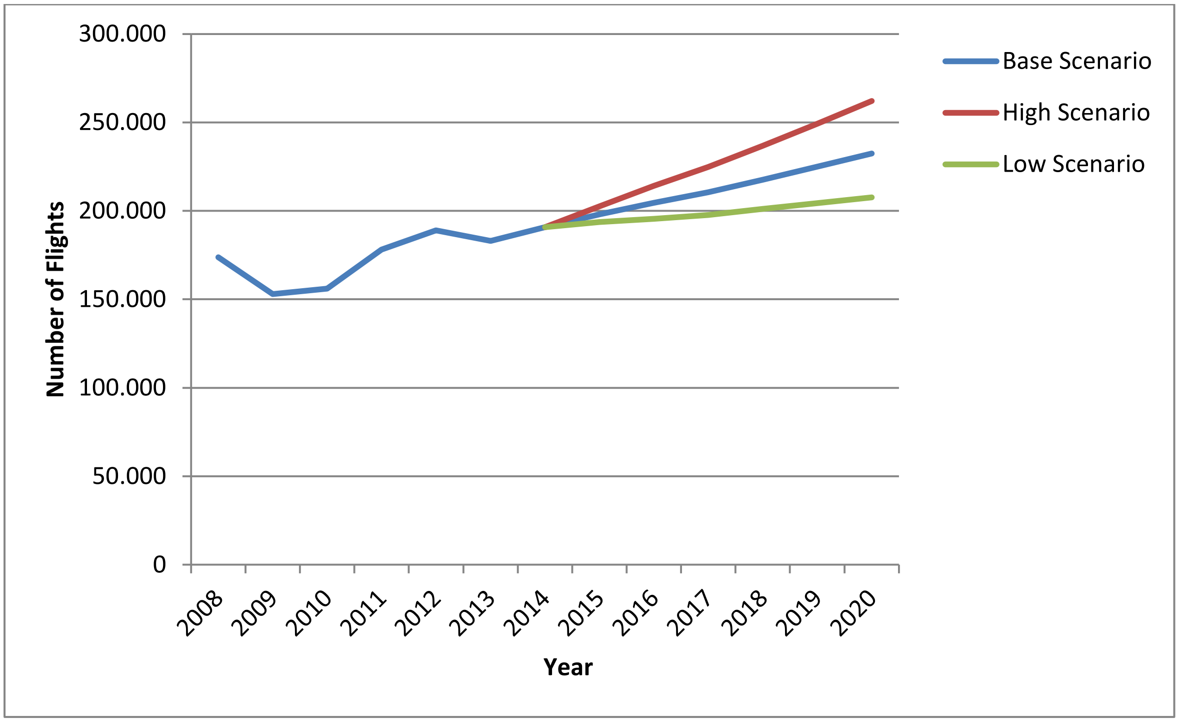


Figure 1. 8. Current flights and forecast for Estonian Airspace

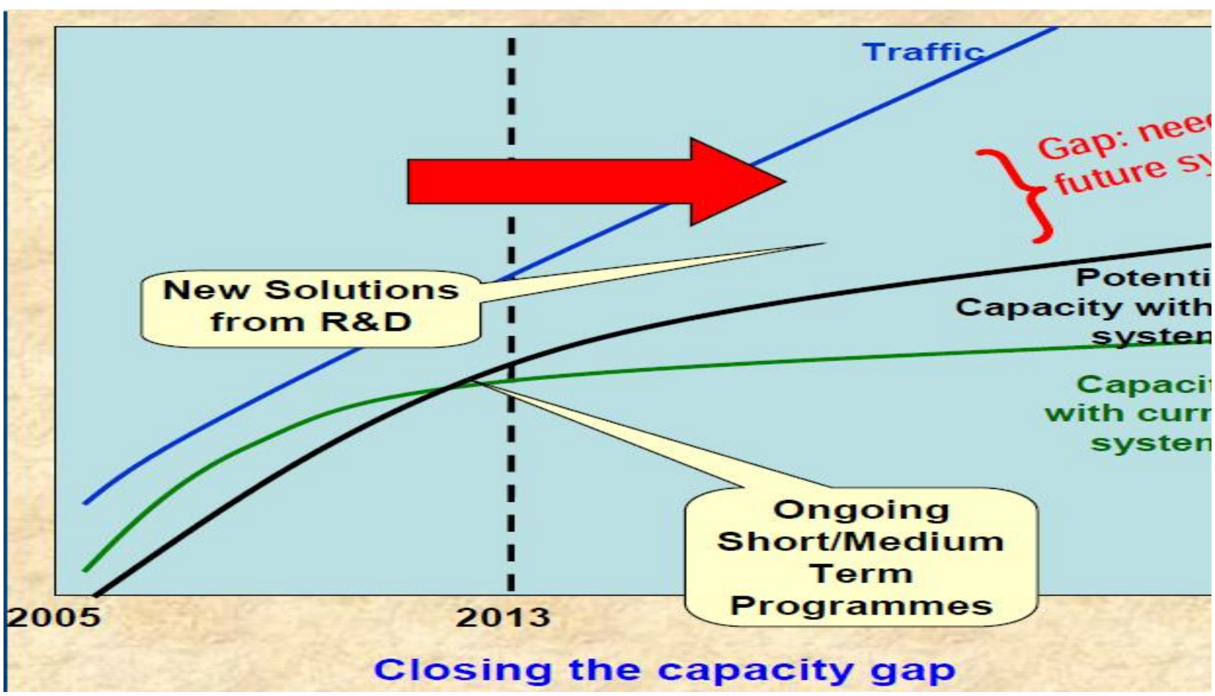


Figure 1. 9. Current and future air traffic in Europe [32]

From the figure (1.9), it is quite obvious that the potential capacity of the current system is far lower than the demand that is going to be in the near future. Traffic growth cannot be sustained through the current fragmented air navigation services organization and ageing ATM technologies. Therefore, a new Air Traffic Management System is required, for the benefit of the European society.

Chapter 2 : AMAN (Arrival Manager)

In aviation terms, “Arrival Management” is a general term given to the process of safely and effectively arranging arrivals into a smooth efficient flow for landing at a destination airport [1]. To balance the flow of inbound aircraft and the capacity at airports, more and more Air Navigation Service Provider (ANSP) use arrival manager systems. These provide decision support to sequence managers in planning inbound flights to optimize capacity, flight efficiency and predictability. All AMAN are based on predictions of an aircraft’s arrival time [3]

Arrival management is the area of ATM that deals with air traffic in the last phase of an arrival flight. It is concerned with the planning and controlling of aircraft that are landing at an airport. At most airports, the ATM system determines a landing sequence that is used by air traffic controllers to efficiently guide aircraft to the runway. It is one area where the different needs of individual flights (e.g., time schedules, preferred flight profiles for landing) become apparent and can lead to problems (e.g. delay). The SESAR Target Concept [21], that describes the future European ATM system, says the following on high density Terminal Maneuvering Area (TMA) operation: “In high density traffic terminal areas (depending on the airport and/or the time), an efficient airspace organization combined with advanced airborne and ground systems capabilities will be deployed to deliver the necessary capacity, maintain safe separation and minimize the environmental impact. The concept recognizes that when traffic density is high the required capacity may only be achieved at the cost of some constraint on individual optimum trajectories.” This definition allows for both ground and air-based systems to be developed to support the arrival management task [20].

AMAN helps to provide sequencing and metering capability for arrivals to a runway, airport or constant point by,

- Creating and managing a sequence using predefined criteria
- Providing spacing between flights to equal the capacity at the constant point
- Provide data to HMI to allow controllers to implement the plan

2 . 1 General Concept of AMAN

2 .1. 1 Aims and objectives of AMAN

The general objective of an Arrival Manager is to provide electronic assistance in the management of the flow of arriving traffic in a particular airspace, to particular points, such as runway thresholds or metering points. When aircraft are predicted to arrive too close after each other, AMAN provides support to the sequence manager at the destination airport in deciding how to influence the 4D trajectories of the aircraft involved based on the predicted Estimated Times of Arrival of those aircraft [3].

However, the main objectives of AMAN are to assist the controller to optimize the runway capacity (sequence) and/or to regulate/manage (metar) the flow of aircraft entering the airspace, such as a TMA. It also aims to provide predictability for its users (both ground and air) and at the same time minimize the impact on the environment, by reduced holding and low-level vectoring [1].

In order to fulfill the marked objectives, the AMAN system provides a sequence at the runway, and also provides an expected or scheduled time for each flight at the runway or at/over different waypoints. As AMAN provides the sequence of aircrafts approaching the runway, it reduces significantly the workload of the Controller. AMAN is quite different from the orbital holding because it is based towards the linear delay absorption and aims to eliminate low-level orbital holding, or at least reduce holding on arrival to a minimum. Safety, Capacity, Efficiency and the Environment are all the improvement target area of the ATM system [6], but these can often be seen to be acting in opposite directions. For instance, capacity at an airport may need to increased, but it may also need to be achieved in a tightly controlled, environmentally-friendly way. AMAN tools strive to assist in combining and balancing those factors and they generally succeed, remaining well-accepted by controllers as useful support tools.

Figure 2. 1. Competing ATM improvement target

2 .1. 2 Working principle of AMAN

This part briefly talks about the general AMAN operations, methods and principles. Although several AMANs are now also used with “coordination” functionality, the upcoming section briefly describes just the sequencing/metering elements.

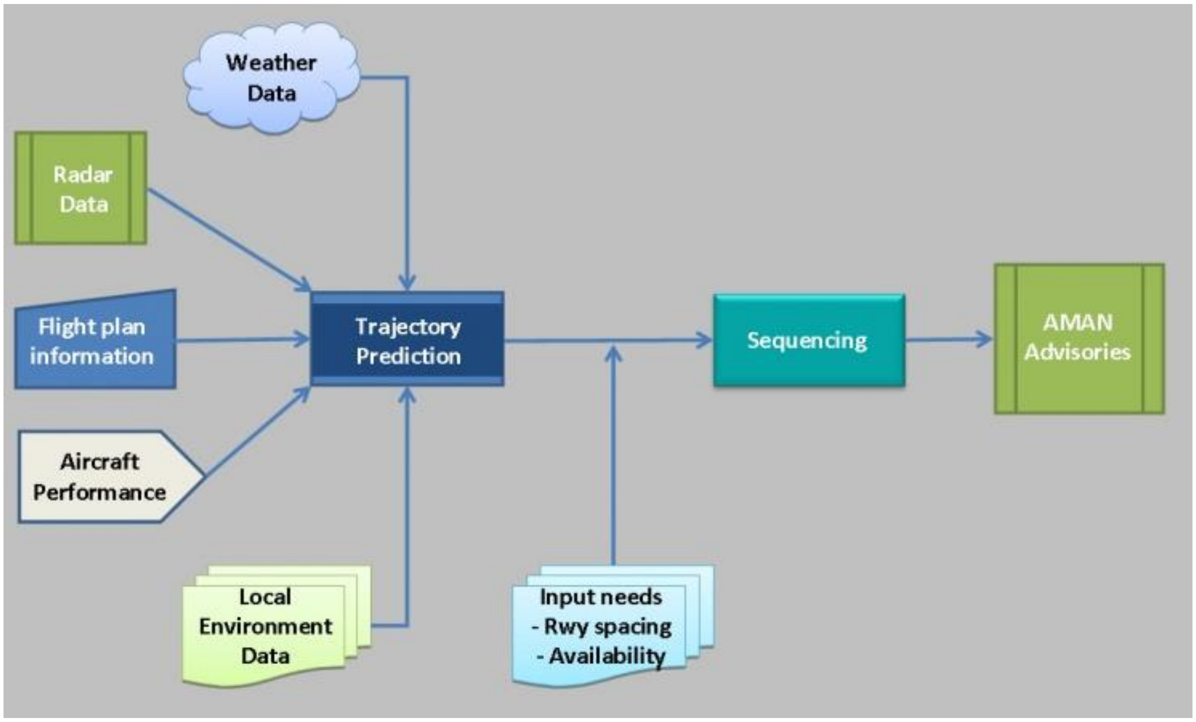


Figure 2. 2. AMAN Functionality

For the AMAN to work properly it needs some inputs data. The input data are then processed in order to predict the aircraft trajectory. Trajectory Prediction is one of the really important pieces for the AMAN to work properly. The AMAN system interacts with several systems, including the host Flight Data Processing System (FDPS) and Radar Data Processing System (RDPS). It uses a combination of flight-plan information, radar information, weather information, local airspace and route information, and an aircraft performance model in its trajectory prediction, resulting in a ‘planed’ time for any individual flight [7]. Apart from the above mentioned input data, manual input of some data can also be made. Manual inputs to the AMAN include insertion of the landing rate or separation on final and/or the cadence of landing for a runway, or “slots” to block a runway for a specified length of time [1].

It is really important that all the input data are as precise as possible because with a small error in the input data the predicted trajectory will be far away from the real trajectory that an aircraft will fly and these incorrect predicted trajectories will lead to some confusion for the controllers and consequently increase the controller's workload.

In the following section a brief description is done on each elements of AMAN:

2 .1. 2. 1 Aircraft Performance model module

Air Traffic Management (ATM) systems, including the AMAN; involve planning of traffic flows that rely on accurate estimation of aircraft performance. The aircraft performance module is a database of information on how different aircraft perform, using either a kinetic or kinematic approach. An aircraft performance model is the core of trajectory predication and therefore plays a central role in the development and evaluation of the future ATM systems [24]. The available data bases can vary, from an extensive range of aircraft types to just a few aircraft models. Some modules use a "comparative" method, where aircraft performance for specific types is "translated" to the performance data of another, similar type of aircraft. In this thesis, Aircraft Performance model is based on BADA 3.6.

2 .1. 2. 2 Trajectory Prediction module

The Trajectory Prediction Module predicts the future progress of individual aircraft on the basis of the current aircraft condition and position, estimates of intent, expected environmental conditions and procedures, and computed models of aircraft performance [1]. Trajectory prediction is the core component of automated systems in Air Traffic Control. Many functionalities of the Decision Support Tool directly rely on an accurate TP: controller posting, workload estimation, arrival sequence, loss of separation detection, and conflict resolution, to name the most prominent ones [25]. The AMAN may possibly use the Trajectory Predictor Engine from the FDPS or the AMAN system may use its own TP process.

2 .1. 2. 3 Weather data model Module:

Correct wind information is an important element of trajectory prediction, both for the aircraft systems (FMS) and for the ground systems calculating the future trajectory of the flight. Wind information can be common for all the airspace in function of altitude layer or possibly linked to a zone/bloc of airspace in function of the altitude. The data can also be loaded at specific periodic intervals (such as 4 or 5 times a day) or more dynamically, in function of currently observed or reported wind information.

2 .1. 2. 4 Flight plan data source and radar data source:

These data are the source of computation process. If this data is not complete or correct, accurate prediction is impossible. If flight data is supplied late (asymmetric airspace with a "short-side") stable planning for the AMAN may be impacted. Radar data may also be used to track the aircraft according to their "plan" in the AMAN.

2 .1. 2. 5 Sequencer module:

The sequencer module if an AMAN uses locally-prescribed sequencing criteria, and can be designed to build a sequence based on relative times (one aircraft being sequence a set time behind the previous) or can mix relative times with fixed times (where a specific times is fixed for a flight in the sequence)

2 .1. 3 Data processing phase in the AMAN system

The radar units collect the aircraft positions; the transponders transmit the corresponding altitudes. The update rate is approx. every five seconds. Track information, horizontal and vertical speeds are derived and serve as primary input source for the arrival manager to derive a picture of the current traffic situation. Horizontal 2D profiles are predicted for each arriving aircraft by a module called waypoint finder. I.e. which route the aircraft may take from its present position to the runway threshold [8].

The AMAN uses this to predict the earliest time of arrival for each aircraft in order to optimize the arrival sequence. Using the separation minima the AMAN assigns a runway and a target time of arrival (TTA) to each aircraft being displayed to the controller by a time scale. It is the controller’s task to implement this sequence (or another one) with the assigned target times by adequate advisories via voice control.

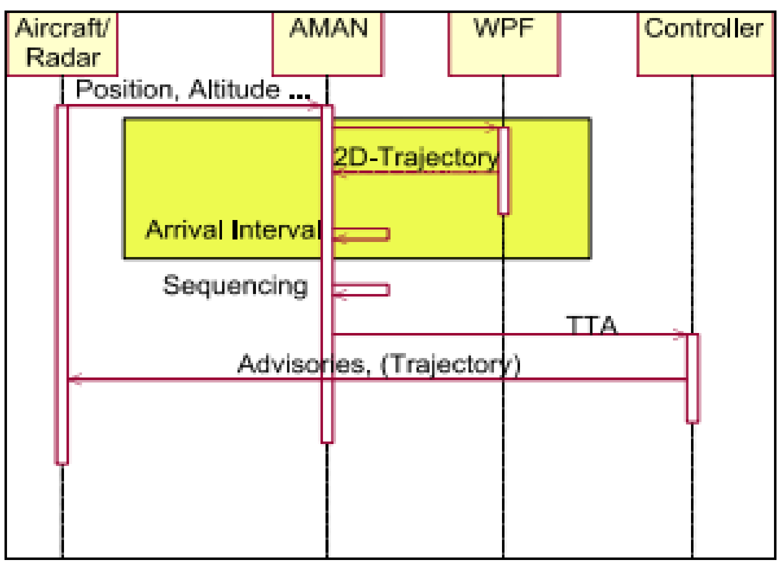


Figure 2. 3. Present Air Ground Communication [8]

In general, AMAN has some defined horizons, during which flights are recognized/ captured, planned, sequenced, re-sequenced if necessary and then ultimately frozen in the arrival process [1]. A position in the sequence is frozen only when the flight enters the stable horizon. The point or distance from the touchdown for these horizons is the matter of local implementation. Some system operate dynamically (with constant updates) until quite late in the flight. The basic process of the current AMAN process is summarized below: [1]

1. Around 100-120 nm from touchdown [22], the aircraft is captured. This distance is often called the AMAN horizon
2. On the ground, the AMAN system computes the aircraft's preferred Arrival Time
3. The flight is the sequence in the flow of traffic, in function of its computed preferred Arrival Time and sequencing criteria
4. The AMAN system displays notification and advisories to the ATCO, who uses them to sequence the aircraft (via Radio telecommunication)
5. The aircraft follows the instructions given by the ATCO

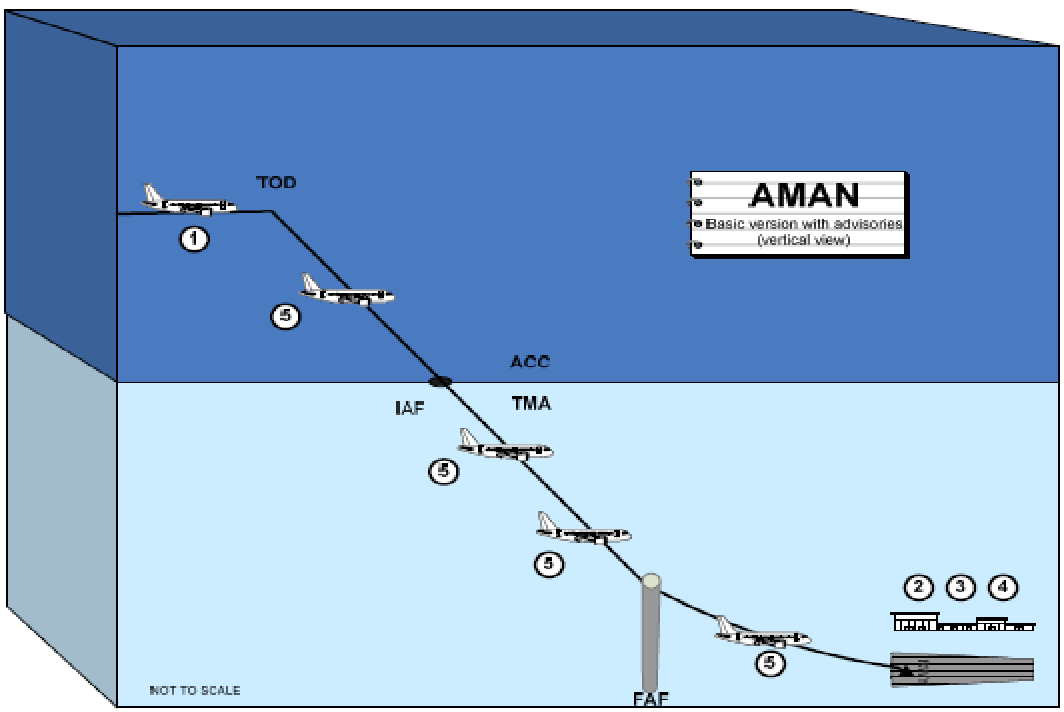


Figure 2. 4. Current AMAN (Vertical View) [1]

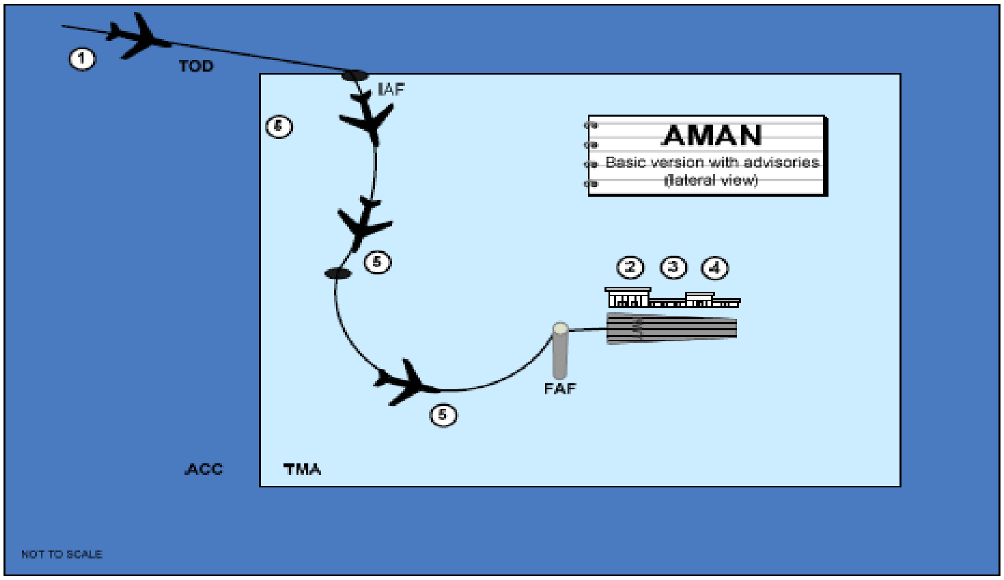


Figure 2. 5. Current AMAN (Lateral View) [1]

2 . 2 Expected Benefits of using AMAN

Regarding the today's situation of major airports, the following benefits can be expected: [8]

- Reduction of flight time in TMA (including reduction of holdings due to a better traffic synchronization)
- Reduction of controller workload due to assistance in planning and implementing the arrival sequence and due to the reduction of voice communication
- Integration of noise abatement procedures like continuous descent approaches (CDA) even in high density traffic situations
- Improved use of landing capacity due to more precise aircraft navigation and higher trajectory predictability

2 . 3 Uncertainty in AMAN

The actual uncertainty for each flight may vary due to for example weather, actual traffic, aircraft navigation capability, or Trajectory Predictor (TP) quality. However, this actual uncertainty is unknown to the operator. Therefore, it is likely that the planner will assume an effective horizon based on experience. Beyond this horizon, the planner will have experienced that decisions are too likely to require revision, and are therefore untrustworthy.

At the lowest levels, the sources of uncertainty become clear. These consist of factors that influence the available capacity (for example the headwind component at landing intervals) and the possible errors in the predicted arrival time themselves. At shorter horizons, these errors may be caused by uncertainty in winds and aircraft behavior. At longer AMAN horizons, especially in the European airspace, the lack of accuracy in the departure time of the inbound aircraft from their origin airport becomes a major contributor in the possibilities for error in the arrival time. The difficulty of handling such ‘pop-up’ flights often forms a limiting factor on the horizon used in operational systems [8].

The uncertainty in the exact arrival times, and the uncertainty in the future conditions at the airport (e.g. wind, visibility, availability of runways) translates to a difficulty in timely deciding on when runway combinations should be changed and the subsequently planning of the exact arrival times. Assigning aircraft to particular runway is generally based on their route to reduce complexity in the terminal airspace. Therefore the effect of arrival time uncertainty in runway assignment is smaller [8].

Delivery accuracy in AMAN is defined as the difference between the actual time of arrival and the scheduled time of arrival. High delivery accuracy is desired to ensure the strategic plan is realized to achieve optimum flows into TRACON and to the runways. [5]

Delivery accuracy is modeled as a product of three processes. The first is the trajectory prediction process, which results in the ETAs; the second is the scheduling process, which determines the STAs from the ETAs; and the third tis the guidance and navigation process, which results in the ATAs. Some of the factors that influence the overall arrival system performance are listed below

- Difference in mean wind between prediction and actuality
- Presence of wind variations (random wind gusts) along the arrival route
- Navigation Performance
- Surveillance Performance
- Timing variability introduced by operations
- Aircraft trajectory prediction model and performance data

2 . 4 AMAN information exchange for ATC

Whether for basic systems or for more advance ones, the information and advisories generated by the system can be forwarded/ exchanged by different means between the AMAN, the AMAN supervisor and the users of the information in sectors upstream and downstream.

Usually this is done

- Via a display of the AMAN (supervisor) screen (timeline) at other controller positions. This can either be incorporated into the ATCOs situational display, or might also be done via a separate AMAN screen or display
- Via a display of an advisory in the aircraft label of particular flight or
- Via a text-based message, summarizing the advisories for a sector

One method of transferring arrival management information electronically, system-to-system, could be via “AMA” messages to adjacent sectors OLDI AMA messages, for “Arrival management” coordination/transfer, contain the following items of data:[23]

- Message Type
- Message Number
- Aircraft Identification
- Departure Aerodrome
- Destination Aerodrome

Based on bilateral agreement, they may also contain one or more of the following items of data: [23]

- Metering Fix and Time over Metering Fix
- Total Time to Lose or Gain
- Time at COP (Coordination Point)
- Assigned speed
- Route

If there is no electronic coordination facilities, AMAN information and required actions could be transferred via VOICE if the controllers are located in the same room or Via PHONE if the controllers are not located at the same room.

2 . 5 Wake Vortex and Separation Minima

Wake Vortex Turbulence is defined as turbulence which is generated by the passage of an aircraft in flight. It will be generated from the point when the nose landing gear of an aircraft leaves the ground on take-off and will cease to be generated when the nose landing gear touches the ground during the landing. Where another aircraft encounters such turbulence, a wake Vortex Encounter (WVE) is said to have occurred.

Wake Vortex generated by aircraft on departure or final approach is one of the main factors defining safe separation minima between two aircraft. Existing ICAO Wake Vortex separation rules (based upon the Heavy, Medium and Light categorization) were implemented over 40 years ago and have in some respect become outdated, resulting in states introducing their own local amendments.

The reason ICAO rules have not previously been updated is that the means to do this was not available. In particular, any change would require the completion of a full safety case to demonstrate that the change was safe to implement.

Due to the lack of measuring technology it was not possible to support the necessary safety arguments with data and therefore the safety of proposed changes could not be proven. However, with the development of measuring technology, e.g. LIDAR and an increased understanding of the physics of wake behavior it is not possible to update the ICAO wake vortex provisions and also develop new advanced wake turbulence related procedures. These will have a positive effect on safety and capacity and could significantly reduce airport delays.

In order to avoid wake vortex turbulence, during the sequencing of the aircrafts in approach phase; the separation minima must me considered to assure the safety of the preceding and succeeding aircraft. The table (3) shows the minimum separation time in second between the preceding and succeeding aircraft between two consecutive landings.

Table2.1. Minimum separation time between consecutive landings [9]

		Preceding Aircraft		
		Heavy	**Medium**	**Light**
Succeeding Aircraft	**Heavy**	102	77	77
	Medium	150	90	90
	Light	210	144	108

Chapter 3 : Extended Arrival Manager

3 . 1 Arrival Management extended to En-route Airspace

The system integrates information from arrival management systems operating out to a certain distance to provide an enhanced and more consistent arrival sequence reducing holding by using speed control to absorb some of the queuing time.

The AMAN horizon shall therefore be extended from the current 100-120 NM to 180-200 NM [22]. This is expected to result in improved arrival flight trajectories for airspace users with efficiency and environmental benefits. The traffic presentation at terminal area entry should be significantly improved with the bulk of traffic sequencing being conducted in the en-route and early descent phases. This will result in more efficient terminal area operations with greatly reduced low altitude path stretching for sequence building purposes. Efficient overall management of the extended arrival operation is essential including the Sequence Manager role which takes on greater importance when AMAN operations are extended to 180-200 NM.

Techniques to manage the AMAN constraints take the form to tools/advice to controllers such as Time to Lose or Gain and speed advice and the initial implementation should adopt this method.

ATS systems in en-route units shall be able to manage arrival constraints in the en-route sectors which will support AMAN operation in the adjacent/subjacent TMAs. This requires specific enhancement in data exchange, data processing and information display at the relevant Controller Working Positions. The impact of arrival management constraints on the en-route sectors is important along with the required co-ordination dialogues between all actors involved in extended arrival management operations. [32]

3 .1. 1 Impact on ground equipment

Current System Capability:
AMAN systems are already deployed at some ATSUs in Europe, although without a common standard the baseline deployments vary significantly.
New Functionality:
AMAN system tools shall be update to provide arrival sequence time information into en route decision making. The ATS systems of upstream ATSUs shall be enhanced to manage AMAN constraints, i.e. data exchange, data processing and information display at controller working position. Further system enablers to be considered include Air-ground coordination of AMAN constraints (e.g. through required time of arrival) which are likely in the next common project – also link to the initial 4D capability utilizing the controlled time of arrival. Data provision to

downstream ATSUs (AMAN) with flight information of arriving flights can be managed to a certain extend and in a first step with current technology. SWIM should be considered as a future enabler for these exchanges. However it must be stressed that ground-ground SWIM trajectory exchange is directly supporting extended AMAN operation when generalized. [32]

3 .1. 2 Impact on airborne equipment

No impact in the initial implementation. Future options may integrate CTA into AMAN and require initial 4D capability on board the aircraft.

3 . 2 Arrivals Management into Multiple Airports

Assistance to multiple airports Arrival Management in the terminal area environment is required especially in view of the emerging use of secondary airports which are located in close proximity to major airport hubs.

This issue shall be addressed by the extension of arrival management horizon into the en-route phase including the arrival management for multiple airports and the integration of departing traffic from airports within the extended arrival management horizon. It should be noted that this does not include the linking of arrival and departure management.

In complex TMA situations with several airports, AMAN capabilities shall comprise the simultaneous optimization of traffic streams to different airports at a time, based upon specific prioritization criteria [32].

3 . 3 Regulatory and standardization needs

Regulatory needs

For AMAN Extended Horizon to en-route airspace and the AMAN for multiple airports, the need is foreseen to have means of compliance issued by the Commission (based on EUROCAE reference documents). If the associated standardization activity is not initiated as soon as possible, the risk of not having the means of compliance available in due time is high, resulting in a non-harmonized deployment of the AF. [32]

Standardization needs

There are currently no standards in place for AMAN. A need has been identified to develop performance standards for the AMAN Extended Horizon to en-route airspace and the Arrival Management into multiple airports functionalities to provide means of compliance with the Interoperability Regulation. The risk of not having them available in due time is medium. The impact would be a non-harmonized deployment of this AF. It is recommended that EUROCAE take action on board as soon as possible. Its progress should be monitored [32].

3 . 4 AMAN Information extension to en-route sectors

A number of ANSPs have already implemented or intend to implement Arrival Management tools in their systems. Most of the implementations are limited to the Ares of Responsibility of the same ANSP. In some cases this means that the flights will be required to alter their trajectory for a limited portion of their flight, leading to drastic tactical changes (e.g. radar vectoring, large speed adjustments) that have an adverse effect both on the controller workload and on the efficiency of the flight. It is anticipated that by extending the time horizon of the AMAN and by involving the adjacent ATSUs (Air Traffic Services Unit) in the process of these adverse effects could be reduced. [33]

The concept of AMAN information extension to en-route is based on the principle that the AMAN will provide the optimum arrival sequence and that the corresponding information will be made visible to the en-route controllers to take early action for the flight that are required to modify their trajectory in order to accommodate the AMAN resolutions [33].

3 .4. 1 Complexity Level

The current European ATM environment includes a wide range of system capabilities, operational procedures, traffic levels, airspace and traffic flow complexity, etc. In order to tallow flexibility for local implementers, it is proposed that the AMAN information extension to En-route sectors allow for three level of complexity for operation and system support. It is also envisaged that, although the most complex level has the biggest potential to bring benefits, some implementers might decide to have a phased implementation in order to minimize the risks and align with upgrade path for their local ATS systems [33].

Complexity Level 1

Level 1 is aimed at environments that have high constraints on the upgrade of the ATS system and/or change of airspace organization and operational procedures. As such Level 1 proposes that the AMAN information is communicated to the En-route sectors using remote terminals from the AMAN tool that is located in the neighboring terminal area. This implies a specific proprietary solution but does not require an upgrade of the En-route ATMS system. The AMAN information would be presented on a standalone display that is not integrated in the en-route system. The en-route controller will have access to the information and will try, depending on the workload and local traffic situation, to alter flights trajectories on a voluntary basis with the aim that the flights are transferred to the terminal area controller in the appropriate sequence under the conditions that are as close as possible to the ones proposed by the AMAN tool. This level of complexity is not expected to require major changes to the airspace organization and design or to the ATC procedures [33].

Complexity Level 2

Level 2 is aimed at environments that allow for an upgrade of the ATS system capabilities in relationship to the required interoperability and integration of the AMAN information. For the Level 2 automated support for exchange of the AMAN information will be required as well as to means to integrate the information in the en-route ATS system for display to the controllers. In this environment the Letters of Agreement will be amended in order specify the roles and responsibilities of the ATSUs, the transfer points for which the information will be exchanged, etc. It is also anticipated that at this level of implementation the number of flights that re transferred to the terminal controller in accordance with the AMAN tool advisories will increase. The modification of the trajectories is the En-route sectors will still occur on a voluntary basis.

Complexity Level 3

Level 3 is aimed environments where the major ATM constraint is the arrival traffic flow. As such it proposes that the neighboring En-route sectors take over some of the workload that is currently with the approach controller. In this environment the expectation is that the en-route controller will transfer flights to the approach controller in accordance with the AMAN tool advisories. As such the AMAN information becomes in the vast majority of the cases a hard constraint that is binding for both parties. In order to be acceptable from an operational point of view and allow some flexibility to controllers this type of operations implies some degree of negotiation between the controllers. As such, Level 3 would require integration of the AMAN tool information in the En-route ATS system, automated support for coordination and transfer including negotiation facilities. In addition the airspace structure, local operational agreements and procedures are expected to be heavily impacted.

Although this level is the most complex in terms of required changes it would also lead to the maximization of the benefits [33].

3 . 5 Area of application

The AMAN information extension to en-route sectors will be applied between two adjacent ATSUs responsible for Area Control Service and Approach Control Service. The complexity of data exchanges, the corresponding time parameter the technology envisaged for the applicable timescales (peer to peer message exchanges) do not permit multiple participating units. This does not preclude an ATSU supported by AMAN to implement multiple bilateral arrangements with neighboring ACCs that feed the arrival traffic flows.

In addition it could be envisaged that in the timescale IP2 new data exchange mechanisms and concept (e.g. data sharing, SWIM) will enable trajectory and flight data sharing between multiple units. The concept of operations for the AMAN information extension to en-route sectors will need to be enhanced for this type of capabilities in order to enable an efficient apportionment of arrival management between participating units.

3.6 Expected Benefits

It is expected that the AMAN information extension to the En-route sectors will bring the following benefits:

- Early notification of arrival requirements on the airborne side to reduce the need for severe sequencing measures should lead to an increase in flight efficiency
- An optimized arrival traffic flow leading to a potential controller workload reduction and capacity increase
- More confidence in the predictability and stability of the arrival sequence
- Reduction in workload for the terminal area controller as a result of the rebalancing of tasks between TMA and En-route
- Early notification of arrival requirements to reduce the need for severe seque3ncing measures leading to ATCO workload reduction

Chapter 4 : Trajectory Prediction

Trajectory Prediction (TP) is the core component of automated systems in Air Traffic Control. Many functionalities of the Decision Support Tool directly rely on an accurate TP: controller posting, workload estimation, arrival sequencing, loss of separation detection, and conflict resolution. As a consequence, TP is the weakness of current automation ATC systems and a major issue in the ATC research community, even more with the new paradigmatic shift toward 4D trajectories in both the SESAR Joint Undertaking and NextGen project [25].

Aircraft trajectories are difficult to predict, and large errors in these predictions reduce the potential operational benefits of some advanced concepts in the Next Generation Air Transportation System [14]. Predicting aircraft trajectories with great accuracy is one of the most operational concepts [10] and automated tools that are expected to improve the air traffic management (ATM) in the near future.

The on-board flight management systems predict the aircraft trajectory using a point- mass model describing the forces applied to the center of gravity. This model is formulated as a set of differential algebraic equations that must be integrated over a time interval in order to predict the successive aircraft positions in this interval. In order to predict the trajectory, the point-mass model requires knowledge of aircraft state (mass, thrust, etc.), atmospheric conditions (wind, temperature), and aircraft intent (target speed or climb rate). [10]

However, many of this information are not available to ground based systems, and those that are available are not know with great accuracy. The current ground-based trajectory predictors make fairly basic assumptions on the aircraft intent using BADA model (see the “airlines procedure” [11]). Nevertheless, these default “airline procedures” may not reflect the reality where the target speeds are chosen by the pilots according to the cost index that is a ratio between the cost of operation and the fuel cost. These costs are specific to each airline operator, and are not available in the public domain [10].

As a consequence, ground-based trajectory prediction is currently fairly inaccurate, compared to the on-board prediction. There are different methods which can be used for the trajectory prediction and they are listed below:

- Point-mass Model
- Regression Methods
- Neural Network Method
- Light Propagation Method[12]

Even though there are different methods which can be used for the trajectory prediction, in this thesis Point-mass Model is used due to its simplicity and its wide range of use for a lot of research works in the field of trajectory prediction.

4 . 1 The Point-mass model

Most of the ground systems use a simplified (Longitudinal +Vertical) point-mass model and sometimes it is also called Total-Energy Model in order to predict aircraft trajectories. The model which is shown in the figure (4.1) shows that the forces are applied at the center of gravity of the aircraft.

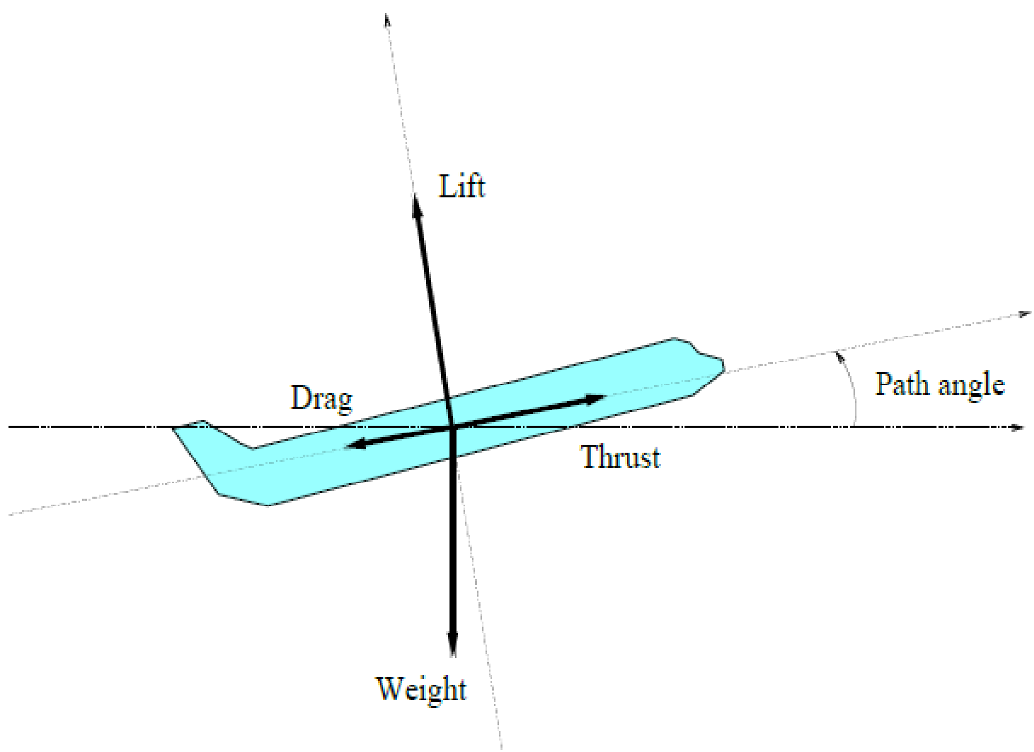


Figure 4. 1. Simplified Point-mass model

It is assumed that the thrust and the drag are collinear to airspeed vector and Lift is perpendicular to those vectors. We obtain the longitudinalacceleration $= \frac{dV_{TAS}}{dt}$. Therefore, projecting the airspeed vector axis, the longitudinal acceleration along the true airspeed (V_{TAS}) axis can be expressed as follows [13]

$$m.\frac{dV_{TAS}}{dt} = T - D - m.g.\sin(\gamma) \tag{4.1}$$

Where D is the aerodynamic drag of the airframe, T is the total thrust; m is the mass of the aircraft, g the gravitational acceleration, and γ the path angle (i.e. the angle between the airspeed vector and the horizontal plane tangent to the earth surface) [10]. Now, introducing the rate of climb/descent $\frac{dh}{dt} = V_{TAS}.\sin(\gamma)$, where h is the altitude in meter, this equation can also be rewritten as follows [11]

$$(T - D).V_{TAS} = m.V_{TAS}.\frac{dV_{TAS}}{dt} + m.g.\frac{dh}{dt} \tag{4.2}$$

However, we need to take into the consideration that the true airspeed is often calculated in knots and altitude is calculated in feet thus requiring the appropriate conversion factors.

4 .1. 1 Controls in Point-mass model

An aircraft can be controlled using different controls like Ailerons, Horizontal stabilizer, vertical stabilizer. Apart from these controls aircraft possess different devices like spoilers, leading-edge slats or trailing edge slats; that are used in different phase of flight according to the need. However, in the aircraft trajectory prediction, without considering the use of devices such as spoilers, leading-edge slats or trailing-edge flaps, there are two independent controls input available for affecting the aircraft trajectory in the vertical plane. These are the throttle and the elevator [11]. These inputs allow any two of the three variables of thrust, speed, or ROCD (Rate of Climb or Descent) to be controlled. The other variable is then determined by the equation (4.2)

In the point-mass model the controls are: [16]

- The engine control setting η which is forced to remain within the range
$$0 \le \eta \le 1$$
- The aerodynamic roll-angle μ, constrained by:
$$|\mu| \le \mu_{max}$$
- The lift coefficient (or angle of attack) which is limited by:

$$C_L \le C_{L_{max}}$$

In the table (4), we can see the summary which gives us the idea about the controlled parameters and calculated parameter used in the trajectory prediction using point mass model.

Table 4. 1. Controls in Point-mass model

Controlled Parameters	Calculated Parameter
Speed , Throttle	ROCD
ROCD, Throttle	Speed
Speed, ROCD	Throttle

To facilitate the calculation of ROCD from the equation (4.2), the equation can be rearranged as follows:

$$(T - D).V_{TAS} = m.V_{TAS}.\frac{dV_{TAS}}{dh}.\frac{dh}{dt} + m.g.\frac{dh}{dt} \tag{4.3}$$

$$\frac{dh}{dt} = \frac{(T - D).V_{TAS}}{mg}\left[1 + \left(\frac{V_{TAS}}{g}\right).\frac{dV_{TAS}}{dh}\right]^{-1} \tag{4.4}$$

From [13] we know that the definition of Energy Share Factor and it can be represented as a function of Mach number $f\{M\}$ [10]

$$ESF = \frac{g.\frac{dh}{dt}}{V_{TAS}.\frac{dV_{TAS}}{dt} + g.\frac{dh}{dt}} \tag{4.5}$$

Using the two equations above, we obtain ROCD as a function of Mach number,

$$\frac{dh}{dt} = \left[\frac{(T - D).V_{TAS}}{mg}\right].f\{M\} \tag{4.6}$$

Actually, using the equation (4.2) to predict a trajectory requires a model of the aerodynamic drag for any airframe flying at a given speed through the air. In addition, we may need the maximum thrust, which depends on what engines the aircraft is equipped with. [Note: in this thesis point mass model given by BADA is used]

In order to be able to use the equation we need to have the knowledge of the initial state (mass, position, speed,..) of the aircraft, and also of the pilot's intents as to how the aircraft will be operated in the future (thrust law, speed law or rate of climb).[10]

4 .1. 2 Equations of Motion

The model adopted to describe the aircraft motion is that of a point mass model with three degree of freedom, commonly used for the trajectory prediction; the equations describe the movement of the aircraft center of mass, considered as a mass-varying body [17]. The scalar equations of motion are formulated based on the following general assumptions: Spherical and non-rotating Earth, rigid and symmetric aircraft, symmetric flight, and thrust parallel to the aircraft aerodynamic velocity. These assumptions are appropriate for subsonic, transport aircraft [19]

The three dynamic equations of force which represent the motion of an aircraft are given below [18]

$$Tcos\varepsilon\ cos\upsilon - mg\ sin\gamma - m\ \frac{dV}{dt} = 0 \tag{4.7}$$

$$T\cos\varepsilon\sin\upsilon - Q + mg\cos\gamma\ \ sin\,\mu + mV\ (\dot{\gamma}\sin\mu - \dot{\chi}\cos\gamma\cos\mu) = 0 \tag{4.8}$$

$$-T\sin\varepsilon - L + mg\cos\gamma\cos\mu + mV\ (\dot{\gamma}\cos\mu + \dot{\chi}\cos\gamma\sin\mu) = 0 \tag{4.9}$$

Now, after applying the assumption mentioned above and applying generic wind, we obtain the following equations [18] [19]

$$m\ \frac{dV}{dt}\ = T - D - mg\sin\gamma + m\dot{w}_V \tag{4.10}$$

$$mV\cos\gamma\ \frac{d\chi}{dt}\ = L\ sin\,\mu + m\dot{w}_\chi \tag{4.11}$$

$$mV\ \frac{d\gamma}{dt}\ = L\cos\mu\ - mg\cos\gamma + m\dot{w}_\gamma \tag{4.12}$$

A part from the dynamic equations we also have Linear kinematic relations,

$$(R_E + h)\frac{d\varphi}{dt} = V\cos\gamma\cos\chi + \ w_1 \tag{4.13}$$

$$(R_E + h)\cos\varphi\ \frac{d\lambda}{dt} = V\cos\gamma\sin\chi + \ w_2 \tag{4.14}$$

$$\frac{dh}{dt} = \ V\sin\gamma - w_3 \tag{4.15}$$

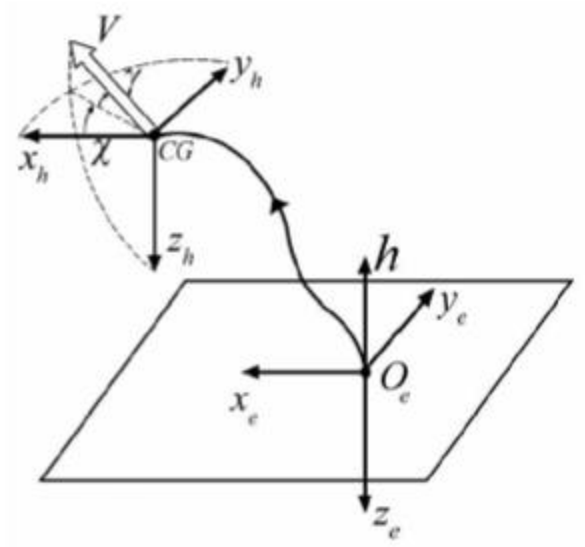


Figure 4. 2. Plain Earth Hypothesis

Where V, χ ,γ are the aerodynamic velocity modulus, heading and path angles; m the aircraft mass; φ , λ the geodetic latitude and longitude; h the altitude; μ, the bank angle; g the gravity acceleration; R_E the Earth radius; t the time; T, L,D the thrust, the lift and the aerodynamic drag; and c the specific fuel consumption. w_1, w_2 , w_3 are the wind components in the local axes system (north, east and down); and $\dot{w}_V$, $\dot{w}_\chi$, $\dot{w}_\gamma$ are wind accelerations given by [19]

$$\dot{w}_V = -\dot{w}_1 \cos\gamma \cos\chi - \dot{w}_2 \cos\gamma \sin\chi + \dot{w}_3 \sin\gamma \tag{4.16}$$

$$\dot{w}_\chi = \dot{w}_1 \sin\chi - \dot{w}_2 \cos\chi \tag{4.17}$$

$$\dot{w}_\gamma = \dot{w}_1 \sin\gamma \cos\chi + \dot{w}_2 \sin\gamma \sin\chi + \dot{w}_3 \cos\gamma \tag{4.18}$$

In this formulation V,χ,γ, m, φ, λ, and h are state variables; T, L and μ are control variables; and t is an independent variable [19].

Chapter 5 : Experimental Setup for TP Simulator

Implementing the equations of point mass model presented in BADA 3.6 and making some assumptions, a Trajectory prediction simulator is constructed. This simulator gives us an idea about the flight time of aircrafts once it enters the Lithuanian airspace until it lands in the Vilnius Airport. The simulator follows the structure presented in the figure (6.1) and the description on each function is presented later on.

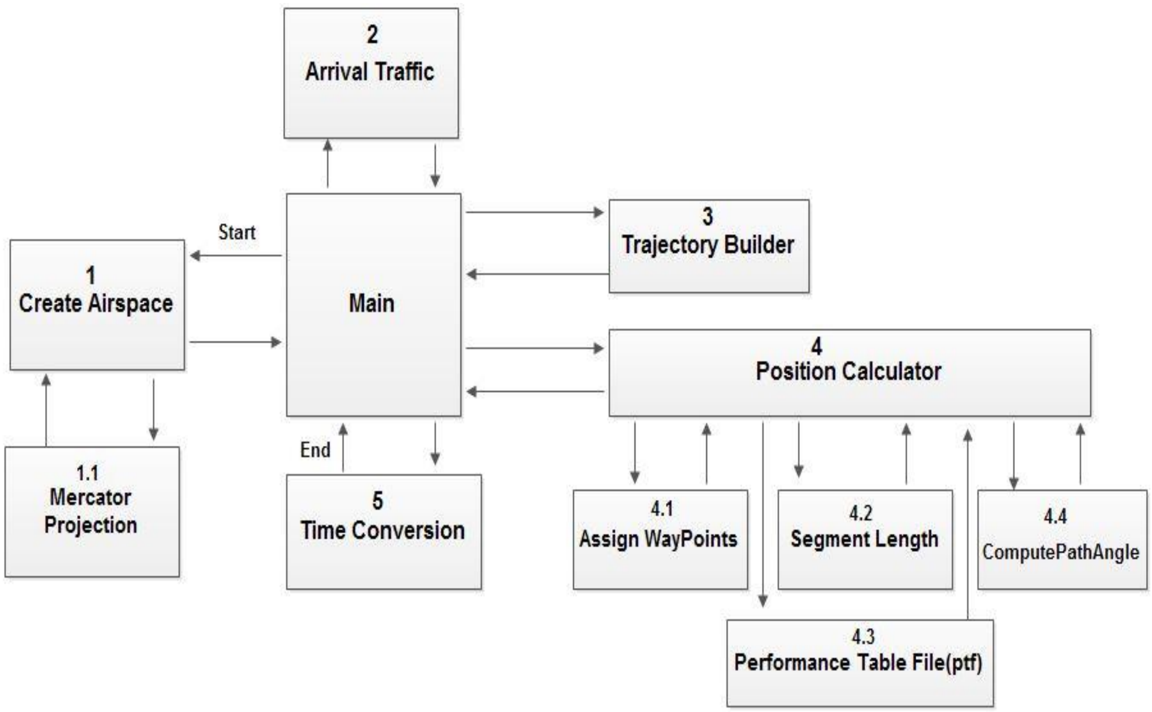


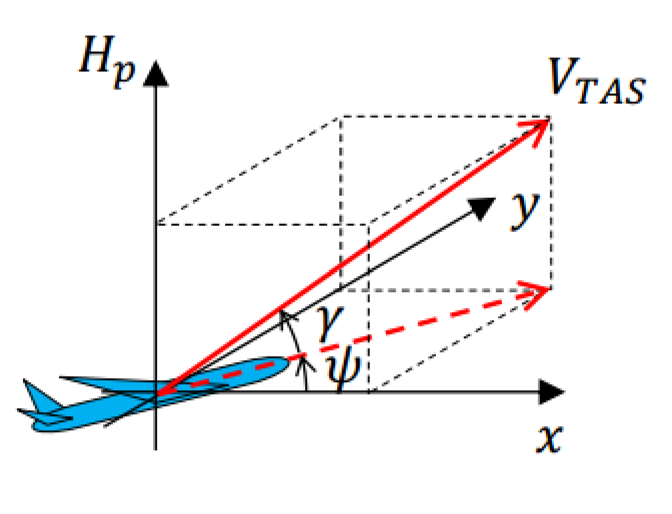
Figure 5. 1 : Basic Structure of Trajectory Prediction Simulator

We can see in the above figure (5.1) that the data processing in the simulator starts and ends in the main program. However, in order to end the whole process it goes through a series of sub-functions that can be observed in the above figure.

In order to obtain the results some pre-assumptions were made which are listed below:

- Constant head wind of 4 knots
- Constant velocity throughout the leg but the velocity changes with the change of leg
- Constant bank angle, which implies an instantaneous change in heading
- Aircraft mass not taken into consideration

Constant headwind of 4 knots is assumed after analyzing all the METAR file of that particular day and it is intended to take the worst case scenario assuming the head wind. Mass is considered constant or the effect of mass is not considered due to the lack of information on mass of each aircraft when they are entering the Lithuanian Airspace. Nevertheless, to make the simulations and the calculation more realistic, the true airspeed of each aircraft is obtained from BADA 3.6 depending upon the flight level when reached a particular waypoint.



$$X = V_{TAS} \,.\cos\gamma \,.\cos\psi \,. t$$
$$Y = V_{TAS} . \cos\gamma \,.\sin\psi \,. t$$
$$h = V_{TAS} . \sin\gamma . t$$

Figure 5. 2. Equations used for lat, lon and height calculation

Finally, for the calculation of latitude, longitude and height of the aircraft, the relation shown in figure (5.2) is used. In the above figure X, Y, γ, ψ,t represent latitude, longitude, flight path angle, heading and time respectively.

5 . 1 Description of MATLAB functions

5 .1. 1 Main

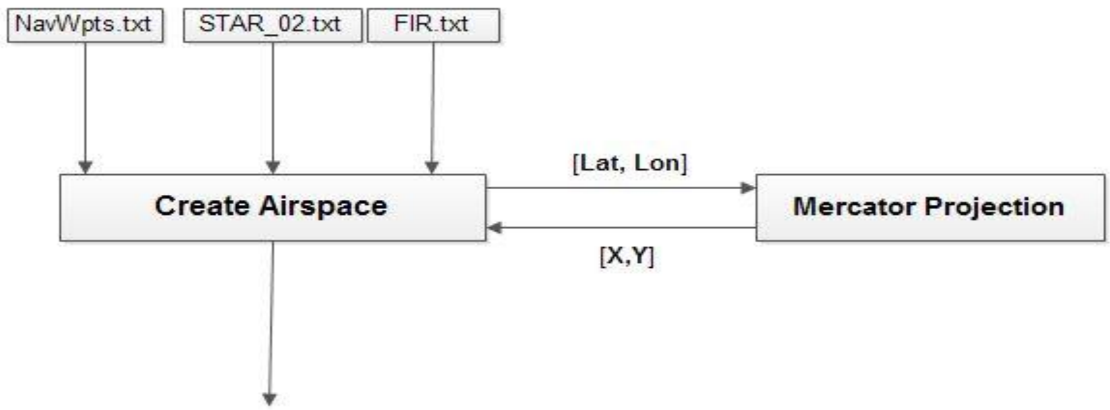
The function Main is the core of this whole program. It works at the center point which receives and gives back the necessary parameters to other functions. This function basically has for different text files namely:

- **NavWpts.txt**: It contains the list of all the Navigation waypoints.
- **STAR_02.txt**: It contains the list of waypoints that form a leg for the STAR02.
- **FIR.txt**: It contains the list of points that bound the Vilnius FIR.
- **Arrival.txt**: It contains the list of all the arrival traffic on 04/09/2014 to Vilnius Airport.

[Note: For the detailed structure of files and its parameters consult ANNEX D]

5 .1. 2 Create Airspace

This function takes as an input three different text file and helps in the creation of the Lithuanian Airspace. In this function a sub-function **Mercator Projection** is used which takes latitude and longitude in degrees as an input and transform them in x and y coordinates in Kilometers. Finally, it plots the Lithuanian Airspace and gives back a data structure (Airspace) with Waypoint 1, Waypoint2, coordinates of Waypoint1 and Waypoint2, Heading and corresponding FL at Waypoint1 and Waypoint2.



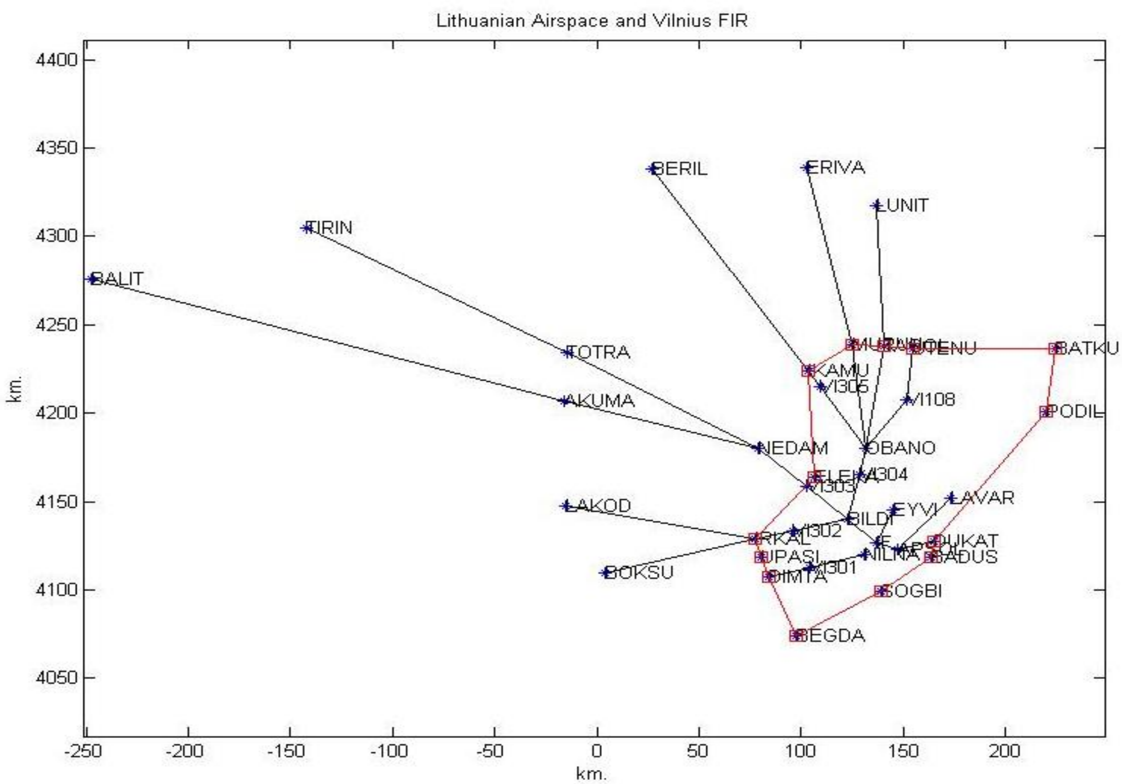


Figure 5. 3. Vilnius FIR and some part of Lithuanian Airspace

5 .1. 3 Arrival Traffic

This function takes as an input the arrival.txt (see Annex D for details on the parameters of the file) file and gives back a structure with the flight plan of each aircraft arriving to Vilnius Airport.

Figure 5. 4. Arrival traffic function with Flight Plan constructor

5 .1. 4 Trajectory Builder

This function takes as an input the collection of data structure prepared in first and second step which are called Airspace and Flight Plan respectively. The output of this function is a structure (**Trajectory**) with the list of waypoint that an aircraft needs to follow within Lithuanian Airspace till it lands to Vilnius Airport.

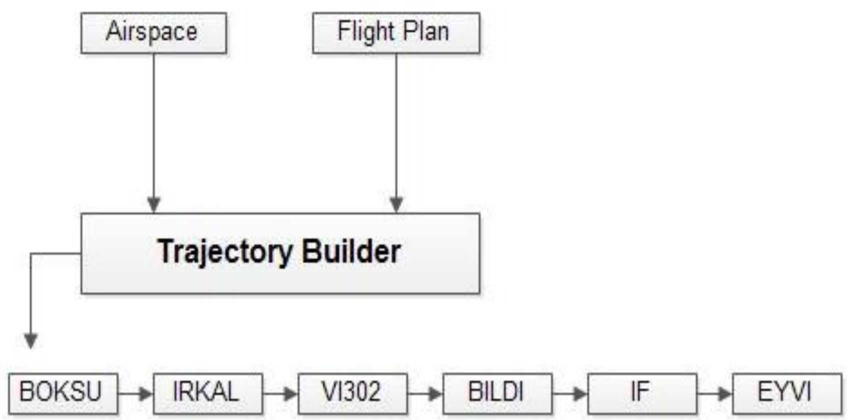


Figure 5. 5. Trajectory Builder in TP Simulator

In this example if an aircraft enters from the waypoint BOKSU it needs to pass from IRKAL, VI302, BILDI, IF and EYVI.

5 .1. 5 Position Calculator

5 .1. 5. 1 Assign Waypoints

This function takes an input the Flight plan, trajectory and gives back the model of aircraft that is being used for the particular case. This model of aircraft will be further used in the function (Performance Table file)

5 .1. 5. 2 Segment Length

This function takes and input a structure with the coordinates of two waypoints and gives back the distance between those points

5 .1. 5. 3 Performance Table file

This function takes as an input the model of aircraft and the flight level at which the aircraft is flying. Depending upon the model of aircraft this function access to the collection of Aircraft performance files extracted from BADA 3.6 and gives back the true airspeed at that particular Flight Level.

5 .1. 5. 4 Compute Path Angle

This Function calculates the path angle that is needed to fly while passing from a waypoint to another. It takes as an input the Flight Levels of two different waypoints and gives back the path angle in radians.

The function Position Calculator takes as an input Airspace, Trajectory and Flight Plan. A part from these inputs, this function needs the output given by the function like Assign waypoints, Segment Length, Performance Table file and Compute Path Angle.

Using all these data it predicts the position of aircraft at each second and finally it stores the time taken by aircraft to pass from a waypoint to another waypoint. The output of this function is the structure (predicted time) which has the collection of time needed to pass from a point to another for every flights of the day.

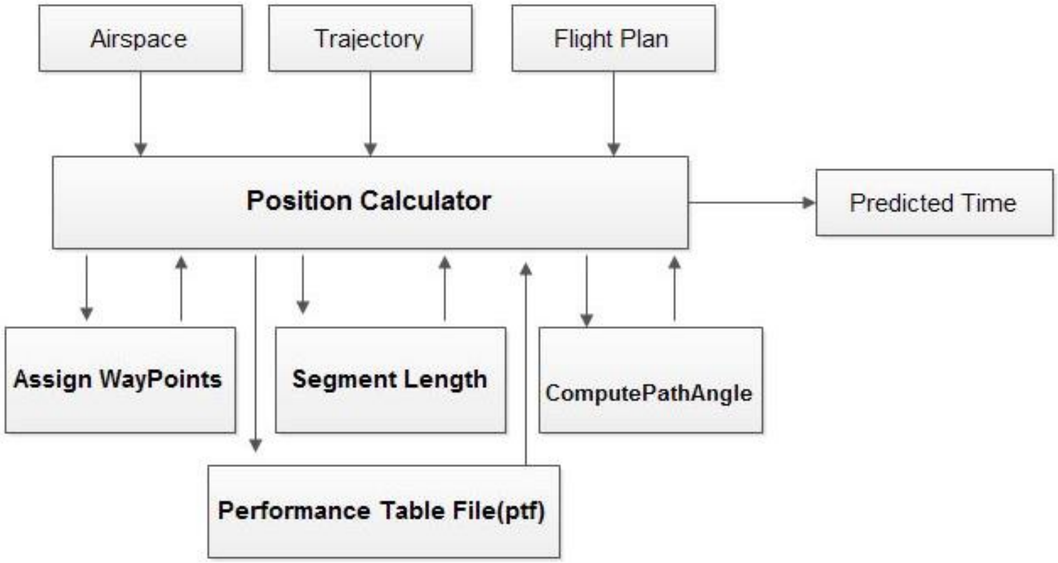


Figure 5. 6. Position Calculator structure and its functions

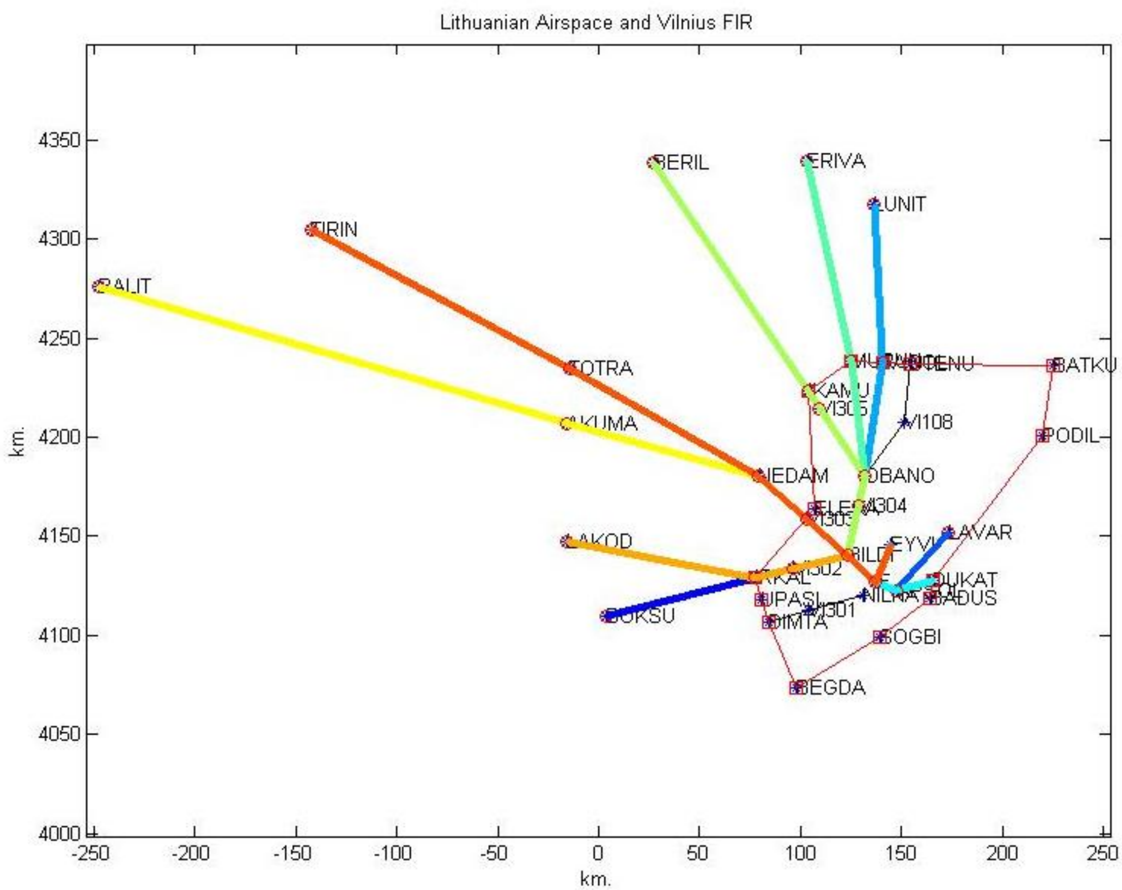


Figure 5. 7. Different Flights with their flight trajectories

5 .1. 6 Time Conversion

This function takes as an input the predicted time in the position calculator section, makes the sum of time that is taken by aircraft from the entry to Lithuanian airspace to the landing and finally writes a text file with all the time for each aircraft of the arrival traffic.

Figure 5. 8. Time Conversion function with its inputs and outputs

5 . 2 Result analysis of the Simulator

After finishing the whole simulation and obtaining the predicted_time.txt file with the time for each aircraft, we need to proceed to check the reliability of the obtained data.

[Note: consult Annex F for the time on each aircraft]

Table 5. 1. Mean Flight time between TP simulator and Flight plan prediction

	Initial Flight Plan Prediction	**TP Simulator**
Mean flight time (sec)	1192	1106
No of Flights	60	60

In the beginning we first see the descriptive statistics results. Mean value clearly indicates that the result obtained by the TP Simulator is better than the initial Flight Plan prediction. However, to validate this result we are applying some relevant statistical test.

In this particular case paired t-test has been conducted because we have two samples in which observation on one sample can be paired with the observation in the other sample(i.e. initial flight plan prediction can be compared with the TP simulator). In order to conduct the paired t-test we have to make a series of hypothesis

- TP simulator time is less than or is better than initial flight plan prediction time
- Null hypothesis, i.e. no difference between two time

After making this hypothesis and executing the Minitab program to calculate the t and p-value, the following result is obtained.

t-value = -3.8993 and p-value = 0.0001247

5 .2. 1 Interpretation of the obtained result:

P-value is less than 0.05 at 5 percent level of significance means it rejects the null hypothesis and average time for each flight for TP simulator is better than the initial Flight plan prediction.
The mean flight time calculated by TP simulator of each aircraft in Lithuanian airspace is lower than that of the initial flight plan prediction. This means that, lower the time they are flying in Lithuanian airspace, lower will be the workload on the controllers during the approach and ultimately it will contribute in increasing the capacity of a given sector, control tower and consequently the capacity of an airport.

Moreover, having the detailed time information of the aircraft's arrival at a particular waypoint makes it easier for controllers the work of sequencing and merging.

Chapter 6 : Statistics of arrival and departure in Vilnius

The above table shows the average number of departure and arrival per day in a particular month. The above table (6.1) and table (6.2) give us a clear picture that the number of flights departing and arriving to Vilnius Airport is on rise.

Table 6. 1. Average number of Arrivals and departures per day (a)

	International and Internal Departures				**International and Internal Arrivals**			
Months	**2014**	**2013**	**change**	**growth**	**2014**	**2013**	**change**	**growth**
January	41.4	38.2	3.1	8.2%	41.0	38.4	2.6	6.8%
February	42.5	37.6	4.9	13.0%	41.9	37.5	4.4	11.8%
March	44.0	37.2	6.8	18.2%	43.2	37.4	5.8	15.5%
April	49.7	41.7	8.1	19.4%	48.7	41.9	6.8	16.3%
May	53.3	42.7	10.6	24.9%	52.6	42.6	10.0	23.5%
June	55.2	45.3	10.0	22.0%	54.6	45.3	9.3	20.5%
July	54.1	47.3	6.8	14.3%	53.4	47.4	6.0	12.7%
August	53.7	47.0	6.7	14.3%	53.4	46.4	7.0	15.1%
September	56.8	51.3	5.5	10.8%	56.2	50.9	5.3	10.5%
October	55.4	49.7	5.7	11.4%	54.6	48.9	5.6	11.5%
November	48.1	46.2	1.9	4.2%	47.7	45.8	1.9	4.1%

Table 6. 2. Average number of Arrivals and departures per day (b)

	International and Internal Departures				International and Internal Arrivals			
Months	**2013**	**2012**	**change**	**growth**	**2013**	**2012**	**change**	**growth**
January	38.2	34.7	3.5	10.2%	38.4	35.1	3.3	9.3%
February	37.6	35.4	2.1	6.0%	37.5	35.4	2.1	5.9%
March	37.2	36.1	1.1	3.1%	37.4	36.1	1.2	3.4%
April	41.7	40.1	1.6	3.9%	41.9	40.4	1.5	3.7%
May	42.7	42.7	0.0	0.0%	42.6	42.8	-0.2	-0.4%
June	45.3	45.5	-0.2	-0.44%	45.3	45.4	-0.1	-0.22%
July	47.3	42.8	4.5	10.6%	47.4	42.8	4.6	10.9%
August	47.0	43.4	3.6	8.3%	46.4	43.3	3.5	8.1%
September	51.3	43.0	8.3	19.4%	50.9	42.8	8.1	19.0%
October	49.7	42.6	7.1	16.7%	48.9	42.7	6.2	14.5%
November	46.2	39.5	6.7	17.0%	45.8	39.0	6.8	17.3%
December	41.2	37.1	4.1	11.1%	40.3	36.5	3.8	10.3%

The growth figures for departure and arrival for each month of year 2013 and 2014 are really impressive with almost double figure growth at each month. These statistical data can confirm us that the number of movements of aircrafts in Vilnius airport will be in growth in 2015 as well.

6 . 1 Arrivals and departures on 04/09/2014

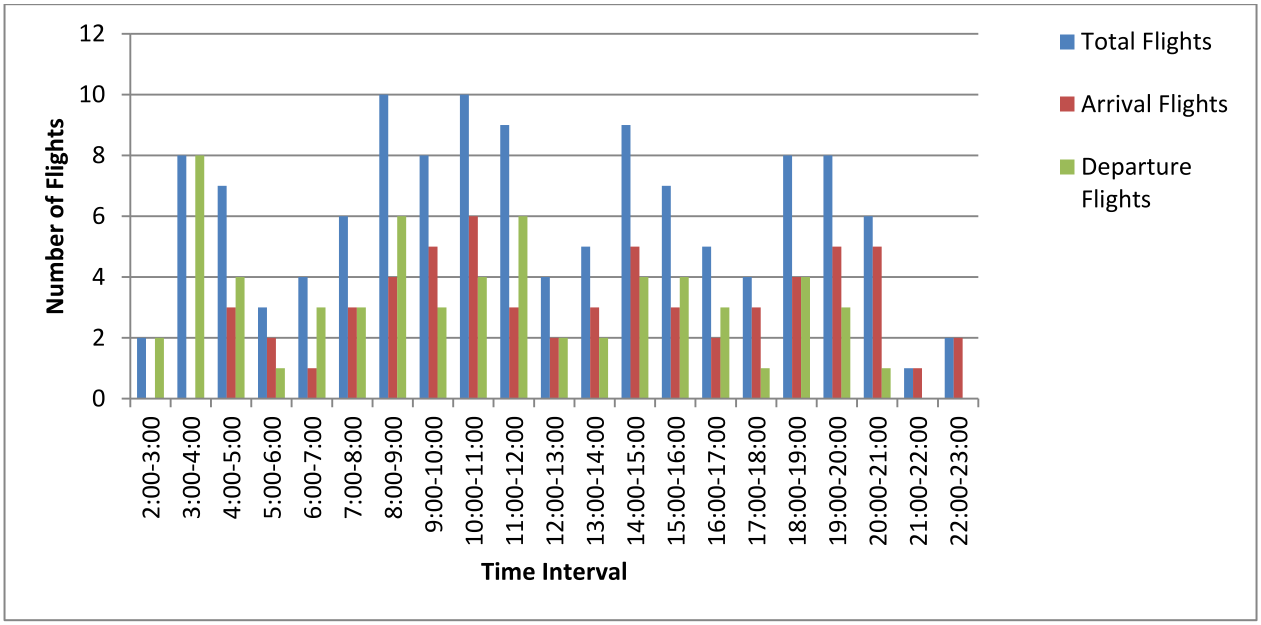


Figure 6. 1. Arrivals, Departures and total number of flights

The Vilnius International Airport has a Single Runway (RWY 02/ RWY 20 see Airport Layout and Runway configurations in Annex E) and the number of operations per hours is relatively lower than its capacity. We can see in the above figure (6.1), the total number of flights per hour is not higher than 10 flights per hour. The airport is operating far below its potential capacity and provided that in near future if the traffic flow increase to Vilnius airport, the airport can handle the traffic without any major problems.

6 . 2 Arrival Traffic analysis Vilnius Airport (04/09/2014)

A detailed analysis of arrival traffic to Vilnius International Airport on 4th September 2014 is done. After analyzing the traffic using NEST, it was found that on that particular day all the arrival flights were using STAR 02 and consequently landing on Runway (RWY 02). We can observe in the above table (6.3), there is higher concentration of flights that are entering the Lithuanian airspace via waypoint BOKSU which leads the use of IAF (Initial Approach Fix) BILDI. On the other hand, the number of flights entering to Lithuanian airspace from Belarusian airspace (waypoints LAVAR and DUKAT) are quite small.

Table 6. 3. Entry Waypoints for STAR 02 and distance to EYVI

Entry Points	Distance (NM)	IAF	Distance (NM)	End Point	No of Entries
BERIL	124.08	BILDI	21.96	EYVI	6
BOKSU	67.94	BILDI	21.96	EYVI	25
BALIT	216.7	BILDI	21.96	EYVI	3
DUKAT	10.4	APSOL	17.17	EYVI	7
ERIVA	109.04	BILDI	21.96	EYVI	6
LAKOD	77.97	BILDI	21.96	EYVI	1
LAVAR	21.4	APSOL	17.17	EYVI	4
LUNIT	96.32	BILDI	21.96	EYVI	7
SOGBI	25.63	EYVI		EYVI	1
LISOG	97.57	BILDI	21.96	EYVI	0
VABER	59.91	NILNA	16.21	EYVI	0
TIRIN	169.7	BILDI	21.96	EYVI	1

According to [22], in order to implement the AMAN; the aircraft is captured around 100-120 NM from the touchdown and this distance is called the AMAN horizon. Most of the entry points to the Lithuanian airspace fulfill this requirement of the AMAN horizon.

However, in the case of Vilnius there are some waypoints (LAVAR and DUKAT) which are so close to the Airport from which the aircrafts enter the Lithuanian airspace. If AMAN is to be implemented in the Vilnius International Airport, some special agreement must be made with the Belarusian ANSP so that the flights enter the Lithuanian airspace with suitable speed and flight level necessary for the functioning of the AMAN in Vilnius Airport. Making these adjustments in the flight level and speed in the Belarusian airspace prevents the aircrafts from doing drastic maneuver to land in Vilnius Airport and it consequently leads to more efficient and safe flight till the touchdown.

6 . 3 Runway capacity Assessment using FAA Method

In this section detailed explanation of the procedures to calculate the runway capacity using FAA method is presented.

Hourly capacity can be calculated as follows:

1. Select the runway-use configuration that is available in [37] which best represents the use of the airport during the hour of interest.
2. Select the Figure number for capacity
3. Determine the Percentage of Class C and D aircraft operating on the runway component and calculate the mix index
4. Determine Percent of arrivals
5. Determine the hourly capacity base from graph (C*)
6. Determine the percentage of tough and go operations during VFR operations and determine the touch and go factor (T). Note: In the case of IFR touch and go factor is 1
7. Determine the location of exit taxiways (measured from the threshold at the approach end of the runway) and determine the exit factor (E)
8. Calculate the hourly capacity of the runway component with

$$C = C^{*}.T.E \tag{6.1}$$

Finally, the runway capacity is obtained to be **46 operations/ hour**. [Note: Step by step calculation of the Vilnius Airport Runway capacity can be consulted in Annex D]. Even we have obtained 46 operations/ hours it may not be the optimal one because the overall study of taxiway capacity, gate capacity, and the bottleneck of the system must be calculated to give the final affirmation regarding the capacity of the airport. However, this number can give us an idea regarding the number of operations that can be carried out in this runway provided the high presence of traffic in Vilnius airport.

Conclusions

The objective of the thesis was to develop a trajectory prediction simulator which would assist us in calculating more precise arriving time. To build the simulator MATLAB have been used as the principal software for the code development and all the data processing. However the NEST was used to filter arrival traffic and to prepare the necessary input files for the simulator.

It is important to remark that this topic is not new for the aviation sector; hundreds of research project has been done for improving the result and increasing the reliability on it. Trajectory prediction being the core part of AMAN, more research must be done on this topic to increase the level of reliability on the resolution provided by AMAN.

Uncertainty in the prediction of arrival time plays a vital role in providing erroneous arrival time to the controller which leads to some conflicts creating problem in sequencing of the arrival traffic and ultimately increasing the workload of the controller and affecting negatively on the capacity of the airport. Lack of departure times of the inbound aircraft from their origin airport becomes a major contributor in the possibilities for error in the arrival time.

When aircrafts are predicted to arrive too close after each other, AMAN provides support to the sequence manager at the destination airport in deciding how to influence the 4D trajectories of the aircraft involved based on the predicted estimated time of arrival. As AMAN provides the sequence of aircrafts approaching the Runway, it reduces significantly the workload of the controller and increasing the capacity of the airport.

Vilnius airport is operating with really low number of operations per hour than its potential capacity. However, with the current infrastructure available in Vilnius airport it can handle the increasing traffic for some years still. There is no need of immediate implementation of AMAN in Vilnius airport but its implementation must be considered as a long term plan.

To sum up, the thesis and the results obtained can be of great help and a useful information tool for the students willing to work with this topic. Some future work can be done taking the variable mass and calculating the drag including the effects of flaps, landing gear etc. during the approach phase. Implementing these considerations in the trajectory prediction, predicted time for the arrival would be more precise.

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APPENDIX

In this part a brief explanation is done on BADA and the flight mechanics during the descent phase of a particular aircraft (A340). The appendix A talk about the general descent equations, some considerations regarding angles and different flight parameters. Apart from the flight mechanics, in appendix B explanation on BADA model is provided.

Appendix A : Flight Mechanics in Descent

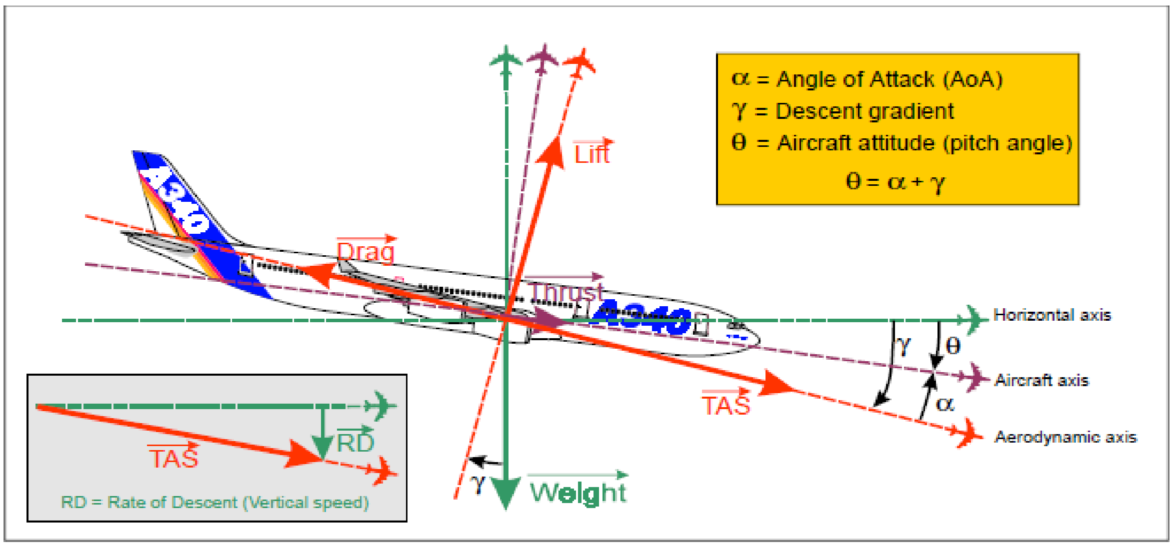


Figure A. 1. Balance of Forces in descent [36]

- The angle of attack (α) represents the angle between the aircraft axis and the aerodynamic axis (speed vector axis tangent to the flight path)
- The descent gradient (γ) represents the angle between the horizontal axis and the aerodynamic axis
- The aircraft attitude (θ) represents the angle between the aircraft axis and the horizontal axis (in a ground reference system)
- The rated of descent (RD) represents the vertical component of the aircraft´s speed. It is negative and expressed in feet per minute

A . 1 Descent Equations

While climb is due to excess thrust, descent is, on the other hand, caused by a lack of thrust. Therefore, the descent gradient and the rate of descent, which depend on the difference (Thrust- Drag), are negative.

$$T * \cos \propto = D + mg * \sin \gamma \quad (A.1)$$

$$L = mg * \cos \gamma \quad (A.2)$$

A . 2 Descent Gradient

The descent gradient (γ) and the angle of attack (α) are usually small enough so that:

$$\sin\gamma \cong \tan\gamma \cong \gamma\ (in\ radian) \tag{A.3}$$

$$\cos\gamma \cong 1\ and\ \cos\alpha \cong 1 \tag{A.4}$$

As a result, the descent equations are:

$$T = D + mg * \gamma \tag{A.5}$$

$$L = mg \tag{A.6}$$

Therefore,

$$\gamma = \frac{T - D}{mg} \tag{A.7}$$

As we know that the descent is carried out at idle thrust configuration (i.e. Thrust close to zero), the descent gradient is consequently:

$$\gamma = \frac{-D}{mg} \tag{A.8}$$

By introducing the Lift to drag ratio (L/D), as the weight value is close to the lift one ($Lift = mg * \cos\gamma$), the descent angle becomes:

$$\gamma = -\frac{D}{L} \tag{A.9}$$

At a given weight, the magnitude of the descent gradient is minimum. When the drag is minimum, or when the lift-to-drag ratio is maximum. The minimum descent angle speed is, therefore, green dot speed.

A . 3 Rate of Descent (RD)

The Rate of Descent (RD) corresponds to the vertical component of the TAS.

$$RD = TAS * \sin\gamma \cong TAS * \gamma \tag{A.10}$$

$$RD = -TAS * \frac{D}{mg} \quad or \quad RD = \frac{-TAS}{L/D} < 0 \tag{A.11}$$

Therefore, at a given aircraft weight, the rate of descent is minimum, when *TAS*Drag* is minimum.

A . 4 Speed Polar

The figure (A.2) below illustrates both thrust, and drag forces, as opposed to True Air Speed.

The above equations indicate that, for a given weight:

- The descent angle (γ) is proportional to the drag force, which is at its minimum at green dot speed.
- The rate of descent (RD) is proportional to the power of the drag force. As $RD = TAS * \gamma$, the minimum rate of descent is obtained for a TAS lower than green dot (when dRD/dTAS = 0)

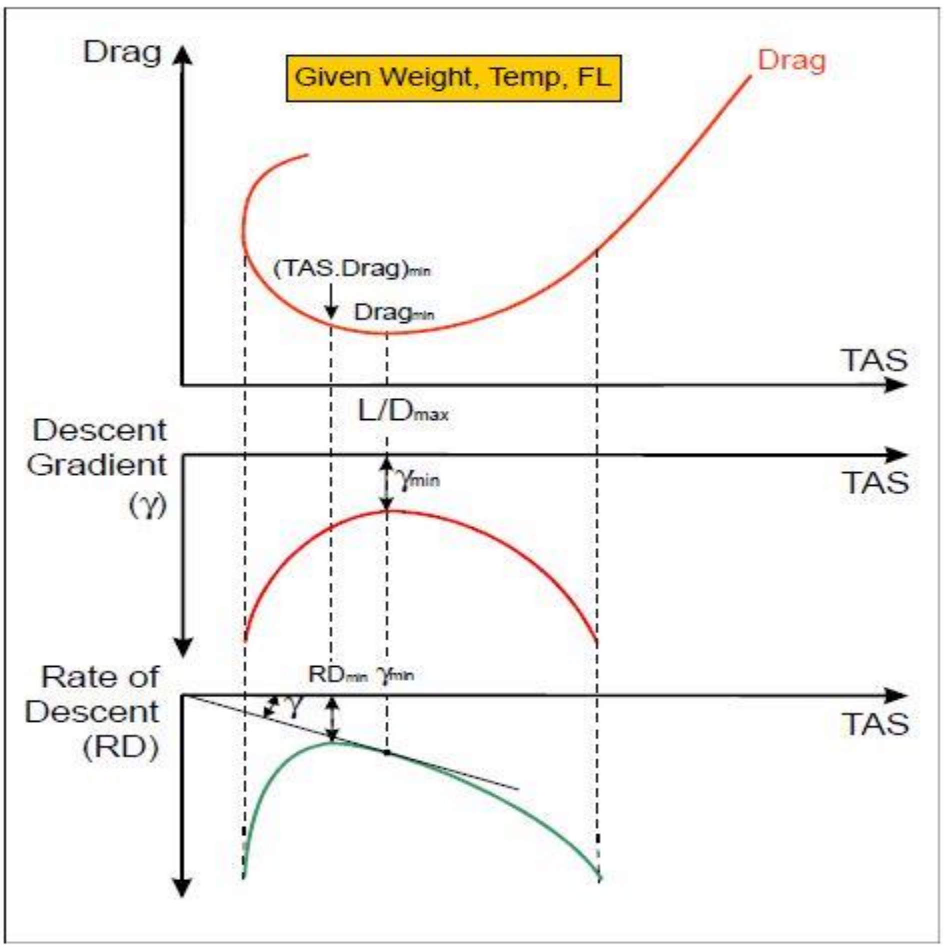


Figure A. 2. Drag Curve and Speed Polar [36]

A . 5 Influencing Parameters

A .5. 1 Altitude Effect

During the descent phase, air density increases, so that for a given aircraft weight and a given true air speed, the drag force also increases. As the descent gradient and rate of descent are proportional to drag, an increase in their magnitude should be observed.

Nevertheless, as the descent is never performed at a given TAS, but at a given Mach or a given IAS, it is not possible to conclude. The following figure (A.3) represents the evolution of the descent gradient and the rate of descent, versus the altitude for a given descent profile M0.82/300 knots /250 knots.

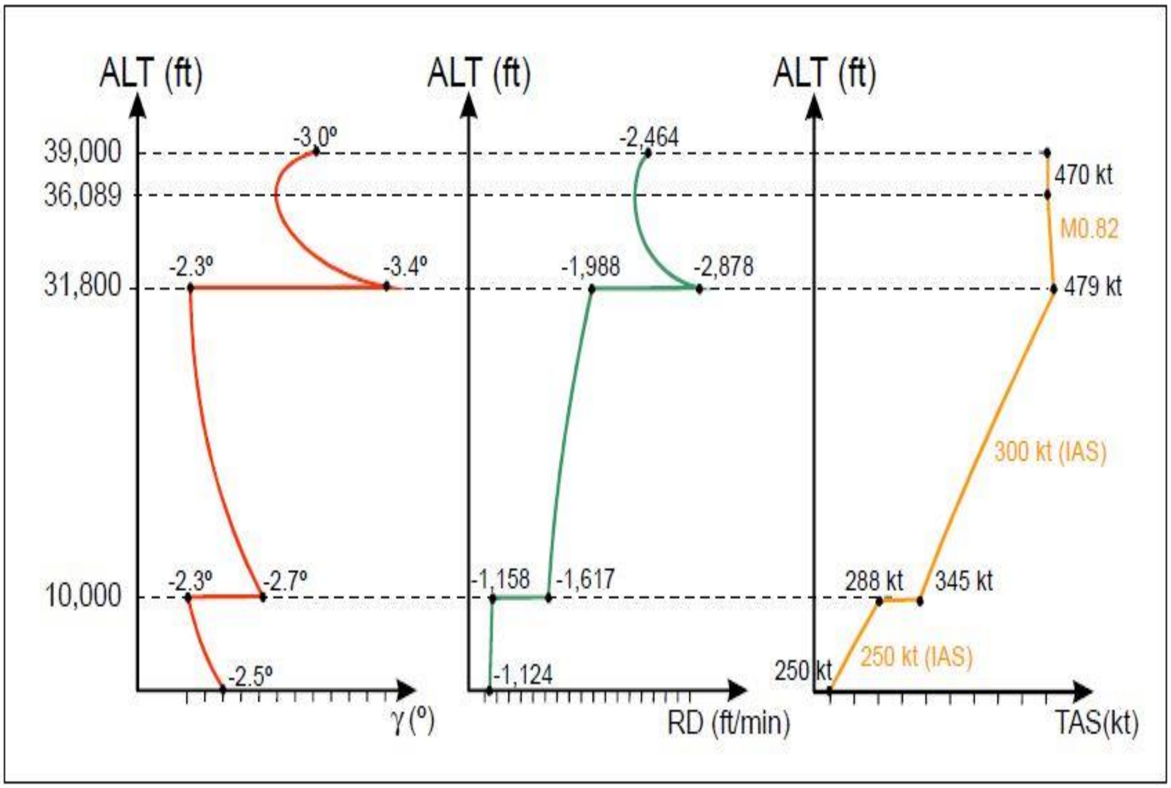


Figure A. 3. A330 example- Descent Gradient (**γ**) and Rate of Descent (RD) versus Altitude and TAS [36]

It is quite difficult to assess descent parameters (gradient and rate), as they only depend on drag and not on thrust (which is assumed to be set to idle)

A .5. 2 Temperature Effect

As for pressure altitude, the temperature effect is difficult to assess. Indeed, at a given altitude, an increase in temperature causes a reduction in air density. As a result, drag also decreases, and it could be convenient to conclude that the magnitude of the gradient at rate of descent is thus reduced.

Nevertheless, the TAS is not constant during the descent. For a given Mach or IAS, TAS increases with temperature, thus compensating for drag reduction. This is why descent parameter variations versus temperature are not really significant.

A .5. 3 Weight Effect

Green dot speed (minimum gradient) is a function of weight. Figure (A.4) below shows that, in the standard descend speed range (from green dot to VMO), the rate and gradient of descent magnitudes are reduced at higher weights.

Indeed, the balance of forces during descent indicates that:

$$L = mg * \cos\gamma \;=\; {}^{1}\!/_{2}\, \rho * S * TAS^2 * C_L \qquad \text{(A.12)}$$

At a given TAS, a higher weight means that a higher lift coefficient (C_L) is needed to maintain the balance of forces. This is achieved by increasing the angle of attack (α) and reducing the descent gradient (γ). As $RD = TAS * \gamma$, the rate of descent is also reduced at higher weights.

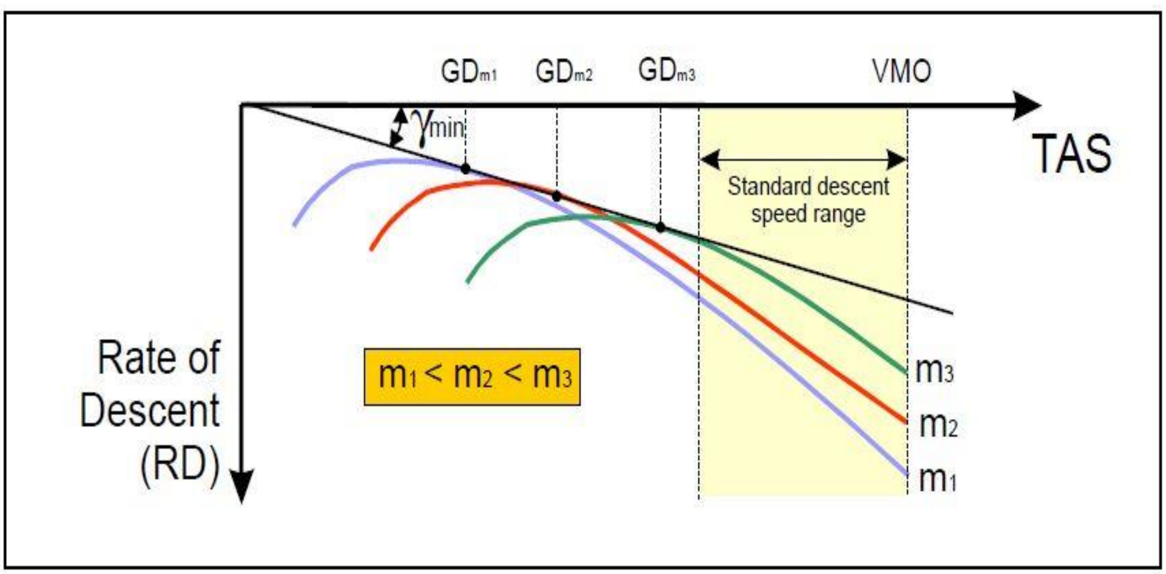


Figure A. 4. Gradient and Rate of Descent versus speed and Weight [36]

As a conclusion, in the standard descent speed range:

Weight ↗ ➡ Descent gradient ↘

Rate of descent ↘

A .5. 4 Wind Effect

As shown in the figure (A.5) below, the air gradient (γ_a) remains unchanged, whatever the wind component. So, the fuel and time necessary to descend from the Top of Descent (ToD) to the final level remain unchanged.

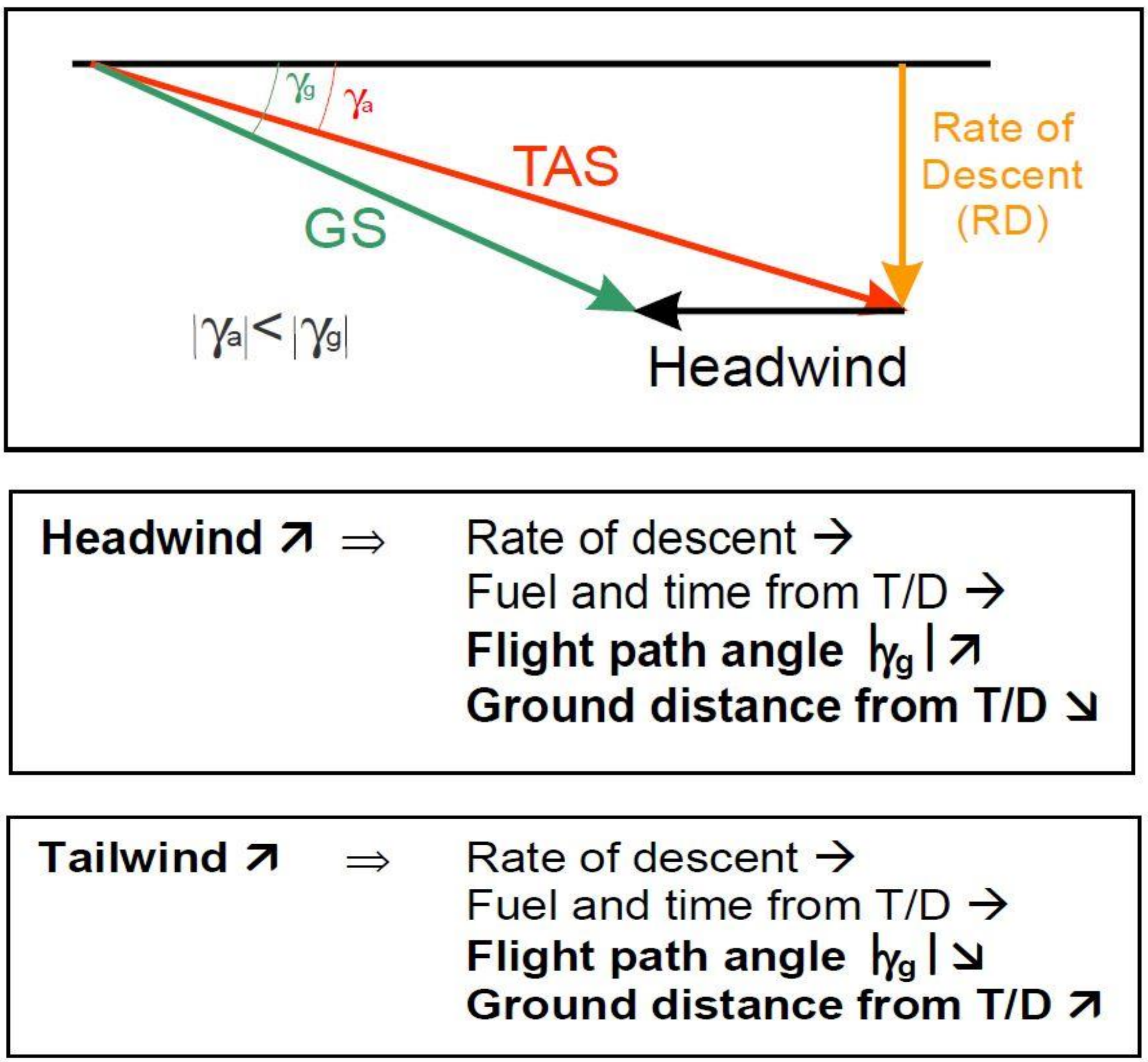


Figure A. 5. Wind effect of different parameters for head and Tail wind [36]

Appendix B : BADA 3.6

(ASCII—American Standard Code for the Interchange of Information)

Base of Aircraft Data (BADA) is an aircraft performance database based on the kinetic approach developed and maintained by the Eurocontrol Experimental Centre (EEC). BADA is a collection of ASCII files which specifies operation performance parameters, airline procedure parameters and performance summary tables for 295 aircraft types. This information is designed for use in trajectory simulation and prediction algorithms within the domain of Air Traffic Management (ATM).

BADA 3.6 provides operations and procedures data for a total of 2295 aircraft types. For 91 of these aircraft types, data is provided directly in files. These aircraft types are referred to as being directly supported. For the other 204 aircraft types, the data is specified to be the same as one of the directly supported 91 aircraft types. This second set of aircraft types is referred to as being supported through equivalence.[11]

B . 1 BADA Files

BADA consists of different types of files with different set of parameters in it. File structure describes the files in which the BADA aircraft parameters are maintained. Five types of files are identified:[11]

- Synonym Files listing the supported aircraft types
- Operations Performance Files (OPF) containing the performance parameters for a specific type
- Airline Procedure Files (APF) containing speed procedure parameters for a specific aircraft type
- Performance Table Files (PTF) containing summary performance tables of true air speed. Climb/ descent rates and fuel consumption at various flight levels for a specific aircraft type
- Global Parameters File (GPF) containing parameters that are valid for all aircraft or a group of aircraft for instance all turboprops or all military aircraft.

B . 2 BADA Model Overview

B .2. 1 Model Structure and Main Features

The APM adopted by BADA is based on a mass-varying, kinetic approach. This approach models an aircraft as a point and requires modeling of underlying forces that cause aircraft motion. The structure of BADA APM is represented in figure (B.1)

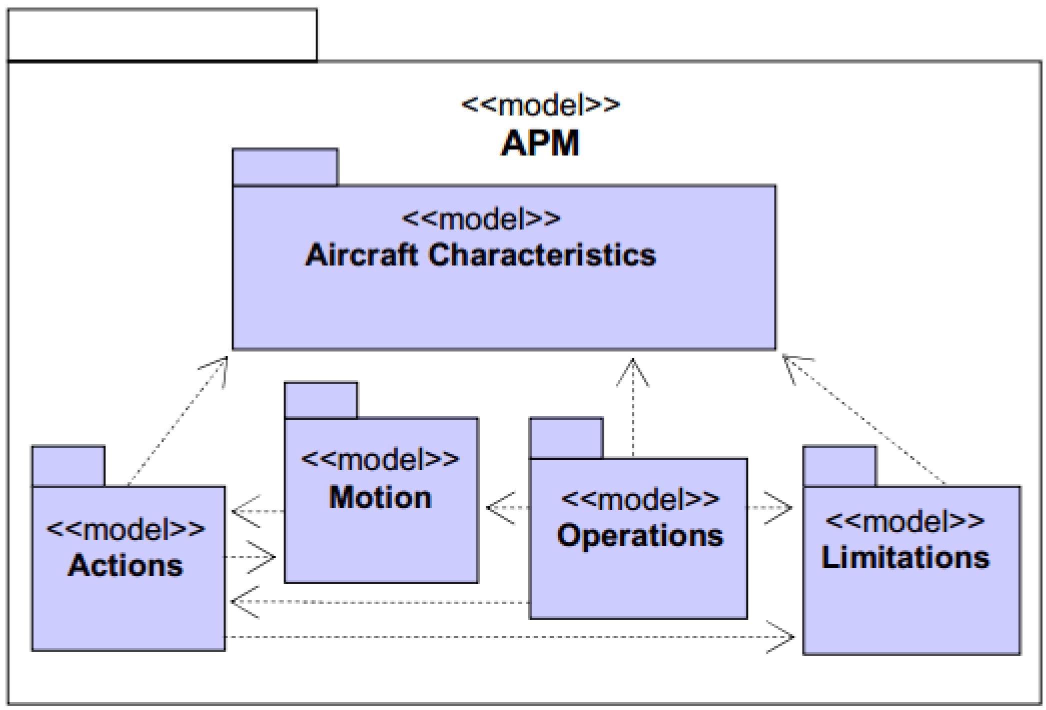


Figure B. 1. BADA model structure and features[11]

As we can see in the above figure (B.1), the BADA APM model is divided in 5 different models, namely Actions, Motion, Operations, Limitations and Aircraft characteristics. The dependencies among the models are represented with dashed arrows (which point towards the models that the one at the origin of the arrow depends upon).

B .2. 2 Actions

This model allows computing the forces acting on the aircraft which cause its motion. There are three categories of actions: aerodynamic (namely drag D and lift L), propulsive (thrust T) and gravitational (weight W). Since BADA accounts for mass variation, the propulsive model provides an associated model to compute fuel consumption F.

B .2. 3 Motion

Total Energy Model or TEM relates the geometrical, kinematic and kinetic aspects of the aircraft motion, allowing the aircraft performances and trajectory to be calculated. TEM equates the rate of work done by forces acting on the aircraft to the rate of increase in potential and kinetic energy, that is:

$$(T - D).V = mg.\dot{h} + m.V.\dot{V} \tag{B.1}$$

Where h is altitude, $\dot{h}$ is vertical speed, V is true airspeed and m is aircraft mass. To facilitate calculations, equation (B.1) can be rearranged and vertical speed expressed as

$$\frac{dh}{dt} = \left[\frac{(T - D).V_{TAS}}{mg}\right].V.ESF \tag{B.2}$$

Where g is the gravitational force and Energy Share Factor

$$\mathrm{ESF} = (1 + \frac{V}{g}\frac{dV}{dh})^{-1} \tag{B.3}$$

The variation of mass is accounted for through the fuel consumption model:

$$\dot{m} \ = -F \tag{B.4}$$

Equations (B.2) and (B.4) together form an Ordinary Differential Equations (ODE) system which can be posed with the respective initial or boundary conditions at each flight segment to compute the aircraft trajectory is, then the result of concatenating the solutions of a sequence of such motion problems.

B .2. 4 Operations

Although the ODE system above governs any possible motion, different ways of operating the aircraft result in different trajectories. For instance, flying constant Mach number leads to the following specific form of equation (B.3)

$$ESF \ = \ (1 + \frac{\kappa.R.\beta}{2g}.M^2)^{-1} \tag{B.5}$$

Where κ is the air adiabatic index, R is the specific gas constant, β is the temperature gradient of the particular atmosphere layer considered, M is Mach number.

Analogously, flying constant calibrated airspeed (CAS) leads to different form of equation (B.3) and so on for other flight regimes other than constant CAS/ Mach. The operational model is responsible for capturing those aspects (such as ESF), which are neither directly related to actions nor motion laws, but which are necessary to incorporate into the problem of computing aircraft motion, the knowledge about the way in which the aircraft is operated.

The operations model is conceived to fill the gap between Actions and motion models. Thus, provided that the way of operating the aircraft is known (e.g constant CAS), the Operations model provides the features that are needed to bring actions and motions together thereby closing the mathematical problem to compute the resulting aircraft trajectory. E.g. the model expressed in Equation (B.5)

B .2. 5 Limitations

Limitations restrict the aircraft behavior in order to keep it between certain limits to safeguard the safe operation of the aircraft, or limit the equipment degradations. The applicable limitations have been classified into four categories, namely geometrical, kinematic, dynamic and environmental. Geometrical limitations include the maximum certified altitude, maneuver limited altitude etc. Kinematic limitations refer to speed limitations such as maximum operation airspeed/ Mach (VMO/MMO), low and high speed buffet, landing gear and flaps speed limits and the speeds that serve to define maneuver envelope. Dynamic limitations include throttle limits for standard rating and aircraft weights such as the maximum takeoff weight (MTOW), maximum payload (MPL) etc. Finally, environmental limitations include stand for the environmental envelope.

B .2. 6 Aircraft Characteristics

Each aircraft is described with a set of coefficients which represent characteristics used by the previous models, but that are intrinsic to the aircraft, such as the aerodynamic reference area, wingspan, etc.

Appendix C : Runway Capacity Assessment FAA method

In this section detailed explanation of the procedures to calculate the runway capacity using FAA method is presented.[9] [37]

Hourly capacity can be calculated as follows:

1. Select the runway-use configuration that is available in [] which best represents the use of the airport during the hour of interest.
2. Select the Figure number for capacity
3. Determine the Percentage of Class C and D aircraft operating on the runway component and calculate the mix index
4. Determine Percent of arrivals
5. Determine the hourly capacity base from graph (C*)
6. Determine the percentage of tough and go operations during VFR operations and determine the touch and go factor (T). Note: In the case of IFR touch and go factor is 1
7. Determine the location of exit taxiways (measured from the threshold at the approach end of the runway) and determine the exit factor (E)
8. Calculate the hourly capacity of the runway component with

$$C = C^{*}.T.E \tag{C.1}$$

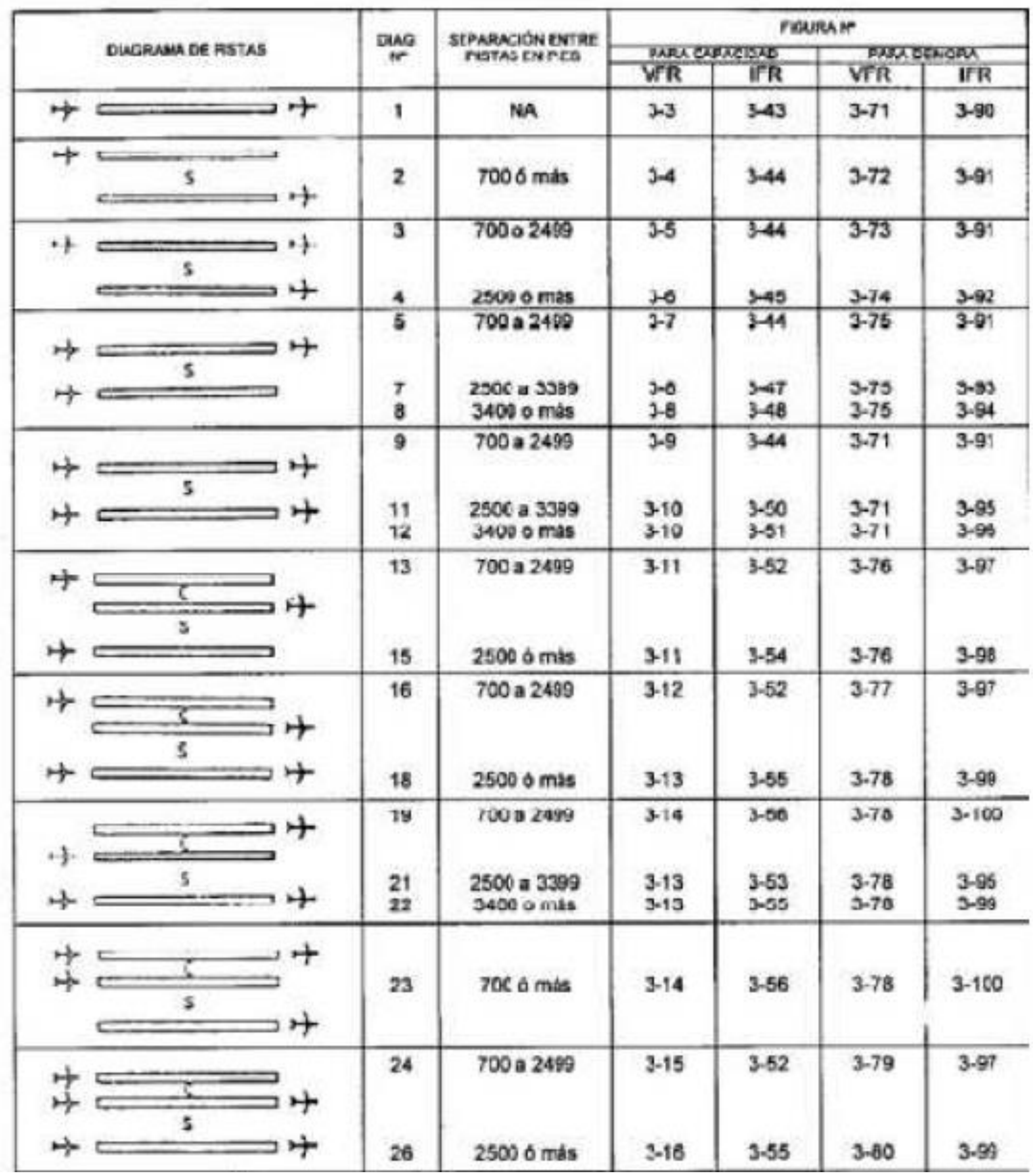


DIAGRAMA DE PISTAS	DIAG Nº	SEPARACIÓN ENTRE PISTAS EN PIES	FIGURA Nº PARA CAPACIDAD		FIGURA Nº PARA DEMORA	
			VFR	IFR	VFR	IFR
	1	NA	3-3	3-43	3-71	3-90
	2	700 ó más	3-4	3-44	3-72	3-91
	3	700 a 2499	3-5	3-44	3-73	3-91
	4	2500 ó más	3-6	3-45	3-74	3-92
	5	700 a 2499	3-7	3-44	3-75	3-91
	7	2500 a 3399	3-6	3-47	3-75	3-93
	8	3400 o más	3-8	3-48	3-75	3-94
	9	700 a 2499	3-9	3-44	3-71	3-91
	11	2500 a 3399	3-10	3-50	3-71	3-95
	12	3400 o mas	3-10	3-51	3-71	3-96
	13	700 a 2499	3-11	3-52	3-76	3-97
	15	2500 ó más	3-11	3-54	3-76	3-98
	16	700 a 2499	3-12	3-52	3-77	3-97
	18	2500 ó más	3-13	3-55	3-78	3-99
	19	700 a 2499	3-14	3-56	3-78	3-100
	21	2500 a 3399	3-13	3-53	3-78	3-96
	22	3400 o más	3-13	3-55	3-78	3-99
	23	700 ó más	3-14	3-56	3-78	3-100
	24	700 a 2499	3-15	3-52	3-79	3-97
	26	2500 ó más	3-16	3-55	3-80	3-99

Figure C. 1. Runway Use diagram [37]

As we can see in Annex E that the Vilnius airport has one Runway which is used for both arrival and departure purpose, therefore the diagram that best suits our case is diagram no 1. Now, we need to proceed for the calculation of Percentage of Class C and D aircraft operating on the runway component and calculate the mix index. To do this, arrival traffic for the month of august 2014 and September 2014 is taken and the average of class C aircrafts and class D aircrafts is taken and finally the mix index is calculated using the following formula:

$$Mix\ Index = C + 3 * D \tag{C.2}$$

After analyzing the traffic we have obtained that the percent of C class aircraft operating in Vilnius airport is 96.82 while there is insignificant presence of D class aircraft. Therefore the mix index is of **96.82.**

For the calculation of percent of arrivals the following formula is used

$$PA = \frac{A + 0.5(T\&G)}{A + DA + T\&G} * 100 \tag{C.3}$$

Where, A= Number of Arriving aircraft in the hour

DA= Number of Departing aircraft in the hour

T&G= Number of T&G in the hour

In this case, due to the lack of information regarding the number of aircrafts that do T&G and moreover its effect is reasonably low in the above equation, the touch and go factor is neglected. Therefore we obtain **PA = 50.36%**

Using the above obtained PA **and** mix index we can calculate the C* using the figure (C.2). For the calculation of hourly capacity the following relation is used

$$C = C^{*}.T.E \tag{C.4}$$

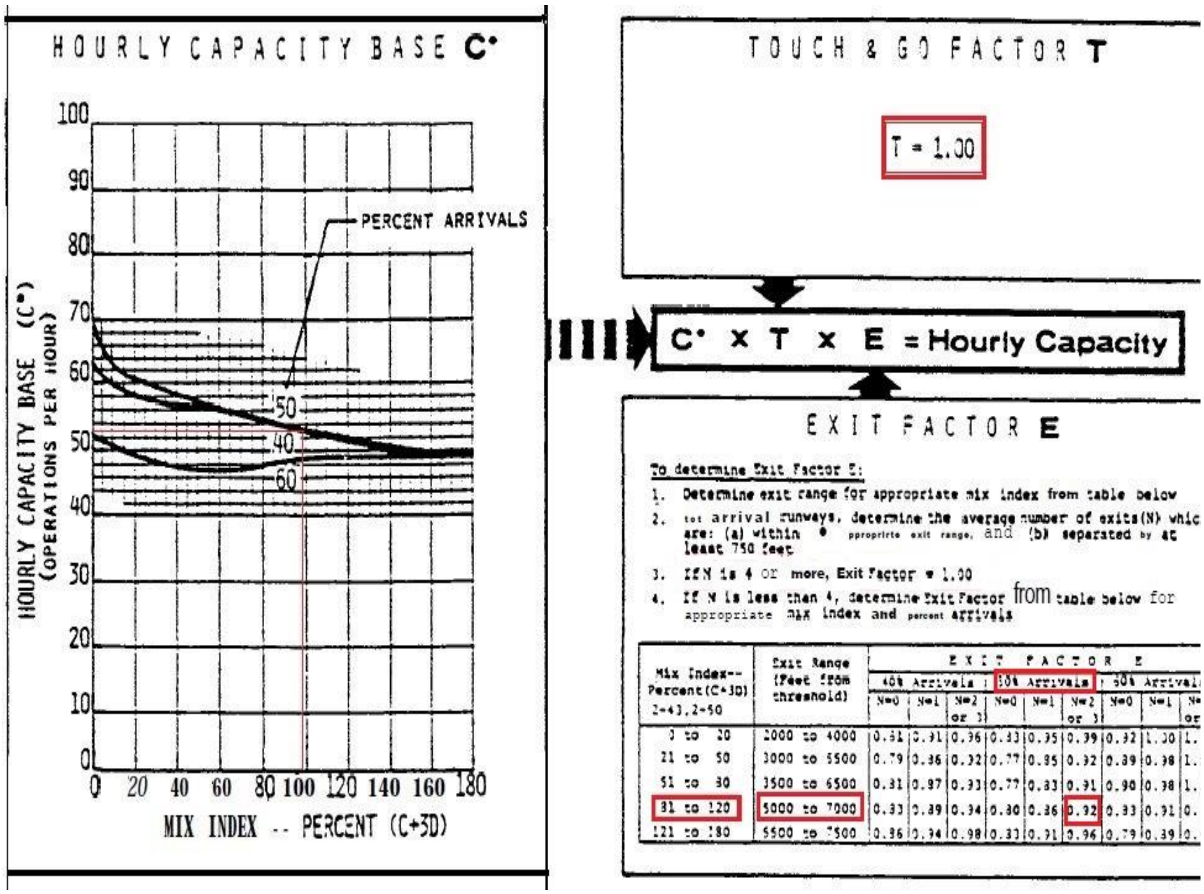


Figure C. 2. Vilnius Airport capacity calculation [37]

As we are only calculating the capacity for the IFR case, the Touch and go factor is supposed to be 1. Using the table provided in figure (C.2) we can calculate the exit factor (E). Exit factor is calculated using the mix index and the distance to the taxiway from the threshold at the approach end of the runway. As the number of exit taxiway is 2 and are within the range of 5000ft-7000ft, the exit factor is 0.92.

Therefore the capacity of the runway is,

$$C = 51.1.0.94 = 46\frac{Ops}{Hour}$$

Appendix D: Software Used, Database and Input Files

D . 1 Software's used

In order to complete the thesis successfully a series of software's are used. Some of them are MATLAB R2013a, NEST and Minitab17

D .1. 1 MATLAB R2013a

MATLAB® is the high-level language and interactive environment used by millions of engineers and scientists worldwide. It lets you explore and visualize ideas and collaborate across disciplines including signal and image processing, communications, control systems, and computational finance.

It has a lot of utilities and high capability for numeric computation, data analysis and visualization, Programming and algorithm development and application development and deployment. However, in this thesis it is used as a major tool for the development of the trajectory prediction simulator. Its capability for the high speed data processing and its simple programming language made it suitable software for the development of the simulator.

D .1. 2 NEST (Network Strategic Tool)

NEST is a single simulation tool for network capacity planning and airspace design-resulting from the merge of SAAM and NEVAC. It is a stand-alone desktop application combines the powerful airspace design capabilities of SAAM with the capacity analysis functionalities and user-friendliness of NEVAC.

NEST is s scenario-based modelling tool used by the EUROCONTROL Network Manager and the Air Navigation Service Providers (ANSPs) for the following purpose. [39]

- Designing and developing the airspace structure
- Planning the capacity and performing related post operations analyses
- Organizing the traffic flows in the ATFCM strategic phase
- Preparing scenarios to support fast and real-time simulations
- For ad-hoc studies at local and network level

NEST is used to optimize the available resources and improve performance at network level. In this thesis it is basically used to filter the arrival and departing traffic. Moreover, it is used to find out the route that a particular aircraft flies once it enters the Lithuanian Airspace and finally it was also used to find the STAR that was used during its arrivals of the aircrafts. [39]

D .1. 3 Minitab17

Minitab is powerful statistical software which is capable of solving difficult statistical problems and is capable of plotting the necessary graphs for its easy interpretation. In this thesis, it is used to do the paired t-test and calculate the p- value of the obtained predicted time from the TP simulator.

D . 2 STATFOR Database

The EUROCONTROL Statistical Forecasting service (STATFOR) processes air traffic statistics at European and regional level, from (inter alia) CFMU and CRCO data, and produces traffic forecasts. These forecasts take into account different sets of assumption, e.g. economic growth, airline productivity, competition from other means of transport, as well as the ‘maximum aircraft movements per year’ at congested airports. [38]

The STATFOR medium term traffic forecasts are based on ”traffic flows” between a number of Origin/ Destination Zones (ODZ). An ODZ corresponds to a major airport or group of airports. STATFOR provides traffic growth forecasts for different ODZ pair and for the countries overflown. At present STATFOR models approximately 100 individual ODZ pairs giving around 9000 individual flows.

STATFOR also provides a short term traffic forecast. This, combined with the alternative capacity profiles based on the high and low traffic forecast, enables ANSPs to formulate capacity plans according to local traffic requirements and variations. [38]

D . 3 Input files

As mentioned in the chapter (5.1.1), in this part the details on the parameters of the input files are given.

Navigation Waypoints file

This text file consist the list of all the Navigation waypoints with their coordinates, that are in Lithuanian airspace and which are correspondingly liked with the STAR 02.

waypoint	Latitude	Longitude
BOKSU	541827.0N	0230333.0E

D .3. 1 STAR file

This text file consist the list of waypoints that form a leg of the given STAR02. Apart from the waypoints it has the heading and flight-level information for that particular leg.

Waypoint 1	Waypoint 2	Heading	FL1	FL2
BERIL	IKAMU	146.3	220	190

In the above example, in order to fly from BERIL to IKAMU; an aircraft must fly with the heading 146.3 degrees and it needs to be at FL 220 at BERIL and descend till FL190 until reaching IKAMU.

D .3. 2 FIR file

This text file consist the list of all the waypoints that for a leg and that bound a space for the Vilnius Flight Information Region.

Waypoint 1	Waypoint 2
UTENU	TAGOL
TAGOL	MURUN

D .3. 3 Arrival file

This text file contains the flight plan information for the arrival traffic of Vilnius Airport.

1	2	3	4	5	6	7	8
B738	M	953	BOKSU	953	1012	LIRA	740

Now in this part all up listed parameters are explained in detail

1. **B738** :- Type of Aircraft
2. **M** :- Wake turbulence category, in this case M refer to medium category
3. **953** :- Entry time to Lithuanian Airspace (9:53 Hours)
4. **BOKSU** :- Entry point to Lithuanian Airspace
5. **953** :- Entry time to Lithuanian Airspace sector (9:53 Hours)
6. **1012** :- Arrival time to the Vilnius Airport (10:12 Hours)
7. **LIRA** :- ICAO code of the Airport of origin
8. **740** :- Departure time from the airport of origin (7:40 Hours)

D .3. 4 Aircraft Performance File

This text file consist the information on the performance parameters of a given aircraft.

FL	TAS (Kts)	ROCD	Fuel flow	Area
080	280	1660	8	122.6

100	289	1700	7.8	122.6
120	367	2600	7.6	122.6

The above example is taken for an aircraft A320 and the performance parameters listed is extracted for descent phase from the BADA 3.6 database.

Appendix E : Aerodrome and STAR charts

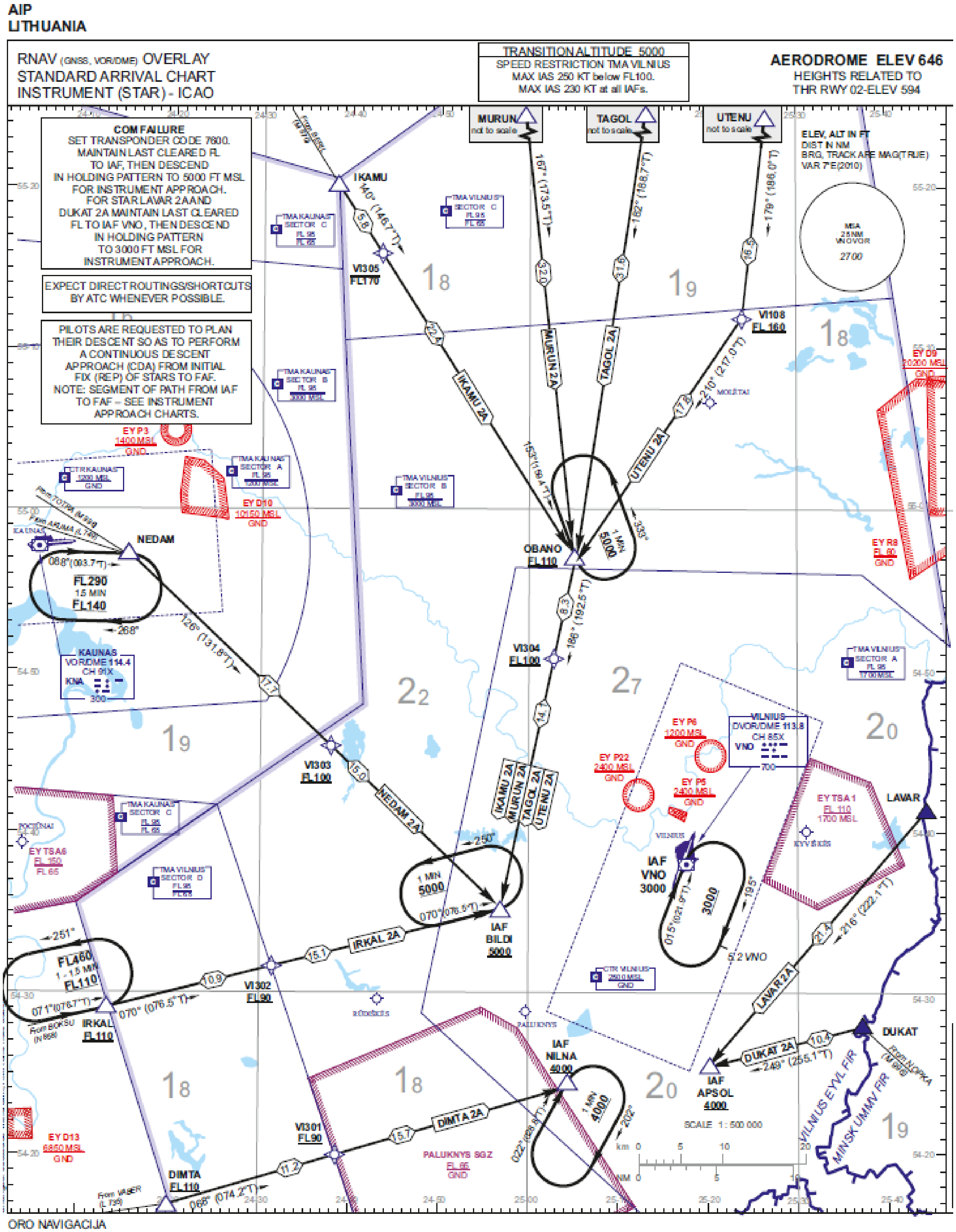


Figure E. 1. STAR 02 Vilnius Airport

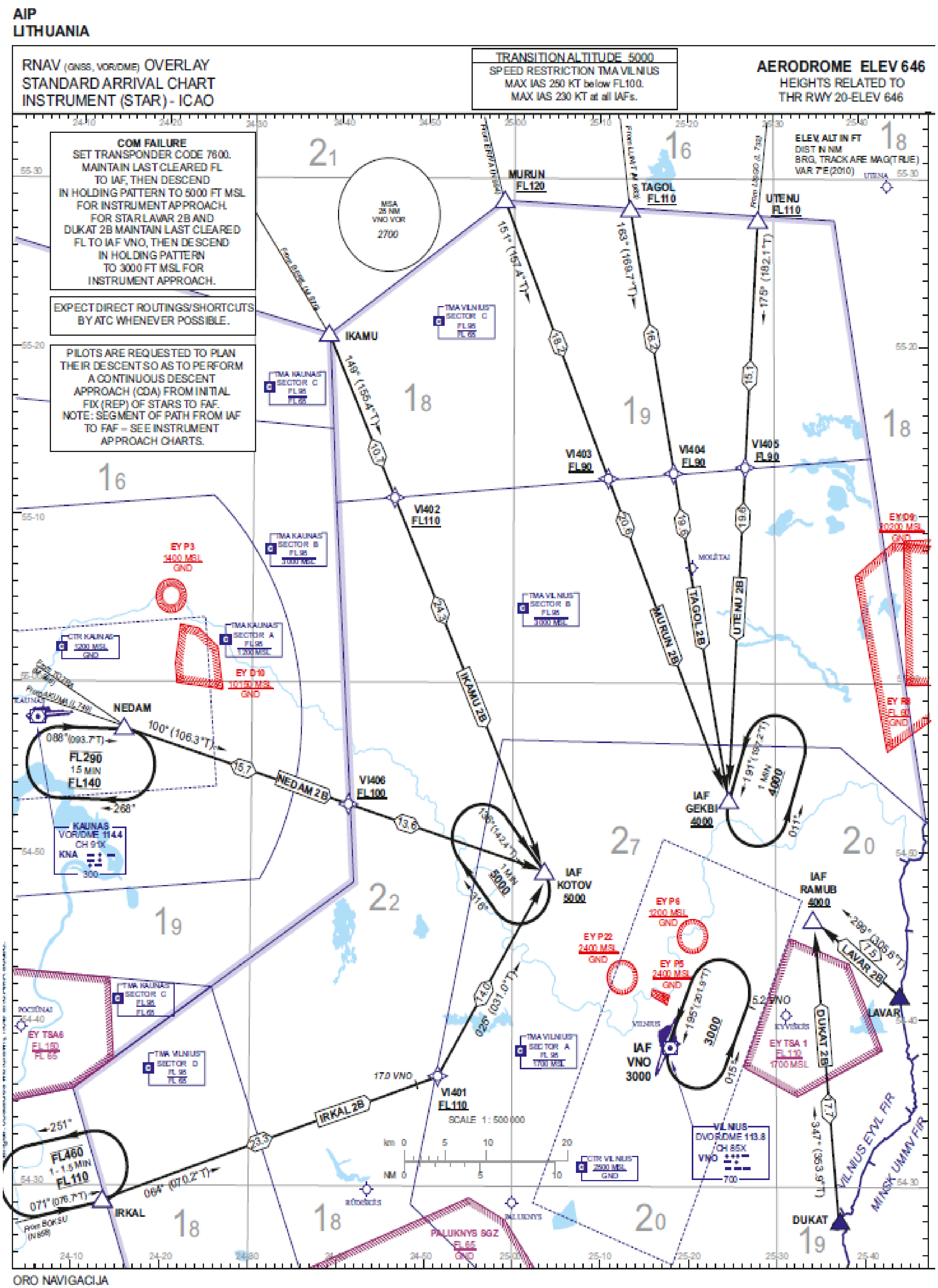
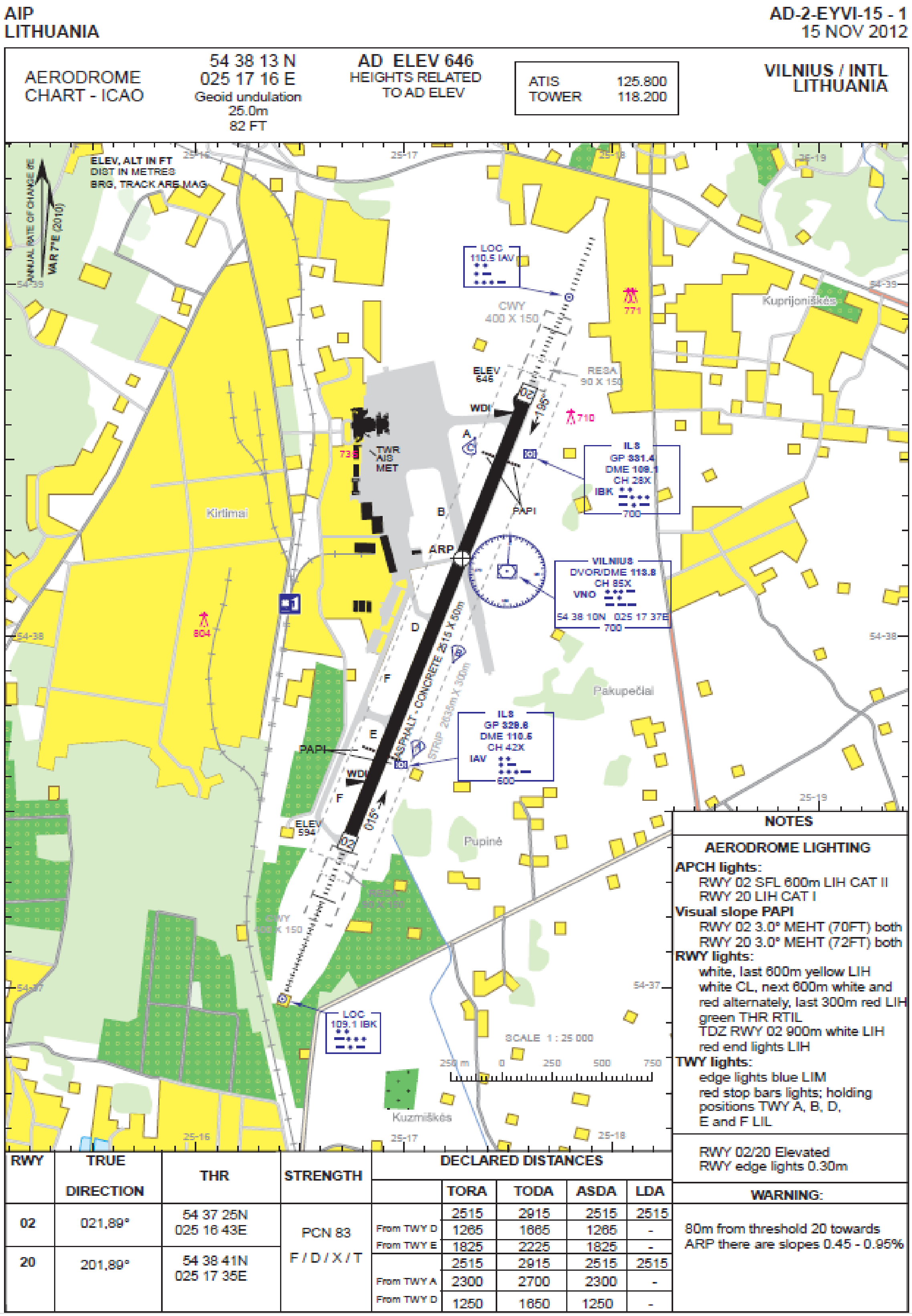


Figure E. 2. STAR 20 Vilnius Airport



RWY	TRUE DIRECTION	THR	STRENGTH	DECLARED DISTANCES	TORA	TODA	ASDA	LDA
02	021,89°	54 37 25N 025 16 43E	PCN 83 F / D / X / T		2515	2915	2515	2515
				From TWY D	1265	1665	1265	-
				From TWY E	1825	2225	1825	-
20	201,89°	54 38 41N 025 17 35E			2515	2915	2515	2515
				From TWY A	2300	2700	2300	-
				From TWY D	1250	1650	1250	-

Figure E. 3. Aerodrome chart Vilnius Airport

Appendix F : Obtained results from TP Simulator

Below is the table representing the initial flight plan time and the predicted time for different arriving aircraft which are represented in second. It is also presented the model of aircraft involved, entry waypoint and the entry time.

Aircraft	Entry Point	Entry time	Initial Flight plan Time	TP simulator time
TRIN	BOKSU	3:40	1920	1836
B738	LAVAR	4:32	660	420
B733	BOKSU	4:28	1080	926
E145	LUNIT	5:15	1260	1313
CRJ1	DUKAT	5:35	480	328
E145	LUNIT	5:56	1320	1313
DH8C	ERIVA	7:09	1620	1767
B738	BERIL	7:13	1440	1496
E145	LUNIT	7:24	1260	1313
SB20	BERIL	7:37	1620	1580
CRJ1	BALIT	7:38	2220	2188
A320	BOKSU	8:24	1080	876
B738	BOKSU	8:26	1080	921
CRJ1	BOKSU	8:42	1140	909
PA27	BOKSU	8:37	1500	2142
A320	DUKAT	9:22	300	323
AT75	LAVAR	9:36	660	520
F70	BOKSU	9:33	1080	932
E145	BOKSU	9:43	1140	984
CL60	BOKSU	9:45	1200	919
B738	BOKSU	9:53	1140	921
A320	BOKSU	10:00	1020	876
B733	BERIL	10:24	1560	1501
DH8C	ERIVA	10:38	1500	1767
A321	BOKSU	10:56	1080	890
E145	BOKSU	11:30	1140	984
E145	BOKSU	11:46	1020	984
CRJ1	BALIT	11:54	2160	2188
B735	DUKAT	13:08	540	328
A320	LUNIT	12:55	1560	1141

Aircraft	Entry Point	Entry time	Initial Flight plan Time	TP simulator time
E145	BOKSU	13:47	1080	984
B735	ERIVA	13:44	1440	1353
A320	TIRIN	13:42	1860	1707
SB20	BERIL	13:58	1620	1580
E145	LUNIT	14:28	1560	1313
E145	BOKSU	15:08	1080	984
D228	DUKAT	15:27	300	552
A320	DUKAT	15:51	480	323
A320	BOKSU	15:44	1140	876
E145	LUNIT	15:51	1080	1313
B735	LAVAR	16:53	600	425
DH8C	ERIVA	16:50	1680	1767
E145	LUNIT	17:18	1380	1313
B733	ERIVA	17:56	1440	1353
B738	BERIL	18:00	1500	1496
A320	DUKAT	18:20	480	323
LJ35	BOKSU	18:18	900	886
B738	BALIT	18:19	2460	2108
B738	BOKSU	18:46	1320	921
A320	LAVAR	18:59	660	397
A320	DUKAT	19:46	420	323
A320	BOKSU	19:44	900	876
A320	BOKSU	19:57	1020	876
E145	BOKSU	20:10	1020	984
CRJ1	LAKOD	20:09	1200	982
SB20	BERIL	20:10	1680	1580
B733	ERIVA	20:24	1260	1353
E145	BOKSU	21:10	1020	984
E145	BOKSU	21:48	1080	984
A320	BOKSU	22:02	1080	876