Optimization of RNAV Departure Procedures
With Respect to Environmental Criteria

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Abstract

In recent years, air traffic has shown an exponential growth, a result of the increasing demand for air transportation. This growth has led to environmental concerns regarding keeping air transportation sustainable, with aviation noise at the forefront of these concerns. To answer these concerns, aviation regulators have imposed new rules and certifications to make sure that noise levels do not overstep safety thresholds, as that would be hazardous to public health.

In parallel, and also as consequence of the increasing demand for air transportation, Lisbon's main airport, Humberto Delgado, is expected to experience higher demand than it can currently deal with. One solution that is currently being explored in order to tackle this issue is the use of Air Base No. 6 of Montijo - currently a military air base - as an auxiliary aerodrome as a way to add to Humberto Delgado airport's maximum capacity.

With all of this in mind, in this dissertation, departure trajectories were designed for Montijo's Air Base with emphasis on Noise Abatement, as an academic study of the noise section of this on-going project. For this purpose a detailed noise model was developed, capable of modelling any desired trajectory and calculating the noise levels it creates for nearby communities. Furthermore, an analysis was made to assess the impact noise has on those communities. After a thorough research on common Noise Abatement Procedures, some of these were applied and compared between themselves based on that criteria.

Keywords: Aviation Noise, Noise Abatement Procedures, Montijo (LPMT), Portela+1

1 Introduction

1.1 Context

Several tools have been developed to facilitate the study of noise, such as the design of Noise Contours, which assess the impact of noise in different regions around an airport, based on different operations throughout the day. For this to happen, it is necessary to use mathematical models capable of making simulations of any procedure based on real data to design realistic maps, avoiding the need to do practical tests of those procedures. As a complement to these maps, GIS (Geographical Information Systems) can be used as they contain valuable information about the population on a certain area, which allows to clearly differentiate the areas in which the population density is higher and the ones where it is lower. Naturally, it is preferable to have a lower noise impact in areas with a higher density.

With all this information, it becomes possible to implement algorithms of optimization of procedures with respect to environmental, population and economic criteria.

1.2 Problem Description

In Portugal, Lisbon's main airport Humberto Delgado (ICAO: LPPT) has reached 20 million passengers transported in 2015, which represents an increase of 10.7% in relation to the previous year. The number of movements in the airport has been equally increasing. [1] According to ANA, the Airport Authority of Portugal, an increase of the maximum number of movements per hour in Lisbon is to be expected for the near future, from the current 40 that the airport can operate to a total of 72. [2] In response to this expected increase, the solution that has been most considered is the usage of Montijo's military airbase as an auxiliary airport to Humberto Delgado's. This on-going national project is currently known as “Portela[1] +1”. As such, it is necessary to make the necessary studies that can enable and validate this solution. Due to the fact that noise can have a bigger impact over populations near an operating airport, this dissertation has the main objective of optimizing the departure trajectories with the aim of minimizing the noise impact over nearby populations.

For this effect, a noise model was developed, allowing to make simulations for different aircraft and assess the impact of noise for different operational procedures, in an accurate and convenient way; this model was used alongside a geographical information system of the region of Lisbon to define realistically optimized trajectories with respect to community annoyance near the airport.

1.3 Theoretical Background

1.3.1 Noise Measurement

There are different scales used for the measurement of noise, taking into account different frequencies and durations of noise patterns. One scale stands out for this study, as it represents the perception of human ear to noise. To reproduce the sensitivity of the ear to the mid frequencies, it is used a decibel scale corrected by an A-weighted filter, in such way to reduce the low and high frequency components of the given sound. This scale is called the A-Weighted Sound Level, L_A, being given in dBA.

The equivalent continuous sound level can also be defined, $L_{A_{eq}}$, representing the sensation with which the human ear effectively perceives sound during a time period T, and can be calculated using Equation (1-1). [3]

$$L_{A_{eq}} = 10 \times \log\left[\frac{1}{T}\int_0^T 10^{\frac{L_A}{10}} dt\right] \qquad (1\text{-}1)$$

The European Committee also proposed as an indicator of ambient noise the so called Day-Evening-Night Level, L_{DEN}, based on $L_{A_{eq}}$ throughout a whole day, with penalties for nighttime and evenings periods.

According to the World Health Organization (WHO), the threshold of annoyance to continuous noise is 50 dBA for L_{DEN}, and few people are disturbed by values up to 55 dBA. On the other hand, for the Organization for Economic Co-operation and Development (OECD), values above 65 dBA of L_{DEN} are unacceptable – the black regions of noise –, and levels from 55 to 65 dBA do not ensure acoustical comfort to residents in those areas – the grey regions. [3] [4]

1.3.2 Airport and Aircraft Operations

Current procedures are, in general, based in the use of ground navigation aids stations, infrastructures, and aircraft navigation system which enable navigating from one navaid to another. [5]

Modern operations are moving towards a new concept - the Performance-Based Navigation (PBN); it has the goal of facilitating airspace design, traffic flow and improved access to runways, providing a basis for designing and implementing new and more efficient flight paths. Additionally, this change allows for many more benefits, such as a better safety and more control of gaseous emissions and noise levels. [6]

An implementation of PBN is the use of Area Navigation (RNAV) in departure procedures to allow for a reduction of flight track dispersion in Standard Instrument Procedures (SID) was proposed to better contain noise contours. Area navigation (RNAV) is defined by Clausing [7] as “*a method of instrument flight rules (IFR) navigation that allows an aircraft to choose any course within a network of navigation beacons, rather than navigate directly to and from the beacons. This can conserve flight distance, reduce congestion, and allow flights into airports without beacons.*”

1.3.3 Noise Abatement Procedures

Noise Abatement Procedures (NAP) are a variety of flight procedures that can be situationally implemented with the aim of reducing or redistributing noise around an airport, both during approach and departure procedures, through different methods.

Knowing that the profile of a flight path is the vertical component of an aircraft trajectory (also known as its altitude), and the ground track is the projection of that trajectory onto the ground, there is a wide variety of methods to control a procedure in terms of noise impact, comprising of combined adjustments of the flight path’s ground track and profile in the most diverse ways, along with

[1] Until May 2016, this airport was known as Aeroporto da Portela.

adjustments in the power setting during the procedure, aimed to provide noise relief for some communities.

ICAO has also promulgated their standard profile NADPs (Noise Abatement Departure Procedures) to ensure that the necessary safety of flight operations is maintained while minimizing noise exposure on the ground. Its first procedure, ICAO-A, is aimed to provide noise reduction near the airport, as opposed to the ICAO-B procedure, which is aimed for distant communities, as represented in Figure 1-1. [8]

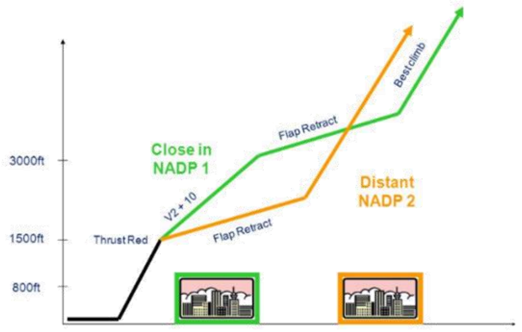

Figure 1-1 - ICAO-A (NADP1) and ICAO-B (NADP2) profile representations. [9]

2 Noise Model

The noise modeled developed was based on the recommendations present on the second volume of Document 29 by ECAC.CEAC [10] – Europe's largest and longest-standing aviation organization and part of the ICAO air transport global community, with the mission of promoting the continued development of a safe, efficient and sustainable European air transport system [11].

Typically, modelling systems comprise of three main elements, starting by an input of airport and aircraft data, such as the runway heading, the aircraft's engines' and flaps' coefficients, and a set of procedural steps to be modelled. The model then processes the given input and converts it into a flight path, which is then used to calculate the resulting noise levels to observers located in the ground, and create a noise contour around the given airport. Several flights can also be modelled throughout a period of 24h to calculate the L_{DEN} resulting from the modeled flights.

2.1.1 ANP Database

The ANP database is an international online data resource to be used for airport noise contour modelling purposes, being frequently updated and currently the most commonly used database for noise modeling [12]. It contains aircraft and engine performance coefficients for a wide range of commercial aircraft; this information is supplied by the manufacturers and database managers themselves.

2.2 Aircraft Performance

One of the most important parameters needed for the definition of a flight path is the propulsive force produced by each engine of the aircraft. For aerodynamic and acoustical calculations, this parameter is named the *Corrected Net Thrust* F_n/δ, and is given by:

$$\frac{F_n}{\delta} = E + F \cdot V_C + G_A \cdot h + G_B \cdot h^2 + H \cdot T \quad (2\text{-}1)$$

Where:

– F_n is the net thrust per engine [lbf];

– δ is the air pressure ratio, the ratio between the ambient air pressure at the aircraft's altitude and the standard air pressure at mean sea level $p_0 = 101.325$ kPa [13];

– V_C is the calibrated airspeed [kt];

– T is the ambient temperature at the aircraft's altitude [K]; and

– E, F, G_A, G_B, H are engine thrust constants or coefficients [lb, lb.s/ft, lb/ft, lb/ft^2, lb/K, respectively], obtained from the ANP database.

2.3 Flight Path Segmentation

A trajectory or flight path is defined as the full description of the motion of aircraft in space and time. Along with the net thrust evolution throughout the flight, it is the information required to calculate the noise resulting from an aircraft flying along any realistic departure path.

A segmentation method to describe the flight path was followed, approximating it by a series of contiguous straight segments both for the ground track and the profile of the aircraft. This approximation gives a good balance between computation times and noise accuracy, as suggested in ECAC Doc.29. This method is based on the use of the comprehensive ANP database.

Within the method of segmentation, it is possible to define a flight path based on a series of procedural steps used as an input These are instructions given to flight crews via AIPs[2] and aircraft operational manuals, consisting on specific instructions on the power and flaps settings, airspeeds, rate of climb and operations to follow in general.

2.4 Single Event Noise Calculation

The most common metrics used in modern aircraft noise indices is the single-event Sound Exposure Levels (SEL), L_E, which takes into account all the sound energy in an event. The maximum instantaneous level in the event, L_{max}, was also modeled as it is easier to model. Both of these were modeled in a different scale, using an A-Weighted filter to represent the human ear's sensitivity to the mid frequencies, resulting in L_{AE} and L_{Amax} respectively. [10]

The calculation of noise levels in each segment is based on tabulated data from the international ANP database, which gives values for L_{max} and L_E as functions of propagation distance d and the noise-related power parameter $P \equiv F_n/\delta$ for different aircraft, through NPD (Noise-Power-Distance) tables and curves, such as the one represented in Figure 2-1.

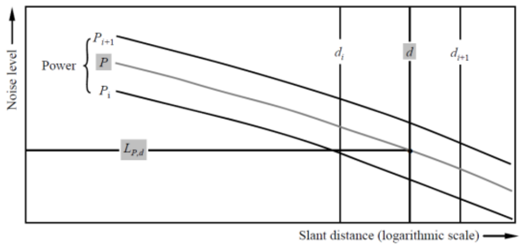

Figure 2-1 - Interpolation in a noise-power-distance curve. [10]

The data contained in this database is normalized to standard reference conditions, such as the weather conditions and the aircraft's groundspeed, and has to be corrected and adjusted for the conditions it is being used on.

2.5 Cumulative Noise Calculation

As stated, cumulative noise metrics such as L_{DEN} take into account multiple events throughout a period of time, including penalties of 10 dBA for nighttime flights (from 23h00 to 07h00) and 5 dBA for evening (from 19h00 to 23h00) periods, as given by Equation (2-2). [10]

$$L_{DEN} = 10 \log \left[\frac{t_0}{T_0} \sum_{i=1}^{N} g_i \times 10^{\frac{L_{E,i}}{10}} \right] + C, \quad (2\text{-}2)$$

Where:

– N is the number of aircraft noise events during the specified reference time period: $T_0 = 86400$ s.

– The level $L_{E,i}$ corresponds to the single event noise exposure level of the i-th noise event.

– The coefficient $g_i = 10^{\Delta i/10}$ is a time-of-day dependent weighting factor, varying between 1, 3.162 or 10 for day-time, evening, and night-time events respectively.

2.6 Noise Contour

For any of these metrics, a noise contour can finally be drawn for assessment of noise impact around an airport area. For this effect, a fixed-spacing or regular grid of fictional observers was created around the airport, and these noise metrics were calculated for each of those locations. The result is a matrix containing noise data at structured locations around an airport, with the center of each square representing the respective area.

3 Noise Impact on Communities

To assess the impact that aviation noise has on communities near an airport, a specific parameter was introduced. This parameter is defined as the sleep disturbance caused to a local community by a single flight operation, and is based on both the noise level received and the population density at the respective location. The aim is to reduce this parameter as much as possible around the airport by applying different noise abatement procedures and choosing the one which provides better results.

3.1 Awakenings

It is possible to introduce the concept of Awakenings, which gives a measure to quantify the sleep disturbance based on empirical data, under the definition that it is the upper bound to the number of people expected to awake due to a single nighttime flyover. This correlation between aircraft noise exposure and sleep disturbance was based on research done by the Federal Interagency Committee on Aviation Noise (FICAN) in 1997 [14]. The relationship, shown in Equation (3-1) and

[2] Aeronautical Information Publication contains the aeronautical information essential for air navigation.

graphically shown in Figure 3-1, gives the percentage of expected awakenings in the area.

$$\%Awakenings = \\ = 0.0087 \cdot (SEL_{indoor} - 30)^{1.79} \quad (3\text{-}1)$$

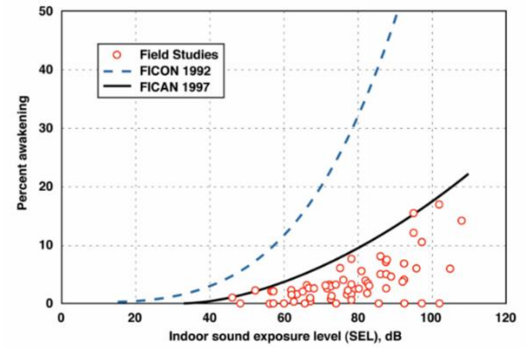

Figure 3-1 - FICAN proposed sleep disturbance dose-response relationship. [15]

This parameter can be combined with the population density in the same area from the GIS to obtain the exact number of people expected to awake due to a single nighttime flyover. It is relevant to mention that, since the individuals in question are assumed to be inside their home, the SEL value has to be corrected to the sound absorption of a typical home - which is around 20.5 dBA -, resulting in SEL_{indoor}. [16] [14]

3.2 Processing GIS

There are different databases and sources of GIS data. In this dissertation, all the population information was obtained from Portugal's National Institute of Statistics (INE), which contains data from a study made in 2011. For the purposes of assessing the sleep disturbance due to noise, the most important parameters is the population density, giving the average number of individuals in each location.

Keeping in mind that the aim here is to study the population density in certain areas, based on the noise contour grid developed, it was convenient to represent the GIS information in a regular grid with the same spacing and coordinates as the one in the noise model, instead of the irregular cells in which the original GIS information is defined.

4 Experimental Validation

In order to give meaning to any of the results obtained in any model, it is necessary to validate it first; in this case, it was essential to prove that the noise levels due to aircraft flights obtained from the model developed are accurate. For this purpose, noise levels due to real flights, measured at noise measuring stations, were compared to model predictions to assess the accuracy of the developed model.

This validation process is divided into two stages: the first one makes use of the original flight paths data, and uses them as input to calculate the resulting noise levels at the stations' locations; the second one attempts to simulate the respective flights through procedural steps and then calculates the resulting noise levels.

4.1 Noise Validation

For this effect, real flight data for a few flights was collected for LPPT, along with the noise levels measured in dedicated noise monitoring stations for different noise metrics.

This data was provided by TAP and ANA and includes two sets of three flights each. The first one corresponds to common departure procedures, contemplated in project ATAEGINA[3], departing from Lisbon's main airport, while the second set refers to modified procedures for noise studies. Since the data includes the aircraft's position, airspeed and engines parameters, it is possible to reproduce the exact flight path and use it for the application of the noise model.

Due to the lack of information about the weather conditions for the dates at which the flights occurred, standard conditions for air temperature, pressure and density were assumed. The error and the variance between the modeled noise levels and the real ones at each station were then calculated, and are plotted in function of the altitude in Figure 4-1. Analyzing these errors allows to predict further errors in other flights, and thus empirically correct the noise levels for any defined procedure; ideally, a higher number of real results is needed to improve the error prediction algorithm.

[3] Airline TriAls of Environmental Green flIght maNAgement functions is a project which includes Portuguese companies such as NAV Portugal EPE, ANA-Aeroportos de Portugal and TAP, aiming at developing systems which enable environmentally sustainable flight operations.

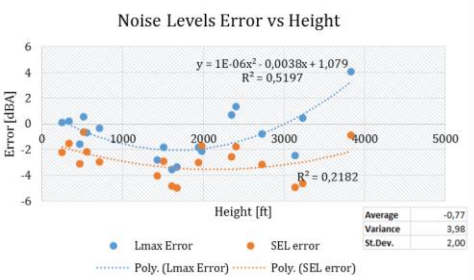

Figure 4-1 - Noise level error at monitoring stations.

The modeled values give a maximum deviation of around 5dB from the real value which, despite not being perfect, is enough to serve the purposes of this analysis given the lack of further information such as weather conditions, wind speed and direction or humidity.

A regression model was made using a second degree polynomial function to predict the error associated with the noise model for the referred interval. It is important to stress that due to the lack of available data, higher values for the coefficient of determination (R-squared) parameter, which typically defines how well the regression model predicts future outcomes, were not possible. Nonetheless, this error prediction algorithm is expected to increase the noise modelling accuracy regarding the noise levels within this interval in further procedures. Figure 4-2 shows a graphical representation of the average standard deviation in each station before and after the error prediction algorithm. A summary of the obtained results is given in Table 4-1.

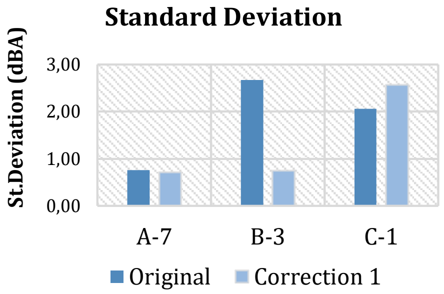

Figure 4-2 - Graphical representation of the standard deviation obtained for L_{max} each station.

– A-7 represents the station closest to the airport: the aircraft is still flying below 1,000 ft, as seen in the first cluster in Figure 4-1;

– B-3 represents the second station, and the aircraft is flying at around 1,500 ft in average;

– C-1 represents the station farther from the airport, with the aircraft flying above 2,000 ft in average at this point.

Table 4-1 - Overview for the errors of L_{max} in the original and the corrected model.

Overview		Original Model	Corrected Model
Mean [dBA]	$\mu = \frac{1}{N}\sum_i error_i$	-0.77	0.15
St. Deviation [dBA]	σ	2.00	1.33
Variance [dBA^2]	σ^2	3.98	1.77

Although there was not enough diversity in real noise levels available data, it was the most reliable way to validate the model and have an estimate of its accuracy for observers located at any distance from the flight path. Furthermore, the available data is restricted to these three stations, therefore any conclusion taken from these results and graphs are only significant for this interval.

4.2 Flight Path Validation

While the previous section could give a good estimate on the accuracy of the noise levels calculated by the model for a real trajectory, it is still necessary to assess the reliability of noise levels calculated through a trajectory modeled by following a defined set of procedures. These sets of procedures are an attempt to replicate the previously modeled flights as best as possible. A balance to minimize the errors of the position, airspeed and power parameter simultaneously was made; this balance was defined by the introduction of a cost function that should be minimized and takes into account these three parameters with equal weightings. This set of procedural steps had to be adjusted by trial-and-error, but an initial guess could be made, based on the evolution of the aircraft's airspeed and profile.

This set of procedures only covers the profile of the modeled flight; nevertheless, the calculation of the profile is also function of the bank angle - which is associated with the ground track. The model described by ECAC suggests considering the profile and ground track independent for simplicity. However, to solve this flaw, an iterative approach to model the flight was taken. In the initial guess for the profile, a straight path is assumed with bank angle equal to zero throughout the whole flight. Afterwards, turns are made by the user to try and replicate the real path. Both paths are visually represented in real time on a map, making it simple to make accurate turns. Along with this turn, the bank angle also changes in that segment. After this path is defined, the set of procedures is re-iterated, this time with the correct bank angles throughout the flight.

Table 4-2 provides a summary for the obtained results both with and without the empirical correction. As can be seen, the errors obtained are slightly higher than the ones from the previous section. This is due to the fact that both the flight trajectory and the aircraft's airspeed - both of which correlate with its power parameter - are not exactly the same as the real ones.

Table 4-2 - Average deviation and variance for corrected and uncorrected models.

	St.Deviation (dBA)	Variance (dBA^2)
Uncorrected	2.85	8.11
Corrected	2.20	4.86

Overall, according to the available data measured by noise monitoring stations, the flight path and noise models developed show results with a good degree of accuracy, making it possible to make an accurate noise impact study for virtually any flight and any location desired, such as Montijo's Air Base.

5 Application to Montijo Airport

5.1 Population Analysis [GIS]

Using the QGIS software with conjunction with the data obtained from the INE, it was possible to obtain a grid containing the population density around Lisbon, as shown in Figure 5-1. The grid created has a 1km x 1km area in each cell and the population density values are based on an average number of individuals in each Section that belongs in the grid cell. The color gradient represents the population density obtained from QGIS, with a background for the same area of interest as seen in Google Maps. The area in red indicates the location of Montijo's airbase.

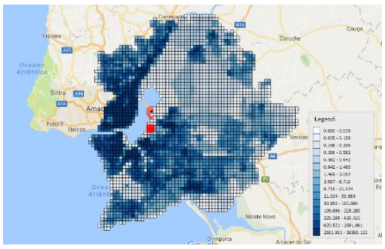

Figure 5-1 - Population density grid map for area of interest around Montijo.

5.2 Montijo Air Base

As mentioned, the airport in study is the Montijo Air Base (ICAO: LPMT) which is currently a Portuguese Air Force's military air base located in Montijo, near Tejo river. It consists in two runways: RWY 01/19, and RWY 08/26; only the former was used for this dissertation.

5.3 Aircraft, Movements and Schedules

Before finally start designing departure routes, it is necessary to define what flights exactly will be modelled, based on their final destinations and the aircraft being used, which will have an effect on the route the aircraft will follow after taking off. Based on the fact that this aerodrome is expected to be used by the low-cost airlines such as Ryanair and EasyJet that currently fly from and to LPPT, some assumptions were made.

Keeping in mind that EasyJet typically operates with Airbus A320-214 and A319-111 aircraft and Ryanair with Boeing 737-8AS, these were the models for which the model was used. Nonetheless, since the ANP database does not include A320-214 and A319-111 models, the most similar available ones were used instead: A320-211 and A319-131, respectively.

Statistical data for air traffic distribution for LPPT provided by NAV for July 23rd 2013 shows the most common routes that aircraft take during their departure operations. As such, a total of six routes was modeled, with three heading towards North/Northeast (IXIDA, IDBID and INBOM) and the remaining three heading towards South/Southwest/Southeast (BUSEN, GANSU, GAIOS). Furthermore, all the flights from EasyJet and Ryanair occurring on August 26th that departed from LPPT were found in ANA Aeroportos de Portugal website with the respective flight numbers, and then flight data for these was collected through the use of the website FlightRadar24. With this information, a schedule could be made, along with the departure routes taken, which will followed during the calculation of the L_{DEN} noise metric.

5.4 Procedures

The process followed to the design of procedures was organized in several steps. Initially, a standard trajectory that flies towards a desired point to which the procedure refers to (for example IXIDA). Profile-wise, it follows the standard profile procedures described in the ANP database for the aircraft in question for an ICAO-A and an ICAO-B procedure. Afterwards, different iterations of ground-track NAPs were applied to that flight. Noise contours and the calculation of Awakenings was then made for all modeled flights, with the one providing the lowest value for the latter being chosen as the optimal path.

6 Results

6.1 Standard NAPs

The approach to analyze departure procedures started by designing two sets of trajectories for each of the six different exit points. These sets correspond to Turn Restriction NAPs and Multi-Turn NAPs, with three to four different iterations of the NAP being modeled for each set of NAPs. In summary, each trajectory is defined by and categorized into (1) Runway, (2) Exit Waypoint/Route, (3) type of NAP, (4) iteration of the NAP, and (5) profile procedure. A total of 154 trajectories were initially modeled following this approach, and Figure 6-1 shows all of these projected over the map of Lisbon. All paths were modeled for an Airbus A320-211.

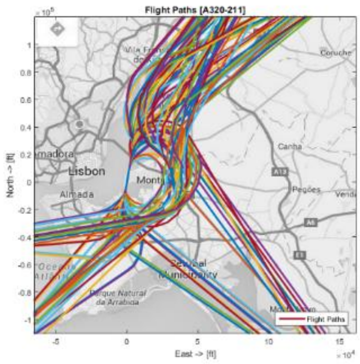

Figure 6-1 - Full set of modeled trajectories for Airbus A320-211.

The Standard ground-track NAPs followed consisted in Turn-Restriction NAPs and Multi-Turn NAPs. The former comprise of different iterations of where the initial turn is made, while the latter consist of different turns made at a certain point before heading towards another point. These two sets of NAPs are represented Figure 6-2 and Figure 6-3

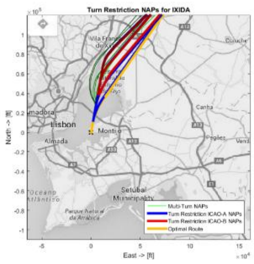

Figure 6-2 - Turn Restriction NAPs.

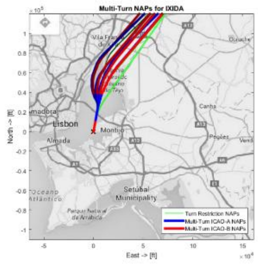

Figure 6-3 - Multi-Turn NAPs.

The Awakenings parameter was calculated for each of these trajectories, with the obtained results shown in Figure 6-4, with the optimal route highlighted in yellow and resulting in 1905 Awakenings, as opposed to the worst route, which resulted in around 4500 Awakenings.

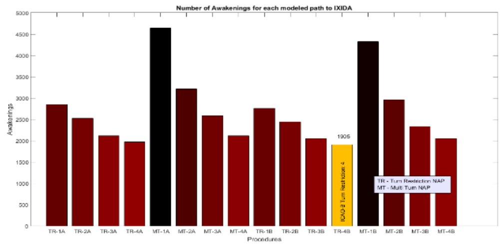

Figure 6-4 - Bar chart for the Awakenings parameter obtained for each trajectory modeled.

Extending this method to all of the Exit Points, the trajectories with optimal number of Awakenings for each route were selected and are shown in Figure 6-5.

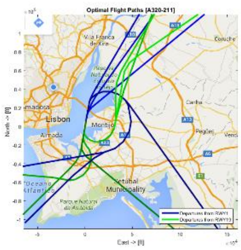

Figure 6-5 - Optimal Flight Paths with respect to the Awakenings parameter.

Despite not having been mentioned, all flights modeled comply with airspace rules, not overstepping danger and restricted areas' boundaries.

6.2 Custom Procedures

It is possible to obtain flight paths further optimized in terms of noise annoyance by designing the trajectories giving a higher focus on population density information, rather than follow any ground-track NAP specifically. These trajectories were modeled in this second phase, following ICAO-A and ICAO-B procedures.

Taking as an example the route towards BUSEN through RWY01, the optimal route obtained using Standard NAPs resulted in 4764 Awakenings. A new iteration of this route was made, aimed to avoid the high density populations near the Northwest coast of the Setúbal Peninsula, as shown in Figure 6-6. A wider turn could not be made as it would lead to flying over the Danger Area D10, as seen in Figure 6-7. This new path leads to an improvement of around 30% in terms of Awakenings, reducing it from 4764 to 3273.

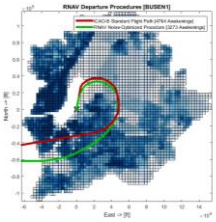

Figure 6-6 - Comparison between standard NAP and custom path to BUSEN.

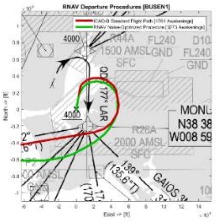

Figure 6-7 - Comparison between standard NAP and custom path to BUSEN.

While a slightly wider turn is not possible, it is possible to go around area D10 and thus making the climb over areas with a lower population density, as represented in Figure 6-8. This path would lead to a further improvement of approximately 27% when compared to the previous short turn, reducing the number from 3273 to 2387. Nevertheless, while the aim is to avoid every high population density area, in reality such paths may not be viable when taking into consideration other equally important parameters such as fuel consumption and gaseous emissions. This new path results in a much larger distance traveled until reaching a certain point when compared to the short turn, leading to higher fuel consumption and emissions.

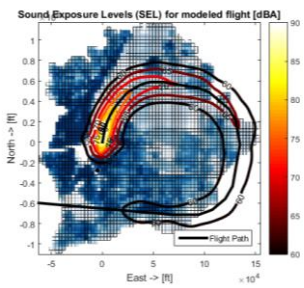

Figure 6-8 - Long Turn custom path, going around Danger area D10.

In a last experiment, a lateral separation of 3 NM in relation to area D10 was taken into account when designing the short-turn vs long-turn trajectories, as shown in Figure 6-9. Flight Operations Specialists during a meeting at NAV Portugal suggested this 3 NM separation as a safety margin due to ground track dispersion, since real flights might not follow the designed flight track meticulously. Similarly, the long turn provides with a lower Awakenings parameter, with a 30% reduction from 3669 for the short turn, to 2591 for the longer one, also coming at the cost of a higher fuel consumption and emissions due to the longer path towards the exit route.

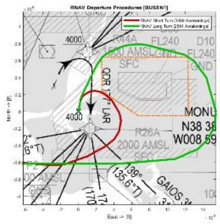

Figure 6-9 - Comparison between new short and long turn flight paths, with a safety margin for area D10.

6.3 L_{DEN} Noise Metric

Since L_{DEN} is a parameter that takes into account all flights that occur in a 24-hour period, the flights approaching the aerodrome should be taken into account as well. An accurate way to model approaches was not developed in this program yet, and thus simplistic approximate flights were designed instead. For this purpose, two different RNAV standard arrival procedures were designed, one for each runway. Both are assumed to depart from airports in Europe, and as such come from East.

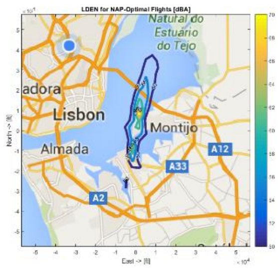

Figure 6-10 - L_{DEN} in area of interest based on the schedule mentioned.

As can be seen in the figure, areas with an L_{DEN} higher than 65 dBA are either located in the aerodrome or in the Tejo River, which leads to no issues in regards to community annoyance. Nonetheless, there is a small region south of Montijo where the noise levels are higher than 55 dBA, which despite not being ideal, is inevitable due to its proximity to the aerodrome.

7 Conclusions and Future Work

There are many aspects to study alongside with noise abatement, in a collective project which involves the cooperation of specialists in different subjects to obtain balanced results. It's impossible to focus exclusively on noise to create viable procedures, because a low noise impact on communities can come at the cost of a high fuel consumption and emissions indices of Greenhouse Gases, which is unreasonable both economically and environmentally. Implementing these effects in the model is a first step to complement this topic to design trajectories for Montijo.

It is important to mention that the awakenings parameters is an attempt to objectify a community impact, which is subjective and typically unquantifiable, through statistical data. Many characteristics are standardized for the areas in which the studies were made in, and can differ in different ones.

Taking into account the interference between flights departing and approaching LPPT will have a huge impact in any procedure for either aerodrome; as well as aircraft approaching LPMT itself. A re-structuration of the airspace in Lisbon's TMA will be made (or rather is currently in progress) taking into account factors such as this one, and danger/restricted areas, and a new study can be made by reiterating the process of designing flight paths in this dissertation, but with the new updated rules and charts. Furthermore, excellent cooperation between NAV Portugal and Portuguese Air Force is essential for the success of this project.

8 References

[1] Lieutenant-Colonel C.Fernandes, Interviewee, *Private Communication.* [Interview]. 4 April 2016.

[2] Expresso, "Expresso | Aeroporto do Montijo à vista," 6 January 2016. [Online]. Available: http://expresso.sapo.pt/economia/2016-01-06-Aeroporto-do-Montijo-a-vista. [Accessed 16 March 2016].

[3] EUROCONTROL, "Environmental Issues for Aviation | Eurocontrol," EUROCONTROL, 2016. [Online]. Available: http://www.eurocontrol.int/articles/environmental-issues-aviation. [Accessed 20 April 2016].

[4] World Health Organization, "Night Noise Guidelines for Europe," WHO, 2009.

[5] EUROCONTROL, "Conventional Navaids | Eurocontrol," Eurocontrol, [Online]. Available: http://www.eurocontrol.int/articles/conventional-navaids. [Accessed 26 April 2016].

[6] D. Nakamura and W. Royce, "Operational Benefits of Performance-Based Navigation," Boeing, 2008.

[7] D. J. Clausing, The Aviator's Guide to Navigation (4th ed.), New York: McGraw-Hill, 2006.

[8] International Civil Aviation Organization, "Noise Abatement Procedures, Vol.1 Part V," in *Document 8168 "PANS-OPS"*, ICAO, 2004.

[9] ICAO, "Flight Procedures, Vol.1," in *Doc.8168*, (5th Edition). ICAO, 2006.

[10] European Civil Aviation Conference, "Report on Standard Method of Computing Noise Contours around Civil Airports," in *ECAC.CEAC Doc.29*, (3rd Edition). ECAC, 2005.

[11] ECAC-CEAC, "About ECAC - ecac-ceac.org," [Online]. Available: https://www.ecac-ceac.org/. [Accessed August 2016].

[12] EUROCONTROL, "ANP - Eurocontrol Experimental Centre," EUROCONTROL, 26 January 2009. [Online]. Available: https://www.aircraftnoisemodel.org. [Accessed 8 August 2016].

[13] International Organization for Standardization, Standard Atmosphere - ISO 2533:1975, ISO, 1975.

[14] Federal Interagency Committee on Aviation Noise, "Effects of Aviation Noise on Awakenings from Sleep," FICAN, 1997.

[15] N. P. Miller, "How Many People Could be Awakened by a Full Night of Aircraft (or other) Noise Events?," Harris Miller Miller & Hanson Inc., 2009.

[16] S. H. a. H. G. Visser, "Optimization of RNAV Noise and Emission Abatement Departure Procedures," 9th AIAA Aviation Technology, Integration, and Operations Conference, South California, 2009.