Inclusion of noise-related constraints in departure procedure optimization

An Amsterdam Airport Schiphol Case Study

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Inclusion of noise-related constraints in departure procedure optimization

An Amsterdam Airport Schiphol Case Study

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The undersigned hereby certify that they have read and recommend to the Faculty of Aerospace Engineering for acceptance of a thesis entitled “Inclusion of noise-related constraints in departure procedure optimization” by J.W.M.J. Haagen in partial fulfilment of the requirements for the degree of Master of Science.

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Summary

The ever-increasing use of aircraft, together with the on-going urbanization causes increasing noise nuisance due to aviation. This is attenuated by the positioning of airports close to densely populated areas. For this reason the majority of the large airports in the world indicate that noise is one of the limiting factors in the expansion of the airport [10].

Four areas exist in which aircraft noise can be reduced, the first and most evident of which is the creation of noise by the aircraft itself. Over the past decades aircraft engines have shown a positive trend in the reduction of noise production. Currently this improvement appears to reach a plateau such that possible reductions are not as significant any more. The second area of reduction is the implementation of regulations, for example to ban or curfew noisier aircraft types. The third method is land-use management & planning, which focuses on adjusting the land-use to accommodate aircraft noise. The last category of improvements is found in the adjustment of operational procedures. Adjusting these procedures has shown significant opportunities with respect to reducing community noise.

One solution of adjusting operational procedures is the adjustment of near-airport operations of aircraft. It is shown that community noise can be taken into account in the design of aircraft terminal procedures, such that significant gains are reached. Previous research shows that a single aircraft track can be optimized for community noise, while for example including constraints resulting from RNAV regulation. More recent research shows the application of multi-event optimizations which optimize the lateral aircraft tracks for multiple aircraft simultaneously. Although the results of these optimizations proved significant improvements in terms of community noise, still two problems remain open-ended, which prohibit (or limit) the practical implementation of the results.

- The multiple aircraft departures, which currently often show dispersed flight tracks, are being concentrated onto one track. This concentration of flights onto one track allows a reduction in community noise but causes peak loads in noise at the same time. The increased technical capabilities allow aircraft to accurately follow predetermined tracks which causes problems equal to the described problem in the near future.
- By repositioning aircraft tracks (and the resulting noise) the total amount of noise nuisance decreases. At the same time an increase in noise received at some locations due to the creation of new noise (noise that is new for a location). The new noise has proven to cause significant resistance to the implementation of new aircraft tracks.

This thesis questions the desirability of solely focussing on the reduction of one specific community noise metric, of which the amount of people highly annoyed and awakenings have been used in the past. Instead this research aims to find to which extent peak noise loads and new noise can be taken into account in the optimization of aircraft tracks. To investigate this a newly created optimization tool is extended. To be able to optimize flight trajectories the optimization tool uses a noise model, an aircraft model, population density information and a dose-response relationship. These parts of the optimization tool are used by a dynamic optimization algorithm that calculates the optimal aircraft
trajectory for any given cost function.

Since the estimation of community noise is realistically done using a cumulative (multi-event) noise metric, the day-evening-night weighted level is used. To estimate the average human response to the levels of noise, a dose-response relationship is used. The selected dose-response relationship represents a continuous curve for all applicable levels of noise.

To be able to investigate the desirability of either concentrating or dispersing aircraft tracks a multi-event optimization is implemented that allows to optimize two aircraft (Boeing 737-300 and Boeing 747-400) tracks simultaneously, for the lateral tracks as well as the altitude and speed profiles. The optimization adheres to regulations and guidelines by including these regulations and guidelines using constraints. The application of discontinuous constraints is done using multi-phase definitions and step functions.

To be able to create solutions that are equal to each other in terms of noise nuisance, constraints with respect to noise nuisance are implemented within the optimization tool. This novelty converts the optimization problem from finding the optimum combination of fuel and community noise to finding a minimum cost function value while assuring a pre-defined level of community noise. This in turn allows to include new types of noise metrics in the cost function of the optimization.

Finally two new noise metrics are found/created and implemented. Peak noise loads are minimized by adding the aggregate sound energy ratio to the cost function, which is the sound energy ratio resulting from the day-evening-night weighted level metric. At the same time the aforementioned noise constraint is applied to ensure a pre-defined level of community noise. Equal to reducing peak loads, new noise is reduced by including a quantification of new noise in the cost function. New noise is quantified by applying an exponential function based on the level of new noise.

The optimization tool is applied to three departure trajectories which are all based on Standard Instrument Departures currently in use at Amsterdam Airport Schiphol. First of all optimizations are performed to determine the extent to which community noise can be reduced (not taking into account new noise and peak noise loads). The results are subsequently used to set noise constraint levels, to be able to optimize for peak noise loads and new noise.

Significant savings in terms of community noise can be gained by redesigning each of the three departures that were assessed. It is found that when noise constraints are included in the optimization this reduces the space in which solutions can be found, equal to the application of any other constraint in the optimization. It is seen that the closer the noise constraint is set to the absolute minimum amount of people highly annoyed, the smaller the solution space becomes. This allows to conclude that there is a direct trade-off between the strictness of the noise constraint and the cost function value.

Including the aggregated noise exposure ration in the cost function allows to reduce peak noise levels while the amount of people highly annoyed is kept equal by setting a constraint. There is no tendency to separate the two aircraft tracks from which it is concluded that separating aircraft tracks is not as effective as expected for reducing $L_{DER}$. It is found that increasing the speeds of the aircraft, especially in the first phase of the departures, reduces peak noise loads by decreasing the exposure times. Increasing the altitude of the aircraft also reduces peak loads though the noise contours are widened. This behaviour can however be superseded when this is required to be able to satisfy the required maximum amount of people highly annoyed.

Including a quantification of new noise in the cost function allows to reduce the amount of new noise.
The results of the optimization cost function can be called significant at the very least. The extent to which new noise stays perceptible is dependent on the severity of the changes required by the constraint on the amount of people highly annoyed. It is shown that when aircraft tracks are repositioned flight track dispersion should be applied to reduce new noise peaks, this should however be done only as long as this does not cause a undesirable increase in the amount of people highly annoyed.

To create solutions that are more realistic it is advised to implement more types of aircraft, as the current mix of aircraft departing from Amsterdam Airport Schiphol is currently represented by only two aircraft types. To ensure the applicability of the resulting aircraft tracks, the solutions must be RNAV-compliant, further research should therefore be performed to apply the required regulations and guidelines. Although the current optimization is performed for two aircraft simultaneously, separation between the aircraft types and between the other types of flight operations around AAS is not taken into account. Finally in the current model the atmospheric conditions are set to the International Standard Atmospheric conditions. This implies that no seasonal or daily atmospheric variations are taken into account. Since wind conditions and temperature have an influence on noise propagation and aircraft behaviour, a more elaborate noise model should be incorporated in FORT.
Acknowledgements

The work that now lies before you is the result of a twelve month master thesis at the Delft University of Technology, Faculty of Aerospace Engineering, department of Air Transport and Operations. During these months many people offered help in various ways, for which I would like to express my gratitude.

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Kevin Haagen
Delft, the Netherlands
May 1, 2015.
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# Nomenclature

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<th>Symbol</th>
<th>Description</th>
<th>Unit</th>
</tr>
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<tbody>
<tr>
<td>$m_f$</td>
<td>Fuel flow</td>
<td>$[kg/s]$</td>
</tr>
<tr>
<td>$C$</td>
<td>Vector with path constraints</td>
<td></td>
</tr>
<tr>
<td>$f$</td>
<td>Vector with dynamic constraints</td>
<td></td>
</tr>
<tr>
<td>$u$</td>
<td>Control vector</td>
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</tr>
<tr>
<td>$x$</td>
<td>State vector</td>
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<tr>
<td>$J$</td>
<td>Jacobian</td>
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<td>$a$</td>
<td>Base number in the quantification of new noise</td>
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<td>$C_D$</td>
<td>Drag Coefficient</td>
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<td>$C_L$</td>
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<td>$FC$</td>
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<td>$g_0$</td>
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<td>$h$</td>
<td>Altitude</td>
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<td>$HA$</td>
<td>People highly annoyed</td>
<td>$[%]$</td>
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<td>$inhab$</td>
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<td>$J$</td>
<td>Performance Index/Cost Function</td>
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<td>$k$</td>
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<td>$L$</td>
<td>Aircraft lift</td>
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<td>$L_{AE}$</td>
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<td>Level Day-Evening-Night</td>
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<td>$L_{night}$</td>
<td>Night level</td>
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<tr>
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<tr>
<td>$n$</td>
<td>Number</td>
<td>$[-]$</td>
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<td>$N_{tot}$</td>
<td>Weighted amount of occurrences of an event</td>
<td>$[-]$</td>
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<tr>
<td>$NN$</td>
<td>New noise metric</td>
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<tr>
<td>$p$</td>
<td>Pressure</td>
<td>$[N/m^2]$</td>
</tr>
</tbody>
</table>
\[ R \] Radius \[ [m] \]
\[ R \] Specific gas constant of air \[ [m^2/s^2K] \]
\[ S \] Wing area \[ [m^2] \]
\[ SEL \] Sound Exposure Level \[ [dBA] \]
\[ SER \] Sound Exposure Ratio \[ [-] \]
\[ SPL \] Sound Pressure Level \[ [dB] \]
\[ T \] Temperature \[ [K] \]
\[ T \] Thrust \[ [N] \]
\[ T \] Total time \[ [sec] \]
\[ t \] Time \[ [sec] \]
\[ T_1 \] Reference Time \[ [sec] \]
\[ U \] Closed set to which \( u \) belongs
\[ u \] Control variable
\[ V \] Speed \[ [m/s] \]
\[ W \] Weight \[ [N] \]
\[ w \] Weighting value \[ [-] \]
\[ X \] Axis direction
\[ x \] Positional Coordinate in the RD coordinate system \[ [m] \]
\[ x \] State variable
\[ y \] Positional Coordinate in the RD coordinate system \[ [m] \]
\[ Z \] Axis direction
\[ z \] Altitude \[ [m] \]

**Greek Symbols**

\[ \alpha \] Angle of attack \[ [rad] \]
\[ \alpha_T \] Thrust angle of attack \[ [rad] \]
\[ \chi \] Heading \[ [deg] \]
\[ \Delta L_A \] A-weighting filter value \[ [dBA] \]
\[ \Delta \] Difference \[ [%] \]
\[ \Gamma \] Normalized thrust setting \[ [-] \]
\[ \gamma \] Flight path angle \[ [rad] \]
\[ \gamma \] Ratio of the specific heats of air \[ [-] \]
\[ \lambda \] Temperature lapse rate \[ [K/m] \]
\[ \mathcal{L} \] Lagrange part of the cost function \[ [-] \]
\[ \mu \] Bank angle \[ [rad] \]
\[ \Phi \] Mayer part of the cost function \[ [-] \]
\[ \rho \] Air density \[ [kg/m^3] \]
\[ \theta \] Pitch angle \[ [rad] \]

**Subscripts**

0 Initial
0 Reference value
2  Take-off Safety
annoy  Of the amount of people highly annoyed
avg  Average
b  Relative to the aircraft’s body
B733  Of the B733
B744  Of the B744
CAS  Calibrated Airspeed
Climb  During the climbing phase
e  Effective
e  Relative to the Earth surface
f  Final
final  Final
flight  Of a specific flight/track
fuel  Of fuel
HA  People Highly Annoyed
Init  Initial
max  Maximum
min  Minimum
nI  Number of grid points with an increase in noise
nP1  Number of grid points with a perceivable increase in noise
new  In the new situation
old  In the old/benchmark situation
RD  In the Rijksdriehoeks coordinate system
Take – Off  At/during Take-Off
TAS  True Airspeed
tot  Total
true  The true amount
ZF  Zero Flaps

Abbreviations

$CO_2$  Carbon dioxide gas
2D  2-Dimensional
AAS  Amsterdam Airport Schiphol
AMSL  Above mean sea level
AS  Air Services
ATC  Air Traffic Control
ATS  Air Traffic Services
B733  Boeing 737-300 aircraft type
B744  Boeing 747-400 aircraft type
CBS  Dutch Statistics Netherlands
DAE  Differential Algebraic Equation
<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>DER</td>
<td>Departure End of Runway</td>
</tr>
<tr>
<td>DME</td>
<td>Distance Measuring Equipment</td>
</tr>
<tr>
<td>EU</td>
<td>European Union</td>
</tr>
<tr>
<td>FAA</td>
<td>Federal Aviation Administration</td>
</tr>
<tr>
<td>FAR</td>
<td>Federal Acquisition Regulation</td>
</tr>
<tr>
<td>FBD</td>
<td>Free Body Diagram</td>
</tr>
<tr>
<td>FICAN</td>
<td>Federal Interagency Committee on Aviation Noise</td>
</tr>
<tr>
<td>GES</td>
<td>Gezondheidskundige Evaluatie Schiphol</td>
</tr>
<tr>
<td>GIS</td>
<td>Geographic Information System</td>
</tr>
<tr>
<td>ICAO</td>
<td>International Civil Aviation Organisation</td>
</tr>
<tr>
<td>IF</td>
<td>Initial Fix</td>
</tr>
<tr>
<td>INM</td>
<td>Integrated Noise Model</td>
</tr>
<tr>
<td>INTLAB</td>
<td>INTerval LABoratory</td>
</tr>
<tr>
<td>ISA</td>
<td>International Standard Atmosphere</td>
</tr>
<tr>
<td>KIAS</td>
<td>Knots Indicated Airspeed</td>
</tr>
<tr>
<td>KLM</td>
<td>Royal Dutch Airlines</td>
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<td>LVNL</td>
<td>Air Traffic Control the Netherlands</td>
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<td>MAG</td>
<td>Magnetic Heading</td>
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<td>MATLAB</td>
<td>MATrix LABoratory</td>
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<td>MTOW</td>
<td>Maximum Take-Off Weight</td>
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<td>NADP</td>
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<td>NASA</td>
<td>National Aeronautics and Space Administration</td>
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<td>NLP</td>
<td>Non-Linear Programming</td>
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<tr>
<td>NM</td>
<td>Nautical Mile</td>
</tr>
<tr>
<td>NNC</td>
<td>Non-Noise Certified</td>
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<tr>
<td>NOISHHH</td>
<td>Combination of Noise and ‘SHHH’</td>
</tr>
<tr>
<td>NOMOS</td>
<td>NOise MOnitoring System</td>
</tr>
<tr>
<td>NPD</td>
<td>Noise-Power-Distance</td>
</tr>
<tr>
<td>OIS</td>
<td>Obstacle Identification Surface</td>
</tr>
<tr>
<td>P-RNAV</td>
<td>Precision RNAV</td>
</tr>
<tr>
<td>PAM</td>
<td>Pampus</td>
</tr>
<tr>
<td>PDG</td>
<td>Procedure Design Gradient</td>
</tr>
<tr>
<td>PHA</td>
<td>People Highly Annoyed</td>
</tr>
<tr>
<td>RF</td>
<td>Constant Radius Arc</td>
</tr>
<tr>
<td>RIVM</td>
<td>Dutch National Institute for Public Health and the Environment</td>
</tr>
<tr>
<td>RNAV</td>
<td>Area Navigation</td>
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<td>RNP</td>
<td>Required Navigation Performance</td>
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<td>RPM</td>
<td>Radau Pseudospectral Method</td>
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<tr>
<td>RWY</td>
<td>Runway</td>
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<tr>
<td>SER</td>
<td>Sound Exposure Ratio</td>
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<tr>
<td>SID</td>
<td>Standard Instrument Departure</td>
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<tr>
<td>SLST</td>
<td>Sea Level, Standard Day</td>
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</table>

xx
<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>SNOPT</td>
<td>Sparse Non-linear OPTimizer</td>
</tr>
<tr>
<td>SPY</td>
<td>Spijkerboor</td>
</tr>
<tr>
<td>SQP</td>
<td>Sequential Quadratic Programming</td>
</tr>
<tr>
<td>STAR</td>
<td>STandard Arrival Route</td>
</tr>
<tr>
<td>TF</td>
<td>Track to a Fix</td>
</tr>
<tr>
<td>TNO</td>
<td>Netherlands Organisation for Applied Scientific Research</td>
</tr>
<tr>
<td>U.S.</td>
<td>United States</td>
</tr>
<tr>
<td>UK</td>
<td>United Kingdom</td>
</tr>
<tr>
<td>VHF</td>
<td>Very High Frequency</td>
</tr>
<tr>
<td>VOR</td>
<td>VHF Omnidirectional Range Station</td>
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</tbody>
</table>
Chapter 1

Introduction

Ever since the invention of powered aircraft by the Wright brothers in 1903 the use of aircraft has been increasing. The development of jet engines increased the opportunities for aviation even further. Aviation has shown double digit growth from 1945 to 1973 [27] and even now a doubling of aircraft in service is expected by 2032 [8]. The combination of the ever increasing use of aircraft and urbanization increases noise nuisance, especially around airports. The increased awareness of noise nuisance and its risks call for a regulated balance between public well-being and economical opportunities.

Since aircraft engines are the main source of aircraft noise, the trend is to constantly improve engines in term of their noise footprints. Since the late 50’s there has been a shift in the emphasis that is being put on the design of aircraft engines. In the early years the focus was on increasing the performance of the engine, as this was a limiting factor for aircraft development. Over the decades this focus has shifted towards increasing the efficiency of the engines. This efficiency first of all consists of reducing the fuel usage of the engine, but the reduction of the produced noise is increasingly addressed as well. Figure 1.1 shows the history of the development of engine noise.

ICAO and the FAA (Federal Aviation Administration) have created a 4-stage system, with a stage 5 being added in 2018 [15]. This system consists of certification criteria used to categorize aircraft into chapters, as shown in ICAO Annex 16 [32]. The first airliners are not covered by Annex 16 and are referred to as Non-Noise Certified (NNC) aircraft. Chapter two aircraft are certified prior to 1977. The third chapter of aircraft include aircraft certified up to 2006, this includes the modern aircraft (Boeing 737-300). Chapter 4 started in 2006 and includes the new types of aircraft. In the Netherlands chapter 1 and 2 aircraft are prohibited to land.

By improving engines in term of their noise footprint and by banning noisy aircraft types the amount of noise produced per take-off has been decreased, while at the same time the total number of aircraft movements has increased. Since 2003 Amsterdam Airport Schiphol (AAS) has used a system enforcing limited amounts of noise in 60 noise enforcement points. In this system separate limits are set for day-time noise and night-time noise. Figure 1.2 shows the results of noise monitoring around Schiphol. Currently a preferential runway system is used at Schiphol, which prioritizes the combinations of runways in use, based on noise production.

The preferential runway system at Schiphol, which is tailored for minimizing noise nuisance, is an example of another category of solutions to aircraft noise. Besides reducing aircraft noise produced by the aircraft itself and applying bans and curfews to noisier aircraft, it is also possible to adjust the operations of the aircraft to ensure the least amount of community noise. Community noise is the noise received by the entire community, which differs from general noise in that it combines the noise at locations with the inhabitants at these locations. Significant opportunities are identified when
Figure 1.1: Trend in engine noise production, as shown by NASA. [25]

Figure 1.2: Noise monitoring around Schiphol. [34]

aircraft operations are adjusted such that noise nuisance is taken into account [31]. One of these opportunities is to tailor arrival and departure procedures such that noise nuisance is taken into account. By including community noise in the design of the aircraft route, as well as the altitude, speed and engine setting of the aircraft, noise nuisance can be reduced.

Work performed previously

Although extensive research has been done into noise abatement departure and arrival procedures, the inclusion of community noise in the design of noise abatement routes has been studied less. Torres [45] optimizes noise exposure in a point directly under a 2-dimensional flight track while Prats et al. [36] minimize the amount of noise received in a number of densely inhabited areas. Gradient-based optimization techniques have been implemented in the NOISHHH tool, which is developed, tested and used extensively by the Delft University of Technology. The tool is applied for the optimization
of aircraft tracks with respect to their noise impact. Visser and Wijnen [48] apply the tool for example to the optimization of departures while Hogenhuis et al. [23] do this for arrivals.

Since the noise impact in communities near airports logically should be assessed for aggregate noise levels instead of single event noise, the body of research has been extended to include cumulative noise metrics. The latest research shows optimizations performed for multiple aircraft simultaneously. This is done by Braakenburg et al. [9] for a small regional airport, whereas Dons [21] performs similar research for a large international hub airport. Dons [21] performs 2-dimensional optimizations of aircraft routes in order to minimize community noise, while noise of other departures and arrivals is included in the optimization using a noise carpet. The daily traffic at Amsterdam Airport Schiphol is categorized to twelve aircraft categories which are assumed to follow a common ground track. Furthermore a simultaneous optimization for two aircraft tracks is performed. The latter turns out to be problematic: the interference between tracks in the optimization cause inferior results as compared to individual optimizations [12].

Recently a new gradient-based optimization tool has been created using the experience gained with the NOISHHH tool at the Delft University of Technology. Using this new tool results in reduced calculation times for similar problem set-ups. Together with the ever increasing computational power this creates opportunities for further inclusion of community noise in the optimization of aircraft procedures.

**Problem description**

Both Dons [21] and Braakenburg [9] prove that significant savings in terms of community noise (sleep disturbances and the amount of people highly annoyed) are possible while reducing fuel burn as well. At the same time these research efforts leave two problems open-ended, as was already identified by Dons [21]:

1. Within the previously mentioned research projects the dispersed aircraft tracks (in the real situation) are replaced by one concentrated flight track. By concentrating these flights onto one track the inhabitants living directly underneath this new track experience peak loads in terms of noise. These **peak loads** cause decreased amounts of received noise for a large part of the community, while they cause significant increases in the received noise of a smaller group of inhabitants. Figure 1.3 shows the results in terms of the change in noise footprint when aircraft tracks are optimized for community noise, as compared to the current situation. Figure 1.4 shows the change in the amount of people highly annoyed per noise interval, when aircraft tracks are optimized for community noise. Both figures show the aforementioned peak loads. Due to increased technical capabilities of aircraft there is an increasing ability to accurately follow predetermined tracks. This trend causes problems equal to the described problem in the near future.

2. The opening of the Polderbaan at AAS on the 3rd of February 2003 significantly reduced the amount of noise received by a large amount of inhabitants surrounding AAS. Due to the use of Polderbaan the amount of complaints actually increased, however. This is shown in Figure 1.5. Figure 1.5 characterizes another problem that occurs when aircraft tracks (and the resulting noise) are repositioned. Although the total amount of received noise decreases, an increase in noise received at some locations is found due to the creation of new noise (noise that is new for a location). Air Services Australia states that ‘most people do not find a change in noise level below 3 dBA to be perceptible’.

Both problems reduce the social (possibly also the political) acceptability of the implementation of routes and procedures that reduce the total noise nuisance. At the same time there is the great diffi-
Figure 1.3: Relative noise differences between a solution resulting in minimum community noise and the current situation. [12]

Figure 1.4: Comparison of the amount of people highly annoyed per 4 dBA noise interval for the current and the optimized situation as shown in. [12]

culty in setting preferences between the various levels of noise nuisance, peak loads and new noise (for example: is it better to increase noise to a group of 100 by 50% such that 100000 have 10% reduced noise?) For the latter reason the number of inhabitants is no longer taken into account when estimating the environmental impact in terms of peak loads and new noise.
Thesis description
This thesis questions the desirability of solely focussing on the reduction of one specific noise metric, of which the amount of people highly annoyed and awakenings have been used in the past. Instead, the creation of peak loads and new noise are included in the optimization as well. The following research objective is posed:

To investigate how new constraints and new noise metrics can be used as solutions to peak loads and the creation of new noise in noise optimized departure procedures, by creating an optimization tool that includes these constraints and metrics and subsequently comparing the resulting track(s) to benchmark situations.

Summarizing, the peak loads and the creation of new noise are taken into account by:

- Extending a new optimization tool
- Implementing noise constraints and new noise metrics in the new tool
- Modelling departure procedures
- And finally comparing resulting tracks to benchmark situations

In line with this research objective, the following research question is posed:

‘To what extent can peak loads and the creation of new noise be included in the creation of noise optimized departure procedures while the result in terms of previously used noise metrics are equal and how do the resulting aircraft tracks and procedures change?’

Method
One adjustment that is made to the new optimization tool is a conversion from a single-event optimization to a multi-event optimization tool. This allows to perform a single optimization for multiple aircraft tracks in terms of both their lateral and longitudinal plane. This adjustment is done to be able to investigate the desirability of concentrating or separating aircraft tracks.

In addition to modelling noise nuisance also metrics for peak loads and new noise are implemented. The weighted sound exposure ratio metric exponentially grows with increasing noise exposure and is therefore used to suppress peak loads. An exponential function is used to quantify and reduce new noise, based on the difference between the actual noise level and benchmark noise levels.
A case study has been done to show the capabilities of the tool, as well as to draw conclusions from the optimization results. To draw these conclusions the results are compared to benchmark situations. Conclusions are drawn with respect to the possible improvements, the resulting aircraft tracks as well as opportunities for AAS.

No previous research is found that includes noise in the optimization as a constraint instead of in the cost function. Furthermore Dons [12] states that a multi-event optimization in the lateral plane already proves to be problematic. This thesis implements noise as a constraint and optimizes for two independent tracks in both lateral and longitudinal planes simultaneously. In doing so the current body of knowledge and tools is significantly extended.

This report
Chapter 2 discusses the basics of noise abatement and noise metrics. Also general information, guidelines and regulations with respect to departure procedures are shown. The architecture of the new optimization tool is treated extensively in Chapter 3. Chapter 4 discusses the set-up of the three case-studies in depth. Chapter 5 shows the results of the case study such that conclusions and recommendations can be presented in Chapter 6.
Chapter 2

Aircraft Noise Abatement, Regulations & Guidelines

This chapter shows the theoretical knowledge required for this thesis. The basics of noise and noise abatement are discussed (Section 2.1), together with guidelines (Section 2.2) and regulations (Section 2.3) that are used in this research.

2.1 Noise Abatement

The first thing to be discussed when elaborating on noise and noise abatement in general are the basic metrics of noise. Of the vast amount of noise metrics available, only the metrics used in this thesis are treated.

2.1.1 Noise Metrics

Sound consists of pressure differences with respect to the ambient (static) pressure. The sound source generates a pressure difference, oscillating around the ambient pressure. The effective (sound) pressure is the root-mean-square of the instantaneous pressure level over the period under consideration. Noise metrics are divided into instantaneous sound metrics, metrics over the period of one event and metrics over a specific time span (one day, one week etc.). [40]

The metric to express instantaneous sound is the Sound Pressure Level (SPL). This is not completely instantaneous either as it uses the effective pressure, which is calculated over the period of at least one complete sound wave. SPL is found using Equation 2.1, in which $p_e$ is the effective pressure and $p_{e0}$ is a reference pressure. The SPL unit is deciBel (dB). [40]

$$SPL = 10 \cdot \log_{10} \frac{p_e^2}{p_{e0}^2}$$  \hspace{1cm} (2.1)

The sound pressure level describes the sound as it is produced. When sound is perceived by the human ear however, two mechanisms influence the sound level perceived. ‘If two tones of equal frequency are compared, the ear judges the sound with the highest sound pressure level as the sound with the highest loudness’ [40]. The human ear is furthermore not equally sensitive to sound of all frequencies. If, for example, sound at 20 Hz frequency is compared to sound at 2500 Hz (at equal SPL), the difference in perceived sound is as much as 51.8 dB [40]. One method for implementing the sensitivity of the ear to specific frequencies is called A-weighting. The easiest way to apply this weighting is to generate the frequency spectrum of the sound in order to add the weighting filter. This filter is approximated by Equation 2.2 and is only a function of frequency ($f$), as shown in Figure 2.1. [40]

$$\Delta L_A = -145.528 + 98.262 \cdot \log_{10}(f) - 19.509 \cdot \log_{10}(f)^2 + 0.975 \cdot \log_{10}(f)^3$$  \hspace{1cm} (2.2)
\[ L_A = SPL + \Delta L_A \] (2.3)

Aircraft fly-overs do not create instantaneous sound, instead these flyovers generate sound over a longer period of time. The Sound Exposure Level (SEL) expresses the perceived sound of an entire event (i.e. one aircraft flyover). The SEL is the continuous integral of \( L_A \), normalized to one second, as shown in Equation 2.4. In this equation \( T_1 \) is the total time of the event and \( L_{AE} \) is the SEL. [40]

\[ L_{AE} = 10 \cdot \log_{10} \left[ \frac{1}{T_1} \int_0^{T_1} 10^{\frac{L_A(t)}{10}} \, dt \right] \] (2.4)

Finally the total amount of noise at an airport can not be judged by the amount of noise produced in one event. For this reason the noise of multiple events must be expressed in one metric, which is done in so-called cumulative metrics. One cumulative metric that is often used is the Day-Evening-Night weighted level (\( L_{DEN} \)). Noise produced during night time is often considered more inconvenient than noise produced during the day and for this reason a weighting based on the time of the event is included in the (\( L_{DEN} \)) metric. The weighting of an event is based on the time of occurrence (day/evening/night) and is shown in Table 2.1. \( L_{DEN} \) is calculated using Equation 2.5, in which \( L_{AE}(t) \) is the SEL level as a function of time \( t \), \( w(i) \) is the day/evening/night weighting as a function of time and \( T_1 \) is the reference period.

\[ L_{DEN} = 10 \cdot \log_{10} \left[ \frac{1}{T_1} \sum_{t=0}^{T_1} w(t) \cdot 10^{\frac{L_{AE}(t)}{10}} \, dt \right] \] (2.5)

### Table 2.1: \( L_{DEN} \) penalty factors, \( w(i) \), as a function of the time of occurrence.

<table>
<thead>
<tr>
<th>Period</th>
<th>Penalty Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Day (07h00-19h00)</td>
<td>( w=1 )</td>
</tr>
<tr>
<td>Evening (19h00-23h00)</td>
<td>( w=3.16 )</td>
</tr>
<tr>
<td>Night (23h00-7h00)</td>
<td>( w=10 )</td>
</tr>
</tbody>
</table>

#### 2.1.2 Dose-Response relationships

The day-evening-night weighted level expresses cumulative noise as it is perceived by human. These values are not tangible, however. It is therefore common practise to express noise in terms of the average human response to noise, which is often done using dose-response relationships. A commonly used dose-response relationship is the probability of awakening due to the SEL level of an event. The
type of dose-response relationship that has been used at the Delft University of Technology is created by FICAN [16].

Since one of the goals of this thesis is to perform multi-event optimizations, either the noise of the events has to be accumulated into one event, or another noise metric has to be used. Following previous research that performs multi-event optimizations, the $L_{DEN}$ metric is used to express multi-event noise. Using the $L_{DEN}$ metric the dose-response relationships often give a percentage of people highly annoyed, shortly ‘annoyance’, as a response. Three of these $L_{DEN}$-annoyance relationships are discussed, these are shown in Figure 2.2.

![Figure 2.2: Comparison between dose-response relationships.](image)

The first dose-response relationship is the equation provided by Miedema & Oudshoorn [33], who have combined 27081 observations, collected over 19 studies. Each of these observations is specifically done for aircraft noise. The result is the model seen in Equation 2.6. The European Union (EU) advises using this relationship as an estimation for the percentage of people highly annoyed ($HA$).

$$HA = -9.199 \cdot 10^{-5} (L_{DEN}-42)^3 + 3.932 \cdot 10^{-2} (L_{DEN}-42)^2 + 0.2939 \cdot (L_{DEN}-42)$$

(2.6)

According to Engelen [13], TNO (Netherlands Organisation for Applied Scientific Research) has performed a refinement on the dose response relationship published in ‘Exposure-response relationships for transportation noise’ (1997). TNO has determined Equation 2.7 based on research performed on the perception of noise nuisance in several countries. From Figure 2.2 it is seen that the Equation predicts values that are close to Miedema & Oudhoorn’s predictions.

$$HA = 0.53 \cdot (L_{DEN}-42) + 0.0285 \cdot (L_{DEN}-42)^2$$

(2.7)

The last dose-response relationship that is shown is the equation created by the Dutch Gezondheidskundige Evaluaties Schiphol (GES). GES used questionnaires between 1997 and 2002 for the creation of a more recent dose-response relationship. This research is performed under local conditions at Schiphol, therefore the composition of the population as well as local environmental factors are taken into account. Equation 2.8 is found by TNO (together with RIVM, the Dutch National Institute for Public Health and the Environment) using the data created by GES. The curve is based on research participants that received 39 to 65 dB(A) $L_{DEN}$ values. Engelen [13] states that extrapolation of the curve is possible numerically, however this is not supported by the results of the research. It is seen
that this model differs from the other two models. This is due to the fact that the model is based solely on data collected around AAS, apparently the local conditions significantly influence the responses to aircraft noise.

\[ HA = \left( \frac{e^{-8.11001+0.1333L_{DEN}}}{1 + e^{-8.11001+0.1333L_{DEN}}} \right) \cdot 100 \tag{2.8} \]

2.1.3 Noise Abatement

Aircraft noise originates partly from the engines and partly from the aircraft frame (airframe noise). To reduce noise nuisance the International Civil Aviation Organisation (ICAO) promotes a so-called ‘Balanced Approach’. According to ICAO [28] this approach means that work is done in 4 areas: reduction at the source, land-use planning and management, operational procedures and operating restrictions.

The logical solution to the noise problem is to tackle the noise at the source: the aircraft engine and aircraft frame. Indeed aircraft and engine manufacturers have been focussing on this over the last decades. Figure 1.1 shows the reduction in noise produced by aircraft engines over the last 50 years. It is seen, however, that the decrease in engine noise is reaching a plateau. Due to this, additional solutions to aircraft noise are to be investigated.

One of the other solutions to aircraft noise is land-use planning and management which consists of anything done to the spatial arrangement and geography around the airport. This includes: zoning, mitigation (i.e. insulation or making sure that inhabitants leave the noisy area) and financial measures (i.e. tax incentives). Operating restrictions can also be applied to restrict the airlines from specific operations. Examples of this are [8]:

- Restriction on using specific runways during night time.
- Exclusion of aircraft based on the aircraft stage.
- Engine run-up restrictions.

Even without adjustments to the aircraft, land, or land-use, noise nuisance can be reduced. One of the ways to further reduce noise nuisance is by adjusting the use of the aircraft such that less noise is generated above/in noise sensitive areas. Another advantage of adjusting operational procedures is that it can be applied to the existing fleet. To apply these operational procedures often minor/no changes have to be made to the existing fleet. Adjusting operational procedures has already proven its potential for decreasing noise nuisance, while at the same time decreasing fuel cost and flight time. ICAO [31] discusses the results of a Research and Development project, which shows a potential improvement due to adjusted departure procedures of:

- 2 to 9 dB noise reduction per departure.
- 23% to 42% reduction in noise contour areas per departure.
- 90 to 630 kg CO₂ savings per departure.
- 60 to 440 pound fuel savings per departure.

2.2 General Information and Guidelines

This section treats the basics and basic guidelines of departure procedures. Departure procedures have more flexibility in terms of lateral and vertical movement compared to arrival procedures. Arrival procedures often have the last phase of the flight fixed (glide slope interception and glide slope phase), while in the first phase of the arrival the flight tracks are often determined by ATC (Air Traffic Control) vectoring.
2.2.1 Standard Instrument Departure (SID)

The departure procedure consists of way points that have to be overpassed at/below specific heights and speeds such that the aircraft keeps sufficient spacing to other departing/arriving aircraft. The Standard Instrument Departures (SIDs) are pre-defined procedures, executed directly upon request by ATC. SIDs have multiple purposes [41]:

- Reduction of workload for both ATC and the pilot.
- Separation of incoming and departing traffic.
- Limitation/reduction of community noise.

A SID specifies the lateral movement of the aircraft and, to an extent, the climbing pattern of the aircraft. According to ATC the Netherlands [2] the SID ends at a designated way point, where the aircraft continues on an Air Traffic Services route (ATS). The departure procedure is finished once the aircraft starts the ATS route.

2.2.2 Area Navigation

The classical aircraft navigation network is based on way points that are usually related to land-based beacons which means that aircraft fly from way point to way point. This system has the advantages that it is simple for the user and requires unsophisticated on-board systems. One disadvantage is, however, that the aircraft has little lateral freedom. Due to the fixed path often aircraft have to fly longer distances (more fuel cost and environmental burden) and, more importantly, there is no flexibility in adjusting the flight path to reduce noise nuisance. For these reasons area navigation (RNAV) is increasingly used. RNAV way points do not necessarily coincide with any beacon; they are imaginary way points. These way points are used to guide the aircraft along the RNAV route.

One group of RNAV routes require the aircraft to be equipped with special navigation equipment, which is called ‘Required Navigation Performance’ (RNP). This means that there is an on-board monitoring and alerting system, that keeps track of the navigation accuracy. An RNP of 1 means that a navigation system must be able to calculate its position within 1 Nautical Mile (NM) 95% of the time. When flying an RNP RNAV route this means that the flight track of the aircraft is more predictable, as the aircraft accurately follows the predetermined route. Also the flight tracks of several aircraft flying the same route overlap.

2.3 Regulations

This section describes the restrictions, procedures and regulations with respect to departures. These regulations are split up into general regulations, regulations related to RNAV and regulations related to noise abatement.

2.3.1 General Regulations

The general description of a take-off procedure starts with the take-off roll (the ground phase). Since this phase can not be altered, this phase is left out in the optimization. Following ICAO, the airborne part of the procedure starts once the aircraft is 5 ft above the (end of the) runway [29]. Often the aircraft is told to fly a specific SID, which is initiated directly after take-off. The general description of SIDs are found in the textual descriptions accompanying the SID charts. In these descriptions two types of turns are found. The first type of turn is initiated at/before/by a fix or facility (example: ‘At 7.0 PAM turn left to track 054 MAG to intercept PAM 015 to ANDIK’). The other type of turn is the turn occurring at an altitude/height (example: ‘At 500 ft AMSL turn right (turn MAX 220 KIAS) to intercept SPL 106 to IVLUT’). Particular SIDs exist that are only available to specific categories of aircraft, this is however not common practise.
During the flight there are general procedures and regulations to be adhered to. These regulations are discussed in ICAO Doc 8168 [29, 30]. It is assumed that all runways at the Dutch airports are free of obstacles. First of all ICAO poses a limit to the maximum bank angle that an aircraft can have, which is a function of the altitude of the aircraft. Below 305 m (1000 ft) the bank angle should be below 15 deg while between 305 m (1000 ft) and 915 m (3000 ft) the bank angle should be below 20 deg, above this interval the bank angle should be below 25 deg. Furthermore the first segment of the flight, up to 120 m (400 ft), must be straight, unless the initial and final heading of the aircraft do not differ by more than 15 deg. The departure procedure ends when the aircraft continues to the ATS route. For AAS this is at 6000 ft altitude, above a specific way point.

2.3.2 RNAV Regulations
ARINC 424 is a database that serves as a standard for transmission of data for assembly of airborne system navigation databases. The data base has 23 leg types described by their path and terminator. The termination is the condition that causes the navigation computer to continue to the next leg. Although there are 23 leg types available for RNAV, none of the manufactured equipment uses all of them. The Radio Technical Commission for Aeronautics states that only three of them should be used for noise abatement procedures as these result in a fixed ground path. This is necessary to ensure that the optimized flight track can be flown exactly in all circumstances [37]:

- Initial Fix (IF) defines a database fix as a point in space and is only required to define the beginning of a route or procedure [14].
- Track to a Fix (TF) defines a great circle track over the ground between two known database fixes and is the preferred method for specification of straight legs [14].
- Constant Radius Arc (RF) leg defines a constant radius turn between two databases fixes, lines tangent to the arc, and a center fix [14].

TF and RF are seen as legs or actual routes, whereas the IF is simply a point in space at which the route is initiated, due to this only the TF and RF legs are used in the optimizations. Figure 2.3 shows the difference in flight track dispersion of the route flown between two way points without a fixed track, and between two way points in a fixed radius configuration.

2.3.3 Noise Abatement Regulations
For noise abatement procedures specifically the following adjustments are made to the regulations mentioned in Subsection 2.3.1 [29]:

- Turns should not be required unless the aeroplane has reached a height of not less than 150 m (500 ft).
- When an adequate provision is made for an acceleration phase, the limit of 15 deg bank angle can be overcome.
- Initial power or thrust reductions shall not be executed below a height of 240 m (800 ft) above the aerodrome elevation.
ICAO [29] describes two Noise Abatement Departure Procedures (NADP), which are vertical profiles that define the combination of speed, altitudes and thrust used to reduce received noise. NADP I is designed to alleviate noise close to the aerodrome. NADP I is shown graphically in Figure 2.4 and consists of the following steps:

- The first phase of the take-off consists of maximum thrust, at a speed of $V_2 + 10 kts$ to $V_2 + 20 kts$.
- At 240 m (800 ft) altitude power/thrust is reduced. Speed is maintained at $V_2 + 10 kts$ to $V_2 + 20 kts$.
- At 900 m (3000 ft) the aircraft is accelerated to en-route climb speed. The flaps/slats are retracted.

**Figure 2.4: NADP 1 Procedure [29]**
NADP II is designed to alleviate noise distant from the aerodrome. NADP II is shown graphically in Figure 2.5 and consists of the following steps:

- The first phase of the take-off consists of maximum thrust, at a speed of $V_2 + 10\text{ kts}$ to $V_2 + 20\text{ kts}$.
- At 240 m (800 ft) the aircraft is accelerated smoothly towards $V_{ZF}$ such that flaps and slats are retracted. Furthermore thrust is reduced at 800 ft altitude.
- At 900 m (3000 ft) the aircraft is accelerated to en-route climb speed.

![Figure 2.5: NADP 2 Procedure [29]](image-url)
Chapter 3

Fixed Wing Optimization Research Tool

The experiences gained by designing, building and using NOISHHH have been used by the Delft University of Technology to develop a gradient based optimization tool for the optimization of aircraft tracks. The ‘Fixed Wing Optimization Research Tool’ (FORT) is to be used mainly for research purposes. The tool is created in a MATLAB\(^1\) (MATrix LABoratory) environment. The basic layout of FORT is equal to the basic layout of NOISHHH, as shown in Figure 3.1. The core of the FORT tool is a dynamic trajectory optimization framework, which is combined with a dynamic aircraft model, an aircraft noise model, a Geographic Information System (GIS) and a noise dose-response relationship to form the FORT tool. The basics of optimal control theory, as discussed subsequently, apply to FORT. The FORT tool has been extended and adjusted such that it can be used for the research objective of this thesis.

![Figure 3.1: Basics of the FORT optimization framework.](image)

3.1 Optimization Methodology and implementation

This section treats a general description of the optimization problem (Subsection 3.1.1) and how this theory is used in the FORT optimization tool (Subsection 3.1.2).

3.1.1 Basic Optimization Theory

Since the trajectory of an aircraft is described by a set of continuous variables, optimization algorithms based on optimal control can be used [6]. The basics of optimal control theory is shown subsequently.

\(^1\)http://mathworks.com/products/matlab/
The state of any system that is optimized is described by so-called state variables \( x_i, i = 1, 2, \ldots, n \) which are included in vector \( x \). A dynamic system develops/changes in time, it is therefore a time-dependent system in which the state variables develop in time. The system can be subjected to inputs/variables that influence the states which are called control variables \( u_k, k = 1, 2, \ldots, m \) and are contained in vector \( u \). State and control values are limited by (path) constraints. Control constraints are described by a closed set \( U \) to which \( u \) belongs. Initial and final conditions of both states and controls are included as well, together with the initial and/or final time \( t_0 \) and/or \( t_f \). The dynamic system is described by a set of first-order differential equations, which is a function of the states themselves, control variables and time (see Equation 3.1). For a system in motion these differential equations are the equations of motion.

\[
\dot{x} = f(x(t), u(t), t); \quad t_0 \leq t \leq t_f
\]  

(3.1)

The vector \( f \) is seen as a set of dynamic constraints: constraints on the dynamic behaviour of the system. These constraints define the behaviour of the system itself.

The optimal solution is found using Optimal Control Theory. Using this theory a performance index (or objective/cost function) \( J \) is created, which is essentially the output/result to be minimized. The goal of Optimal Control Theory is to find a set of matching state and control variables that results in a minimum value for \( J \). \( J \) is shown in Equation 3.2:

\[
J = \Phi(x(t_f), t_f) + \int_{t_0}^{t_f} \mathcal{L}(x(t), u(t), t) \, dt
\]  

(3.2)

This basic set-up of an optimization problem is called the Bolza Problem. The cost function consists of two parts. The first part, \( \Phi \), is a function of the final conditions and/or time. This is called the Mayer part of the cost function and is calculated at the end of the optimization iteration, once the required final conditions and time are known. The second part of the cost function, \( \mathcal{L} \) is a function of the continuous states, controls and time. This is called the Lagrange part of the cost function and is the integration over time of a function of state and control variables.

The general optimization problem is found in Equation 3.3. That is to find the feasible control function \( u(t) \) that generates a solution with minimum performance index \( J \). This solution should satisfy the dynamic constraints \( f \), specified boundary conditions \( \phi \) and path constraints \( C \).

\[
\min_{u(t) \in U} J = \Phi(x(t_f), t_f) + \int_{t_0}^{t_f} \mathcal{L}(x(t), u(t), t) \, dt
\]  

(3.3)

Subject to:

\[
\dot{x} = f(x(t), u(t), t)
\]  

(3.4)

\[
\phi(x(t_0), t_0, x(t_f), t_f) = 0
\]  

(3.5)

\[
C(x(t), u(t), t) \leq 0
\]  

(3.6)

### 3.1.2 Optimization method of FORT

FORT uses a direct optimization method that is gradient based. Gradient based optimization methods use gradients to find the direction towards an optimal solution and to determine a termination criterion to check the optimality of the solution. Using a gradient based optimization method often reduces the
required computational effort. In direct optimization methods the continuous, infinite-dimensional optimization problem is converted to a finite-dimensional non-linear programming (NLP) problem. FORT uses a parametrization/collocation method to have parameters representing the state and control variables. This NLP problem is solved using a numerical solver. An advantage of direct optimization methods is that there is less sensitivity to initial guesses of the solution to the problem. [22]

The dynamics of the problem are approximated using Radau quadrature, the method used is the so-called Radau Pseudospectral Method (RPM) [17] which generally shows good behaviour for problems having a fixed initial or final time [26]. Within the RP method, Radau quadrature is used to prescribe the locations of the discretization points in the time domain. RPM uses Lagrange polynomials to approximate the DAEs describing the vehicle’s dynamics. These Lagrange polynomials coincide with the DAEs at the discretization points. The dynamic constraints (Equation 3.1) are subsequently converted into algebraic equations using orthogonal collocation. Finally, state, control and boundary constraints are treated as algebraic inequalities in the NLP problem. [22]

The finite-dimensional NLP problem that is created is solved using a numerical solver called Sparse Nonlinear OPTimizer (SNOPT)\(^2\). Solving the NLP problem means that the cost function value is minimized while constraints are satisfied. When the first derivatives of the cost function and the constraints are supplied to SNOPT this often increases the numerical efficiency [18]. These derivatives are found using automatic differentiation. SNOPT uses Sequential Quadratic Programming (SQP) to solve the NLP problem. Within SNOPT the optimality of the solution is checked using the values of the derivatives combined with the slack in constraints. Infeasibility is heavily penalized and added to the cost function, such that when minima are searched for, infeasibilities are minimized automatically. [22]

One important limitation of RPM is the need to avoid discontinuities in the cost function, vehicle dynamics and constraints. In gradient-based optimization gradients are used to find the direction towards an optimal solution and a termination criterion to check the optimality of the problem. Discontinuities increase the complexity of finding the direction towards the optimal solution and disrupt the termination criterion. The basic optimization theory is extended such that a multi-phase problem can be optimized. Phases are used to be able to include discontinuities. The simplest explanation for the difference between a single-phase optimization and a multi-phase optimization is that the latter consists of several single-phase optimizations, which are linked by sets of linkage constraints. Although the implementation of different phases potentially increases the accuracy of the model, it also increases the numerical complexity of the problem. The order of phases is to be defined beforehand, essentially reducing the freedom within the optimization. It is stressed that the phases are not necessarily linked together. Phases (or sets of phases) might be completely independent from other (sets of) phases, or multiple phases might be linked to the same initial phase. Figure 3.2 shows possibilities of linkages.

### 3.2 Aircraft Model

The optimization of aircraft trajectories is done using a point-mass model of the aircraft which includes the aerodynamics of the aircraft itself. Within the optimization the atmospheric conditions are equal to the International Standard Atmosphere (ISA), and furthermore no wind conditions are taken into account. The aircraft model assumes a flat, non-rotating Earth and coordinated flight. The equations of motion of the point-mass model allow finding an appropriate set of state and control variables.

\(^2\)http://www.sbsi-sol-optimize.com/asp/sol_product_snopt.htm
The state vector, $\mathbf{x}$, consists of 6 states:

$$
\mathbf{x} = \begin{pmatrix}
    x \\
    y \\
    h \\
    V \\
    \chi \\
    W
\end{pmatrix}
$$

In which:
- $x$ and $y$ are the positional coordinates in a local Cartesian coordinate system.
- $h$ is the altitude of the aircraft in m.
- $V$ is the true airspeed (TAS) of the aircraft in m/s.
- $\chi$ is the true compass heading of the aircraft. North is equal to $0 \text{ rad}$ and/or $2\pi \text{ rad}$, South is equal to $\pi \text{ rad}$.
- $W$ is the weight of the aircraft in Newton (N).

The behaviour of the aircraft is influenced by three controls. The following control vector, $\mathbf{u}$, is used:

$$
\mathbf{u} = \begin{pmatrix}
    \Gamma \\
    \gamma \\
    \mu
\end{pmatrix}
$$

In which:
- $\Gamma$ is the normalized thrust setting. $\Gamma$ ranges from 0 (minimum thrust) to 1 (maximum thrust). $\Gamma$ is dimensionless. The relation between $\Gamma$ and thrust ($T$) is:

$$
T = (T_{\text{max}} - T_{\text{min}})\Gamma + T_{\text{min}}
$$

- $\gamma$ is the flight path angle of the aircraft in radians.
- $\mu$ is the bank angle of the aircraft in radians. Right wing down is defined as a positive bank angle.

Figure 3.3 shows free body diagrams (FBD) of the aircraft in horizontal and lateral planes. In these figures:
• $X_e$ and $Z_e$ are the $x$ and $z$ axis relative to the Earth surface. The direction of $Z_e$ therefore coincides with the direction of the altitude $h$.
• $X_b$ and $Z_b$ are the $x$ and $z$ axis relative to the aircraft.
• $L$ is the lift vector.
• $D$ is the drag vector.
• $W$ is the weight vector. This vector is always parallel to the $Z_e$ axis.
• $\alpha$ is the aircraft angle of attack, which is the angle between the aircraft body axis and the wind speed vector, $V$.
• $\theta$ is the aircraft pitch angle, which is the angle between $X_b$ and $X_e$, such that:

$$\theta = \gamma + \alpha$$

(3.10)

• $T$ is the thrust vector.
• $\alpha_T$ is the thrust angle of attack: the angle between $T$ and $V$.

The following assumptions are made to reduce the amount of variables and to remove dependencies within the system of equations:
• $T$ is in the direction of $V$, i.e. $\alpha_T = 0$.
• $D$ is in the opposite direction of $T$. The drag, $D$, is also in opposite direction of $V$.

Combining the assumptions with the information found in the free body diagrams, the following equations are found:

$$\dot{x} = V \cdot \cos \gamma \cdot \sin \chi$$

(3.11)

$$\dot{y} = V \cdot \cos \gamma \cdot \cos \chi$$

(3.12)

$$\dot{h} = V \cdot \sin \gamma$$

(3.13)

The differential equation describing the heading rate, $\dot{\chi}$, is shown in Equation 3.14.

$$\dot{\chi} = \frac{g_0}{W} \tan \mu$$

(3.14)

This equation is found by combining Equation 3.15, 3.16 and 3.17. Equation 3.15 is found from Figure 3.3 (b), Equation 3.16 is the equation for circular motion and Equation 3.17 is the equation for centripetal forces. In these equations $g_0$ is the gravitational acceleration at sea level, $R$ is the radius of the turn in $m$ and the mass of the aircraft is $m$ in kg.

$$W = L \cdot \cos \mu$$

(3.15)

$$V = \dot{\chi} R$$

(3.16)

$$m \frac{V^2}{R} = L \sin \mu$$

(3.17)

Applying Newton’s second law of motion to Figure 3.3 (a) gives the equation for the derivative of the true airspeed:

$$\dot{V} = \frac{g_0}{W} (T - D - W \sin \gamma)$$

(3.18)

The only parameter influencing the aircraft weight is the fuel flow towards the engines. The derivative of the aircraft weight is therefore:

$$\dot{W} = m_f \cdot g_0$$

(3.19)

In which $m_f$ is the fuel flow of the aircraft in kg/s. This fuel flow is dependent on atmospheric conditions and the thrust setting ($\Gamma$). Engine models are included of the engine types used in the
optimization. These models are too extensive to be described in this section. Within these models the engine setting (take-off thrust and en-route climb thrust) is selected. The normalized thrust setting ($\Gamma$) is not included explicitly in this system of equations, however the thrust ($T$) and the fuel flow ($m_f$) are dependent on this setting.

The six state derivatives are included as Differential Algebraic Equation (DAE) in the optimization. These differential equations are dependent on parameters that are defined by the aircraft types. These parameters include for example: drag coefficients, engine characteristics, aircraft weight, wing surface area etc. Each of these parameters is treated in Section 4.2, where the entire set-up of the cases themselves are treated.
3.3 Noise Model

In FORT noise values (as well as derivatives) are found using the noise engine of the so-called Integrated Noise Model (INM). The INM noise engine is treated in this section. In Section 3.6 the implementation of the derivatives within the optimization itself is treated.

The INM model is used in the United States (U.S.) for FAR part 150 noise planning and FAA order 1050 environmental impact assessments. INM has been developed by the FAA. Only specific parts of the software package are used in FORT. The INM noise engine uses empirical Noise-Power-Distance (NPD) data to estimate noise, in this estimation operation mode (arrival/departure) is taken into account as well as thrust setting, source-receiver geometry, acoustic directivity and other environmental factors. The noise model outputs are either noise contours for an area or noise levels at pre-selected locations. FORT uses SEL as output, calculated at specified points within a grid.

The SEL levels in the NPD tables are listed per engine type. The stored data is relevant under reference conditions which is adjusted such that the calculated values represent actual conditions. Three adjustments are made to the NPD tables within the noise model itself:

- **Noise fraction adjustment.** The SEL levels defined in the tables are valid for segments of infinite length. In reality these segments have a finite length.
- **Speed adjustment.** The reference speed is 160 knots ($kts$) $V_{TAS}$. Any speed above or below this value is corrected.
- **Lateral attenuation adjustment.** The grid points that are not directly underneath the flight path of the aircraft are affected by ground reflection, refraction, airplane shielding and other ground effects. For these grid points additional adjustments are done.

For more information on these adjustments the reader is advised to read [46].

**Noise model input**

To calculate the entire noise footprint over a pre-specified grid the noise model requires a complete description of the aircraft track, as well as the thrust levels. The noise model requires:

- Aircraft lateral position: $x$ and $y$.
- Aircraft altitude: $h$ in meters.
- Aircraft true airspeed, $V$ in $m/s$.
- Aircraft thrust, $T$ in $N$.
- Grid data.

**Noise model output**

In a multi-phase optimization the GPOPS outputs are segments of the final trajectory (the separate phases). These phases are combined into one trajectory before the noise model calculates the noise levels of the entire event. Within this solution the track consists of segments of the flight, from node to node (see Figure 3.4).

The output of the noise model consists of SEL levels at the pre-specified grid points. To calculate the corresponding day-evening-night weighted levels these values are first converted to the **Sound Exposure Ratio (SER)**. This is done using Equation 3.20:

$$SER = 10\left(\frac{L_{AP}}{10}\right)$$  \hspace{1cm} (3.20)

---

Since the aim of the research is to optimize for multiple events over a period of time the $L_{DEN}$ metric is used. Equation 2.5 shows the relation between the $SER$ levels of events and the resulting $L_{DEN}$ value. The number of events times the weights of each departure/aircraft type is calculated based on benchmark data, which is called $N_{tot}$. $N_{tot}$ is the weighted amount of occurrences of an event, which are used, together with the $SEL$ levels of each of the departures, to calculate $L_{DEN}$. Combining Equation 3.20 with Equation 2.4 the following equation is found:

$$L_{DEN} = 10 \cdot \log_{10} \sum_{i=1}^{N} (N_{tot_i} \cdot SER_{flight_i})$$

In which $N_{tot_i}$ is the weighted amount of events of a track, $SER_{flight_i}$ is the SER level of the track and $i$ is the amount of separate departure procedures/aircraft types.

### 3.4 Geographic Information System

Since the dose-response relationship calculates the average response in a percentage value, this value is multiplied by the amount of inhabitants at each of the grid points to get a tangible value for the total impact of noise on the entire community. To be able to do so data on population is required. The dataset containing this information is called the Geographic Information System (GIS).

Using population density data the population is mapped/represented by concentrations of inhabitants at specified grid points. These grid points can be regularly spaced or grid points can be made using $k$-means clustering. The GIS used is supplied by the Dutch Statistics Netherlands (CBS). The data is shown in Figure 3.5. The Cartesian coordinate system used in this thesis is called the ‘Rijksdriehoeks’ (RD) coordinate system.
Figure 3.5: Population density data used in this thesis. Data is provided by the Dutch CBS.
The purple lines indicate runways at Amsterdam Airport Schiphol.

3.5 Dose-Response Relationship

Since the aim of this thesis is to implement a multi-event optimization, a multi-event noise metric is used. Section 2.1.2 shows three relationships between $L_{DEN}$ and the percentage of people highly annoyed. These relations allow to quantify the noise impact such that this can be used to optimize for. It is seen that both the equations created by Miedema & Oudshoorn and TNO require a cut-off at 42 dB to find positive values of percentage of people highly annoyed. Implementing these equations, with the cut-off, proved problematic for two reasons:

- As the optimization progresses, grid points are added and removed (because grid points start receiving more than 42 dB, while others are reduced to values below 42 dB). This causes discontinuities in the cost function and the derivatives of the cost function, which cause numerical difficulties within the optimization. Since the derivatives are used to generate a new guess, the search direction of this new guess is less accurate. Furthermore the derivatives are used to estimate the degree of optimality.

- Using the cut-off reduces the amount of grid points that are included in the optimization significantly. This limited set of grid points often generates derivatives that insufficiently force the aircraft track into a direction.
For this reason the dose-response relationship provided by GES is used. Engelen [13] states that extrapolation of the curve is possible numerically, however this is not supported by the results of the research. This 39 dB cut-off is however not used in the optimization. Removing this cut-off should be done with care as the optimization could focus on reducing annoyances at $L_{DEN}$ levels below 39 dB. The amount of people highly annoyed at a grid point is found by multiplying Equation 2.8 with the amount of inhabitants at a grid point:

$$n_{HA_i} = \left( \frac{e^{-8.11001+0.1333 \cdot L_{DEN_i}}}{1 + e^{-8.11001+0.1333 \cdot L_{DEN_i}}} \right) \cdot inhab_i$$

(3.22)

In which $n_{HA_i}$ is the amount of people highly annoyed in grid point $i$ and $inhab_i$ is the amount of inhabitants at grid point $i$. The total amount of people highly annoyed is found by summing $n_{HA_i}$ over all grid points.

### 3.6 Complete integration of blocks

This section describes how all previously mentioned building blocks of FORT are combined in the optimization tool. This is best done using the drawing of the detailed layout of the tool, as shown in Figure 3.6. In this figure the blue blocks have been described previously. The orange blocks are added parts of information needed within the optimization which are discussed in Chapter 4. Green blocks represent information that is created and used in next steps.

![Figure 3.6: Overview of the detailed layout of FORT.](image)

To initialize FORT first geographical information (the grid) is implemented, together with an initial guess. The initial guess is a complete description of a trajectory which forms the first step in the first iteration. The closer the initial guess is to the optimal solution, the less iterations are needed to
converge to the optimal solution. The initial guess and grid data are combined with information on
the general set-up of the optimization. This general set-up includes:

- The aircraft model. This is the set of differential equations shown in Section 3.2.
- Aircraft parameters: the parameters that define the behaviour of the aircraft. These include for
  example: engine characteristics, aircraft weight, and drag characteristics. These are unique per
  aircraft type and are discussed in Chapter 4.
- Initial and final conditions per phase. If the states need to have specific values at the start and
  end of a phase, this is defined.
- State & Control limits. The limits to states and controls are defined as well.
- Linkages and linkage constraints. The linkage constraints form a specific set of initial and final
  conditions. The required linkages between phases are defined.
- Other types of constraints are defined, together with their limit values. These can be continuous
  (path) constraints or constraints at the start/end of phases (so-called event constraints).

This entire set of information is combined into one problem (which is basically a set of objective
variables and constraints that is optimized). The cost function is added to the problem as well. INT-
LAB calculates the derivative values (all derivatives except noise-related derivatives) numerically.

The entire set of values, limits and derivatives is sent to a program (the purple block in Figure 3.6)
that creates and inserts all noise-related values and derivatives. The required information (x, y, h,
T, V and GIS) of each trajectory is combined, and sent to the noise model. The noise model creates
matrices with SER values over all pre-defined grid points, per aircraft trajectory. The noise model
also creates the derivative values of SER to each of the state and control parameters (J_{SER}). The
calculation of the derivatives of other noise-related metrics are discussed in Subsection 4.4.2.

Using the noise model output, the noise values and derivatives are calculated. These calculations
have already been discussed (see Section 3.3 and 3.5). These numbers are added analytically to the
total problem description. The analytical calculation and addition of these noise derivates lead to a
significant reduction in FORT convergence time.

This combined total description is sent to SNOPT, which creates a new set of state and control vari-
ables that form a new solution to the problem. This new solution is subsequently checked for opti-
mality and feasibility on which the decision for a new iteration is based.
Description of the Cases

To answer the research questions several different cases are optimized, the results are then analysed to draw conclusions. The implementation of these cases within FORT is treated in this chapter. In short, multi-event optimizations are performed for two aircraft types, the Boeing 737-300 and the Boeing 747-400. The amount of daily departures from Amsterdam Airport Schiphol is categorized to either aircraft type to create a representation of the daily air traffic departing from Schiphol.

4.1 Amsterdam Airport Schiphol

Amsterdam Airport Schiphol (AAS) is one of the busiest airports in Europe. The strategic position of AAS in Europe allows using AAS as a hub for connecting flights, which means that passengers use AAS as a connection between two segments of their flights. Besides hub transfers AAS also accommodates point-to-point flights.

The skies above the southern part of the UK, the Netherlands, Germany, Belgium and France are very busy in general. Due to the large amounts of air traffic a great challenge for air traffic control (ATC) is created, as ATC separates all flights while maximizing capacity, while avoiding delays as much as possible.

Schiphol is located in the Randstad, which is a densely populated area in the Netherlands. The Randstad consists of the largest parts of the provinces of Noord-Holland and Zuid-Holland and includes the four largest cities of The Netherlands. The location of AAS within the Netherlands is depicted in Figure 4.1.

Schiphol’s growth is limited due to the close proximity of surrounding municipalities as shown in Figure 4.2. AAS is surrounded by the cities of Hoofddorp, Uithoorn, Aalsmeer, Amstelveen, Amsterdam and Haarlem. The close proximity of noise-sensitive areas means aircraft noise should be taken into account as this noise is the limiting factor in the expansion of AAS. Noise measurements and regulation at AAS specifically is treated in Subsection 4.1.2. The noise sensitivity problem of Schiphol is what makes investigating noise abatement departure procedures there interesting.

4.1.1 Runways and Runway usage

AAS has six runways of which three are parallel. The location, direction and names of these runways are depicted in Figure 4.3. Since AAS functions as a hub for airlines, hourly peaks are seen in both the amount of departures and the amount of arrivals. Using a hub implies that multiple aircraft should land shortly after another, to reduce turn around times of the aircraft (for further explanation on this please read [11]), which causes alternating peaks in departures and arrivals. During peaks 100 aircraft per hour are departing/landing and usually 2 arrival and 1 departure runways are active, or 2 departure and 1 arrival runway.
AAS is located close to the North-Sea, meaning that AAS often has to deal with windy conditions which change during the day as well. AAS adjusts runway usage based on demand and weather conditions. Runway usage for departures over 2014 is shown in Figure 4.4 while Appendix B shows the SID charts of the three most-used runways for departures.

4.1.2 AAS Noise and Noise Regulation

When the Polderbaan (18L, 36R) was opened in 2003, a noise enforcement system was implemented. This system consisted of 60 enforcement points located around the airport. These are points at which the day-night average noise ($L_{DEN}$) is calculated (over 35 points), together with the night average ($L_{night}$) (over 25 points). When there was a chance of exceeding the legally determined maximum noise at a point, the runway preferences were adjusted accordingly.

The flight records of all traffic are saved (radar data) by the air traffic control in the Netherlands (LVNL - Lucht Verkeersleiding Nederland). Using this data the noise produced by the aircraft is estimated. Combining this data with the flight tracks allowed to re-estimate $L_{DEN}$ and $L_{night}$ after the event. It should be stated that, besides noise, also risk and emissions are taken into account in the LVNL calculations.
Figure 4.2: Overview of communities surrounding AAS. [19]

Figure 4.3: Overview of AAS’ runways. [5]
The preferential runway system

The new system does not steer as much on the values of noise at the noise enforcement points. Instead, there is a preferential runway system that dictates when to use which runways, in which direction and for which types of traffic. The preferences in this runway system are shown in Table 4.1, 4.2 and 4.3. In these tables good visibility is defined as: a visibility of at least 5000 m, the cloud base is above 1000 ft and during daylight. Marginal visibility is defined as: visibility of at least 1500 m and the cloud base should be above 300 ft.

Table 4.1: Preferential runway system at AAS during daytime (06:00-23:00) with good visibility. [42]

<table>
<thead>
<tr>
<th>Preference</th>
<th>Arrival 1</th>
<th>Arrival 2</th>
<th>Departure 1</th>
<th>Departure 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>06 (36R)</td>
<td>36L (36C)</td>
<td>Departure 1</td>
<td>Departure 2</td>
</tr>
<tr>
<td>2</td>
<td>18R (18C)</td>
<td>24 (18L)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>06 (36R)</td>
<td>09 (36L)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>27 (18R)</td>
<td>24 (18L)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 4.2: Preferential runway system at AAS during daytime (06:00-23:00) with good and marginal visibility. [42]

<table>
<thead>
<tr>
<th>Preference</th>
<th>Arrival 1</th>
<th>Arrival 2</th>
<th>Departure 1</th>
<th>Departure 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>36R (36C)</td>
<td>36L (36C/09)</td>
<td>Departure 1</td>
<td>Departure 2</td>
</tr>
<tr>
<td>6</td>
<td>18R (18C)</td>
<td>18L (18C/24)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Noise monitoring is used at AAS. The result of the ‘NOise MOnitoring System’ (NOMOS) are publicly available [34]. There are 24 fixed-base measurement stations constantly monitoring noise, and there is one mobile unit [8].

4.1.3 Available flight data

A set of data is available containing all recorded flights tracks of aircraft departing and landing from/at AAS on a single day. Figure 4.5 shows a plot of each of these tracks, the data of which is recorded on 22 October 2010. On this day a total of 1211 aircraft movements are recorded, of which 611 are departures. The average daily amount of movements in 2014 equalled 1200 [3].

In previous research [21] this data set is analysed completely to be able to create the aircraft mix per runway and per operation type (for each SID and Standard Terminal Arrival Route, STAR) separately.
Table 4.3: Preferential runway system at AAS during night time (23:00-06:00). [42]

<table>
<thead>
<tr>
<th>Preference</th>
<th>Arrival</th>
<th>Departure</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>06</td>
<td>36L</td>
</tr>
<tr>
<td>2</td>
<td>18R</td>
<td>24</td>
</tr>
<tr>
<td>3</td>
<td>36C</td>
<td>36L</td>
</tr>
<tr>
<td>4</td>
<td>18R</td>
<td>18C</td>
</tr>
</tbody>
</table>

Figure 4.5: Radar track data of all flight operations at AAS on 22 October 2010. White lines are arrival tracks, blue lines are departures. [21]

Hartjes [21] describes how all 51 aircraft types are categorized to twelve representative aircraft. The weighted amount (Day-Evening-Night weighting) of each of these representative aircraft types is shown in Appendix C. In this appendix only relevant runways and departure directions are shown. These twelve aircraft types are categorized to two aircraft types, based on their weight, which is described in Subsection 4.2.1.

4.2 Aircraft parameters and dynamics

Although computational power is ever increasing, optimizing multiple aircraft/tracks simultaneously still proves to be complex and tedious. Furthermore, to be able to optimize for different aircraft/tracks also detailed models including drag, engine and fuel flow characteristics for each of the aircraft types are required. Two very accurate models are available at the Delft University of Technology: the models of the Boeing 747-400 (B744) and the Boeing 737-300 (B733). For these reasons it is chosen to perform multi-event optimizations for two aircraft types simultaneously. The categorization of the 12 representative aircraft types used in [21] is performed subsequently.
4.2.1 Categorization of aircraft types

The categorization of the twelve aircraft types is done only based on maximum take-off weight (MTOW). The light aircraft group is represented by the B733. The heavy aircraft group is represented by the B744. The MTOW of the B733 is 63 tons, the MTOW of the B744 is 363 tons. The boundary between the two aircraft types is set at half the difference between the two which means that aircraft with an MTOW greater than 213 tons are represented by the B744. All twelve aircraft types, together with their MTOW and representative aircraft, are shown in Table 4.4.

Table 4.4: Overview of categorization of aircraft types.

<table>
<thead>
<tr>
<th>Aircraft</th>
<th>Alias</th>
<th>MTOW [kg]</th>
<th>Representative Aircraft</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fokker 70</td>
<td>F70</td>
<td>39009</td>
<td>B733</td>
</tr>
<tr>
<td>Fokker 100</td>
<td>F100</td>
<td>44452</td>
<td>B733</td>
</tr>
<tr>
<td>Boeing 737-300</td>
<td>B733</td>
<td>62820</td>
<td>B733</td>
</tr>
<tr>
<td>Boeing 737-400</td>
<td>B734</td>
<td>68039</td>
<td>B733</td>
</tr>
<tr>
<td>Boeing 737-800</td>
<td>B738</td>
<td>79016</td>
<td>B733</td>
</tr>
<tr>
<td>Airbus A320</td>
<td>A320</td>
<td>77000</td>
<td>B733</td>
</tr>
<tr>
<td>Boeing 757-200</td>
<td>B752</td>
<td>115666</td>
<td>B733</td>
</tr>
<tr>
<td>Boeing 767-300</td>
<td>B763</td>
<td>184612</td>
<td>B733</td>
</tr>
<tr>
<td>Boeing 777-200</td>
<td>B772</td>
<td>297557</td>
<td>B744</td>
</tr>
<tr>
<td>Boeing 747-400</td>
<td>B744</td>
<td>362874</td>
<td>B744</td>
</tr>
</tbody>
</table>

4.2.2 Description of the Boeing 737-300

Figure 4.6 shows a B733 in KLM colours at AAS. In 1984 Boeing started the production of the Boeing 737 Classic family. Production started with the Boeing 737-300 after which production of the longer 737-400 and the shorter 737-500 also started. In 1998 the B733 was replaced by a member of the 737 NextGen family, the Boeing 737-700.

The Boeing 737-300 is equipped with two CFM56-3B1 engines. More specific information of the B733 model is found in Table 4.5. The B733 is modelled to require a take-off field length of 2100 m.

Table 4.5: Boeing 737-300 characteristics as used within FORT. [20, 7]

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capacity</td>
<td>128 (+2 crew)</td>
</tr>
<tr>
<td>Length</td>
<td>33.4 m</td>
</tr>
<tr>
<td>Wing Span</td>
<td>28.9 m</td>
</tr>
<tr>
<td>Height</td>
<td>11.1 m</td>
</tr>
<tr>
<td>Wing Area (S)</td>
<td>105.4 m</td>
</tr>
<tr>
<td>Operating Empty Mass</td>
<td>32700 kg</td>
</tr>
<tr>
<td>Maximum Take-Off Mass</td>
<td>62820 kg</td>
</tr>
<tr>
<td>Fuel Capacity (FC)</td>
<td>18000 kg</td>
</tr>
<tr>
<td>Maximum Payload Mass</td>
<td>15710 kg</td>
</tr>
<tr>
<td>Cruise Speed</td>
<td>M=0.76</td>
</tr>
<tr>
<td>Range (Typical)</td>
<td>5275 km</td>
</tr>
<tr>
<td>Engines</td>
<td>2 * CFM56-3B1</td>
</tr>
<tr>
<td>Maximum Thrust</td>
<td>2 * 88964 N at SLST</td>
</tr>
</tbody>
</table>

1http://arubaspotter.blogspot.nl/2014_03_13_archive.html
2SLST means Sea Level, Standard Day
The aircraft drag coefficient, $C_D$, is calculated using Equation 4.1.

$$C_D = C_{D_0} + C_{D_1} \cdot C_L + C_{D_2} \cdot C_L^2$$  \hspace{1cm} (4.1)$$

In Equation 4.1 $C_L$ is the aircraft lift coefficient and $C_{D_0}$, $C_{D_1}$ and $C_{D_2}$ are drag coefficients. The values for these coefficients are found by combining available flap setting data [20], in order to reduce the amount of required phases.

4.2.3 Description of the Boeing 747-400

Figure 4.7\(^3\) shows a picture of a KLM B744 landing at the Polderbaan at AAS. KLM was the first airline to use the B744 as a commercial aircraft on 7 February 1989. The B747-400 is the improved version of the B747-300 and is the most sold Boeing of the 747 family. The production stopped in 2005 when the model was replaced by the B747-800.

The Boeing 747-400 is equipped with four General Electric CF6-80C2B1F engines. More information of the B744 model is found in Table 4.6. The B744 is modelled to require a take-off field length of 3300 m.

The aircraft drag coefficient, $C_D$, is calculated using Equation 4.1. The coefficients are found by combining available flap setting data, in ways equal to [20]. This is done in order to reduce the amount of required phases.

\(^3\)http://straatkaart.nl/2141CM-1Jweg-NY/media_fotos/landing-klm-boeing-747-400-polderbaan-fi8/
4.3 Description of the phases

The optimization problem consists of optimizing two departure tracks simultaneously. Each of these tracks are split up into three phases (six in total). By setting discontinuous path constraints between the phases, adherence to regulations during the take-off is ensured. The regulations include the thrust reduction point as well as the straight flight phase and bank angle limitations.

The general set-up of the phases and connections between the phases are shown in Figure 4.8. It is seen that phases 1, 2 and 3 are linked (the B733 track) in points 3 and 5. Phases 4, 5 and 6 are also linked (points 4 and 6) but independent of phases 1, 2 and 3. Separate initial conditions apply to phase 1 and 4 (point 1 and 2), the same goes for the final conditions of the two tracks (point 7 and 8).

Each of the phases has unique properties such that they differ from the phases they are connected to. These differences are implemented using initial and final conditions on states and controls, as well as implementing path and event constraints. The general description of each of the phases in found in Table 4.7. This section treats the initial and final conditions, the state and control limits, the event constraints and the path constraints for all phases.

4.3.1 Initial and final conditions

In this subsection the initial and final conditions of both tracks are treated.

Boeing 737-300

The initial mass of the B733 is set at 75 % payload (12 tons) and 75 % fuel weight (13.5 tons). With this the total initial aircraft mass at take-off is set at 58 tons, which is 92 % of the maximum take-off
Table 4.6: Boeing 747-300 characteristics as used within FORT.

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capacity</td>
<td>42 (up), 24 (first), 32 (business), 302 (economy)</td>
</tr>
<tr>
<td>Length</td>
<td>70.67 m</td>
</tr>
<tr>
<td>Wing Span</td>
<td>64.44 m</td>
</tr>
<tr>
<td>Height</td>
<td>19.4 m</td>
</tr>
<tr>
<td>Wing Area (S)</td>
<td>541.16 m</td>
</tr>
<tr>
<td>Operating Empty Mass</td>
<td>178756 kg</td>
</tr>
<tr>
<td>Maximum Take-Off Mass</td>
<td>362874 kg</td>
</tr>
<tr>
<td>Fuel Capacity (FC)</td>
<td>163396 kg</td>
</tr>
<tr>
<td>Maximum Payload Mass</td>
<td>63917 kg</td>
</tr>
<tr>
<td>Cruise Speed</td>
<td>M= 0.85</td>
</tr>
<tr>
<td>Range (Typical)</td>
<td>11454 km</td>
</tr>
<tr>
<td>Engine Model</td>
<td>4 * PW4056</td>
</tr>
<tr>
<td>Maximum Thrust</td>
<td>4 * 254,260 N at SLST</td>
</tr>
</tbody>
</table>

Table 4.7: General description of the unique properties of the phases.

<table>
<thead>
<tr>
<th>Phase</th>
<th>Path Constraint (continuous)</th>
<th>Thrust setting</th>
<th>Control limit (continuous)</th>
<th>State limit (end of phase)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/4</td>
<td>( \frac{dx}{dt} = 0 )</td>
<td>( T = T_{Take-Off} )</td>
<td>( \Gamma = 1 )</td>
<td>( z \geq 400 \text{ ft} )</td>
</tr>
<tr>
<td>2/5</td>
<td>( \mu \leq \mu_{max} )</td>
<td>( T = T_{Take-Off} )</td>
<td>( \Gamma = 1 )</td>
<td>( z \geq 800 \text{ ft} )</td>
</tr>
<tr>
<td>3/6</td>
<td>( \mu \leq \mu_{max} )</td>
<td>( T = T_{climb} )</td>
<td>( \Gamma = \text{Free} )</td>
<td>( z = 800 \text{ ft} )</td>
</tr>
</tbody>
</table>

Figure 4.8: Overview of the general set-up of the six separate phases.

The required take-off length is set at 2100 m with which the starting point for each runway used is shown in Table 4.8. This table also shows the initial headings which coincide with the runway headings. The initial altitude is set at 5 ft, which is the altitude at which a normal DER starts (see Section 2.3.1). The initial (calibrated) airspeed of the B733 model is set at \( V_2 \) \([44]\) plus 10 knots (161 kts) by including an event constraint.

The Boeing 737-300 ends up at the final point of the SID. For the SPIJKERBOOR and ANDIK de-
partures this is the ANDIK point. For the NYKER, IVLUT, ARNEM and LUNIX departures this is the PAM way point. The final (calibrated) speed is equal to the maximum speed below 10000 ft altitude (Flight Level 100), which is 250 kts. The final altitude is set at the maximum altitude during the SIDs which is 6000 ft (Flight Level 060). The final speed is implemented as an event constraint, the final altitude is simply a final state value. All initial and final conditions are summarized in Table 4.8.

**Boeing 747-400**

The initial mass of the B744 is set at 60 % payload (38 tons) and 75 % fuel weight (125 tons). With this the total initial aircraft mass is set at 58 tons, which is 94 % of the maximum take-off mass. The B744 has relatively more fuel than payload, as the aircraft departing from AAS are usually scheduled to fly long distances. The required take-off length is set at 3300 m such that the starting points for each runway is shown in Table 4.8. The initial heading coincides with the runway heading and the initial altitude is set at 5 ft. The initial (calibrated) airspeed of the B744 model is set at $V_2$ plus 10 knots (183 kts). The final conditions of the B744 coincide with the final conditions of the B733. The initial and final speed are included as an event constraint which is treated in Subsection 4.3.3. All initial and final conditions are summarized in Table 4.8

<table>
<thead>
<tr>
<th>Boeing 737-300</th>
<th>Boeing 747-400</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial Mass (kg)</td>
<td>57982.5</td>
</tr>
<tr>
<td>Take-off point RWY24 ($x_{RD}, y_{RD}$) (km)</td>
<td>(112,479)</td>
</tr>
<tr>
<td>Take-off heading RWY24 (deg)</td>
<td>237.95</td>
</tr>
<tr>
<td>Take-off point RWY36L ($x_{RD}, y_{RD}$) (km)</td>
<td>(109,481)</td>
</tr>
<tr>
<td>Take-off heading RWY36L (deg)</td>
<td>3.25</td>
</tr>
<tr>
<td>Take-off speed (kts)</td>
<td>161</td>
</tr>
<tr>
<td>End-Point ANDIK ($x_{RD}, y_{RD}$) (km)</td>
<td>(147,528)</td>
</tr>
<tr>
<td>End-Point PAMPUS ($x_{RD}, y_{RD}$) (km)</td>
<td>(135,483)</td>
</tr>
<tr>
<td>Final Altitude (ft)</td>
<td>6000</td>
</tr>
<tr>
<td>Final speed (kts)</td>
<td>250</td>
</tr>
</tbody>
</table>

### 4.3.2 State & Control Limits

The entire optimization problem (all states and controls) are bounded with upper and lower limits. These limits are in almost all cases not active in the solution, instead they are set to filter out odd behaviour. One example of this is that the heading is limited between $-720 \text{ deg}$ and $+720 \text{ deg}$, which is done to avoid multiple $360 \text{ deg}$ turns in the solution.

One limit that is always active is the limit on the engine control setting. In Subsection 2.3.3 it is shown that thrust reductions are not allowed before an altitude of at least 800 ft is reached. This is implemented in the optimization by fixing the engine control setting at its maximum value (1) during the first two phases of the two flights (phase 1, 2, 4 and 5).

The minimum and maximum state values for $x, y, z, \chi$ and $W$ at the start of phase 1 and 4 are used to set the initial conditions. The minimum and maximum state values for $x, y$ and $z$ at the end of phase 3 and 6 are used to set the final conditions. Lastly the boundary between phase 1-2 and phase 4-5 (which means the end of the straight flight segment) is at least at 500 ft altitude and the boundary between phase 2-3 and phase 5-6 (which means the point of thrust reduction) is at least at 800 ft altitude.
4.3.3 Event Constraints

Event constraints allow to set a value for a specific variable at the start and/or end of each phase. In this optimization event constraints are used to fix the calibrated airspeed value at the start of the first and the end of the last phase. The initial true airspeed, \( V_{TAS_{init}} \), is converted to \( V_{CAS_{init}} \) using Equation 4.2:

\[
V_{TAS} = \sqrt{\frac{2\gamma p}{\gamma - 1 \rho}} \left[ \left( \frac{1 + \frac{\rho_0}{\rho} \left( \frac{1}{\gamma} - \frac{1}{2\gamma} \frac{p_0}{\rho_0} V_{CAS}^2 \right)^{\frac{\gamma+1}{\gamma-1}} - 1 \right) \right]^{\frac{\gamma-1}{\gamma}}
\]  
(4.2)

Subscript \( 0 \) indicates a value at sea level. \( p \) is pressure, in \( N/m^2 \), \( \rho \) is air density in \( kg/m^3 \) and \( \gamma \) is the ratio of the specific heats of air which is dimensionless. These event constraints are implemented as difference equations, in which the following condition is met at the start of phase 1 and 4:

\[
V_{CAS_{init}} - V_{CAS} = 0
\]  
(4.3)

The same is done for the final speed of the aircraft:

\[
V_{CAS_{final}} - V_{CAS} = 0
\]  
(4.4)

Which is active at the end of phase 3 and phase 6.

4.3.4 Path Constraints

Path constraints are used to limit a parameter value during the trajectory itself (continuously). In total four different types of path constraints are used. The first path constraint prevents the aircraft from descending and is shown in Equation 4.5. This constraint is active during all 6 phases.

\[
\frac{\partial h}{\partial t} = \dot{h} \geq 0
\]  
(4.5)

The second type of path constraints aims to ensure that the aircraft are flying straight until an altitude of at least 500 ft is reached. This is ensured by implementing Equation 4.6, which is only active during the first phase of both flights (phase 1 and 4).

\[
\frac{\partial \chi}{\partial t} = \dot{\chi} = 0
\]  
(4.6)

The third path constraints aims to ensure that the maximum bank angle limit is not exceeded. This maximum bank angle is a function of altitude as shown in Subsection 2.3.1. It is seen that there are three distinct levels of the maximum bank angle: 15 deg, 20 deg and 25 deg. There are two methods to apply this type of constraint, the first method is to add two extra phases to the problem description to implement three discontinuous path constraints. This solution increases the numerical complexity of the problem. Furthermore the order of the phases is predefined, which is often a non-intuitive process. The second method to apply the path constraint is to create a step function that approximates the maximum bank angle as a function of altitude, as shown by Equation 4.7 and Figure 4.9. This second method is opted for.

\[
\mu_{max} = \frac{5}{\pi} \cdot \left[ \arctan(z - 304.8) + \arctan(z - 914.2) \right] + 20
\]  
(4.7)
Figure 4.9: Maximum bank angle as a function of altitude. This limit is used as a path constraint in the optimization.

This equation is implemented twice as difference equation, in which the positive and negative bank angles are limited. Two constraints are included instead of one, as taking the absolute value of the bank angle would introduce a discontinuity in the constraint function. These path constraints are applied during the second and third phase of both flights as the first flight already requires to be straight.

\[ \mu_{\text{max}} - \mu \geq 0 \] (4.8)

\[ \mu_{\text{max}} + \mu \geq 0 \] (4.9)

The last path constraint that is implemented prevents the aircraft from decreasing their calibrated airspeed (\( V_{\text{CAS}} \)). The conversion from \( V_{\text{TAS}} \) to \( V_{\text{CAS}} \) is used here such that:

\[ \dot{V}_{\text{CAS}} \geq 0 \] (4.10)

To implement this, the derivative of \( V_{\text{CAS}} \) is found, this is done using the following equation:
\[ V_{CAS} = \sqrt{2p_0} \left[ \frac{\gamma}{\rho_0} \right]^{\frac{\gamma - 1}{\gamma}} \left[ \frac{V_{2} T_{AS} \left( \frac{\gamma - 1}{2} + 1 \right)}{p} - \frac{\gamma V_{2} T_{AS} \left( \frac{\gamma - 1}{2\gamma} + 1 \right)}{\gamma - 1} \right] \right]^{\frac{1}{\gamma - 1}} + 1 \]  

(4.11)

In which:

\[ \frac{\partial p}{\partial h} = -\frac{g_0 \rho_0}{RT_0} \left( \frac{T}{T_0} \right)^{-\frac{\gamma}{\gamma + 1}} \]  

(4.12)

\[ \frac{\partial p}{\partial h} = -\frac{\rho_0 \lambda}{T_0} \left( \frac{g_0}{R \lambda} + 1 \right) \left( \frac{T}{T_0} \right)^{-\frac{\gamma}{\gamma + 2}} \]  

(4.13)

In these equations:

- Subscript 0 indicates a reference value.
- \( p \) is pressure, in \( N/m^2 \).
- \( \rho \) is air density in \( kg/m^3 \).
- \( T \) is temperature in Kelvin \( K \).
- \( \gamma \) is the ratio of the specific heats of air which is dimensionless.
- \( \lambda \) is the temperature lapse rate in \( K/m \).
- \( g \) is the temperature lapse rate in \( m/s^2 \).
- \( R \) is the specific gas constant of air \( m^2/s^2 K \).
4.4 Cost function

This section treats the creation of the several cost functions used in the optimizations. Before the cost functions are shown first the new noise metrics that are implemented are discussed, after which the Jacobians of the noise metrics are discussed as well.

4.4.1 New noise metrics

Previous research has focussed only on reducing total community noise while peak noise loads and new noise are not taken into account. In this research focus is still on reducing the amount of people highly annoyed, though peak loads of noise and new noise are also taken into account. Besides optimizing for the minimum amount of people highly annoyed the aim of this research is to see to which extent new noise and peak loads of noise can be taken into account in the optimization of departure tracks. To indicate and optimize for peak loads and/or new noise first these are to be quantified. For this reason two new noise metrics are introduced.

Test runs of the optimization have shown that indeed the cost and constraint functions need to be continuous, as discussed in Chapter 3. When non-continuous cost function were used this caused numerical difficulties and FORT was unable to successfully converge. This limitation prohibits the use of types of cost function that would otherwise have been quite useful, such as the amount of people/grid points within a certain L\text{DEN} contour. For this reason two other types of functions were used to quantify new noise and annoyance, which are shown subsequently.

**Weighted Sound Exposure Ratio**

A noise metric that is used much less often is referred to as ‘Weighted Sound Exposure Ratio’. This name is appropriate especially when the original sound energy ratio, \( \frac{E}{E_0} \), is multiplied by the weight, \( w(i) \), and the number of occurrences, \( n(i) \), to find its value. The resulting value is equal to \( L_{\text{DER}} \) in the following equation:

\[
L_{\text{DER}} = 10^{\frac{L_{\text{DEN}}}{10}}
\]  

(4.14)

When \( L_{\text{DER}} \) is calculated in this manner, the term ‘Weighted Sound Exposure Ratio’ is not intuitive however. The term ‘Aggregate Sound Exposure Ratio’ is proposed for this metric. This is, however, a new term.

The \( L_{\text{DER}} \) noise metric is especially useful in light of the purpose of this thesis, as the aggregate sound exposure ratio exponentially grows with increasing \( L_{\text{DEN}} \) value. This means that if this value is used in the cost function, the focus is increasingly put on reducing noise in grid points exposed to high \( L_{\text{DEN}} \) values. Including the aggregate sound exposure ratio in the cost function of the optimization should therefore lead to a reduction in peak loads. Equation 4.14 calculates the \( L_{\text{DER}} \) value in one grid point, for the total value (not taking into account the amount of inhabitants) the \( L_{\text{DER}} \) value is summed over all grid points:

\[
L_{\text{DER,tot}} = \sum_{i=1}^{N} L_{\text{DER}_i}
\]  

(4.15)

In which \( i \) is the grid point, \( N \) is the total amount of grid points and \( L_{\text{DER}_i} \) is the \( L_{\text{DER}} \) value in grid point \( i \).
New Noise Metric
The other new noise metric, which is developed to quantify and reduce new noise, is newly created. Unfortunately no noise metric is known that allows the estimation of new noise. The function used to quantify new noise must satisfy three requirements:

- The function should increasingly value the amount of new noise. For example: an increase of 12 dB must be penalized stronger than four times an increase in 3 dB.
- The function should avoid focus being put on creating great reductions. Within the optimization the focus should be put on reducing new noise, instead of decreasing old noise. Equations that generate a negative outcome when there is a decrease in noise proved to be unsuitable as FORT then focusses on creating a reduction in noise for many grid points, instead of reducing the increase in noise in a limited amount of grid points.
- The function should be smooth over the entire range of decreasing and increasing $L_{DEN}$ values.

For these reasons an equation in the form of Equation 4.16 is opted for:

$$NN = a^{(L_{DEN,new} - L_{DEN,old})}$$ (4.16)

In which $a$ is any number greater than 1. To generate $NN$ values that are of a reasonable magnitude, $a = 3$ is proposed. Just as with the $L_{DER}$ function Equation 4.16 calculates new noise for one grid point. The total amount of new noise is found by summing all new noise values over the entire grid.

4.4.2 Noise Jacobians
One of the adjustments that reduces calculation times within FORT is the analytical addition/creation of the noise derivatives, this is discussed in Chapter 3. For this reason the creation of these noise Jacobians is discussed in this subsection. The derivatives of $SER$ per aircraft track are retrieved from the INM noise engine directly. These are derivatives to each of the objective variables, for each of the grid points. The Jacobian of $L_{DEN}$, $J_{L_{DEN}}$ is calculated using:

$$J_{L_{DEN}} = \frac{10}{ln(10)} \left( \sum_{i=1}^{N} N_{tot,i} \cdot J_{SER,flight,i} \right)$$ (4.17)

Since there are three noise metrics included in the separate cost functions (amount of people highly annoyed, $L_{DER}$ and $NN$), Jacobians for each of these metrics are calculated as well. The derivative of Equation 3.22 allows calculating the Jacobian of the amount of people highly annoyed:

$$J_{n_{HA}} = \sum_{i=1}^{N} \left[ \frac{0.1333 \cdot e^{-8.11001 + 0.1333 L_{DEN,i}}}{1 + e^{-8.11001 + 0.1333 L_{DEN,i}}} - \frac{(0.1333 \cdot e^{-8.11001 + 0.1333 L_{DEN,i}})^2}{(1 + e^{-8.11001 + 0.1333 L_{DEN,i}})^2} \right] \cdot inhab_i \cdot J_{L_{DEN,i}}$$ (4.18)

In which $J_{n_{HA}}$ is the Jacobian of the amount of people highly annoyed and $J_{L_{DEN,i}}$ is the Jacobian of the $L_{DEN}$ values at grid point $i$. The Jacobian of $L_{DER}$, $J_{L_{DER}}$ at a specific grid point $i$ is calculated using:

$$J_{L_{DER,i}} = \frac{1}{10} \cdot ln(10) \cdot 10^{\frac{L_{DEN,i}}{10}} \cdot J_{L_{DEN}}$$ (4.19)

In which $J_{L_{DEN,i}}$ is the Jacobian of $L_{DEN}$ in grid point $i$. When the $L_{DER}$ value is summed over all grid points the Jacobians are summed as well:

$$J_{L_{DER, tot}} = \frac{1}{10} \cdot ln(10) \cdot \sum_{i=1}^{N} 10^{\frac{L_{DEN,i}}{10}} \cdot J_{L_{DEN,i}}$$ (4.20)
The Jacobian of new noise at one grid point, \( J_{NN,i} \), is calculated using:

\[
J_{NN,i} = ln(3) \cdot 3^{L_{DEN_{new,i}} - L_{DEN_{old,i}}} \cdot J_{L_{DEN,i}}
\]  

(4.21)

In which \( i \) indicates the grid point number, \( L_{DEN_{new}} \) is the new \( L_{DEN} \) value and \( L_{DEN_{old}} \) is the benchmark \( L_{DEN} \) value. Summing this over all grid points to find the Jacobian of the combined new noise value:

\[
J_{NN,\text{tot}} = ln(3) \cdot \sum_{i=1}^{N} \left[ 3^{L_{DEN_{new,i}} - L_{DEN_{old,i}}} \cdot J_{L_{DEN,i}} \right]
\]  

(4.22)

### 4.4.3 Cost function values

Within the cost functions the B733 fuel is normalized with its fuel minimum solution value and the same is done for the B744. This normalization is done as the solution would otherwise let the B733 make a detour, such that the B744 flies its fuel minimum track. The reason for this is that the B744 requires significantly more fuel to be able to make a detour, as the aircraft is heavier and larger.

If the focus in the optimization is put on reducing the amount of people highly annoyed, the cost function shown in Equation 4.23 is applied.

\[
J = \frac{W_{\text{fuelB733}}}{W_{\text{fuelB733,\text{min}}}} + \frac{W_{\text{fuelB744}}}{W_{\text{fuelB744,\text{min}}}} + \frac{nHA_{\text{tot}}}{W_{\text{fuelB733,\text{min}}} + W_{\text{fuelB744,\text{min}}}} \cdot k_{\text{annoy}}
\]  

(4.23)

In which \( W_{\text{fuelB733}} \) and \( W_{\text{fuelB744}} \) are the minimum fuel burn weights of the B733 and B744 respectively. The so-called annoyance factor, \( k_{\text{annoy}} \), determines to what extent FORT focusses on reducing the amount of people highly annoyed as compared to reducing fuel burn. In the cost function the amount of people highly annoyed is scaled as well.

The Jacobian for the fuel part of the cost function, \( J_{\text{fuel}} \) is directly retrieved from FORT. The Jacobian for the amount of people highly annoyed is scaled and added to this Jacobian:

\[
J = J_{\text{fuel}} + \frac{nHA_{\text{tot}}}{W_{\text{fuelB733,\text{min}}} + W_{\text{fuelB744,\text{min}}}} \cdot k_{\text{annoy}}
\]  

(4.24)

When the optimization is performed for reducing the peak noise loads, \( L_{DER} \) is included in the cost function. This is done using Equation 4.25:

\[
J = \frac{W_{\text{fuelB733}}}{W_{\text{fuelB733,\text{min}}}} + \frac{W_{\text{fuelB744}}}{W_{\text{fuelB744,\text{min}}}} + \frac{L_{\text{DER}_{\text{tot}}}}{W_{\text{fuelB733,\text{min}}} + W_{\text{fuelB744,\text{min}}}} \cdot \frac{1}{1000} \cdot k_{L_{\text{DER}}}
\]  

(4.25)

Which leads to the following Jacobian:

\[
J = J_{\text{fuel}} + \frac{L_{\text{DER}_{\text{tot}}}}{W_{\text{fuelB733,\text{min}}} + W_{\text{fuelB744,\text{min}}}} \cdot \frac{1}{1000} \cdot k_{L_{\text{DER}}}
\]  

(4.26)

Finally the optimizations focussing on reducing new noise use the following cost function:

\[
J = \frac{W_{\text{fuelB733}}}{W_{\text{fuelB733,\text{min}}}} + \frac{W_{\text{fuelB744}}}{W_{\text{fuelB744,\text{min}}}} + \frac{NN_{\text{tot}}}{W_{\text{fuelB733,\text{min}}} + W_{\text{fuelB744,\text{min}}}} \cdot k_{NN}
\]  

(4.27)
With the following Jacobian:

\[
J = J_{fuel} + \frac{J_{NN_{tot}}}{W_{fuel_{B733\min}} + W_{fuel_{B744\min}}} \cdot k_{NN}
\]  

(4.28)

4.5 Noise Constraints

The constraints on the total amount of people highly annoyed are used to create sets of solutions that are comparable to each other in terms of annoyance. In previous research these solutions would have been comparable, because only fuel and the amount of people highly annoyed were taken into account.

In this thesis, however, these seemingly equal solutions are to be improved further. This is done by including either the aggregate sound exposure ratio function value, or the new noise function value, to the optimization. To do so the annoyance is removed from the cost function and included as a constraint.

Noise constraints differ from path and event constraints. The value for noise parameters are dependent on the entire flight track whereas path and event constraints are set for specific phases only, which means that many of the problem derivatives are equal to zero. GPOPS uses this knowledge to decrease calculation time. Within GPOPS’ sparsity pattern the dependency of the state and control values on the constraints are programmed. This sparsity pattern is adjusted to allow the insertion of noise constraints that are dependent on all objective variables to be optimized (i.e. to allow to include a constraint Jacobian that has non-zero derivatives towards all state and control values). Figure 4.10 shows a typical sparsity matrix used in the optimization. The first constraint is the cost function, which is dependent on all objective variables as well. Constraint 1360 is the implemented noise constraint, which is also dependent on all objective variables.
Figure 4.10: Typical sparsity matrix used in the optimization.
Chapter 5

Results

This chapter shows the results when the extended FORT tool is used to optimize aircraft departures. The capabilities of the program are shown by implementing a relatively simple optimization, the SPY2KY departure. This case is subsequently extended to test to which extent FORT can still be applied. Finally one case is presented that uses high traffic loads, to test the applicability of previously found results to this case.

5.1  SPIJKERBOOR 2K(Y) case study

To test and show the capabilities of the newly created FORT tool a case study is performed for the SPY2KY departure from runway 24 at AAS. The close proximity of the city of Hoofddorp to the end of runway 24 makes the SPIJKERBOOR departure (SPY) noise sensitive. Since runway 24 is the most-used runway for departures (Figure 4.4) this case is relevant. The SID of this departure is found in Figure B.1 of Appendix B.

The amount of people highly annoyed (PHA) generated by the SPY departure is dependent on the initiation point and the radius of the first (right) turn. For this reason the SPY2KY P-RNAV departure is created, which uses a fixed-radius turn around Hoofddorp. Due to this RF segment flights are concentrated onto one flight track, which increases peak noise loads. From the recorded flight data it is found that this SID is used by 45 light and 3 heavy aircraft and when the $L_{DEN}$ weighting is applied, effectively 60.2 light departures are modelled and 7.5 heavy departures. The initial and final conditions for this case are discussed in Section 4.3.1.

5.1.1  SPY2KY Benchmark

To be able to indicate the possible improvements in terms of the amount of people highly annoyed and fuel usage a benchmark is created. This is done by modelling the SPY2KY SID which includes the fixed radius turn. To implement the fixed-radius turn the ground track in the benchmark is fixed. The altitude and speed profile of the benchmark is found by modelling the NADPII departure (Figure 2.5) using path and event constraints. Air Traffic Control the Netherlands [2] mentions the following: ‘The use of the noise abatement take-off and climb procedure NADP2 as mentioned in ICAO Doc 8168 Volume I is recommended for all jet aircraft departures from Schiphol Airport. If for operational reasons compliance with the recommended procedure is not possible, NADP1 may be used.’ Using the fixed ground track as well as the path and event constraints the optimization is performed to find the minimum fuel solution.

The result of the benchmark situation is shown in Figure 5.1. The results in terms of fuel usage and the amount of people highly annoyed are shown in Table 5.1. The average fuel is calculated using
Equation 5.1, in which $m_{\text{fuel}_{\text{avg}}}$ is the average fuel mass and $N_{\text{B733}_{\text{true}}}$ and $N_{\text{B744}_{\text{true}}}$ are the true number of heavy and light aircraft used in the optimization. The amount of fuel used by the B733 and B744 are indicated by $m_{\text{fuel}_{\text{B733}}}$ and $m_{\text{fuel}_{\text{B744}}}$ respectively. The set of grid points that is used in the benchmark and the optimizations includes all grid points that are within the 10 dB $L_{\text{DEN}}$ contour of the benchmark. The minimum amount of fuel that is used for the normalization in the cost functions is 517.1 kg and 2081.3 kg for the B733 and B744 respectively.

$$m_{\text{fuel}_{\text{avg}}} = \frac{N_{\text{B733}_{\text{true}}} \cdot m_{\text{fuel}_{\text{B733}}} + N_{\text{B744}_{\text{true}}} \cdot m_{\text{fuel}_{\text{B744}}}}{N_{\text{B733}_{\text{true}}} + N_{\text{B744}_{\text{true}}}}$$  \hspace{1cm} (5.1)

![Figure 5.1: Resulting benchmark noise footprint of the SPY2KY benchmark.](image)

**Table 5.1: Results for the benchmark and the minimum annoyance solution of the SPY2KY departure.**

<table>
<thead>
<tr>
<th></th>
<th>SPY Benchmark</th>
<th>Minimum annoyance</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_{\text{fuel}_{\text{avg}}} \ (kg)$</td>
<td>657.9</td>
<td>638.1</td>
</tr>
<tr>
<td>$m_{\text{fuel}_{\text{B733}}} \ (kg)$</td>
<td>559.9</td>
<td>537.3</td>
</tr>
<tr>
<td>$m_{\text{fuel}_{\text{B744}}} \ (kg)$</td>
<td>2127.7</td>
<td>2149.0</td>
</tr>
<tr>
<td>$n_{\text{HA}}$</td>
<td>35395</td>
<td>22193</td>
</tr>
<tr>
<td>$L_{\text{DER}}$</td>
<td>8.47E+06</td>
<td>7.82E+06</td>
</tr>
</tbody>
</table>

### 5.1.2 Minimizing the amount of people highly annoyed

The extent to which the amount of people highly annoyed can be reduced is found by performing multiple optimizations in which the focus on annoyance ($k_{\text{annoy}}$ in Equation 4.23) is increased. The results of these optimizations in terms of average fuel usage and the amount of people highly annoyed are shown in Figure 5.2. The results of the solution that generates the least amount of people...
highly annoyed (referred to as *minimum annoyance solution*) are shown in Table 5.1. The amount of people highly annoyed is reduced by up to 37.3%, while reducing average fuel usage by 6.5 to 3.0% compared to the benchmark. It is furthermore seen that the B733 fuel is reduced more than the B744 fuel. Figure 5.3 allows to explain this by the fact that the B733 shortens its initial turn, while the B744 cannot do this due to the maximum bank angle constraint.

![Figure 5.2: Results in terms of people highly annoyed versus average fuel burn. The benchmark result is included.](image)

It is seen that in the first phase of the flight, during the first right turn, the aircraft tracks are separated. Due to the lower initial speed and the early take-off point the B733 the aircraft is able to execute a tighter right turn. By performing this right turn the aircraft avoids overflying the largest part of Hoofddorp. Due to the higher initial weight of the B744 it has a higher take-off speed and it uses a longer runway distance. For this reason the B744 is unable to execute an equally tight turn before Hoofddorp. To avoid the city of Haarlem the B744 continues turning slightly longer than the B733, until flying to the North-East. At this point both aircraft tracks start overlapping. Both aircraft pass between Wormerveer and Zaandam, slightly to the South of the Spijkerboor VOR/DME. Both aircraft avoid the city of Hoorn whereas the benchmark flies directly over Hoorn. The greatest differences between the optimized aircraft tracks and the benchmark are found in the first right turn and at the city of Hoorn.

Figure 5.4a shows that in the first ±20 seconds of the flights the B733 and B744 hardly accelerate such that they can climb (Figure 5.6b) to the altitude at which thrust reductions are allowed, as quickly as possible, to be able to reduce thrust and with that the amount of produced noise. At this point both aircraft level off and accelerate such that they pass Hoofddorp at low altitude, at high speeds and with minimum levels of thrust. Flying at low altitudes means that the noise contour is small due to lateral attenuation while flying fast reduces the exposure time. Both aircraft climb while they are in the sparsely inhabited area between Haarlem and Wormerveer. When passing between Zaandam and Wormerveer both aircraft level off again, such that they are able to reduce thrust when passing this noise sensitive area. Both aircraft climb to their final altitude while they are in the sparsely inhabited area North of Purmerend and South of Hoorn. Finally the differences between the benchmark and minimum annoyance solutions in terms of the true airspeed are explained by the difference between calibrated airspeed and true airspeed, due to the differences in altitude. This is discussed in more detail in Section 5.2.2.
Figure 5.3: Minimum annoyance B733 and B744 tracks as compared to the SPY2KY benchmark.

(a) Speed profiles of the B733 and B744 as compared to the benchmark.

(b) Altitude profiles of the B733 and B744 as compared to the benchmark.

Figure 5.4
Figure 5.5: The noise constrained, fuel minimum lateral track.

Figure 5.5 shows the solution of the optimization in which a noise constraint is applied close to the minimum amount of people highly annoyed (22200 people highly annoyed versus 22193). Figures 5.6a and 5.6b show equal comparisons in terms of the speed and altitude profiles. It is concluded that when the amount of people highly annoyed is constrained and the optimization is performed for minimum fuel only, the resulting tracks closely resemble the solution of when a mixed fuel/annoyance cost function is used instead.

(a) Comparison between the minimum fuel track and the noise constrained speed profile.  
(b) Comparison between the minimum fuel track and the noise constrained altitude profile.

Figure 5.6

5.1.3 Reducing peak loads

NADP II is designed to alleviate noise distant from the airport (Subsection 2.3.3), while Hoofddorp is located close to runway 24. The combination of the concentration of aircraft tracks and the application of the NADP II procedure results in high peak loads of received noise at Hoofddorp. At the same time the minimum annoyance solution shows behaviour equal to the NADPII departure which allows us to conclude using NADPII is beneficial when taking only the amount of people highly annoyed into account.
A reduction of 7.7\% in $L_{DER}$ is found when comparing the minimum annoyance solution to the benchmark. It could however be that the peak loads can be reduced further, while keeping the solution equal in terms of the amount of people highly annoyed. To assess this possibility a noise constraint is applied that ensures a maximum amount of 22200 people highly annoyed (the minimum annoyance solution results in 22193 people highly annoyed while the benchmark results in 35395 people highly annoyed). In these optimizations Equation 4.25 is applied as the cost function. Multiple optimizations are performed, increasingly focussing on reducing $L_{DER}$ (increasing $k_{L_{DER}}$). The solution resulting in the minimum $L_{DER}$ value is selected and the results are compared to: (1) the benchmark situation and (2) the optimization in which an equal noise constraint is applied but the optimization is performed for fuel only. The results are shown in Table 5.2.

### Table 5.2: Results for the noise constrained (22200) and minimum $L_{DER}$ solution.

<table>
<thead>
<tr>
<th></th>
<th>Benchmark</th>
<th>Minimum Fuel (22200)</th>
<th>Minimum $L_{DER}$ (22200)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_{fuel_{avg}}$ $(kg)$</td>
<td>657.9</td>
<td>638</td>
<td>638.8</td>
</tr>
<tr>
<td>$m_{fuel_{BT33}}$ $(kg)$</td>
<td>559.9</td>
<td>537.3</td>
<td>538</td>
</tr>
<tr>
<td>$m_{fuel_{BT44}}$ $(kg)$</td>
<td>2127.7</td>
<td>2147.5</td>
<td>2150.3</td>
</tr>
<tr>
<td>$n_{HA}$</td>
<td>35395</td>
<td>22201</td>
<td>22200</td>
</tr>
<tr>
<td>$L_{DER}$</td>
<td>8.47E+06</td>
<td>7.88E+06</td>
<td>7.16E+06</td>
</tr>
</tbody>
</table>

Compared to the benchmark, $L_{DER}$ can be reduced by 15.5\% while the amount of people highly annoyed is reduced by 37.8\%. Compared to the noise constrained, minimum fuel solution, $L_{DER}$ is reduced by 9.15\%. The effect of these reductions in terms of peak load is shown in Figure 5.7. From the figure it is seen that only a moderate improvement can be gained. The constraint on the amount of people highly annoyed is placed close to the minimum annoyance solution (22200 vs. 22193), due to this there is little space for the solution to improve in terms of $L_{DER}$. To test this new optimizations are performed in an equal manner, while the noise constraint value is adjusted to a maximum of 30000 people highly annoyed (this is a 15.2\% reduction compared to the benchmark). Subsequently equal comparisons are made, the results of which are shown in Table 5.3.

![Figure 5.7: Results in terms of the amount of grid points above discrete $L_{DEN}$ levels of the minimum $L_{DER}$ solution with a noise constraint of 22200 people highly annoyed, as compared to the constrained minimum fuel solution and the benchmark situation.](image)
Table 5.3: Results for the noise constrained (30000) and minimum $L_{DER}$ solution.

<table>
<thead>
<tr>
<th></th>
<th>Benchmark</th>
<th>Minimum Fuel (30000)</th>
<th>Minimum $L_{DER}$ (30000)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_{fuelAvg}$ (kg)</td>
<td>657.9</td>
<td>616.9</td>
<td>624.1</td>
</tr>
<tr>
<td>$m_{fuelB733}$ (kg)</td>
<td>559.9</td>
<td>519.1</td>
<td>525.2</td>
</tr>
<tr>
<td>$m_{fuelB744}$ (kg)</td>
<td>2127.7</td>
<td>2083.2</td>
<td>2108.1</td>
</tr>
<tr>
<td>$n_{HA}$</td>
<td>35395</td>
<td>30000</td>
<td>30000</td>
</tr>
<tr>
<td>$L_{DER}$</td>
<td>8.47E+06</td>
<td>7.40E+06</td>
<td>5.65E+06</td>
</tr>
</tbody>
</table>

Compared to the benchmark, $L_{DER}$ is reduced by 33.3% while compared to the noise constrained, minimum fuel solution, $L_{DER}$ is reduced by 23.6%. Figure 5.9 shows the decrease in the amount of grid points above discrete $L_{DEN}$ levels, while Figure 5.8 gives an overview of the actual numbers of grid points above discrete $L_{DEN}$ levels. It is seen that the improvement is more significant than when the maximum amount of people highly annoyed is set at 22200. This shows that when the noise constraint is set closer to the minimum annoyance value, the opportunities for further improving the solution diminish.

![Graph](image)

Figure 5.8: Results in terms of the amount of grid points above discrete $L_{DEN}$ levels of the minimum $L_{DER}$ solution with a noise constraint of 30000 people highly annoyed, as compared to the constrained minimum fuel solution and the benchmark situation.

The resulting tracks are compared to the solution in which only the noise constraint is applied while optimizing for fuel only which is shown in Figure 5.10a and 5.10b. When comparing the figures it is seen that the initial turn of the B733 is widened. At the same time the city of Hoorn is avoided more, this is done to decrease the amount of people highly annoyed to compensate for the increased amount of people highly annoyed at Hoofddorp. Due to increased solution space it is possible to increase the amount of people highly annoyed at one location, while it is reduced at other locations. From the figures it is also seen that there is no tendency to separate the two aircraft tracks from which it is concluded that separating aircraft tracks is not as effective as expected for reducing $L_{DER}$.

Figure 5.11a shows that the B733 and B744 both have their speeds increased in the first ± 50 seconds of the flight, as compared to the minimum fuel, noise constrained solution. By increasing the speed the total noise exposure is reduced, which results in reduced peak noise loads. This is done at Hoofddorp as at the beginning of departures the peak noise loads are most apparent. Due to the increased speed and the maximum bank angle constraint the initial turn of the B733 is enlarged. From Figure 5.11b it is seen that the altitudes of both aircraft are lower in the minimum $L_{DER}$ solution as
Figure 5.9: Results in terms of the relative increase in amount of grid points above discrete $L_{DEN}$ levels of the minimum $L_{DER}$ solution with a noise constraint of 30000 people highly annoyed, as compared to the constrained minimum fuel solution.

(a) The resulting flight tracks of the fuel optimized, noise constrained (30000 people highly annoyed) solution.

(b) The resulting flight tracks of the $L_{DER}$ optimized, noise constrained (30000 people highly annoyed) solution.

Figure 5.10
compared to the minimum fuel, noise constrained solution. For the B744 this is caused by flying level for a longer period of time such that thrust is reduced while the aircraft is close to Hoofddorp and Haarlem. For the B733 this is caused by climbing less steeply after passing Hoofddorp, which is possibly also done to reduce thrust levels.

(a) Speed profiles of the B733 and B744. A comparison is made between the minimum fuel, noise constrained (30000 people highly annoyed) solution and the minimum $L_{DER}$, noise constrained (30000 people highly annoyed) solution.

(b) Altitude profiles of the B733 and B744. A comparison is made between the minimum fuel, noise constrained (30000 people highly annoyed) solution and the minimum $L_{DER}$, noise constrained (30000 people highly annoyed) solution.

Figure 5.11

5.1.4 Reducing new noise

From Figure 5.2 it is seen that when going from the benchmark situation to the minimum annoyance solution, the flight tracks are shifted. Due to this shift in flight tracks also the noise is shifted to a new location. This means that a part of the inhabitants have a reduced amount of received noise, while others have an increased amount of noise.

For a clear presentation of new noise, three categories of grid points are created:

- The first category of grid points includes grid points which receive a decrease in noise, as well as grid points that are irrelevant in terms of new noise. All $L_{DEN}$ values below the 39 dB cut-off value of the dose-response relationship are considered irrelevant (see Section 2.1.2).
- The second category represents grid points in which new noise is received, though the increase in noise is small such that the increase cannot be perceived. From Air Services Australia it was found that ‘most people do not find a change in noise level below 3 dBA to be perceptible’ [4].
- The third category consists of grid points that receive a perceptible increase in noise.

Figure 5.12 summarizes the severity and location of new noise of the minimum annoyance solution. In total there are 156 grid points receiving new noise of which 54 receive a perceivable increase in noise. The maximum increase is 9.66 dB.

As the creation of new noise often generates significant resistance, an investigation is performed to see how the creation of new noise can be taken into account when designing new tracks. It was concluded previously that setting a constraint close to the minimum amount of people highly annoyed leaves little space to further improve the solution. To assess what can be done against new noise, as
well as to indicate the relation between new noise and the amount of people highly annoyed, it is chosen to perform multiple sets of optimizations, each with a stricter constraint on the amount of people highly annoyed. In the optimizations Equation 4.28 is applied as the cost function while all L_{DEN,old} values below the 39 dB cut-off value of the dose-response relationship are replaced by 39 dB L_{DEN}. This is done as FORT otherwise focusses on reducing new noise at grid points that end up below 39 dB. For each of the constraint values the minimum new noise solution is found, the results are shown in Table 5.4.

**Table 5.4:** The results in terms of fuel, amount of people highly annoyed and new noise (NN) of constrained minimum NN solutions. The bold entries show constrained solutions which only focus on reducing fuel. n_I is the number of grid points receiving new noise, n_{PI} is the amount of grid points receiving a perceivable increase in noise.

<table>
<thead>
<tr>
<th>m_{fuel,old} (kg)</th>
<th>m_{fuel,old} (kg)</th>
<th>Annoyance</th>
<th>NN</th>
<th>ΔNN (%)</th>
<th>n_I</th>
<th>n_{PI}</th>
</tr>
</thead>
<tbody>
<tr>
<td>616.9</td>
<td>519.1</td>
<td>2083.2</td>
<td>30000</td>
<td>4.11E+04</td>
<td>83</td>
<td>21</td>
</tr>
<tr>
<td>626.3</td>
<td>528.2</td>
<td>2098.2</td>
<td>30000</td>
<td>1.03E+02</td>
<td>24</td>
<td>0</td>
</tr>
<tr>
<td>622.1</td>
<td>523.8</td>
<td>2096.5</td>
<td>26000</td>
<td>5.36E+03</td>
<td>98</td>
<td>23</td>
</tr>
<tr>
<td>631.3</td>
<td>532.1</td>
<td>2118.4</td>
<td>26000</td>
<td>2.23E+02</td>
<td>59</td>
<td>0</td>
</tr>
<tr>
<td>627.9</td>
<td>529.0</td>
<td>2111.8</td>
<td>24000</td>
<td>1.11E+04</td>
<td>96</td>
<td>23</td>
</tr>
<tr>
<td>635.2</td>
<td>533.4</td>
<td>2163.2</td>
<td>24000</td>
<td>5.02E+02</td>
<td>87</td>
<td>2</td>
</tr>
<tr>
<td>632.5</td>
<td>532.8</td>
<td>2128.0</td>
<td>22999</td>
<td>2.64E+04</td>
<td>94</td>
<td>50</td>
</tr>
<tr>
<td>648.8</td>
<td>546.0</td>
<td>2191.7</td>
<td>23000</td>
<td>6.77E+02</td>
<td>91</td>
<td>5</td>
</tr>
<tr>
<td>635.5</td>
<td>535.3</td>
<td>2139.6</td>
<td>22500</td>
<td>5.36E+04</td>
<td>102</td>
<td>54</td>
</tr>
<tr>
<td>678.3</td>
<td>573.0</td>
<td>2257.9</td>
<td>22500</td>
<td>1.05E+03</td>
<td>100</td>
<td>11</td>
</tr>
</tbody>
</table>
It is seen that the amount of people highly annoyed can be reduced to 26000 (-26.4 %) while the average fuel burn is reduced by 4 % and no grid points receives a perceivable increase in noise. When the amount of people highly annoyed is further reduced the amount of grid points that receive a perceivable increase in noise is increased. Since the minimum new noise solution at 23000 people highly annoyed still uses less average fuel than the benchmark, this solution is discussed in more detail. It is seen that by optimizing for $NN$ the amount of grid points receiving a perceptible increase is reduced from 50 to 5 while the maximum $L_{DEN}$ increase is reduced from 7.63 to 3.57 $dB$. The change in new noise is graphically shown in Figure 5.13a and 5.13b.

When comparing the lateral tracks of the minimum fuel, noise constrained solution (Figure 5.14a), with the minimum new noise, noise constrained solution (Figure 5.14b) one characteristic is readily visible. In the minimum $NN$ solution the B733 and the B744 tracks are separated. This separation starts when the city of Zaandam has been passed and does not occur earlier as this would cause an increase in the amount of people highly annoyed in Wormerveer and Zaandam, which is prohibited by the noise constraint. By separating the B733 and the B744 track the noise is spread over a wider area. From the comparison it is seen furthermore that the city of Hoorn is avoided more explicitly because new noise does not affect the Markermeer.

When comparing the altitude profiles of the minimum fuel, noise constrained solution, with the minimum new noise, constrained solution (Figure 5.14a), significant deviations are found. The B733 altitude profile of the minimum new noise solution consists of alternating straight and climbing flight: between $t = \pm 50s$ and $t = \pm 90s$ and between $t = \pm 200s$ and $t = \pm 270s$ the B733 flies horizontally. These segments coincide with overflying Hoofddorp and Zaandam which is beneficial for the amount of people highly annoyed as flying horizontally requires less thrust, due to which the aircraft engines generate less noise. Equal behaviour is found for the B744. Both the B733 and the B744 climb faster after passing Hoofddorp, by increasing the altitude the noise is spread (the contours are widened) and peaks of new noise are removed. Finally in the minimum $NN$ solution the B733 closely passes Purmerend, at this city again the aircraft levels off for aforementioned reasons.
(a) The resulting flights track of the minimum fuel, noise constrained (23000 people highly annoyed) solution.

(b) The resulting flight tracks of the minimum \textit{NN}, noise constrained (23000 people highly annoyed) solution.

\textit{Figure 5.14}

\textit{Figure 5.15}: Altitude profiles of the B733 and B744. A comparison is made between the minimum fuel, noise constrained (23000 people highly annoyed) solution and the minimum \textit{NN}, noise constraint (23000 people highly annoyed) solution.
5.2 Extending the SPIJKERBOOR 2K(Y) case study

It is shown that there are several opportunities for improving the SPY2KY SID that is currently used at AAS. Improvements are possible with respect to the amount of people highly annoyed and peak noise loads, often with a minimum amount of new noise generated. In reality there are two SIDs that start at runway 24 and end at the ANDIK way point. There is the SPIJKERBOOR 2K departure via SPY and the ANDIK 1S departure via PAM which can be seen in Figure B.1 of Appendix B. The available air traffic data shows that the ANDIK 1S departure is used in combination with the SPY2KY departure, as this SID is used by 18 light aircraft and 3 heavy aircraft on the same day. When \( L_{DEN} \) weighting is applied this accounts for 101.2 and 5.2 light and heavy aircraft respectively. ATC has to choose for each departure which type of SID is to be flown. Table C.2 allows to conclude that the ANDIK 1S departure (further referred to as PAM departure) is less noise sensitive, since half these departures are flown during the night. When comparing the two SIDs in Figure B.1 it is seen that the track length of the PAM departure is slightly longer as well, which generally means that the SID requires more fuel. The SPY2KY case is extended to include the PAM SID as well, this case is further referred to as the mixed ANDIK departure/case. The initial and final conditions for this case are discussed in Section 4.3.1.

Since it is not known how the flights can best be distributed over the two tracks, this is to be investigated first. This is done by comparing the optimization results of four different set-ups: (1) all aircraft fly the SPY departure, (2) all aircraft fly the PAM departure, (3) all light aircraft fly the SPY departure, all heavy aircraft fly the PAM departure and (4) is the other way around.

5.2.1 Mixed ANDIK departure Benchmark

The results of the optimizations of each four set-ups need to be compared to the current situation and to do so another benchmark is created. Since the aircraft flying the SPY SID have been modelled previously, the noise produced by the aircraft flying the PAM departure can simply be added to this. The PAM SID is modelled by forcing the aircraft to fly over the way points specified for the PAM SID (Figure B.1), while the NADP II profile is used to model the altitude and speed profiles. The resulting tracks and the noise footprint are shown in Figure 5.16. The set of grid points that is used in the benchmark and optimization includes all grid points that are within the 10 \( dB \) \( L_{DEN} \) contour of the benchmark.

<table>
<thead>
<tr>
<th>Mixed ANDIK Benchmark</th>
<th>Minimum annoyance</th>
</tr>
</thead>
<tbody>
<tr>
<td>( m_{fuel_{avg}} ) (kg)</td>
<td>717.2</td>
</tr>
<tr>
<td>( m_{fuel_{B73}}_{avg} ) (kg)</td>
<td>571.4</td>
</tr>
<tr>
<td>( m_{fuel_{B74}}_{avg} ) (kg)</td>
<td>2248.3</td>
</tr>
<tr>
<td>( n_{HA} )</td>
<td>50766</td>
</tr>
<tr>
<td>( L_{DER} )</td>
<td>3.07+07</td>
</tr>
</tbody>
</table>

5.2.2 Finding which combination of SIDs is optimal

To find out which of the four set-ups is best in terms of people highly annoyed and fuel usage, four separate sets of optimizations are performed, each corresponding to one of the set-ups. Within each of the sets of optimizations \( k_{annoy} \) is increased. The result in terms of average fuel usage and the amount of people highly annoyed is shown in Figure 5.17. In this figure also the benchmark average fuel burn is shown, which now acts as a limit (aircraft are not allowed to burn more than the benchmark fuel). Figure 5.17 shows that the absolute minimum annoyance solution is found by directing all aircraft towards PAM. This departure increases the fuel burn as compared to sending the aircraft...
towards SPY however.

The purple vertical line indicates the benchmark fuel usage which functions as a limit. It is seen that the best intermediate solution satisfying the fuel burn limit is to direct all heavy aircraft to PAM, while all light aircraft should fly via SPY. For this reason this set-up is chosen to be the best set-up given the fuel limits. The solution with a red circle indicates the minimum annoyance solution, the results of which are shown in Table 5.5. The amount of people highly annoyed is reduced by 42.5% while the average fuel burn is approximately equal, as compared to the benchmark. It is seen that the B733 fuel usage decreases, while the B744 fuel usage increases. This confirms that the PAM departure requires more fuel than the SPY departure. Within the cost functions the normalization is done using a fuel mass of 507.15 kg and 2176.9 kg for the B733 and B744 respectively.

Figures 5.18a and 5.18b show the lateral tracks of the B733 and B744 benchmark and the minimum annoyance solution. Looking at the figure the B733 executes an early right turn such that it does not have to fly over Hoofddorp. The B733 track is highly similar to the minimum annoyance solution in the SPY2KY case. The first turn of the B744 is actually enlarged compared to the SID, such that the B744 avoids Uithoorn as well as Weesp. In the benchmark these cities are directly overflown.

The speed profiles and the altitude profiles of both aircraft (Figure 5.19a and 5.19b) show that a minimum amount of people highly annoyed is achieved by flying low and fast. From the speed profiles it is seen that both aircraft have their true airspeed constant between $t = \pm 100s$ and $t = \pm 350s$. The altitude profiles show that both aircraft also fly horizontally between $t = \pm 20s$ and $t = \pm 300s$. By flying low the noise contours are made smaller (lateral attenuation), by flying fast the total noise exposure time is reduced which reduces the perceived noise. The altitude at which both aircraft fly coincides with the altitude at which thrust reductions are allowed, this allows the aircraft to reduce thrust which reduces noise nuisance. The B744 starts climbing once it is above the Markermeer, as there are no inhabitants there. The B733 starts climbing once it has past Zaandam.
Figure 5.17: Overview of the results of the four set-ups in terms of average fuel usage and the amount of PHA.

(a) The benchmark B733 and B744 tracks of both the SPY2KY and PAM departures.

(b) The minimum annoyance flight tracks.

Figure 5.18
(a) The speed profiles of the B733 and B744 in both the benchmark situation and the minimum annoyance solution.

(b) The altitudes profile of the B733 and B744 in both the benchmark situation and the minimum annoyance solution.

Figure 5.19

It was stated before that altitude differences cause differences in the $V_{TAS}$ profile. A 250 kts $V_{CAS}$ speed limitation is implemented, this is also shown graphically in Figure 5.20 which shows the $V_{CAS}$ profiles of the aircraft. This figure shows that the largest part of the flight is flown at maximum $V_{CAS}$, which indeed shows that the differences in $V_{TAS}$ are caused by differences in the altitude profiles.

Figure 5.20: The $V_{CAS}$ profiles of both the benchmark situation and the minimum annoyance solution.

5.2.3 Reducing peak loads

Within the optimization the two aircraft tracks are separated directly after the initial straight flight segment. It is expected that there is little room to further improve the solution with respect to $L_{DER}$, since no peak loads are created by overlapping the flight tracks anyway. The maximum amount of
people highly annoyed is set at 34000, which includes sufficient space for improvement. The same optimization as the SPY2KY case is performed, the results are shown in Figure 5.21. Although the noise constraint is set at a high level, there still proves to be insufficient space to further improve the solution significantly with respect to peak noise loads. This confirms that there are indeed very little possibilities to reduce peak noise loads due to the two aircraft tracks being separated in the mixed ANDIK optimization.

![Figure 5.21: Results in terms of the amount of grid points above discrete L_{DEN} levels of the minimum L_{DER} solution with a noise constraint of 34000 people highly annoyed, as compared to the constrained minimum fuel solution and the benchmark situation.](image)

5.2.4 Reducing new noise

Within the optimization two tracks are used to represent the four tracks in the benchmark, this inherently creates new noise. Also the amount of traffic on each of the tracks is re-allocated, which also increases new noise at some places. It is assumed that not all new noise can be reduced, due to the aforementioned reasons. Figure 5.22 shows the locations at which new noise is perceived when the minimum annoyance solution is implemented. In total there are 197 grid points that receive new noise, of which 128 grid points receive a perceivable increase. The maximum increase is 16.2 dB L_{DEN}.

It is first tried to apply a noise constraint at 38000 people highly annoyed, when optimizing for minimum new noise, to see to which extent new noise can be reduced when sufficient space is included to further improve the solution. The result of the optimization is shown in Figures 5.23a and 5.23b. By optimizing for new noise the total amount of grid point receiving new noise is reduced from 213 to 203, while the amount of grid points receiving perceptible new noise is decreased from 92 to 80. At the same time the maximum increase in noise is reduced from 11.6 to 6.5 dB. It is concluded that both the amount of grid points receiving non-perceptible new noise and the amount of grid points receiving perceptible new noise are decreased.
The improvement in terms of new noise is explained solely by changes in the altitude profiles of both aircraft. At the start of the PAM SID there is no perceivable new noise, for this reason the first ±120 seconds of the altitude of the B744 does not change by including $NN$ in the optimization. Beyond this point the B744 track starts creating new noise which is reduced by delaying the B744 climb. By decreasing the altitude the noise contour is made smaller while the aircraft uses less thrust which also reduces noise. Together these two aspects assure a reduction in new noise due to the B744 track. The B744 climbs as much as possible while it is above the Markermeer, as no grid points are located there. Compared to the fuel minimum, noise constrained solution the B733 climbs earlier. By increasing the altitude of the aircraft the peak levels of new noise are reduced, while the noise is spread over a wider area (lateral attenuation).

As the optimization with a total amount of people highly annoyed of 38000 showed opportunities for improvement, the same type of optimizations are performed for lower constraint values. The results are shown in Table 5.6. It is seen that as the space between the minimum annoyance value and the noise constraint decreases, the opportunities for reducing new noise diminish as well.

Table 5.6: The results in terms of fuel, people highly annoyed and new noise ($NN$) of constrained minimum $NN$ solutions. The bold entries show constrained solutions which only focus on reducing fuel.

<table>
<thead>
<tr>
<th>$m_{fuel_{avg}}$ (kg)</th>
<th>$m_{fuel_{B744}}$ (kg)</th>
<th>Annoyance</th>
<th>$NN$</th>
<th>$\Delta NN$ (%)</th>
<th>$n_I$</th>
<th>$n_{PI}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>679.1</td>
<td>527.9</td>
<td>2266.7</td>
<td>38000</td>
<td>2.09E+08</td>
<td>213</td>
<td>92</td>
</tr>
<tr>
<td>682.4</td>
<td>528.4</td>
<td>2298.8</td>
<td>38000</td>
<td>1.25E+04</td>
<td>-100.0%</td>
<td>203</td>
</tr>
<tr>
<td>686.5</td>
<td>534.3</td>
<td>2284.3</td>
<td>34002</td>
<td>1.45E+06</td>
<td>206</td>
<td>99</td>
</tr>
<tr>
<td>701.2</td>
<td>542.0</td>
<td>2372.8</td>
<td>34000</td>
<td>1.62E+04</td>
<td>-98.9%</td>
<td>189</td>
</tr>
<tr>
<td>692.7</td>
<td>537.4</td>
<td>2323.3</td>
<td>31999</td>
<td>1.19E+06</td>
<td>211</td>
<td>107</td>
</tr>
<tr>
<td>708.6</td>
<td>549.6</td>
<td>2378.9</td>
<td>32000</td>
<td>3.84E+04</td>
<td>-96.8%</td>
<td>184</td>
</tr>
<tr>
<td>703.8</td>
<td>546.5</td>
<td>2355.0</td>
<td>30002</td>
<td>7.84E+06</td>
<td>200</td>
<td>122</td>
</tr>
<tr>
<td>725.7</td>
<td>565.7</td>
<td>2405.4</td>
<td>30000</td>
<td>7.53E+04</td>
<td>-99.0%</td>
<td>183</td>
</tr>
<tr>
<td>712.7</td>
<td>553.5</td>
<td>2383.8</td>
<td>29000</td>
<td>2.20E+08</td>
<td>196</td>
<td>129</td>
</tr>
<tr>
<td>716.9</td>
<td>557.9</td>
<td>2386.5</td>
<td>29001</td>
<td>7.75E+05</td>
<td>-99.6%</td>
<td>180</td>
</tr>
</tbody>
</table>
(a) The resulting noise distribution in terms of new noise when a noise constraint is applied at 38000 people highly annoyed and the optimization is performed for fuel only.

(b) The resulting noise distribution in terms of new noise when a noise constraint is applied at 38000 people highly annoyed and the optimization is done for minimum new noise.

Figure 5.23

Figure 5.24: Altitude profiles of the B733 and B744. A comparison is made between the minimum fuel, noise constrained (38000 people highly annoyed) solution and the minimum $N \cdot N$, noise constraint (38000 people highly annoyed) solution.

5.2.5 Separate optimization of the PAM SID

Table 5.6 shows that new noise can be reduced to a certain extent by including $N \cdot N$ in the cost function. At the same time it is seen that replacing four tracks by two tracks, repositioning tracks and the re-allocation of flights over SIDs causes significant amounts of new noise that can not be removed completely in the optimization. For this reason still 80 grid points receive perceivable new noise while there is an increase of 30.2% in the amount of people highly annoyed, as compared to the minimum annoyance solution. For this reason it is investigated what the possible improvements are in
terms of the amount of people highly annoyed as well as new noise, when four tracks are used such that an equal aircraft mix is sent via SPY2KY and PAM as compared to the benchmark. Since FORT is currently unable to optimize four tracks simultaneously, the PAM SID is optimized individually and the results are combined with the SPY2KY results of the first case.

The minimum annoyance solution of the PAM departure results in a total amount of 16560 people highly annoyed. Figure 5.25 shows the lateral tracks of the minimum annoyance PAM departure. From this figure it is seen that the B733 track is more noise sensitive than the B744 track, this is due to the fact that there is a weighted amount of 101.2 light departures and only 5.2 heavy departures. Apparently increasing the route length of the B744 does not cause a reduction in people highly annoyed, for this reason the B733 makes a larger detour than the B744.

When the noise footprints of the minimum annoyance SPY2KY (22193 people highly annoyed) and the minimum annoyance PAM solution (16560 people highly annoyed) are combined, a solution is found that results in 34957 people highly annoyed, this is a reduction of 31.6 % as compared to the benchmark. Compared to the minimum annoyance solution of the mixed SPY/PAM departure this is an increase of 19.8 % however. The average fuel usage is 701.6 kg, which is a reduction of 0.2% compared to the benchmark and 0.1 % compared to the minimum annoyance mixed SPY/PAM departure. Unless the amount of people highly annoyed should be reduced to below 34957, a four track solution would also be possible (not taking into account the practical implementation of the results).

The main aim of investigating using four tracks instead of two is to see if the amount of new noise could be reduced by implementing this type of solution. This is proven by combining the minimum $\text{NN}$ solution of the SPY2KY case, at a noise constraint level of 23000 people highly annoyed, with the minimum $\text{NN}$ solution of the PAM case, at a noise constraint level of 18000 people highly annoyed. Combining these solutions results in a total amount of 36646 people highly annoyed, which is a reduction of 27.8 % compared to the benchmark, while the fuel usage is reduced by 0.1%. Figure 5.26 shows the resulting new noise in term of the three categories. The figure shows that the aforementioned improvement can be gained while only 5 grid points receive a perceptible increase in noise. It is concluded that this solution is significantly better than the solution resulting in 38000 people highly annoyed presented in Subsection 5.2.4, in terms of noise nuisance, new noise and fuel usage. For this reason it is concluded that a four-track solution would be better here.

![Figure 5.25: Lateral track of the minimum annoyance PAM departure.](image)
5.3 Application to a heavily used track

The SPY2KY SID as well as the mixed ANDIK departure are used by a relatively small amount of aircraft. To show the opportunities for SIDs that are heavier with respect to noise, one last case is presented. In the air traffic data it is found that the departure towards the east is heavily used. This departure direction is used by aircraft flying in the direction of Eastern Europe, Russia and (Eastern) Asia. Due to these destinations a larger amount of heavy aircraft are flying in this direction. From Appendix C it is seen that there is a significant stream of traffic departing in this direction. This stream consists of 476.2 (weighted) light aircraft and 82.3 (weighted) heavy aircraft. The runway that has the highest priority in the AAS runway prioritization system is the Polderbaan (36L) (see Table 4.1). From Figure B.2 it is seen that there are two SIDs from runway 36L towards/over the Pampus VOR/DME, these are the ARNEM 1V departure and the LINUX 1V departure. In the last case that is treated all aircraft depart from runway 36L. The initial conditions are discussed in Section 4.3.1 while all aircraft end in the PAM VOR, at final conditions specified in Section 4.3.1. This case is further referred to as the mixed PAM case.

5.3.1 Mixed PAM benchmark

To be able to compare results to the current situation, a benchmark is again created. This is done by modelling all traffic to fly over the way points of the ARNEM 1V SID (Figure B.2), up to the PAM VOR/DME. The vertical profile is modelled by setting path and event constraints to model the NADP II departure profile. The result in terms of the noise footprint is shown in Figure 5.27. The set of grid points that is used in the benchmark and optimizations includes all grid points that are within the 10 dB $L_{DEN}$ contour of the benchmark.

<table>
<thead>
<tr>
<th></th>
<th>Mixed PAM Benchmark</th>
<th>Minimum annoyance</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_{fuel_{avg}}$ (kg)</td>
<td>627.8</td>
<td>583.7</td>
</tr>
<tr>
<td>$m_{fuel_{B734avg}}$ (kg)</td>
<td>412.1</td>
<td>381.5</td>
</tr>
<tr>
<td>$m_{fuel_{B744avg}}$ (kg)</td>
<td>1632.2</td>
<td>1525.6</td>
</tr>
<tr>
<td>$n_{HA}$</td>
<td>65059</td>
<td>43496</td>
</tr>
<tr>
<td>$L_{DER}$</td>
<td>3.98E+07</td>
<td>3.56E+07</td>
</tr>
</tbody>
</table>

Figure 5.26: New noise distribution of the combined SPY2KY and PAM minimum $NN$ solutions.
5.3.2 Optimizing for annoyance

Equal to previous cases the first thing to be done is to optimize the case for annoyance. By increasing the focus on annoyance ($k_{\text{annoy}}$) an annoyance curve is created. Within the cost function the normalization is done with a minimum fuel mass of 306.54 kg and 1319.7 kg for the B733 and B744 respectively. The results in terms of average fuel usage and the amount of people highly annoyed are shown in Figure 5.28.

The results as compared to the minimum annoyance solution are shown in Table 5.7. The minimum annoyance solution results in 43496 people highly annoyed, which is a 33.1% reduction compared to the benchmark. At the same time average fuel usage is reduced by 7% while the B733 and B744 fuel are decreased approximately equally. Figure 5.29 shows the lateral tracks of the minimum annoyance solution. This figure shows that the lateral tracks differ significantly between the benchmark and the minimum annoyance solution. When comparing the minimum annoyance track to the SID chart of runway 36C (Figure B.3 of Appendix B) it is concluded that the minimum annoyance track coincides with the NYKER 3W and IVLUT 2W SIDs from the Zwanenburgbaan (36C). The resulting altitude and speed profiles of the minimum annoyance solution coincide with the mixed ANDIK case (Figure 5.19).

5.3.3 Reducing peak loads

As the two tracks cover a high amount of flights, concentration of these flights onto two tracks leads to peak loads, it is therefore interesting to assess to which extent and how these peak loads can be reduced. Table 5.7 shows that the minimum annoyance solution has 10.5% less $L_{\text{DER}}$ than the benchmark. By setting the maximum number of people highly annoyed to 50000 sufficient space is created for further improvement of the solution in terms of peak loads. The results of the minimum $L_{\text{DER}}$ solution using this constraint are shown in Figure 5.30, while the improvement compared to the noise constrained minimum fuel solution is shown in Figure 5.31. No differences are found between lateral tracks and speed profiles of the noise constrained, minimum fuel solutions and the noise constrained, minimum $L_{\text{DER}}$ solutions. The differences in peak loads are caused by increased climb speeds of both the B733 and the B744, as shown in Figure 5.32. By increasing the altitude
Figure 5.28: Overview of the results of the four set-ups in terms of average fuel usage PHA.

Figure 5.29: Minimum annoyance B733 and B744 tracks as compared to the mixed PAM benchmark
of the two aircraft the peak noise loads are reduced, while the noise is being spread over a wider area (lateral attenuation). This reduction in peak loads is beneficial for the total $L_{DER}$ value. The minimum $L_{DER}$ solution has a slight (0.8%) increase in fuel usage compared to the noise constrained, fuel minimum solution.

Figure 5.30: Results in terms of the amount of grid points above $L_{DEN}$ levels of the minimum $L_{DER}$ solution with a noise constraint of 50000 people highly annoyed, as compared to the constrained minimum fuel solution and the benchmark situation.

Figure 5.31: Results in terms of the relative increase in amount of grid points above $L_{DEN}$ levels, of the minimum $L_{DER}$ solution with a noise constraint of 50000 people highly annoyed, as compared to the constrained minimum fuel solution.
5.3.4 Assessing the amount of new noise generated

The complete re-allocation of the tracks leads to significant new noise. It is expected that this noise can only be reduced to a large extent when the tracks are placed back to the benchmark location. This is however prohibited as it would break the constraint on the maximum amount of people highly annoyed. Figure 5.33 gives an overview of the extent and location of perceivable new noise. In total 116 grid points receive a noise increase of which 39 grid points receive a perceivable increase in noise. The maximum increase is equal to 23.4 dB.

When a noise constraint is applied that prohibits the amount of people highly annoyed from going above 55000, the minimum fuel solution is compared to the constrained minimum $NN$ solution. Table 5.8 shows a very interesting comparison between key performance indicators of the the minimum annoyance solution, the noise constrained, minimum fuel solution and the noise constrained, minimum $NN$ solution. It is seen that when going from the minimum annoyance solution to the constrained minimum fuel solution to the constrained minimum $NN$ solution, the amount of grid points receiving a (perceivable) increase in noise is increased. At the same time the maximum increase in $L_{DEN}$ decreases significantly. This increase in the total amount of grid points receiving a perceptible amount of noise is explained by the fact that FORT focusses on reducing the highest $L_{DEN}$ increases. As an example: a reduction of an increase of 1 dB when there is a total increase of 15 dB equals a decrease in $NN$ of $9.6 \cdot 10^6$, while an reduction of 1 dB when there is a total increase of 4 dB accounts for $54 \cdot NN$. As the aim of reducing new noise is to reduce the resistance to new tracks, it cannot be judged which of the solutions leads to the smallest resistance: a large increase for a small amount of grid points, or a small increase for a large amount of inhabitants.

Table 5.8: Results for the mixed PAM benchmark (constrained) minimum $NN$/annoyance solutions.

<table>
<thead>
<tr>
<th></th>
<th>Minimum annoyance</th>
<th>Constrained fuel optimum</th>
<th>Constrained $NN$ optimum</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_{fuel avg}$ (kg)</td>
<td>583.7</td>
<td>548.1</td>
<td>562.6</td>
</tr>
<tr>
<td>Annoyance</td>
<td>43496</td>
<td>55000</td>
<td>55000</td>
</tr>
<tr>
<td>$NN$</td>
<td>2.10E+11</td>
<td>1.29E+09</td>
<td>8.96E+06</td>
</tr>
<tr>
<td>$n_1$</td>
<td>116</td>
<td>129</td>
<td>143</td>
</tr>
<tr>
<td>$n_{PI}$</td>
<td>77</td>
<td>91</td>
<td>91</td>
</tr>
<tr>
<td>max $\Delta L_{DEN}$</td>
<td>23.43</td>
<td>17.67</td>
<td>12.79</td>
</tr>
</tbody>
</table>
Figure 5.33: Resulting new noise of the minimum annoyance solution in terms of the location of the three categories of grid points.

The differences between the flight tracks are shown in Figure 5.34a to 5.35. When comparing the lateral tracks of the fuel minimum and \( NN \) minimum solution, the same behaviour found in the SPY2KY case is shown. The B733 and B744 are separated during a part of the flight to spread the produced noise. The B733 and B744 climb earlier in the departure as compared to the fuel optimum solution, this is done such that the aircraft is able to have a segment of constant altitude when it passes more densely populated areas. During this segment of constant altitude thrust can be reduced, which reduces the amount of noise produced while the aircraft is close to noise sensitive areas. Furthermore, increasing the altitude means that peak levels of new noise are reduced, while total noise contour is widened. This results is less peak levels of new noise.
(a) The resulting flight track of the minimum fuel, noise constraint (55000 people highly annoyed) solution.

(b) The resulting flight track of the minimum NN, noise constraint (55000 people highly annoyed) solution.

Figure 5.34

Figure 5.35: Altitude profile of the B733 and B744. A comparison is made between the minimum fuel, noise constrained (55000 people highly annoyed) solution and the minimum NN, noise constrained (55000 people highly annoyed) solution.
Chapter 6

Conclusions & Recommendations

The main goal of this thesis is to examine to which extent peak loads of noise and the creation of new noise can be taken into account when optimizing aircraft tracks. At the same time the total community noise impact should not increase in any way, it should preferably even decrease. For these reasons a newly created aircraft procedure optimization tool has been extended. This chapter presents conclusions drawn from the results presented previously.

6.1 Conclusions

In previous research \[12\] attempts were made to optimize two lateral tracks simultaneously, this turned out to be problematic however. The first novelty shown by the newly developed tool is that multi-event optimizations can be performed, which means that multiple aircraft tracks are optimized simultaneously while regulations and guidelines are included in the problem description. The case studies performed show the simultaneous optimization of two complete aircraft tracks (lateral tracks, altitude and speed profiles). The multi-event optimizations can be done easily and quickly (5-20 minutes per optimization on an Intel Core I7 processor). Multi-event optimizations with respect to the mix of fuel and annoyance can very well be done in the extended FORT optimization tool.

The second novelty shown is that community noise can be included in the optimization as a constraint rather than an optimization criterion. By including community noise as a constraint, a given reduction in community noise is ensured while the solution can be optimized with respect to other criteria. When community noise is included as a constraint there is a direct trade-off between annoyance, fuel usage and other criteria included in the cost function of the optimization.

It has been shown that, while ensuring a significant decrease in annoyance through constraints, the peak noise levels or new noise can be reduced significantly as well. For this purpose, two noise impact criteria have been integrated. This fulfils the research objective posed in this thesis.

Including the aggregated noise exposure ratio in the cost function allows to reduce peak noise levels while the amount of people highly annoyed is limited using a constraint. The reduction of peak noise loads generally requires a minor increase in fuel usage. The direct trade-off between the constraint value and the cost function value results in a solution that improves both on peak loads and the amount of people highly annoyed compared to benchmarks. There is no tendency to separate the two aircraft tracks from which it is concluded that separating aircraft tracks is not as effective as expected for reducing peak noise levels. It is found that increasing the speed of the aircraft, especially in the first phase of the departures, reduces peak noise loads by decreasing the exposure times. Increasing the altitude of the aircraft also reduces peak loads though the noise contours are widened. The effects of constraints on the maximum amount of people highly annoyed can however diminish this behaviour (for example the aircraft must fly at low thrust levels to reduce the amount of people highly annoyed,
due to which it is unable to climb and/or speed up).

The redistribution of flights over several tracks can lead to unavoidable new noise. Including a quantification of new noise in the cost function allows to reduce the amount of new noise. When this quantification exponentially increases with increasing new noise, the focus is on reducing the peak levels of new noise. At the same time the amount of people highly annoyed is controlled using a constraint. The extent to which new noise stays perceptible is dependent on the severity of the changes required by the constraint on the amount of people highly annoyed. The results of including new noise in the optimization cost function can be called significant for a part of the studied cases. One solution to the creation of new noise that can possibly be generalized is found using the tool. It is shown that when aircraft tracks are repositioned flight track dispersion should be applied to reduce new noise peaks, this should however be done only as long as this does not cause an undesirable increase in the amount of people highly annoyed. Lastly changes in the altitude and speed profiles depend on the effects caused by the noise constraint.

6.2 Recommendations

The results presented in this thesis can further be improved if the following points can be addressed.

Within the optimization shown in this study the entire set of aircraft departing from Schiphol is represented by two aircraft types while in reality there are many more aircraft types that depart from Schiphol. To create cases that realistically represent the true aircraft mix, the other aircraft types should be included in the optimization as well. These aircraft can be forced to fly two or more common tracks (as Dons [21] did), or they can each have their separate tracks. To include these aircraft types they should first be modelled and researched.

When designing, testing and applying the FORT optimization tool occasionally solutions could not be found due to numerical difficulties. One of the difficulties found is that the optimization tool is unable to satisfy the termination criterion. FORT thus has difficulties to determine which of the solutions is optimal. Apparently there are solutions that are highly alike in terms of the cost function value. The multi-event aspect of the optimization is one of the causes of this problem as this essentially increases the ways in which an equal cost function value can be found. If the problem description could be adjusted to take this problem into account (for example by adjusting the grid information) this would significantly decrease the time to converge and increase the possibility of convergence. Another aspect of the optimization that has proven to increase the numerical difficulties is the switch between take-off thrust and climb thrust in the engine models. This could be improved by improving the engine models.

FORT uses a noise range of the dose-response relationship used to estimate the amount of people highly annoyed that is not supported by theory. This is done to avoid discontinuities in the cost function. The results can be further improved if a continuous dose response relationship is used that is completely supported by research, or if the dose-response relationship could be applied only to population exposed to noise within the supported range.

FORT’s time to converge is dependent on the amount of grid points that is used for the optimization. This amount of grid points, and thus the time to converge, can be reduced significantly if the amount of grid points is reduced, for example by $k$-means clustering. This is not applied in this thesis as the application of $k$-means clustering would cancel the purpose of this research, which is to reduce new noise and peak loads at locations that are often sparsely inhabited.

To ensure the applicability of the resulting aircraft tracks the solutions must be RNAV-compliant,
further research should therefore be performed in this field. To create RNAV tracks that have fixed ground paths they should be built up of segments of straight flight and constant radius turns. Furthermore the resulting altitude and speed profiles of the aircraft track do not appear to be smooth. For these reasons additional research should be done towards the pilot and passenger acceptability of the resulting aircraft tracks.

Three aspects concerning the cost function of the optimization should be investigated as they could further improve the solutions:

1. Although the application of the new noise equation, as well as the application of the aggregate sound exposure ratio in the cost function of FORT proved successful, further research is required into the dose-response relationship between new noise and noise exposure.

2. Since fuel mass, the amount of people highly annoyed, new noise and aggregate sound exposure ratios all are different metrics, they can not directly be traded off against each other. There might be possibilities for quantifying all of these using one metric, for example a monetary metric. This would allow a direct comparison between the results.

3. The base value of the exponential function used to calculate new noise is chosen somewhat arbitrarily, the effect of changing this parameter could be assessed to be able to draw conclusions from this.

The current optimizations are performed for two aircraft simultaneously but separation between the aircraft types and between the other types of flight operations around AAS is not taken into account. This separation could be taken into account when the minimum distance between trajectories is set within the optimization. Finally also the (runway) throughput capacity is not assessed.

In the current model the atmospheric conditions are set to the International Standard Atmospheric conditions. This implies that no seasonal or daily atmospheric variations are taken into account. Since wind conditions and temperature have an influence on noise propagation and aircraft behaviour, a more elaborate noise model should be incorporated in FORT.
Implementation of noise-related Jacobians

This appendix describes how to create noise-related Jacobians starting with the INM input. This Appendix is based on work performed previously at the Delft University of Technology [43].

From Figure 3.6 it is seen that the following states are first filtered from the intermediate solution. The multiple phases forming one track are merged into one track. This is sent to INM:

\[ \mathbf{x}_{INM} = \begin{pmatrix} x \\ y \\ h \\ V \\ T \end{pmatrix} \]  

(A.1)

Since \( T \) is not a state within the aircraft model (see Equation 3.7). This is calculated manually. Thrust is dependent only on the normalized thrust setting (\( \Gamma \)), which is a control variable. Thrust is obtained from Equation 3.9. The minimum and maximum thrust (\( T_{min} \) and \( T_{max} \)) are in turn dependent on altitude and airspeed [39], which are aircraft states. The partial derivatives of thrust \( T \) to these states/control are described by:

\[ \mathbf{J}_T = \begin{bmatrix} \frac{\partial T}{\partial h} & \frac{\partial T}{\partial V} & \frac{\partial T}{\partial \Gamma} \end{bmatrix} \]  

(A.2)

The derivatives of \( SER \) to the 5 aircraft states are given as output. The INM output Jacobian thus includes:

\[ \mathbf{J}_{INM} = \begin{bmatrix} \frac{\partial SER}{\partial x} & \frac{\partial SER}{\partial y} & \frac{\partial SER}{\partial h} & \frac{\partial SER}{\partial V} & \frac{\partial SER}{\partial \Gamma} \end{bmatrix} \]  

(A.3)

These derivatives are calculated based on the relation between \( T \) and \( \Gamma \), described in Equation 3.9:

\[ \frac{\partial T}{\partial h} = \left[ \frac{\partial T_{max}}{\partial h} - \frac{\partial T_{min}}{\partial h} \right] \cdot \Gamma + \frac{\partial T_{min}}{\partial h} \]  

(A.4)

\[ \frac{\partial T}{\partial V} = \left[ \frac{\partial T_{max}}{\partial V} - \frac{\partial T_{min}}{\partial V} \right] \cdot \Gamma + \frac{\partial T_{min}}{\partial V} \]  

(A.5)

\[ \frac{\partial T}{\partial \Gamma} = [T_{max} - T_{min}] \]  

(A.6)

In these equations \( \frac{\partial T_{max}}{\partial \Gamma} \), \( \frac{\partial T_{min}}{\partial \Gamma} \), \( \frac{\partial T_{max}}{\partial h} \) and \( \frac{\partial T_{min}}{\partial h} \) are found (for each node) from complex functions describing the engine characteristics and standard atmosphere relations (found in [39]).
GPOPS requires the derivative of noise-related metrics towards all states and controls instead:

\[
\mathbf{J}_{SER\text{states}} = \begin{bmatrix}
\frac{\partial SER}{\partial x} & \frac{\partial SER}{\partial y} & \frac{\partial SER}{\partial h} & \frac{\partial SER}{\partial V} & \frac{\partial SER}{\partial \chi} & \frac{\partial SER}{\partial W}
\end{bmatrix}
\] (A.7)

\[
\mathbf{J}_{SER\text{control}} = \begin{bmatrix}
\frac{\partial SER}{\partial \Gamma} & \frac{\partial SER}{\partial \gamma} & \frac{\partial SER}{\partial \mu}
\end{bmatrix}
\] (A.8)

From this it is concluded that only the derivatives of thrust to \( h, V \) and \( \Gamma \) are non-negative. The derivatives with respect to \( T \) are included in the original state and control Jacobians in the following way:

\[
\begin{align*}
\frac{\partial SER}{\partial h}_{\text{tot}} &= \left[ \frac{\partial SER}{\partial h} \right]_{\text{INM}} + \left[ \frac{\partial SER}{\partial T} \right]_{\text{INM}} \cdot \frac{\partial T}{\partial h} \\
\frac{\partial SER}{\partial V}_{\text{tot}} &= \left[ \frac{\partial SER}{\partial V} \right]_{\text{INM}} + \left[ \frac{\partial SER}{\partial T} \right]_{\text{INM}} \cdot \frac{\partial T}{\partial V} \\
\frac{\partial SER}{\partial \Gamma}_{\text{tot}} &= \left[ \frac{\partial SER}{\partial \Gamma} \right]_{\text{INM}} + \left[ \frac{\partial SER}{\partial T} \right]_{\text{INM}} \cdot \frac{\partial T}{\partial \Gamma}
\end{align*}
\] (A.9-11)

Since it is assumed that the received energy ratio is not directly dependent on aircraft heading, aircraft weight, aircraft flight path angle and aircraft bank angle, the following derivatives within \( \mathbf{J}_{SER\text{states}} \) and \( \mathbf{J}_{SER\text{control}} \) are set equal to zero:

\[
\frac{\partial SER}{\partial \chi} = \frac{\partial SER}{\partial W} = \frac{\partial SER}{\partial \gamma} = \frac{\partial SER}{\partial \mu} = 0
\] (A.12)

Since thrust is not directly dependent on position \( (x \text{ and } y) \), \( \frac{\partial SER}{\partial x} \) and \( \frac{\partial SER}{\partial y} \) are taken directly from INM. Finally \( J_{SER} \) as used in Chapters 2, 3 and 4 is \( \mathbf{J}_{SER\text{states}} \) and \( \mathbf{J}_{SER\text{controls}} \) combined.
Appendix B

SID Charts

This section shows the SIDS and accompanying text for the SIDs for runway 24, 18L and 36L.
B.1 Kaagbaan 24

**Figure B.1: SID chart of runway 24**

[Image of SID chart for runway 24 with details on chart layout and coordinates.]
B.2 Polderbaan 36L

The Polderbaan 36L has double SIDs in most directions. Due to this two separate SID charts are available.

![SID chart diagram](image)

**Figure B.2: SID chart, part 1 of 2, of runway 36L [2]**
B.3 Zwanenburgbaan 36C

Figure B.3: SID chart of runway 36C [2]
Appendix C

Analyses of AAS traffic data

This appendix shows the categorization of a part of the AAS departures recorded on 22 October 2010. The result is based on a categorization done by [21]. Only relevant SIDs in relevant directions are treated in this appendix.

Table C.1: Amount of departures per aircraft type. SPIJKERBOOR 2K departure from runway 24.

<table>
<thead>
<tr>
<th></th>
<th>A320</th>
<th>B734</th>
<th>B738</th>
<th>B744</th>
<th>B772</th>
<th>F100</th>
<th>F70</th>
<th>Tot</th>
</tr>
</thead>
<tbody>
<tr>
<td>Day</td>
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<td>11</td>
<td>7</td>
<td>0</td>
<td>1</td>
<td>9</td>
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<td>0</td>
<td>3</td>
<td>1</td>
<td>1</td>
<td>3</td>
<td>1</td>
<td>9</td>
</tr>
<tr>
<td>$Tot_{eff}$</td>
<td>2</td>
<td>11</td>
<td>16.5</td>
<td>3.2</td>
<td>4.2</td>
<td>18.5</td>
<td>12.2</td>
<td>67.6</td>
</tr>
</tbody>
</table>

Table C.2: Amount of departures per aircraft type. ANDIK 1S departure from runway 24.

<table>
<thead>
<tr>
<th></th>
<th>A320</th>
<th>B734</th>
<th>B738</th>
<th>B744</th>
<th>F100</th>
<th>F70</th>
<th>Tot</th>
</tr>
</thead>
<tbody>
<tr>
<td>Day</td>
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<td>2</td>
<td>3</td>
<td>2</td>
<td>0</td>
<td>1</td>
<td>10</td>
</tr>
<tr>
<td>Evening</td>
<td>1</td>
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<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>2</td>
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<tr>
<td>Night</td>
<td>0</td>
<td>2</td>
<td>2</td>
<td>0</td>
<td>3</td>
<td>2</td>
<td>9</td>
</tr>
<tr>
<td>$Tot_{eff}$</td>
<td>5.2</td>
<td>22</td>
<td>23</td>
<td>5.2</td>
<td>30</td>
<td>21</td>
<td>106.4</td>
</tr>
</tbody>
</table>

Table C.3: Amount of departures per aircraft type. ARNEM 2S and LINUX 1S departure from runway 24.

<table>
<thead>
<tr>
<th></th>
<th>A320</th>
<th>B734</th>
<th>B738</th>
<th>B744</th>
<th>B772</th>
<th>B763</th>
<th>B752</th>
<th>F100</th>
<th>F70</th>
<th>Tot</th>
</tr>
</thead>
<tbody>
<tr>
<td>Day</td>
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<td>5</td>
<td>19</td>
<td>9</td>
<td>5</td>
<td>1</td>
<td>0</td>
<td>7</td>
<td>8</td>
<td>66</td>
</tr>
<tr>
<td>Evening</td>
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<td>1</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>3</td>
</tr>
<tr>
<td>Night</td>
<td>2</td>
<td>3</td>
<td>16</td>
<td>2</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>3</td>
<td>4</td>
<td>31</td>
</tr>
<tr>
<td>$Tot_{eff}$</td>
<td>32</td>
<td>35</td>
<td>182.2</td>
<td>29</td>
<td>15</td>
<td>4.2</td>
<td>3.2</td>
<td>37</td>
<td>48</td>
<td>385.6</td>
</tr>
</tbody>
</table>
Table C.4: Amount of departures per aircraft type. ARNEM 3E and LINUX 1E departure from runway 18L.

<table>
<thead>
<tr>
<th></th>
<th>A320</th>
<th>B734</th>
<th>B738</th>
<th>B744</th>
<th>B772</th>
<th>B763</th>
<th>B752</th>
<th>F100</th>
<th>F70</th>
<th>Tot</th>
</tr>
</thead>
<tbody>
<tr>
<td>Day</td>
<td>13</td>
<td>11</td>
<td>24</td>
<td>3</td>
<td>10</td>
<td>0</td>
<td>1</td>
<td>13</td>
<td>13</td>
<td>88</td>
</tr>
<tr>
<td>Evening</td>
<td>4</td>
<td>1</td>
<td>4</td>
<td>5</td>
<td>3</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>6</td>
<td>27</td>
</tr>
<tr>
<td>$Tot_{eff}$</td>
<td>25.6</td>
<td>14.2</td>
<td>36.6</td>
<td>18.8</td>
<td>19.5</td>
<td>6.3</td>
<td>4.2</td>
<td>16.2</td>
<td>32</td>
<td>173</td>
</tr>
</tbody>
</table>
Validating the proper functioning of the dose-response relationship

In Chapter 3 it is discussed that the GES dose-relationship (Equation 2.8) is used in FORT for minimizing noise nuisance. Engelen [13] states that extrapolation of the curve is possible numerically, however this is not supported by the results of the research. The newly created optimization does extrapolate this dose-response relationship, however. This is done to avoid discontinuities caused by cut-offs in the cost function. This appendix aims to prove the validity of using the dose-response relationship without a cut-off.

FORT is considered to function properly if the focus is on reducing the amount of people highly annoyed above 39 dB, which is called the true amount of people highly annoyed, instead of below 39 dB. This conclusion can be drawn by comparing the extent to which the amount of true amount of people highly annoyed is reduced as compared to the reduction in ‘fake’ people highly annoyed.

The first test of the validity of the dose-response function is found when comparing the intermediate solutions when the \( k_{\text{annoy}} \) is increased in the SPY2KY case study. The results of this comparison are shown in Table D.1. The estimated amount of people highly annoyed is represented by \( n_{\text{EPH}} \) while the true amount of people highly annoyed is represented by \( n_{\text{TPH}} \) and the fake people highly annoyed is \( n_{\text{FPH}} \):

<table>
<thead>
<tr>
<th>( k_{\text{annoy}} )</th>
<th>( n_{\text{EPH}} )</th>
<th>( n_{\text{FPH}} )</th>
<th>( \Delta n_{\text{FPH}} ) (%)</th>
<th>( n_{\text{TPH}} )</th>
<th>( \Delta n_{\text{TPH}} ) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>35508</td>
<td>18334</td>
<td>0.0%</td>
<td>17174</td>
<td>0.0%</td>
</tr>
<tr>
<td>0.01</td>
<td>34164</td>
<td>17391</td>
<td>-5.1%</td>
<td>16773</td>
<td>-2.3%</td>
</tr>
<tr>
<td>0.05</td>
<td>29855</td>
<td>15623</td>
<td>-14.8%</td>
<td>14232</td>
<td>-17.1%</td>
</tr>
<tr>
<td>0.1</td>
<td>27586</td>
<td>14867</td>
<td>-18.9%</td>
<td>12719</td>
<td>-25.9%</td>
</tr>
<tr>
<td>0.2</td>
<td>24657</td>
<td>12861</td>
<td>-29.9%</td>
<td>11796</td>
<td>-31.3%</td>
</tr>
<tr>
<td>0.3</td>
<td>23819</td>
<td>12823</td>
<td>-30.1%</td>
<td>10996</td>
<td>-36.0%</td>
</tr>
<tr>
<td>0.4</td>
<td>22919</td>
<td>11897</td>
<td>-35.1%</td>
<td>11022</td>
<td>-35.8%</td>
</tr>
<tr>
<td>0.5</td>
<td>22552</td>
<td>11695</td>
<td>-36.2%</td>
<td>10857</td>
<td>-36.8%</td>
</tr>
<tr>
<td>0.55</td>
<td>22441</td>
<td>11558</td>
<td>-37.0%</td>
<td>10883</td>
<td>-36.6%</td>
</tr>
<tr>
<td>0.6</td>
<td>22395</td>
<td>11300</td>
<td>-38.4%</td>
<td>11095</td>
<td>-35.4%</td>
</tr>
<tr>
<td>0.65</td>
<td>22193</td>
<td>11004</td>
<td>-40.0%</td>
<td>11189</td>
<td>-34.8%</td>
</tr>
</tbody>
</table>

Table D.1 shows unwanted behaviour: it is seen that the true amount of people is reduced to a smaller extent than the amount of fake people highly annoyed. It appears that FORT is focusing on the
reduction of people highly annoyed in the interval below 39 dB. It could however be that this type of behaviour is inherent to the specific set-up of the SPY2KY case. Some explanations of this are:

- The location of Hoofddorp directly at the end of runway forces the aircraft to fly over/around Hoofddorp while significant noise is produced by both aircraft. This causes a large amount of inhabitants to be exposed to relatively high levels of noise. In other words: the location of Hoofddorp with respect to the runway location causes a certain amount of true people highly annoyed that is unavoidable and can not be reduced.
- The relatively low amounts of aircraft flying the SPY2KY SID causes low levels of noise in the later stages of the departure. Due to the lack of a significant amount of noise it could be that the optimization simply reduces the amount ‘fake’ people highly annoyed as there are no more possibilities for reducing ‘true’ people highly annoyed. This can also be seen from the results up to $k_{\text{annoy}} = 0.3$ in Table D.1, it is seen that that initially the optimization reduces the true amount of people highly annoyed to a larger extent than the amount of fake people highly annoyed.

In order to test these hypotheses an equal type of optimization is performed in which the total noise levels are now increased with 5 dB $L_{DEN}$ everywhere. This increase in noise is implemented such that there is a sufficient amount of inhabitants in the 39 dB contour, which actually gives the FORT the possibility of reducing true people highly annoyed. The results of this optimization are shown in Table D.2.

<table>
<thead>
<tr>
<th>$k_{\text{annoy}}$</th>
<th>$n_{\text{EPH}}$</th>
<th>$n_{\text{FPH}}$</th>
<th>$\Delta n_{\text{FPH}}$ (%)</th>
<th>$n_{\text{TPH}}$</th>
<th>$\Delta n_{\text{TPH}}$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>64875</td>
<td>24611</td>
<td>0.0%</td>
<td>40264</td>
<td>0.0%</td>
</tr>
<tr>
<td>0.05</td>
<td>50927</td>
<td>20853</td>
<td>-15.3%</td>
<td>30074</td>
<td>-25.3%</td>
</tr>
<tr>
<td>0.1</td>
<td>45814</td>
<td>18973</td>
<td>-22.9%</td>
<td>26841</td>
<td>-33.3%</td>
</tr>
<tr>
<td>0.15</td>
<td>44101</td>
<td>18111</td>
<td>-26.4%</td>
<td>25990</td>
<td>-35.5%</td>
</tr>
<tr>
<td>0.2</td>
<td>42629</td>
<td>16909</td>
<td>-31.3%</td>
<td>25720</td>
<td>-36.1%</td>
</tr>
<tr>
<td>0.25</td>
<td>41564</td>
<td>16532</td>
<td>-32.8%</td>
<td>25032</td>
<td>-37.8%</td>
</tr>
</tbody>
</table>

When comparing the results shown in Table D.2 and Table D.1 it is found that FORT increasingly reduces the true amount of people highly annoyed, instead of reducing the fake people highly annoyed. This confirms the hypotheses stated previously.

Finally it is found that the mixed PAM departure is used by a significantly increased amount of noise as compared to the SPY2KY departure. This increased amount of traffic increases the noise footprint of the SID, which in turn creates a better case to assess to which extent FORT focusses on the reduction of true annoyances there. Table D.3 shows the results of the optimizations performed for this case. Since the fuel-optimum solution flies straight over Amsterdam the $k_{\text{annoy}} = 0.05$ solution is taken as a reference.

Table D.3 allows to conclude that the dose-response relationship forces FORT to reduce the true amount of annoyances as these cause the largest cost-function gradient. From Table D.1 it is seen that if the minimum amount of true people highly annoyed is met in the solution, FORT will continue by reducing the fake amount of people highly annoyed. It is therefore concluded that FORT functions as required, it is furthermore concluded that this dose-response relationship can be used without diminishing the validity of the optimization results.
Table D.3: Comparison between $n_{EPH}$, $n_{FPH}$ and $n_{TPH}$ when increasing $k_{\text{annoy}}$ in the mixed PAM case study.

<table>
<thead>
<tr>
<th>$k_{\text{annoy}}$</th>
<th>$n_{EPH}$</th>
<th>$n_{FPH}$</th>
<th>$\Delta n_{EPH}$ (%)</th>
<th>$n_{TPH}$</th>
<th>$\Delta n_{TPH}$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.05</td>
<td>73356</td>
<td>32397</td>
<td>0.00%</td>
<td>40959</td>
<td>0.00%</td>
</tr>
<tr>
<td>0.1</td>
<td>57820</td>
<td>31354</td>
<td>-3.22%</td>
<td>26466</td>
<td>-35.38%</td>
</tr>
<tr>
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<td>-51.99%</td>
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<td>16345</td>
<td>-60.09%</td>
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<td>13954</td>
<td>-65.93%</td>
</tr>
<tr>
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<td>29848</td>
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<td>13648</td>
<td>-66.68%</td>
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</table>
Bibliography


