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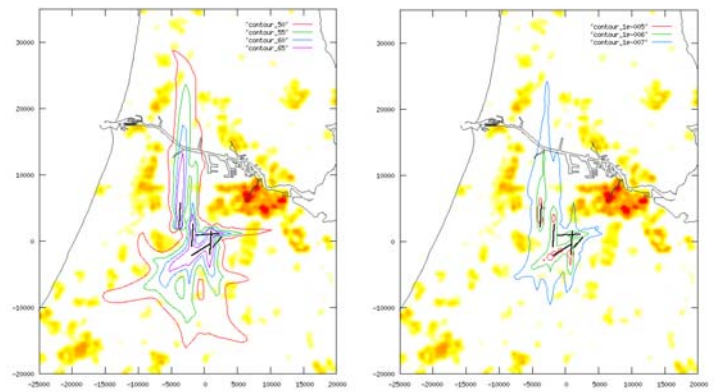
Executive summary

Development of a Runway Allocation Optimisation Model for Airport Strategic Planning



Problem area

For airports with multiple runways, the distribution of flights over different runways is a problem concerning a multitude of often conflicting interests. This report describes the development of a runway allocation optimisation module for use in the strategic domain, including airport master planning.

Description of work

The optimisation module that has been developed provides the user with a balanced annual runway usage scheme for a generic airport, now or for a given future situation. As objectives, the optimisation uses results from a noise model and a third-party risk model, both with respect to population density distribution. Minimising delay is used as the third objective. In addition, operational runway usage, wind conditions and runway capacity are taken into consideration during the multi-objective optimisation. A graphical interactive optimisation procedure has been implemented to assist the user in reaching a satisfactory result.

Results and conclusions

The interactive procedure is very suitable for reaching a final Pareto-optimal solution for this multi-objective planning problem. For a sample problem, the optimiser itself shows improved results with respect to the reference situation under the made assumptions and applied simplifications. The total overall risk reduces by about 30% and the same holds for the indicator estimating annoyance due to aircraft noise.

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Development of a Runway Allocation Optimisation Model for Airport Strategic Planning

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Summary

This paper describes the development of a runway allocation optimisation model to be used for airport strategic planning. It optimises the allocation of flights to runways on an annual basis, with respect to delay, noise and safety. The multi-objective optimisation is subject to a number of constraints, related to operational procedures, runway capacity and weather conditions. To reach a final non-dominated solution for the multi-objective problem, an interactive optimisation method has been implemented. This has resulted in a very convenient and easy-to-use optimisation procedure. Although the model has to be extended to handle more complex operational situations, the results with respect to the reduction of aircraft noise annoyance and total third-party risk are promising.

Contents

Abbreviations

DSS	Decision Support System
FAA	Federal Aviation Administration
GUI	Graphical User Interface
INM	Integrated Noise Model
MILP	Mixed Integer Linear Programming
NATS	National Air Traffic Service
OAG	Official Airline Guide
SEL	Sound Exposure Level

1 Introduction

For airports with multiple runways, the distribution of flights over different runways is a problem concerning a multitude of often conflicting interests. Usually, one of the runways is preferred for noise reasons, where another may be preferred in the sense that it is perceived to be safer for the surrounding community (third-party risk, sometimes referred to as ‘external safety’). However, choosing one of these runways for all flights is not always a good option. Not only could it lead to huge delays in most cases, but under certain weather conditions it may lead to unacceptable risks for the passengers onboard the aircraft. In 1997 an accident occurred at Amsterdam Airport Schiphol illustrating this problem. A passenger aircraft was blown off the runway during landing by a severe crosswind. Later investigation showed that the aircraft was assigned to a certain runway because of noise considerations, where another would have been more appropriate under the wind conditions at that time (Dutch Council for Transportation Safety, 2000).

This example is in fact at the operational level, which is also the level where runway allocation is usually considered (Bolender & Slater, 2000; Isaacson et al., 1997). However, runway allocation is also important for the planning of an airport. For example, when an airport wants to construct a new runway, the location of this new runway together with the new flight allocation regime determines to a large extent the new situation with respect to noise and third-party risk. There are, however, many more aspects planners need to consider in such a situation, including financing the new investment and land acquisition. This illustrates that the planning process is a very complex and demanding task, especially when planners sometimes receive incomplete but also partially overlapping and contradictory information from their multitude of sources. A well-designed Decision Support System (DSS) can in such a situation help to identify solutions with maximum efficiency with respect to the scarce available resources. HARMOS, currently under development at TU Delft, is such a DSS (Wijnen et al., 2008). The main feature of this system is the use of hierarchical multi-objective optimisation techniques, allowing for different stakeholders to set their objectives at the desired system level.

This paper describes the extension of HARMOS with a runway allocation optimisation module. This module provides the user with a balanced runway usage scheme for a generic airport, now or for a given future situation. As objectives, the optimisation uses results from a noise model and a third-party risk model, both with respect to population density distribution. Minimising delay is used as the third objective. In addition, operational runway usage, wind conditions and runway capacity are taken into consideration during the multi-objective optimisation. An interactive method is used to reach a unique final solution that not only meets the requirements but also the preferences of the user.

2 Problem Description

The optimisation model seeks to minimise for two important environmental impacts of airport operation: noise disturbance and the risk for the surrounding community. However, without any further constraints, a minimisation of these objectives could lead to the trivial solution of no more flight operations. Therefore, it is assumed that the optimisation will have to deal with a prescribed amount of traffic. This traffic is specified in a flight schedule, for example, in an OAG-like format.

With the additional constraint of meeting the actual number of flights, this optimisation would still not lead to a satisfactory result, because no runway capacity and delay characteristics are taken into consideration. To solve this, the ultimate (or theoretical) runway capacity is added as a constraint in the optimisation. This capacity is calculated using an analytical airfield capacity model (Horonjeff & McKelvey, 1993). This model also provides an estimate for delay occurrences, based on the capacity used in proportion to the ultimate capacity. The delay results are used for the third objective function of this problem, which should also be minimised. This means that the user will have the possibility to perform a trade-off between the two environment-related objectives and the resulting delays.

The operational runway usage should also be taken into consideration. All modes for which the airport may wish to operate its runways are specified beforehand as runway use configurations. The availability of these configurations with respect to cross- and tailwind is calculated by HARMOS, based on posed operational limits and statistical wind data of the airport under investigation. The same can be done for the availability related to visual conditions, but this has not yet been implemented.

At this moment, only independent runway usage in segregated mode is supported in HARMOS. For the study airport (Amsterdam Schiphol), this is no problem most of the time. However, for other airports, using mixed mode or highly dependent configurations on a regular basis, the optimisation model has still to be extended.

3 Environmental Models

Two different models perform the environmental calculations, one for aircraft noise and one for third-party risk. Both models have in common that they calculate expected levels at a specific location with respect to the airport, based on a certain number of flights. Usually, these calculations are performed for points in a rectangular grid around the airport. Because of the combination of the complexity of the calculations and the high number of computation points, these computations can be very time consuming, especially for noise. For the interactive optimisation this is undesirable, because the user must be able to evaluate the current solution quickly to see whether this solution is satisfactory or not.

To solve this problem, the risk and noise results are pre-processed during an initial calculation run. This initial calculation run is not necessarily performed by the decision advisor (the main user of the system) but can be performed by a domain expert when preparing HARMOS for use at a specific airport. Instead of calculating total levels for noise and third-party risk based on a given amount of traffic, now the individual contributions of all possible movements (all unique combinations of the different runways, tracks and aircraft types) are calculated for all evaluation points within the grid. The results are stored in matrix format. When a new noise or risk evaluation is required during the optimisation process, the actual calculation is only a matter of some matrix additions. This method is able to generate the required results almost instantly. The specific details of the environmental models used are discussed next.

3.1 Noise Model

For the noise calculations, the Integrated Noise Model (INM) version 6.1 has been used (Olmstead et al., 2002). INM is the US FAA’s standard tool for determining the predicted noise impact in the vicinity of airports. A drawback of this model for this specific application is that it requires its own dataset of input, where one of the advantages of a DSS should be the use of a single dataset. Another disadvantage of INM, however somewhat less important, is that it uses its own Graphical User Interface (GUI). Fortunately, INM also uses a database structure for all input and output data. This means that it is possible to set up a noise study and even obtain the results without starting the program. In other words, all required data for a noise study is requested from the HARMOS database and placed into the INM database. INM is then only used to perform the actual calculations, thereafter HARMOS retrieves the results and stores them for later use.

As mentioned, INM is set up to perform the noise calculations for all possible occurring movements. The results for the single flight event computations are provided as Sound Exposure Levels (SEL, notation L_{AE}). The SEL is often used for describing single events, because it incorporates both loudness and duration in a single number. Using the SEL values,

HARMOS is also able to calculate total average noise exposure levels like the Day-Night Level (L_{DN}) and Day-Evening-Night Level (L_{DEN}) often used in land use planning.
The total average noise metrics are then used to draw noise contour levels on a map. Several other indicators can also be calculated, like the areas of certain noise levels or the number of inhabitants within such an area. However, none of these indicators can express the overall noise situation in a single number, which is very desirable for a key performance indicator. Therefore, a dose-response relation has been used for this purpose (Miedema & Oudshoorn, 2001). This relation, based on research in Europe, the US and Australia, estimates the percentage of people feeling annoyed when exposed to a certain aircraft noise level. It is shown in Figure 1 for the metric L_{DEN}, but such a relation also exists for L_{DN}. In mathematical form it is:

$$A = 1.460e^{-5}\left(L_{DEN} - 37\right)^3 + 1.511e^{-2}\left(L_{DEN} - 37\right)^2 + 1.346\left(L_{DEN} - 37\right) \qquad 45 \le L_{DEN} \le 75$$

The relation is only valid from 45 to 75 dB(A), so at levels over 75 dB(A) it is assumed there will be 100% annoyance. The introduced error will be negligible, because the number of people living at locations with noise levels over 75 dB(A) is small. On the other hand, it is assumed that below 45 dB(A) there will be no annoyance at all, which may lead to an underestimation of the number of people feeling annoyed. One should also keep in mind that this key indicator is based on a dose-response relationship, which has a subjective character.

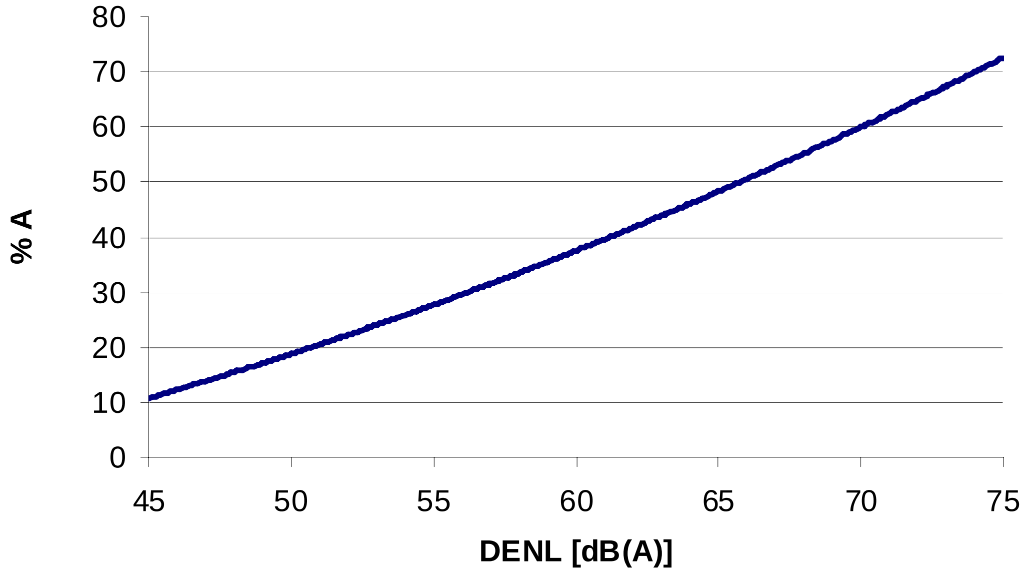

Figure 1: Dose-response relationship: annoyance due to aircraft noise

3.2 Third-Party Risk Model

For the individual risk calculations, the model developed by the UK National Air Traffic Service (NATS) has been selected (Cowell et al., 2000). This model calculates the probability that an individual living permanently at a particular location near an airport will be killed by an aircraft impact in any given year. This is achieved by combining statistical data on crash frequency, location, impact area and consequence.

During the implementation, a modification was made, because originally this model could only calculate the risk for a single runway in a runway coordinate system. Using a coordinate transformation, all computations are now performed in the same (airport) coordinate system. The separate risk contributions of all runways are added to obtain the total individual risk levels for the complete airport.

Again, a single number is preferred to be used as a key performance indicator. For third party risk, such a number can be calculated by aggregating the total individual risk for all people living within the evaluation area. This results in an annual casualty expectancy value.

4 Optimisation Design

4.1 Problem Formulation

The optimisation model, which is a Mixed Integer Linear Programming (MILP) model, can now be generated, using the available data and the previous computations on noise and risk. The allocation decisions the model takes are very similar to the runway usage decisions the air traffic control authorities would make during a year. This does not only include the decisions on which runway configuration will be used at a certain moment in time, but also the distribution of flights over the different runways within that configuration.

The MILP problem consists of a collection of time periods. Such a period represents a small part of a certain year. The duration of these parts is related to the statistical occurrence of both similar traffic patterns and similar wind conditions. Connected to each of those periods a number of options are offered. The options represent runway configurations that can be used under given weather conditions. The selection of one of the options automatically results in certain consequences with respect to noise, third-party risk and delay. These consequences are translated into costs, which are used for the objective functions. More details on the objective functions will be given in the next section.

The model is created such that the solver is forced to select one or a certain combination of some of the options offered for each of the periods. This automatically means that all traffic will be allocated. Because of an analysis preceding the generation of the optimisation model, only feasible configurations will be offered for each period. This means that solutions returned by the solver will automatically be feasible, not only in a mathematical sense, but also from an operational point of view.

A schematic view of the design of the optimisation module is given in Figure 2.

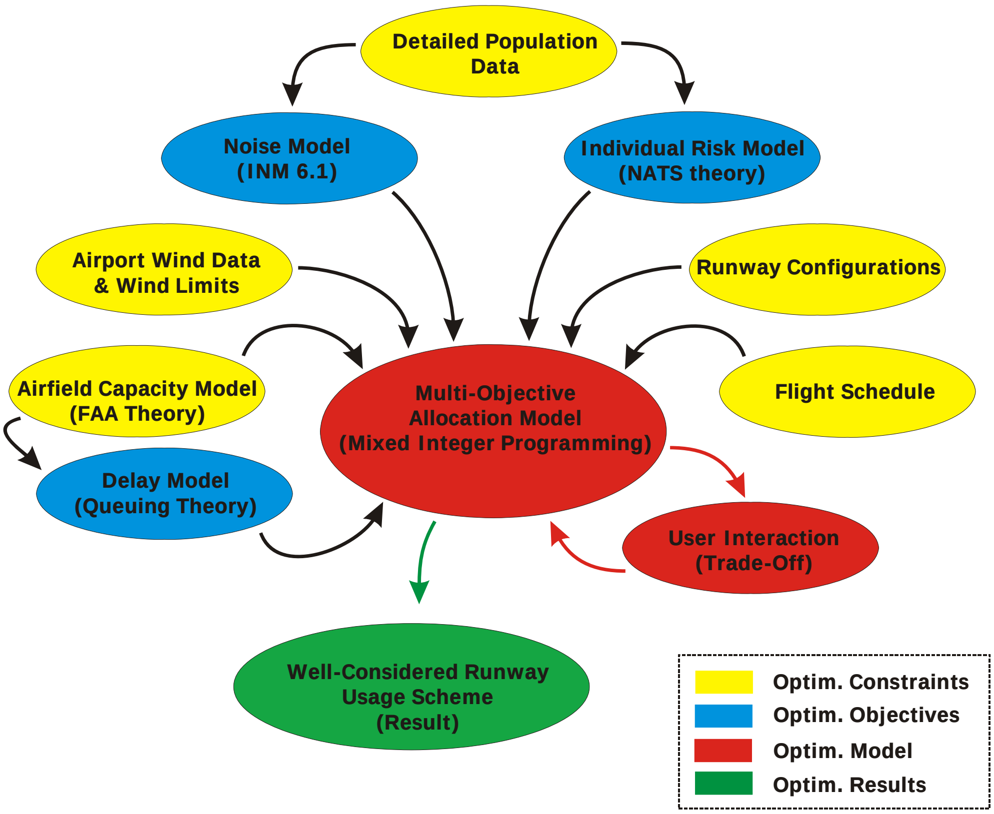

Figure 2: Design of the optimisation module

4.2 Objective Functions

Three different objective functions are used for this problem, one for delay, one for noise and one for third party risk. The delay objective w_1 is a summation of all occurring delays as a function of the selected values for the decision variables. For a single period p, the resulting delay is:

$$w_{1,p} = \sum_{i=1}^{n} a_{i,p} x_{i,p}$$

Subject to:

$$\sum_{i=1}^{n} x_{i,p} = 1 \ \ and \ \ x_{i,p} \geq 0$$

The decision variable x represents a certain runway configuration suitable for that period and, if applicable, also a certain distribution of flights over the active runways. Depending on the situation, x can be a float or an integer. When x is a float, the solver can select a combination of runway configurations for that period; if it is an integer, a single configuration has to be selected. Variable a is the resulting delay related to x. Total annual delay (w_1) is the summation of all delays occurring in all periods.

For third party risk, the objective is similar. For a single aircraft movement, the total risk is calculated by multiplying the individual risk at a certain location with the number of inhabitants. This results in an expectancy value for casualties due to a single movement. Using this number, the resulting risk contribution $b_{i,p}$ resulting from selection of $x_{i,p}$ can be calculated for each of the decision variables. The final objective for risk becomes:

$$w_2 = \sum_{p=1}^{m} \sum_{i=1}^{n} b_{i,p} x_{i,p}$$

The objective function for noise is less straightforward. The problem is that noise annoyance is based on cumulative metrics like L_{DEN} and not on single event metrics like L_{AE}. However, one can be sure that a flight exposing a high number of people to a high SEL will contribute more to the noise annoyance indicator than a flight that exposes less people to a lower level. Based on this observation, a cost function could be used that penalises both high noise levels as well as high number of inhabitants within the accompanying footprint. For this problem, the L_{AE} contour levels for every possible movement are investigated to count the number of people living within certain levels, starting at 60 dB(A). Multipliers are used to apply penalties for higher levels. The default multipliers are 1 for 60 dB(A), 5 for 70 dB(A) and 25 for 80 dB(A). Sensitivity analysis has indicated that the final solution is not very sensitive to change in the multipliers, as long as the higher levels are given priority over the lower levels by means of significantly higher multipliers.

The resulting objective function for noise becomes:

$$w_3 = \sum_{p=1}^{m} \sum_{i=1}^{n} c_{i,p} x_{i,p}$$

where $c_{i,p}$ is the resulting number of people living within SEL contours in a case of selecting the accompanying decision variable $x_{i,p}$.

4.3 Interactive Optimisation Procedure

In order to reach a final solution for the multi-objective optimisation, an interactive procedure has been developed, which is very similar to a procedure developed to solve a production planning problem with four objectives (Michalowski & Piotrowski, 1983). This procedure is based on a weighted sum method, where the new objective is a combination of the three objective functions. There are, however, some important differences when compared to the default weighted sum method. Often, the decision maker determines the weights beforehand, which requires a priori knowledge of the optimisation. Especially for non-experienced users of the optimisation module, this can be a problem, making it hard to reach a satisfactory result. Using this interactive method, the weights are determined automatically such that all three objectives become equally important at the point where they reach their absolute minimum. The objective function for the multi-objective problem becomes:

$$Minimise : 1/m_1 \cdot w_1 + 1/m_2 \cdot w_2 + 1/m_3 \cdot w_3$$

where m is the normalised vector holding the minima of the three single-objective problems. To reach a satisfactory solution, the decision maker is presented with a range for the different objectives together with three possible solutions. Starting from one of these three initial solutions, a new solution can be generated that will minimise for all three objectives simultaneously. At the same time, upper bound values for the objectives can be specified explicitly. In practice, achieved values for some of the objectives should be relaxed if the remaining objective values should be reduced further. If desired, one of the objectives can be given priority over the others during one of the iterations, but this is not required.

A part of the GUI used for this optimisation is shown in Figure 3. Figure 3(a) shows the situation with one of the initial solutions selected. This solution, which is not Pareto-optimal, has been calculated together with two other initial solutions to provide starting points for the optimisation and to determine the ranges for the sliders. Figure 3(b) shows the situation after a single iteration, where delay is allowed to increase a few seconds, compared to the absolute minimum. This solution is Pareto-optimal and if it satisfies the needs of the current user, the optimisation is complete. If not, the user can continue with the new solution or start over from one of the initial solutions.

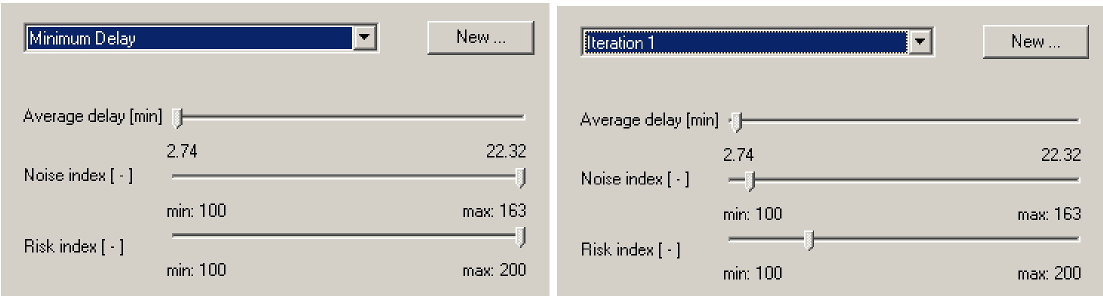

Figure 3: (a) User interface for interactive optimisation procedure: initial solution and (b) user interface for interactive optimisation procedure: possible solution after one iteration

This way of presenting a multi-objective optimisation has turned out to be very convenient and easy to use. No fundamental knowledge concerning the underlying optimisation theory is required. It is expected that users with no optimisation experience will be able to use this optimiser with only a few instructions.

5 Results

In this section, some results of a case study will be presented for Amsterdam Airport Schiphol. In order to evaluate the performance of the optimisation, the optimised results will be compared with a reference scenario. This is the calculated current performance, also generated by HARMOS. The reference scenario results are based on exactly the same amount of traffic and the same computation models. The only difference is that the runway usage percentages are based on the usage projected by the airport authority, instead of calculated by the runway allocation optimiser.

5.1 Case Study 2003

First, the results of the reference scenario are presented in Figure 4. Both figures show the area around the airport, the runways, coastal lines and population density. Figure 4(a) shows contour lines for the noise metric L_{DEN}. The individual risk contour lines are shown in Figure 4(b). The same holds for Figure 5, but now for the optimised results. The optimisation was stopped after a single iteration, with the three objectives as indicated by the sliders in Figure 3(b).
When comparing the results graphically it can be seen that the images look similar, but differences can be identified. At first sight, it looks like more traffic is handled in the North-South direction.
Besides the images, both situations can also be compared using the chosen indicators. For the reference scenario, the estimation for the number of people annoyed by aircraft noise is 98,100. For the optimised scenario, this number has dropped to 69,000. Concerning individual risk, the casualty expectancy value is 0.048 per year for the reference scenario, compared to 0.035 for the optimised scenario. This means that both indicators have dropped by almost 30%.

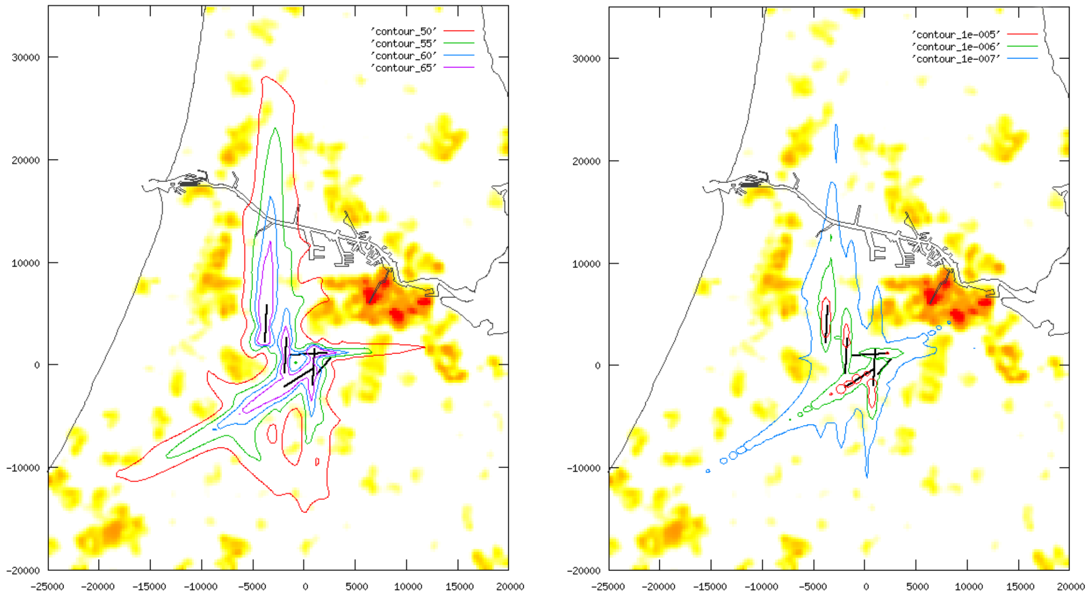

Figure 4: (a) Reference scenario showing LDEN noise contour levels in dB(A) and (b) reference scenario showing individual risk contour levels

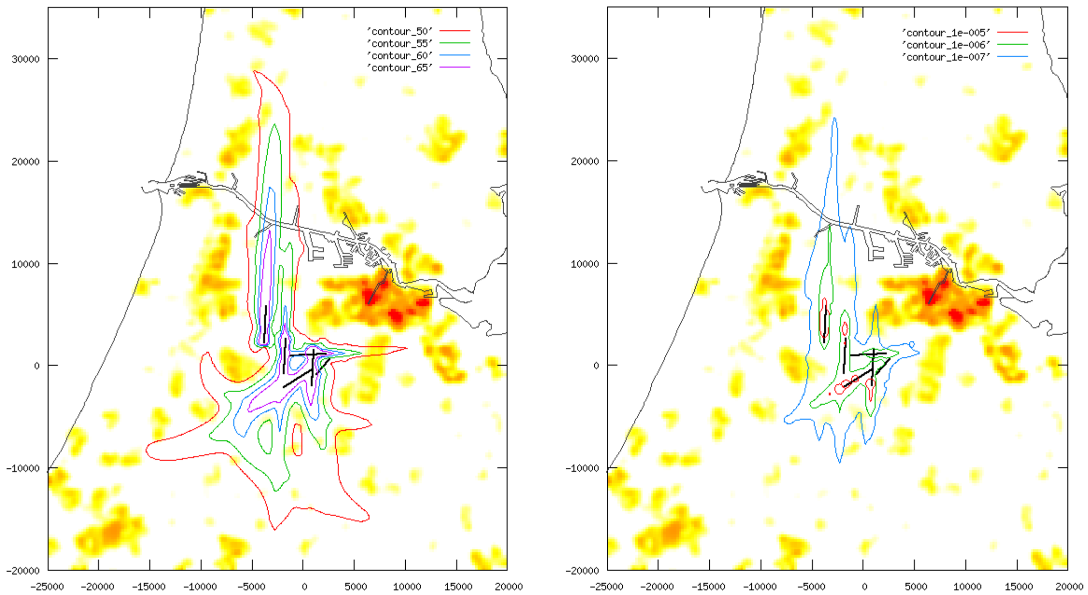

Figure 5: (a) Results after optimisation showing LDEN noise contour levels in dB(A) and (b) results after optimisation showing individual risk contour levels

5.2 Case Study 2010

For a DSS designed for airport planning, the ability to evaluate future scenarios is essential. Although this functionality is still under development for HARMOS itself, the runway allocation optimisation module can already perform such calculations. This section will give an example of such an analysis, but it should be noted that the assumptions made concerning the future are not based on actual forecasting studies.

To predict traffic in 2010, the 2003 schedule has been increased by 24%, which assumes an annual growth of just over 3%. The optimisation procedure followed to obtain the optimal solution that is presented here is the same as described before: starting from the minimum delay solution, delay is allowed to increase a few seconds in order to improve the other two objectives.

The results for third party risk are not presented here, because they look very similar to those presented in Figure 5(b). What is worth mentioning here is that a possibility has been provided to specify an arbitrary reduction in crash rate for future third party risk calculations. A model that can predict this reduction is still to be implemented.

Assuming that the same fleet of aircraft will still serve the airport in 2010, the results for noise are shown in Figure 6(a). Figure 6(b) on the other hand shows the results if development of the fleet is considered. Like for third party risk, a model that is able to predict the impact of new quieter aircraft has not yet been included in HARMOS, but the allocation module is able to perform calculations assuming an arbitrary reduction. For this analysis it has been assumed that there will be a decrease in SEL values of 0.3 dB(A) per year.

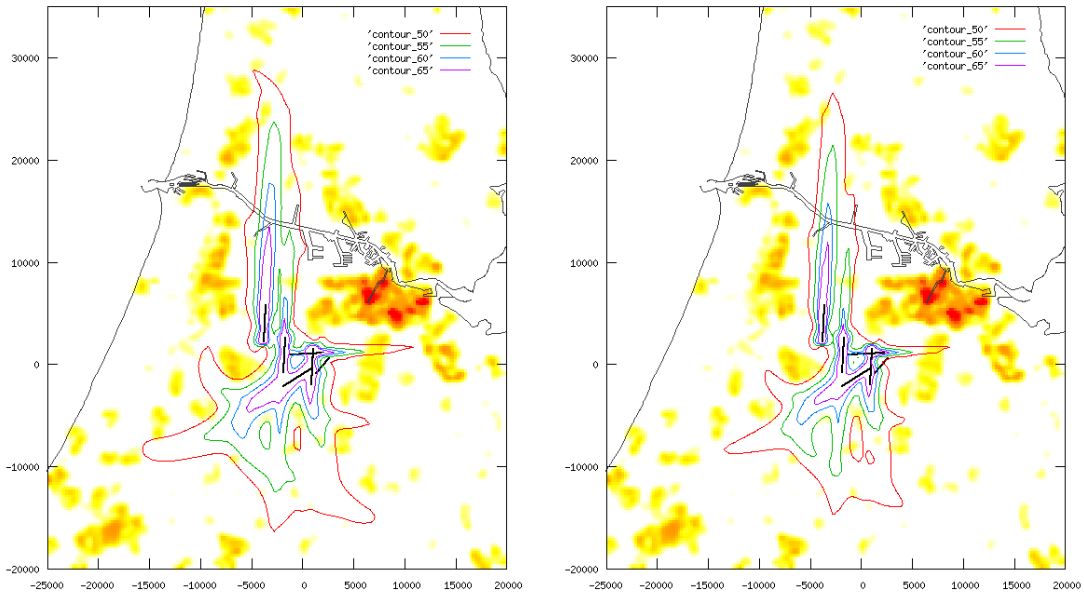

Figure 6: (a) Results for 2010 scenario showing LDEN noise contour levels based on current aircraft fleet and (b) results for 2010 scenario showing LDEN noise contour levels based on newer aircraft fleet

Concerning noise annoyance, the total number of people annoyed is predicted to rise to 75,700 without fleet development, but is estimated to drop even under 2003 levels to 42,800 with fleet development, despite the 24% growth in traffic. A similar observation is made in a cost-benefits analysis for the expansion of Schiphol Airport with two possible new runways (Koning et al., 2002). When accounting for the newer aircraft, the environmental capacity with respect to noise is expected to grow faster than the physical capacity of the runway system.

6 Conclusions

The purpose behind this research, the design of an optimisation module for a DSS for airport strategic planning, has been demonstrated. HARMOS has been extended with a third party risk model and a noise model. Using these results, a MILP model has been generated. The module can assign all yearly flights to the different runways of an airport, while taking into account delay, feasible runway usage combinations, wind conditions and noise and third party risk with respect to the surrounding population. As a result, a balanced runway usage scheme can be determined, not only for the current but also for any predicted future situation.

A graphical interactive optimisation procedure has been implemented in HARMOS for the runway allocation optimiser. It is concluded that this method is very suitable for reaching a final Pareto-optimal solution for this multi-objective planning problem. The user interface is very easy to use, and provides a good insight into the trade-off to be made.

Concerning the results, the optimiser shows improved results with respect to the reference situation. The total overall risk reduces by about 30%. The same holds for the indicator estimating annoyance due to aircraft noise. Unfortunately, these results cannot be directly translated to the actual situation at Amsterdam Airport Schiphol because of some key assumptions and simplifications in the design of the model. Therefore we seek to extend the optimisation module in the near future to handle more complex operational situations, including highly dependent runway usage and capacity under poor visual conditions.

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