



Efficient Use of an Allotted Airport Annual Noise Budget through Minimax Optimization of Runway Allocations

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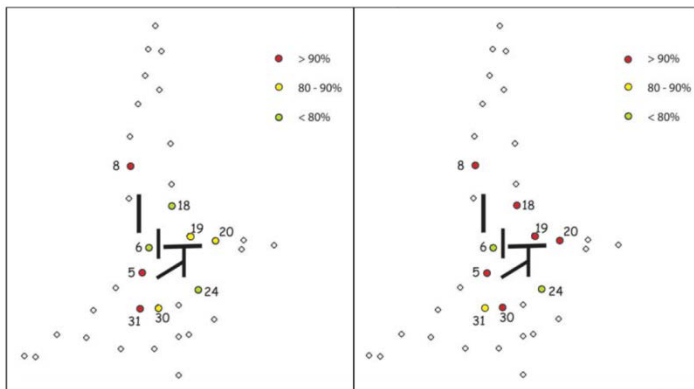
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EXECUTIVE SUMMARY

Efficient Use of an Allotted Airport Annual Noise Budget through Minimax Optimization of Runway Allocations



Problem area

Schiphol airport is a noise-sensitive airport. To manage the noise resulting from flight operations and to mitigate its worst effects, Schiphol airport and responsible authorities have legislated and implemented an extensive set of measures. One of these measures concerned an annual noise budget restriction that stipulated limits for the average annual noise exposure at a number of predefined locations in the vicinity of the airport, known as “enforcement points”. This article presents an optimization approach that aims to minimize the risk of exceeding the limit at any enforcement point by distributing flights over the different runways.

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Knowledge area(s)

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Aircraft Noise
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Optimisation
Runway Allocation
Airport Capacity

Description of work

The noise budget regulations stipulate limits on the annual cumulative noise loads at a large number of enforcement points arranged around the airport. To ensure an equitable distribution of the cumulative noise load at the enforcement points, an efficient allocation and distribution of the annual flight movements over available runways and routes is required that takes weather induced restrictions into account. To this end, a Linear Programming (LP) optimization formulation has been developed that implements a minimax performance criterion. This criterion aims to minimize the maximum cumulative noise load value occurring at any of the enforcement points.

The LP optimisation formulation has been implemented in planning tool, featuring a graphical user interface. The planning concept and the tool are illustrated by presenting a case study pertaining to the operational year 2005 at Schiphol Airport.

Results and conclusions

Due to the large-scale nature of the runway allocation planning problem, combined with limited computational resources, not all of the enforcement points were included in the optimization formulation presented in the case study. Following an analysis, nine strategically located enforcement points were selected for this planning problem. This

proved to be adequate to produce meaningful results. It is shown that the minimax optimization analysis resulted in a rather efficient noise distribution, reducing the maximum noise energy at any of the enforcement points included in the optimization formulation to a level some 10% below the permissible value, without overloading the enforcement points that were not included at the optimization analysis.

Future research will focus on the development of a modeling approach that allows for more enforcement points to be taken into account at a reasonable computational cost, and that will include capacity constraints due to poor visibility conditions.

Applicability

For Schiphol airport, the applicability has been reduced by recent developments in the regulatory system, where the enforcement points will no longer be used.

However, due to its flexible, generic nature the tool and its concepts can also be applied to other airports with similar annual noise budget restrictions.

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
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Summary

This paper presents the development of a runway allocation planning tool that seeks to maximize the permissible number of flight operations into and out of an airport within a given annual noise budget.

Although the model that underlies the planning tool is generic in nature, the tool has been customized for application to a specific airport, viz. Amsterdam airport Schiphol in the Netherlands. The noise budget regulations applicable at Schiphol stipulate limits on the annual cumulative noise loads at a large number of enforcement points arranged around the airport¹. To ensure an equitable distribution of the cumulative noise load at the enforcement points, an efficient allocation and distribution of the annual flight movements over available runways and routes is required that takes weather induced restrictions into account. To this end, a Linear Programming (LP) optimization formulation has been developed that implements a minimax performance criterion that aims to minimize the maximum cumulative noise load value occurring at any of the enforcement points. The numerical results obtained for the operational year 2005 clearly demonstrate the potential of the tool to maximize the yearly number of flight movements within the assigned noise budget.

¹ This article was accepted for publication (17 April 2012), before the ministry announced that the regulatory system described in this article will be replaced by a new system. This new system does not include the noise enforcement points.

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Abbreviations

Acronym	Description
CNEL	Community Noise Exposure Level
GUI	Graphical User Interface
INM	Integrated Noise Model
LVNL	Air Traffic Control The Netherlands
LP	Linear Programming
QC	Quota Count
RVR	Runway Visual Range
RWY	Runway
SEL	Sound Exposure Level
SNAP	Strategic Noise Allocation Planning

1 Introduction

To mitigate the impact of aircraft noise, an array of measures has been developed and implemented at airports located close to sensitive communities. A type of measure that is frequently employed to mitigate the effect of airport noise concerns the enforcement of airport access restrictions, such as operating quota, noise budgets, (nighttime) curfews and restrictions on the operation of certain (noisy) types of aircraft [1].

The application of a noise budget generally places a ceiling on the total amount of noise that may be produced at an airport during a longer period such as a season or a year [2]. Due to their long-term nature, noise budgets are typically based on a cumulative (rather than a single-event) noise metric. In some cases noise budgets restrict operations only during a certain night time period, whilst in other cases the budget may apply during the day as well. In contrast to an operating quota, which imposes a direct limit on the permissible number of movements, the application of a noise budget provides some degree of flexibility in the scheduling of operations owing to the fact that it is based on the aggregation and distribution of all flight movements over an extended period of time. For example, within a given noise budget, the operation of a few noisy aircraft might be exchanged in favor of a larger number of quieter planes. By the same token, the permissible number of movements might be increased through efficient allocation and distribution of the annual flight movements over available runways and routes. Noise budget restrictions, presently in place at various noise-sensitive airports around the globe, can take on several forms depending on the community noise policy objectives sought to be achieved at a particular airport.

At several airports in the UK, including London Heathrow and Manchester airport, a noise budget has been put in place in the form of a “points budget” known as a Quota Count system [3]. Based on ICAO aircraft noise certification data, all arriving and departing aircraft are given a noise classification in terms of a Quota Count (QC), with a noisy aircraft receiving a higher QC than a quieter one. For each inbound and outbound flight, the corresponding QC is then deducted from the points budget that is typically fixed for any given season. This process allows airlines to operate more quiet aircraft in exchange for fewer noisier ones. In Germany, Hamburg airport is subject to noise limits based on the surface area of land around the airport where the noise exposure exceeds a specified L_{eq} energy-equivalent sound level limit (62 dBA) [4]. The airport conducts continuous noise monitoring and reports annually on its operation within the noise budget. At Friedrichshafen Airport in Germany, a similar noise budget restriction is imposed during the six busiest months of the year [3]. Here, a L_{eq} sound level limit of 62 dBA is imposed

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and monitored at a specific location in a village adjacent to the airport. One of the strictest noise-controlled airports in the United States is Long Beach airport. At Long Beach airport a noise budget has been put in place that aims to have no communities exposed to a community noise equivalent level (CNEL) of 65 dBA or greater [3]. To help enforce the noise budget regulations, the airport has an extensive airport noise and operations monitoring system in place [3]. In New Zealand, noise budgets are imposed at the international airports of Auckland and Wellington. At both airports, outside a certain surface area of land around the airport defined on a map, the day-night average sound level L_{dn} should not exceed 65 dBA. At Auckland international airport, an additional area known as Moderate Aircraft Noise Area is defined. At the boundary of this Moderate Aircraft Noise Area L_{dn} should not exceed 60 dBA. Noise monitoring is undertaken in the exposed communities [3].

One of the most noise-sensitive major airports in Europe is Schiphol airport, located near Amsterdam in the Netherlands. To manage the noise resulting from flight operations and to mitigate its worst effects, Schiphol airport and (national and local) authorities have legislated and implemented an extensive set of measures. The noise regulations currently² applicable to Schiphol airport, effective since 2003, also include a noise budget restriction that stipulates limits for the total annual noise volume, as well as for the average annual noise exposure at a number of predefined locations in the vicinity of the airport, known as “enforcement points” [5]. Schiphol airport is the site selected for the case study presented herein.

Consistent with airline seasonal planning, a noise planning is made for Schiphol airport for an operational year that runs from November 1 through October 31 [5]. This implies that on October 31 of a given calendar year, the noise exposure that was accumulated as of November 1 of the preceding calendar year should not exceed the regulatory noise limit specified at any of the enforcement points. The annual usage plan, known as the “operational plan”, is made well ahead of the start of an operational year and relies on a prediction of the cumulative noise exposure in the enforcement points based on a comprehensive traffic forecast. In the usage plan it must be clearly demonstrated that the environmental impact of the planned operations does not result in a noise budget overrun by year-end. The environmental capacity resulting from the usage plan is then apportioned to airlines through the allocation of slots (date and time of departure or arrival for a single aircraft movement). It is readily clear that in order to make maximum use of the available environmental capacity, the annual flight movements should be efficiently distributed over the available runways and arrival and departure routes such that the annual budget is met

² This article was accepted for publication (17 April 2012), before the ministry announced that the regulatory system described in this article will be replaced by a new system. This new system does not include the noise enforcement points.

at every enforcement point. It is inevitable though that differences between the planned and actually executed operations will arise during the operational year. Therefore the noise loads produced at the enforcement points are closely monitored during the operational year. When necessary, operational measures are applied to prevent noise budget exceedance.

At present Schiphol airport has five main runways available, permitting a multitude of runway combinations. Typically, three runways are operated simultaneously in a runway configuration, although configurations that feature one, two or four active runways are also possible. However, due to the often changing weather conditions (notably wind speed and direction), the availability of each runway configuration varies. Clearly, any change in runway combination results in a different traffic distribution around the airport and, as a consequence, in a different noise load distribution.

The steering mechanism presently used to manage the noise load distribution at Schiphol airport is to allocate over time the order of preference of the available runway combinations. Based on safety and efficiency considerations, runway combinations have been set up and ranked in an order of hierarchy in a preference list by the air traffic service provider at Schiphol airport (LVNL) [6]. The potential use of a runway configuration is determined by the prevailing meteorological conditions and when the weather conditions allow more than one runway combination to be used, then the highest combination from the preference list is selected. Each month, the annual noise load at the enforcement points is recalculated using actual traffic as available and projected traffic for the remaining months. Based on the results, the preference list is updated such as to achieve the most balanced noise load accumulation at the enforcement points without exceeding the noise budget limits set by year-end.

Amsterdam Airport Schiphol has developed an optimization tool that aims to accommodate as many flights as possible during an operational year, while minimizing the chance of exceeding the limit values of the enforcement points [5]. The developed optimization tool is used in conjunction with a traffic forecast model, a runway combination selection model and a collection of historic meteorological datasets. It is readily clear that meteorological data forms an important basis for the traffic and noise distribution forecasts. As mentioned earlier, the steering mechanism presently used in the optimization process to manage the noise load distribution is to dynamically adjust the order of preference of the available runway combinations.

In [7] an alternative approach to runway allocation optimization is presented. The multi-objective optimization tool proposed in [7], called SNAP (Strategic Noise Allocation Planning), optimizes the

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allocation of flights to runways on an annual basis with respect to three criteria, viz., noise impact, third party risk and average delay per movement. The multi-objective optimization is also subject to a number of constraints, related to operational procedures, runway capacity and weather conditions. In order to reach a final solution, a trade-off between the three performance criteria needs to be made. The noise criterion considered in SNAP does not relate to average annual noise exposure at predefined locations (i.e., enforcement points), but rather it is based on the number of people expected to be annoyed by annual aircraft noise exposure. In contrast to the optimization algorithm currently in use at Schiphol [5], which steers the traffic distribution indirectly through adjustment of the preference list, SNAP does not make use of a preference list, but rather directly allocates optimal runway configurations.

The present study on environmental optimization of runway allocations builds on the approach taken in SNAP, by extending it to take into account the current noise regulations in place at Amsterdam airport Schiphol that specify noise load limits at discrete enforcement points. The ultimate goal is to maximize the permissible number of flight operations into and out of the airport within the allotted annual noise budget. To achieve this goal, a minimax performance criterion is introduced that aims to minimize the risk of exceeding the limit at any enforcement point by minimizing the maximum noise load value occurring at any of the enforcement points [6]. Unlike in SNAP, third party risk and average delay are not considered as performance criteria in the present study. However, these metrics remain available as performance indicators that can be evaluated a posteriori. The effectiveness of the tool is demonstrated in a case study pertaining to the planning of the operational year 2005 at Amsterdam airport Schiphol.

2 Managing Noise Load Through Runway Allocation

2.1 Runway Combination Selection

In Figure 1 the runway layout at Schiphol airport is presented. Schiphol features six runways in total, including five main runways and one (viz., RWY 04-22) that is primarily used for smaller aircraft and domestic travel. During the day, outside of peak times, the airport often uses one runway for departures and one for arrivals. However, since Schiphol is a hub airport it also needs to accommodate traffic “waves”, i.e., peaks in arriving traffic followed by peaks in departing traffic [6]. During an arrival peak, typically two arrival runways are used. Similarly, during a departure peak two departure runways are operated. Occasionally, two departure and two arrival runways are used simultaneously. During the night always one runway is used for arriving traffic, and one runway for departing traffic.

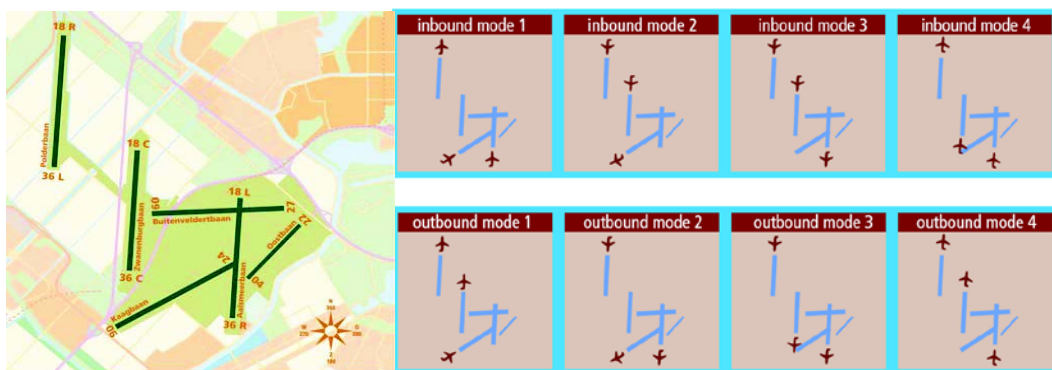


Figure 1 Runway layout (left) and example runway configurations (right) at Schiphol airport

Some of the main factors that influence the choice of the best possible runway combination for a particular situation are, peak period and time, visibility, Runway Visual Range (RVR), cloud base and wind limits. In particular the wind limits have a strong influence on which runway combination is most suitable for a particular situation in a particular period of the day. Landings and take-offs are typically conducted into the wind. However, operations on a runway are sometimes permitted with a slight tailwind. The maximum allowable tailwind is usually about 5 to 6 knots [8]. In addition to a tailwind limit, also a limit to the crosswind component is imposed to guarantee flight safety. The crosswind component is the component of the wind velocity vector that is perpendicular the runway centerline. At Schiphol airport, cross wind limits are imposed that depend on the visibility, cloud base and runway surface condition (dry or wet), which affects the braking action [9].

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As mentioned earlier, predictions of future runway allocations and associated noise load distributions are based on an average of past years meteorological data. Historical wind statistics can be conveniently summarized in the graphical form of a so-called wind rose [8] (see Figure 2). In essence, a wind rose arranges velocity, direction, and frequency of wind occurrences within a certain period of time. Circles on the template represent the wind speed, while the radial lines illustrate the angles or the wind blowing directions. Each cell bounded by two circle segments and two radial lines contains the percentage of time that the winds correspond to a given direction and velocity range. On the wind rose shown in Figure 2, a runway template (shaded rectangle) is placed, representing a one-directional runway. The location, dimensions and orientation of the rectangle are determined by the direction of operation and by the applicable cross and tail wind limits. All wind conditions within the rectangle are essentially covered by the considered runway. It is important to realize that for any given runway configuration to be valid under a particular wind condition, that wind condition (cell) should be contained within the “box” associated to each individual runway available in that configuration.

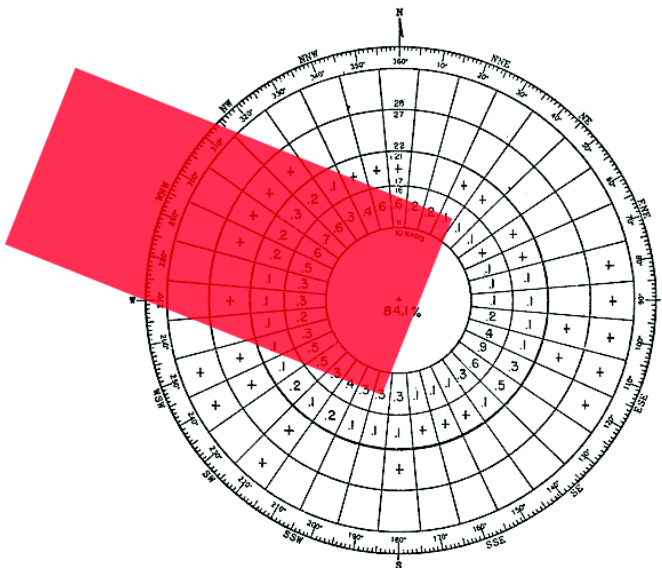


Figure 2 A wind rose and superimposed one-directional runway wind limit template

2.2 Runway Allocations

Runway allocation is the process of assigning a runway to each flight movement. Clearly, runway allocation is to a large extent implicitly determined by the runway combination selection process. Only for configurations that feature multiple runways for departure or landing operations, the runway allocation process also involves distribution of flights over the different runways available in the configuration. When a flight is assigned to a particular runway, the spatial allocation of the noise impact associated to that flight is to a large extent fixed as well. Indeed, the origin or destination of a flight, in combination with the selected runway, usually results in a particular

routing to or from the airport. It is exactly this property that makes runway allocation such an important steering mechanism with respect to noise management.

2.3 Noise Enforcement Points

To limit the noise disturbance for the population around Schiphol, the Dutch government has specified limits for yearly day-evening-night average sound level L_{den} in 35 enforcement point located in the vicinity of the airport (see Figure 3) [5]. A specific L_{den} limit value has been assigned to each individual enforcement point. The noise limit values for the enforcement points are listed in the table displayed in Figure 3. It needs to be noted that L_{den} is a cumulative measure of noise that expresses the total noise effect at a given location of all the aircraft movements taking place within an operational year. The metric L_{den} features weightings of the single event levels depending on the time of day or night at which they occur. In addition to the limits on yearly L_{den} at the 35 enforcement points, also yearly L_{night} (applicable to the night period, 23:00 – 07:00 hr. local time) limits have been imposed at 25 separate enforcement points close to the airport.

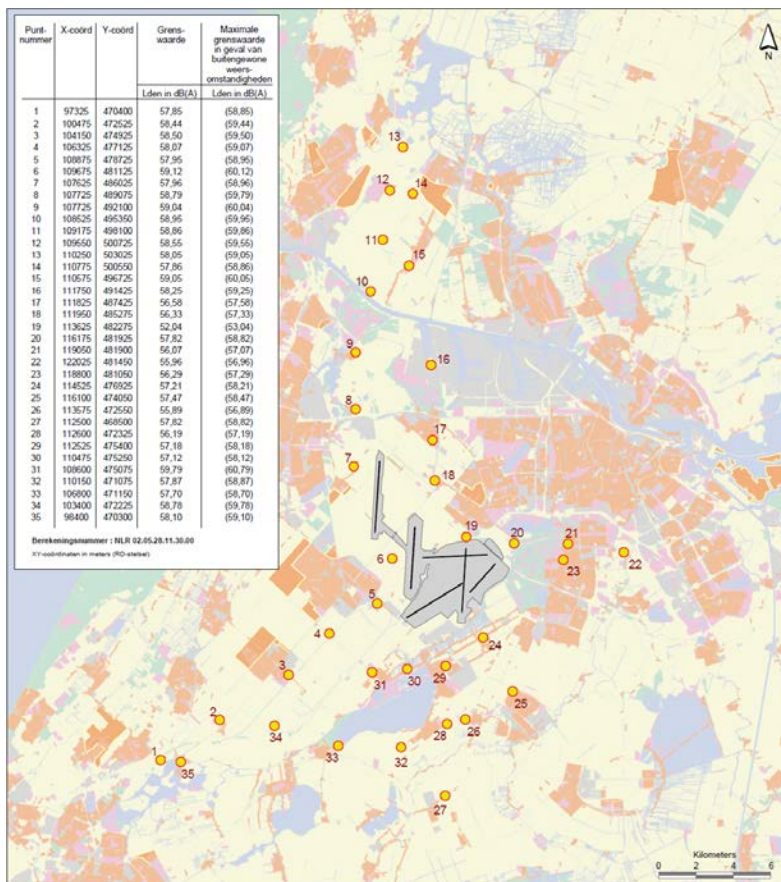


Figure 3 The 35 enforcement points (L_{den}) in the vicinity of Schiphol airport [6]

3 Minimax Formulation of the Runway Allocation Problem

3.1 Conceptual Model Description

In this section a concept description is given of a model that forms the basis for a tool that optimizes the runway allocation for the planned flight movements within an operational year, using a Linear Programming (LP) formulation [10]. The main inputs for the model are identified wind patterns and traffic patterns.

In a first step, a wind rose analysis is conducted as described in Section 2.1, using the weather history from the year 1951 until 2005 [7]. The outcome of this analysis is a list containing for each cell of the wind rose the historic occurrence percentage of the associated wind condition. Next, for each cell in the list it is determined which runway combinations are available, based on the prevailing cross and tail wind limitations. All cells that share the same list of available runway configurations are clustered in a “wind pattern”. For Schiphol airport only 19 unique wind patterns were identified [6].

In a next step, the traffic patterns and their associated noise load distributions are determined. Based on the flight schedule for the operational year (also taking into account projected charter operations) it is determined for each hour of the year how many arrivals and departures take place and by what aircraft type. With $365 \times 24 = 8,760$ hours in a year, this gives 8,760 traffic samples. To limit the scale of the optimization problem to be formulated, similar traffic samples are aggregated into “traffic patterns”. In this context “similar” is defined as, (i) the same number of departures, (ii) the same number of arrivals, and, (iii) same period of the day (Day, Evening, Night). Table 1 provides an example of a traffic pattern.

Table 1 An example of a traffic pattern

Pattern 33
Arrivals: 10
Departures: 7
Traffic sample occurrence: 3x
Arriving a/c: 12x B747, 14x B737, 4x A320
Departing a/c: 10x B737, 9x A320, 2x MD11
Period of the day: evening

When for example the 2005 schedule of Schiphol is considered, this approach aggregates the 8,760 yearly traffic samples into about 2,000 unique traffic patterns. One of the advantages of the selected form of aggregation is that it preserves the capability to (a posteriori) assess average runway delays using a queuing model, which for each runway requires as inputs, the number of traffic movements per hour and the traffic mix [7]. Also note that specific information regarding the time of day is needed to enable Lden noise load calculations at the enforcement points.

In the model formulation, each traffic pattern is combined with each wind pattern, resulting in a list of unique combined “situations” (see figure 4). This list represents every situation that can occur during a year, combined with the probability that it occurs. In the optimization formulation, an allocation decision for each of these unique situations has to be made. Here, a decision boils down to the choice of one of the available runway configurations, and in the case of multiple arrival/departure runways also the percentages of distribution over the two runways. For each unique combined situation it now has to be checked which of the available runway configurations have sufficient capacity to handle the traffic. Runway configurations that are available but supply insufficient capacity are discarded. After this, a check is made whether there are some situations with no available runway configurations at all. If so, these unique situations are removed from the model to prevent that the LP problem formulation becomes infeasible.

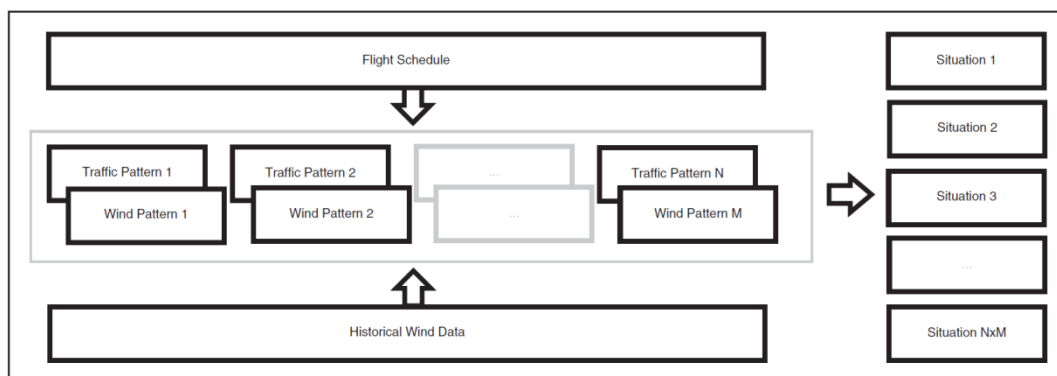


Figure 4 Schematic view of the modeling approach

To select the optimal runway configuration, the LP problem formulation needs to contain information on the consequence of each allocation choice. Therefore the noise cost for the usage of each available runway configuration is determined for each unique combined situation. Note that the noise contribution values have to be determined separately for each enforcement point, since the noise load accumulation in each enforcement point needs to be recorded. In this study the methodology for conducting the noise load calculations has been principally based on the approach taken in SNAP [7]. Similar to SNAP, the allocation tool proposed herein relies on the

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well-known Integrated Noise Model (INM) for noise impact assessment[11]. INM has been the Federal Aviation Administration’s standard tool for airport noise assessments for decades and is probably the most widely used tool for community noise assessment throughout the world [1]. In this study, INM is used to calculate the outdoor Sound Exposure Level (SEL) resulting from each individual flight movement at each specified observer location.

The spatial distribution of noise caused by a departing or approaching aircraft depends not only on the assigned runway, but also on the route leading to the runway (when considering an arrival) or the route leading from the runway (when considering a departure). In total, 104 routes have been defined for Schiphol airport [6]. To calculate the noise of a flight movement, a flight path is synthesized by combining one of the existing departure/arrival routes, with a standard INM profile (vertical flight path) for the considered aircraft type. It needs to be noted that for the purpose of noise calculations, each aircraft type in the annual flight schedule is substituted by one of 15 standard types, representing various noise categories. The calculated noise levels, stored in a data file, are thus unique for a certain aircraft type, a certain flight procedure (arrival or departure), and a given runway in conjunction with one of the associated tracks. The noise cost for the usage of each available runway configuration can now be determined upfront for each unique combined situation through aggregation of individual flight movement results. In the case that a runway configuration features multiple departure and/or arrival runways, the noise cost for the usage of each individual runway needs to be assessed. More specifically, the noise cost for each possible mode of a configuration needs to be determined. In this context, a mode is a combination of a specific departure and a specific arrival runway of a certain configuration. Table 2 gives the possible modes of each of the four configuration types considered [6].

Table 2 The possible modes for each configuration type (A = Arrival; D = Departure)

Configuration Type	Available Modes (k)
1A + 1D	(1) single departure runway combined with arrival runway
2A + 1D	(1) arrival runway 1 combined with the single departure runway
	(2) arrival runway 2 combined with the single departure runway
1A+ 2D	(1) departure runway 1 combined with the single arrival runway
	(2) departure runway 2 combined with the single arrival runway
2A+2D	(1) departure runway 1 combined with arrival runway 1
	(2) departure runway 1 combined with arrival runway 2
	(3) departure runway 2 combined with arrival runway 1
	(4) departure runway 2 combined with arrival runway 2

When determining the noise cost of an allocation choice, it is assumed that each departure/arrival route connected to a specific runway is used equally often on average. Therefore, the noise cost is the average of the noise cost calculated for each departure/arrival track separately.

In the present model runway delay is neither an optimization criterion nor an operational constraint. Instead, a constraint on runway throughput capacity has been introduced. Evidently, the average delay per flight movement that will result from the planning model directly depends on the throughput capacity level that has been specified for each runway. The delay calculations can be performed once the allocation optimization process has been completed, thus allowing assessing the delay consequences of the allocation choices that have been made. The model calculates the arrival and departure delay for all the allocated traffic, and subsequently takes the weighted average. The delay calculations are based on a steady state M/G queuing model as presented in [7]. It is recalled that in [7], also an analysis is provided that clearly shows the effects of trading-off average delay per flight movement against noise impact.

3.2 Performance Criteria

As outlined previously, the noise regulations applicable to Schiphol airport stipulate noise limits for yearly day-evening-night average sound level L_{den} at 35 enforcement points. The L_{den} value at a given location for a certain period can be calculated using the following equation [12]:

$$L_{den} = 10 \cdot \log \left[\sum_{n=1}^{n_{flights}} w_n 10^{\frac{SEL_n}{10}} \right] - 10 \cdot \log \left[\frac{T_{den}}{\tau} \right], \quad (1)$$

where $n_{flights}$ is the number of flight movements within the considered period T_{den} , SEL_n is the Sound Exposure Level of the n^{th} flight, w_n is an adjustment factor for the n^{th} event (enabling to penalize movements occurring during the evening or night), and τ is a reference period of one second.

The fact that the L_{den} metric is logarithmic in nature hampers its direct use in a linear optimization formulation. For this reason, rather than to consider the SEL value of a flight movement, its associated acoustic energy level is considered:

$$\frac{E_n}{E_0} = 10^{\frac{SEL_n}{10}} \quad (2)$$

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where E_0 is a reference sound exposure. Substitution of Eq.(2) into Eq.(1) yields:

$$L_{den} = 10 \cdot \log \left[\sum_{n=1}^{n_{flights}} w_n \frac{E_n}{E_0} \right] - 10 \cdot \log \left[\frac{T_{den}}{\tau} \right] \quad (3)$$

Instead of using L_{den} , cumulative acoustic energy

$$\left[\sum_{n=1}^{n_{flights}} w_n \frac{E_n}{E_0} \right] \quad (4)$$

is now addressed in the optimization formulation.

In this study two distinct energy-based performance criteria have been considered. The first criterion aims to minimize the average energy at an enforcement point through the minimization of the summated energies of the noise at all the enforcement points. This principle is illustrated in Figure 5a. The second objective function is a minimax criterion that aims to minimize the maximum noise load value (in terms of cumulative energy) occurring at any of the enforcement points. In practical terms the minimax criterion has been implemented as the minimization of a limit value L , where L is always larger or equal than the noise load at any individual enforcement point. The minimax principle is illustrated in Figure 5b.

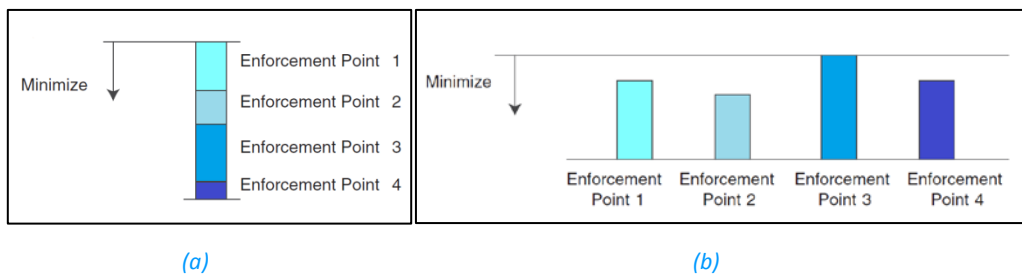


Figure 5 Illustration of the two energy-based performance criteria

3.3 Mathematical Model

In this section, the LP model for the noise allocation problem is defined.

3.3.1 Decision variables

The variables that are used to define the noise allocation problem are provided in Table 3.

Table 3 Overview of decision variables

variable	bounds	description
real $x_{i,j}$	$0 \leq x_{i,j} \leq 1$	fraction of instances that configuration j is selected in situation i
real $w_{i,j,k}$	$0 \leq w_{i,j,k} \leq 1$	fraction of the traffic assigned to mode k of configuration j for situation i
real L	$0 \leq L \leq 1$	minimax criterion , expressed as a fraction of the imposed cumulative energy limit

By defining $x_{i,j}$ as a real-valued variable, rather than as a binary-valued variable, it may occur that multiple configurations are assigned in a given situation i . Suppose that situation i occurs ten times in an operational year. A value $x_{i,j} = 0.7$ then implies that in seven out of the ten instances that situation i occurs, configuration j is selected. When desired, a decision variable $x_{i,j}$ can be defined as binary-valued rather than real-valued. In this case, a single unique configuration is assigned to a situation i . It needs to be noted though that the introduction of binary variables significantly increases the overall computational burden. In the case study presented in Chapter 4, all decision variables are assumed to be real-valued.

3.3.2 Cost coefficients

The coefficients entered in the performance criteria are stated in Table 4.

Table 4 Overview of the cost coefficients

coefficient	description
$C_{i,j,k,l}$	noise cost at enforcement point l for mode k of configuration j in situation i
p_i	the occurrence percentage of situation i
q_i	the DEN (Day-Evening-Night) multiplier for situation i

3.3.3 Constraints

The constraints applicable to the noise allocation problem are:

1) Configuration choice:

$$\sum_{j=1}^{j=s_i} x_{i,j} = 1, \quad \forall i = 1, \dots, r \quad , \quad (5)$$

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where r is the total number of situations considered, and s_i the maximum number of configurations available for situation i . The configuration choice constraint ensures that in each instance in which a particular situation occurs always a runway configuration is assigned.

2) Runway distribution:

$$x_{i,j} = \sum_{k=1}^{k=t_j} w_{i,j,k} \quad , \quad \forall i = 1, \dots, r, \quad \forall j = 1, \dots, s_i \quad (6)$$

where t_j is the maximum number of modes available for runway configuration j . The runway distribution constraint ensures that the traffic fractions summated over all modes k of a configuration j in situation i do not exceed the total traffic assigned to configuration j in situation i .

3) Runway capacity:

Applicable for runway configurations of the type 2A + 1D and 1A + 2D (see Table 2):

$$w_{i,j,k} A_i \leq 0.9 C_A x_{i,j} \quad , \quad \forall i = 1, \dots, r, \quad k = 1, 2 \quad (7)$$

$$w_{i,j,k} D_i \leq 0.9 C_D x_{i,j} \quad , \quad \forall i = 1, \dots, r, \quad k = 1, 2 \quad (8)$$

Applicable for runway configurations of the type 2A + 2D (see Table 2):

$$(w_{i,j,1} + w_{i,j,3}) A_i \leq 0.9 C_A x_{i,j} \quad , \quad \forall i = 1, \dots, r \quad (9)$$

$$(w_{i,j,2} + w_{i,j,4}) A_i \leq 0.9 C_A x_{i,j} \quad , \quad \forall i = 1, \dots, r \quad (10)$$

$$(w_{i,j,1} + w_{i,j,2}) D_i \leq 0.9 C_D x_{i,j} \quad , \quad \forall i = 1, \dots, r \quad (11)$$

$$(w_{i,j,3} + w_{i,j,4}) D_i \leq 0.9 C_D x_{i,j} \quad , \quad \forall i = 1, \dots, r \quad (12)$$

where A_i and D_i are, respectively, the amount of arriving and departing aircraft in situation i , C_A and C_D are, respectively, the specified arrival and departure throughput capacity for a single runway. A 90% load factor has been defined to reduce the theoretical capacity limit into a practical capacity limit. The runway capacity constraints are applied only to runway configurations that feature multiple departure and/or arrival runways. The runway constraints preclude traffic overloading on a given runway, helping to achieve acceptable average delay per flight movement. Note that constraints (9) and (11) relate to runway 1, whilst constraints (10) and (12) relate to runway 2.

and (12) are associated to runway 2 of the 2A + 2D runway configuration. It is recalled that no constraints are needed for the overall set of configurations, since configurations with insufficient capacity for a given situation were already removed upfront from the list of available configurations.

4) Noise load at enforcement points

Applicable in conjunction with the minimum average energy criterion:

$$\sum_{i=1}^{i=r} p_i q_i \sum_{j=1}^{j=s_i} \sum_{k=1}^{k=t_j} c_{i,j,k,l} w_{i,j,k} \leq Lim_l, \quad \forall l = 1, \dots, v \quad (13)$$

where v is the total number of enforcement points, and Lim_l is the imposed noise load limit at enforcement point l . The noise load constraints evaluate the cumulative noise loads in the enforcement points and force the resulting values to be smaller than the imposed limits.

Applicable in conjunction with the minimax criterion:

$$\sum_{i=1}^{i=r} p_i q_i \sum_{j=1}^{j=s_i} \sum_{k=1}^{k=t_j} c_{i,j,k,l} w_{i,j,k} \leq L \square Lim_l, \quad \forall l = 1, \dots, v \quad (14)$$

The noise constraint (14) is similar in behaviour to constraint (13), except that the permissible value at the enforcement point is reduced by a factor L , a value we seek to minimize in the minimax criterion.

3.3.4 Objective functions

When using the minimum average cumulative energy criterion:

$$\min Z = \sum_{i=1}^{i=r} p_i q_i \sum_{j=1}^{j=s_i} \sum_{k=1}^{k=t_j} \bar{c}_{i,j,k} w_{i,j,k} \quad (15)$$

where:

$$\bar{c}_{i,j,k} = \sum_{l=1}^{l=v} c_{i,j,k,l}, \quad \forall i = 1, \dots, r, \quad \forall j = 1, \dots, s_i, \quad \forall k = 1, \dots, t_j \quad (16)$$

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is the noise cost for mode k of configuration j in situation i aggregated over all enforcement points.

When using the minimax criterion:

$$\min Z = L \quad (17)$$

is the objective function.

3.3.5 Solver and user interface

To handle the noise allocation problem outlined above, Linear Programming (LP), one of the most commonly employed operations research methods for large-scale problems, has been successfully used [10]. More specifically, a commercial LP package called CPLEX has been employed [13]. The noise allocation planning tool has been implemented in Java. The Java application allows to call CPLEX directly [6]. Figure 6 shows a typical screen shot of the Graphic User Interface (GUI) of the runway allocation planning tool that has been developed. Calculations have been performed using a standard PC featuring a Pentium 4 3.00GHz CPU and 2GB of RAM.

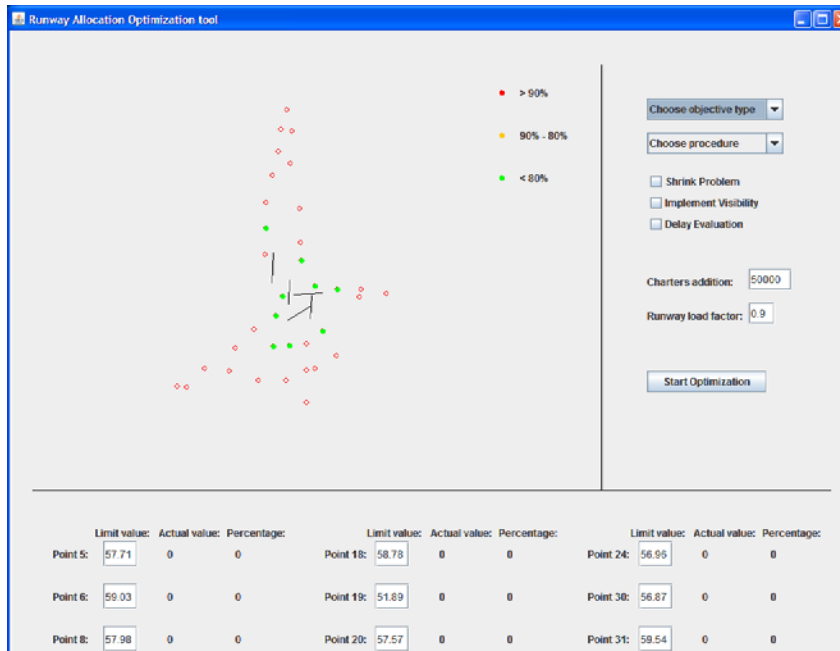


Figure 6 A sample screen shot of the Java/CPLEX based runway allocation optimization tool

4 A Case Study for Schiphol Airport

4.1 Assumptions

To illustrate the developed planning concept, a case study is presented pertaining to the operational year 2005. Processing of the 2005 flight schedule resulted in about 2000 unique traffic patterns. Similarly, processing of the historic wind data produced 19 unique wind patterns. The historic wind data set that has been used to predict the wind conditions for 2005, covers the measurement period from 1951 to 2005 (over 460,000 hours). Combination of the identified wind and traffic patterns leads to about 38,000 unique situations, to each of which a runway configuration and mode assignment needs to be made. In the model 30 different runway configurations have been considered for Schiphol airport, including 13 1A+1D configurations, 8 2A+1D configurations, 8 1A+2D configurations and 1 2A+2D configuration. As an illustration, Table 5 lists the available configurations of the type 2A+1D.

Table 5 Double-arrival single-departure runway configurations at Schiphol airport

Configuration	Arrival 1	Arrival 2	Departure
14	06	36R	36L
15	18R	18C	24
16	18R	18C	18L
17	27	36C	36L
18	27	18R	24
19	18R	22	24
20	18R	22	18L
21	06	09	09

Combined with the fact that 35 enforcement points need to be considered, it is readily clear that a very large scale optimization problem results. To keep the computational burden within reasonable limits, the number of enforcement points taken into account in the present concept development study was reduced from 35 to 9. Evidently, these 9 enforcement points were selected such that no runway could be used unrestricted without contributing to the overall noise load development. This led to the choice of the 9 enforcement points displayed in Figure 7. It is readily clear that the fact that only 9 enforcement points out of the 35 were imposed compromises to some extent the validity of the outcome of the model. Since the noise load accumulation in the remaining 26 enforcement points is not accounted for, there is relatively more freedom in the allocation process which may potentially lead to different allocation choices. Of course, it is possible to a posteriori evaluate the actual noise load accumulated in

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those 26 remaining enforcement points, enabling to detect possible anomalies. Fortunately, no such anomalies were encountered in the present study. It is important to note that there is no fundamental problem in scaling-up the optimization problem to include all 35 enforcement points.

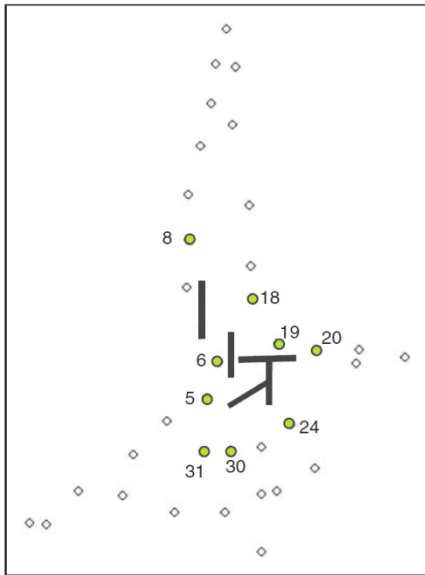


Figure 7 The nine enforcement points incorporated in the optimization model

In addition to the reduced number of enforcement point taken into account, several other limitations of the model need to be mentioned. First of all, the model entirely ignores the 25 enforcement points used during the night time hours. Also, reduced visibility conditions, which influence the availability of runway configurations, have not been taken into account. Another limitation relates to the flight schedule. The original schedule does not include charter operations and to allow for this all charter flights actually recorded for 2005 have been artificially added to the schedule and distributed evenly over the year. In reality this is probably not the case. It needs to be noted though that, in principle, most of the above limitations can and will be removed in follow-on studies.

4.2 Optimization Results

In Figure 8 the optimization results are displayed for both the minimum average energy criterion and the minimax criterion for the operational year 2005.

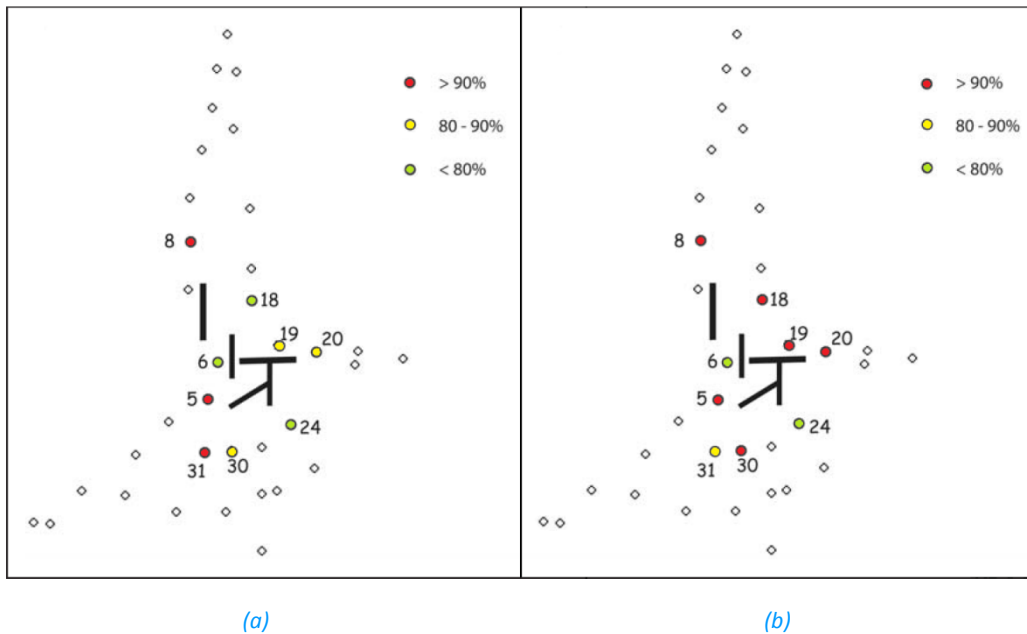


Figure 8 Optimization results for the planning of the operational year 2005

Tables 6 and 7 summarize the numerical results for, respectively, the minimum average energy criterion and the minimax criterion. As can be seen from Figure 8a and Table 6, in the minimum average energy solution, the traffic is concentrated in the area south-west from the “Kaagbaan” (runway 06-24), and to the north of the “Polderbaan” (18R-36L). For the Polderbaan this is probably caused by the fact that no enforcement points are located near the approach/departure path of this runway, resulting in only a moderate contribution of flight movements to the objective function. For the Kaagbaan the reason is probably that during certain weather situations (i.e. wind from the west or south-west), no other runways are available. It can be seen that relatively few flights are assigned to the “Buitenveldertbaan” (09-27). This was to be expected due to the fact that enforcement points are placed in the direct vicinity of the runway, thus contributing significantly to the objective function. The observed behaviour closely resembles reality, where the Polderbaan and Kaagbaan are the preferential runways, whilst the Buitenveldertbaan is avoided as much as possible.

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Table 6 Optimal planning results for the minimum average energy criterion

<i>Location</i>	<i>L_{den} Limit Value (dB)</i>	<i>L_{den} Actual Value (dB)</i>	<i>Percentage (%)</i>
Point 5	57.71	57.71	100
Point 6	59.03	55.91	48.8
Point 8	57.98	57.98	100
Point 18	58.78	54.79	39.9
Point 19	51.89	51.40	89.3
Point 20	57.57	50.15	18.1
Point 24	56.96	54.37	55.1
Point 30	56.87	52.82	39.4
Point 31	59.54	59.31	94.8

Table 7 Optimal planning results for the minimax criterion

<i>Location</i>	<i>L_{den} Limit Value (dB)</i>	<i>L_{den} Actual Value (dB)</i>	<i>Percentage (%)</i>
Point 5	57.71	57.33	91.5
Point 6	59.03	57.22	65.9
Point 8	57.98	57.60	91.5
Point 18	58.78	58.40	91.5
Point 19	51.89	51.51	91.5
Point 20	57.57	57.19	91.5
Point 24	56.96	54.70	59.4
Point 30	56.87	56.49	91.5
Point 31	59.54	58.98	87.8

From Table 7 and Figure 8b it can be seen that in the minimax solution the traffic is more spread out over the various runways to ensure a balanced noise load development. The enforcement points are kept below their limit values as much as possible. To realize this, runways that are not noise preferential also have to be used. This actually leads to a higher overall cumulative noise value (higher average energy value at the enforcement points). This is demonstrated in Table 8, which compares the characteristic values of the two results. Note that in this comparison the cumulative energy levels obtained for the two criteria have been expressed as a ratio relative to the total noise energy value that was actually recorded at Schiphol airport in 2005 [6].

The results in Table 8 clearly reveal that whilst the use of the minimum average energy criterion leads to a cumulative energy level that is significantly lower than the actually realized result (about 15%), the cumulative energy level is considerably higher than the actually realized result

when the minimax planning approach is used (some 10%). This appears to be realistic. Since Schiphol aims to realize a balanced development of noise load by spreading the traffic, it relies on an approach similar in nature to the minimax approach. However, the actual noise spreading will never be as balanced as in the minimax approach taken here, simply because the minimax optimization approach does not rely on (i.e., is not constrained by the use of) a preference list, but rather always directly allocates the optimal configurations.

Table 8 Comparison of the optimal planning results for the two performance criteria

Objective	Total Noise Energy Ratio	Av. Departure Delay (min.)	Av. Arrival Delay (min.)	Solution Time (min.)
Av. Energy	0.846	0.96	2.30	17
Minimax	1.105	0.99	2.46	102

Table 8 also includes results pertaining to average delay per flight movement. It can be seen from the table, that the average delay values do not differ very much for both cases. The average delay values are modest, corresponding to the applied runway acceptance rate which has been set at 90% of the theoretical capacity limit.

In table 8, a marked difference can be observed between the two cases with respect to the required computational effort. Indeed, the calculation time needed to establish an optimal solution is significantly higher for the minimax formulation.

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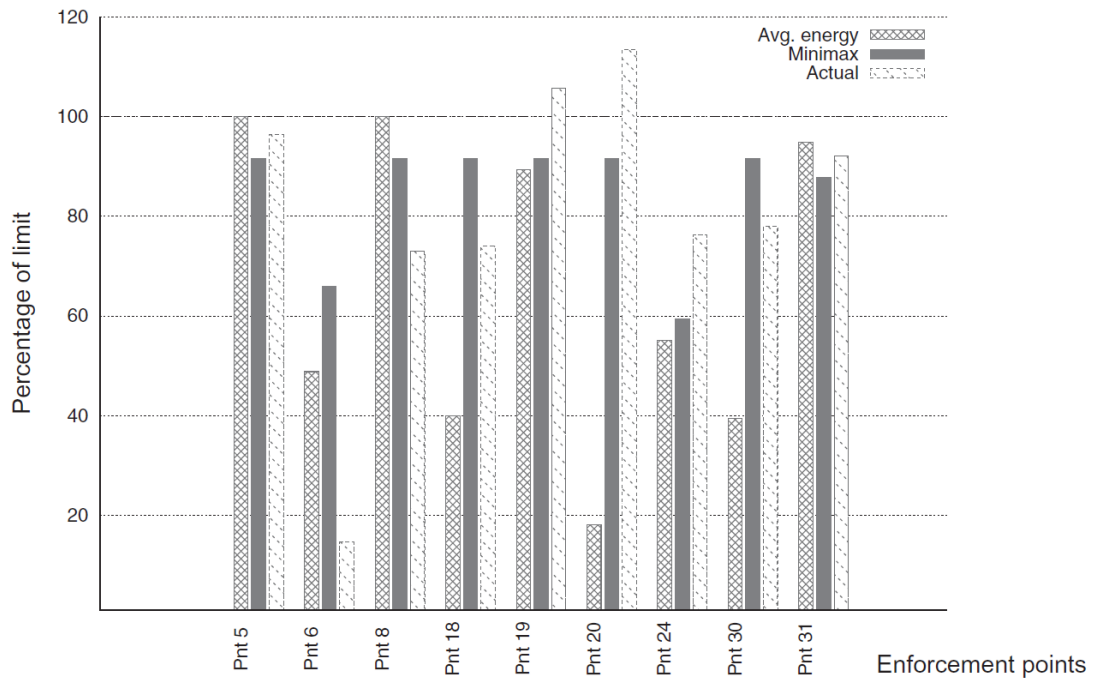


Figure 9 Comparison of results obtained for the two criteria, minimum average energy (Objective 1), and minimax (Objective 2) with the actual realized noise loads at Schiphol [6]

Finally, in Figure 9 a comparison is given of the noise loads at the enforcement points obtained for the two optimization criteria and the actual noise load recorded at Schiphol airport in the operational year 2005.

Although the results obtained in the minimax optimization are in a much closer agreement with the actually realized noise load distribution in comparison to the minimum average energy solution, the differences are still significant. As indicated earlier, this is likely in part due to the fact that in the minimax approach a variety of simplifying assumptions has been made, most notably the use of a limited number of enforcement points. Unlike for the actual result, the minimax solution provides a margin (in terms of energy) with respect to the noise limit of nearly 10% at 6 of the 9 enforcement points. The margin at the 3 remaining points is even larger.

5 Conclusions

The goal of this study was to develop a runway allocation optimization tool that seeks to maximize the permissible number of yearly flight movements within a specified noise budget. In this context a noise budget is to be understood as a set of regulations specifying that outside a certain surface area of land around the airport, community noise levels should not exceed certain specified annual limits. Although the runway allocation tool has been developed with a particular example airport in mind, viz., Schiphol airport, the model underlying the tool is sufficiently generic to permit application to other airports that are subject to similar noise budget restrictions. To enable an efficient use of the available noise budget, a minimax optimization model has been formulated that aims to reduce the risk of exceeding the noise limit at any point along the boundary of the protected area. In the case of Schiphol airport, a noise budget is imposed at a discrete number of specified points, called enforcement points, located on the boundary contour of the protected area.

Due to the large-scale nature of the runway allocation planning problem, combined with limited computational resources, not all of the enforcement points were included in the optimization formulation presented in this study. Nevertheless, the number and distribution of the enforcement that were selected proved to be adequate to produce meaningful results. Indeed, the minimax optimization analysis resulted in a rather efficient noise distribution, reducing the maximum noise energy at any of the enforcement points included in the optimization formulation to a level some 10% below the permissible value, without overloading the enforcement points that were not included at the optimization analysis. Future research will focus on the development of a modeling approach that allows for more enforcement points to be taken into account at a reasonable computational cost, and that will include capacity constraints due to poor visibility conditions.

It needs to be noted that as of November 1, 2010, a new set of experimental noise regulations has been put into place at Schiphol airport, for the duration of a period of two years. The primary goal of the new set of regulations is to minimize the expected number of annoyed people, the same objective as used in the original SNAP tool that formed the basis for the present development. However, the existing regulations pertaining to the noise budget imposed at the enforcement points remains in principle intact. For this reason, the continued development of the minimax runway allocation optimization remains of considerable interest for Schiphol airport. Due to its flexible, generic nature the tool can be applied to other airports with similar annual noise budget restrictions as well.

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