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Flexible Arrival & Departure Runway Allocation Using Mixed-Integer Linear Programming

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This study focuses on research in flexible arrival and departure allocation. A model has been developed by which flights can be allocated to runways, while optimizing for fuel and noise. Currently, the runway usage at airports with multiple runways, such as Amsterdam Airport Schiphol (AAS), is the result of a trade-off between minimizing noise exposure to the environment and maximizing capacity. It does not take into account fuel burn and the ensued emissions for the current and near future demand in flights. This study tries to address this issue by developed a model using Mixed-Integer Linear Programming (MILP) which can allow flights to be allocated to runways, while optimizing for fuel and noise and capacity is taken into account indirectly by minimizing the extra fuel burn cost of delay.

In 1973 the Federal Aviation Administration (FAA) established the following definition on runway capacity, being "the maximum number of aircraft operations that an airfield can accommodate during an hour when there is a continuous demand for service"[1]. This runway capacity is dependent on several factors, including runway system layout, demand characteristics, operational constraints and local conditions all have their effect on the total performance of an airport's capacity[2] and more efficient utilization of available infrastructure at airports could address the growing demand for capacity[3]. Complex airport, such as Amsterdam Airport Schiphol (AMS), may benefit from optimizing their runway performance. Currently, the runway usage is described by a preference list established by several stakeholders and makes an important trade-off between minimizing noise exposure to the environment and maximizing capacity[4]. However, the existing model does not take into account fuel burn and the ensued emissions for the current and near future demand in flights. The research focuses on the development of an optimization model to include these factors with respect to runway allocation.

I. Runway use at Amsterdam Airport Schiphol

AAS has a complex runway system with a total of six runways. The layout is depicted in Figure 1[4]. As indicated by the red crosses, the Polderbaan and the Aalsmeerbaan are only used to and from one direction due to respectively the towns of Aalsmeer and Hoofddorp being at the other ends. The Oostbaan is primarily used for small general aviation and for landing aircraft during strong south westerly wind conditions.

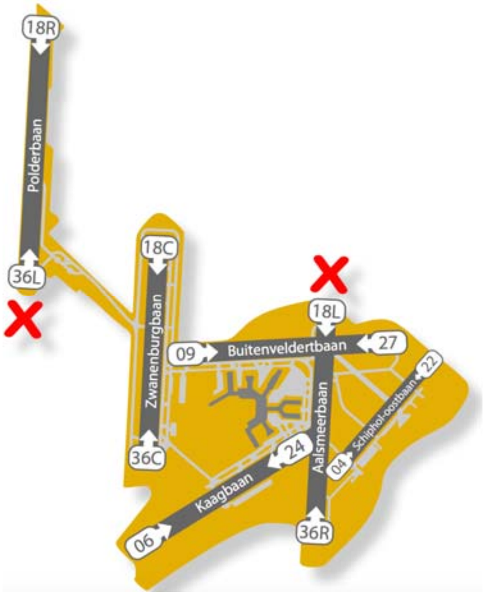

Figure 1: Runways at Amsterdam Airport Schiphol[1]

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In order to reduce the environmental impact, such as noise exposure and emissions, while maintaining safety and efficient handling of the aircraft flow, the preference list of using these runways, shown in Table 1. This list is primarily dependent on several factors, which are: visibility, wind conditions, cloud base, precipitation, Uniform Daylight Period (UDP), peak periods, runway availability and anticipation of peak periods.

Visibility	Preference	L1	L2	S1	S2
Good	1	06	(36R)	36L	(36C)
Visibility $>$ 5,000 m	2	18R	(18C)	24	(18L)
Cloud base $>$ 1,000 ft	3	06	(36R)	09	(36L)
Within UDP	4	27	(18R)	24	(18L)
Good or marginal	5a	36R	(36C)	36L	(36C)
Visibility $>$ 1,500 m	5b	18R	(18C)	18L	(18C)
Cloud base $>$ 300 ft	6a	36R	(36C)	36L	(09)
	6b	18R	(18C)	18L	(24)

Table 1: Runway preference list at AAS during daytime (06:00 - 23.00)

Schiphol airport is subject to inbound and outbound peak hours of which there are approximately six every day. If these peaks follow each other in a short time span, there is possible overlap on runway assignment (due to congestion). In order to handle the traffic in such occasions, two arrival and departure runways are used simultaneously. This is depicted in Figure 2. Adhering to the first preference, the Aalsmeerbaan (landing 36R) and Zwanenburgbaan (start 36C), are respectively used as additional runways. If the total traffic volume and its distribution over a period are at a low level, it may suffice to use only one departure and one arrival runway. For the first preference, the Kaagbaan (06) and Polderbaan (36L) are then in use. The procedures for runway track preference with multiple departure and arrival runways are not explicitly taking into account for this research.

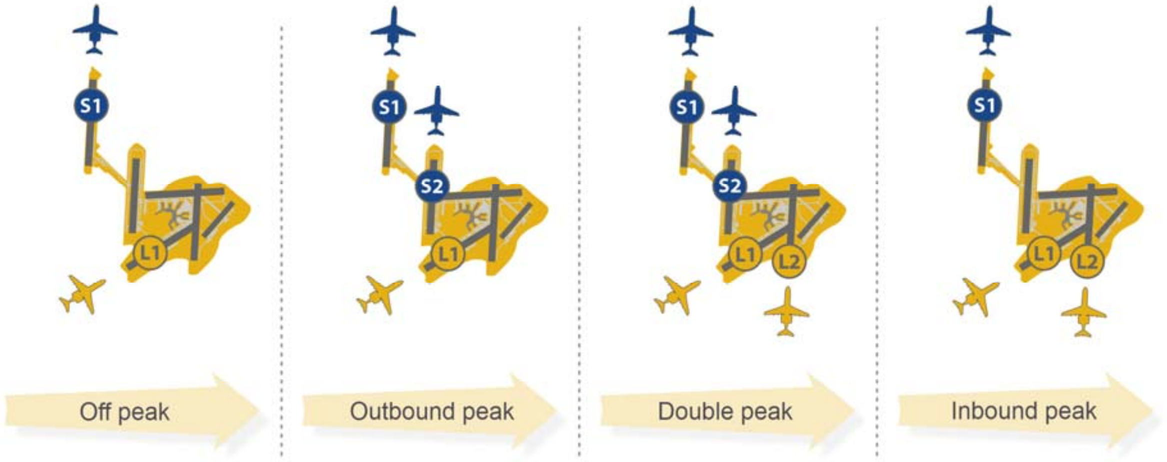


Figure 2: Runway use at Amsterdam Airport Schiphol[1]

For air traffic at Schiphol Airport strict regulations are in place. The discussed preference list from Table 1 has been established with taking into account minimizing environmental impact. Noise plays a key factor. In Table 2 the regulations for noise hindrance are observed. The criteria focus on the amount of aircraft movements as well as the noise hindrance to the environment. The average noise load during a 24 hour period from 00.00h to 24.00h is described using the day evening nigh weighed noise metric, L_{den}. The average noise load during a night period from 23.00h to 07.00h is described by L_{night}. Both parameters are used to indicate the noise hindrance measured from an observer's location during a one year period. For calculations of Lden the movements are multiplied by a given penalty value. By taking the summation of the noise load of individual observer points, with corresponding aircraft movements, results in the average noise load.

Aspect	Agreement
Air traffic movements criteria	Until 2020 max. 510,000 aircraft movements annually, of which max 32,000 between 23.00h and 07.00h
Equivalence criteria[2]	The use of AAS needs to meet criteria for equal protection of the environment: - max. 12,800 houses with noise hindrance of 58 dB(A) L_{den} or more - max. 180,000 severe noise hindrance of 48 dB(A) L_{den} or more - max. 11,100 houses with noise hindrance of 48 dB(A) L_{night} or more - max 49,500 severe sleep disturbances with noise hindrance of 40 dB(A) L_{night} or more

Table 2: Noise Regulations at AAS[4]

An important novel element of noise restrictions on AAS is the “Maximale Hoeveelheid Geluid (MHG, maximum amount of noise). The MHG for 2016 is calculated to be 60.45 dB(A) as annual average for full day operations. It is a maximum allowable cumulative measure for noise produced within the boundaries of equivalence criteria. Together with the equivalence criteria and the preference list for runway allocation, the total noise hindrance on the environment is regulated.

II. Runway Allocation Model

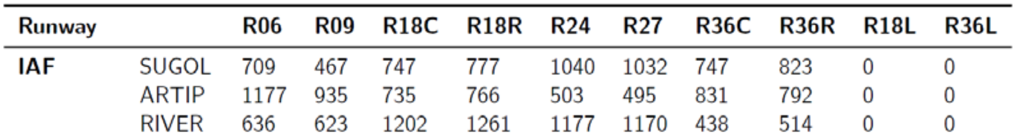
The runway allocation model developed for this study is able to assign aircraft to runways based upon an optimization trade-off between fuel usage and noise exposure to the environment. In doing so, a multitude of scenarios may be simulated using the model. Different allocation schemes can be tested and the possibilities of potential gains in fuel and noise reduction are researched. Emission outcomes, since taken linear to fuel, are equally researched. The model has been developed[5] generically so that scaling up of the problem size is possible. Other airports, a larger set of aircraft and aircraft types, different arrival and departure operations can all be added to the model due to the generic characteristics. This is favorable for future academic and industry research in ultimately finding an efficient optimized trade-off between fuel use and noise exposure and possible expansion towards other fields of study. This section describes other requirements and important assumptions made.

A. Schedule

The runway allocation model works with an input feed of a flight schedule, which consists of real flight data of arriving and departing aircraft. Several important elements are extracted from this flight schedule:

- Actual Landing Time (ALDT) or Actual Take-Off Time (ATOT)
- Flight ID
- Aircraft MTOW category
- IAF for arrivals, SECTOR for departures

For this research the arrival time at the Initial Approach Fix (IAF) is needed for arriving aircraft. Accordingly, the Actual Landing Time is adapted to find the time at IAF using a Time to Runway matrix, shown in Table 3, which indicates what the minimal flying time is for an aircraft from each IAF to each runway. These times are assumed to be aircraft type independent.



Runway		R06	R09	R18C	R18R	R24	R27	R36C	R36R	R18L	R36L
IAF	SUGOL	709	467	747	777	1040	1032	747	823	0	0
	ARTIP	1177	935	735	766	503	495	831	792	0	0
	RIVER	636	623	1202	1261	1177	1170	438	514	0	0

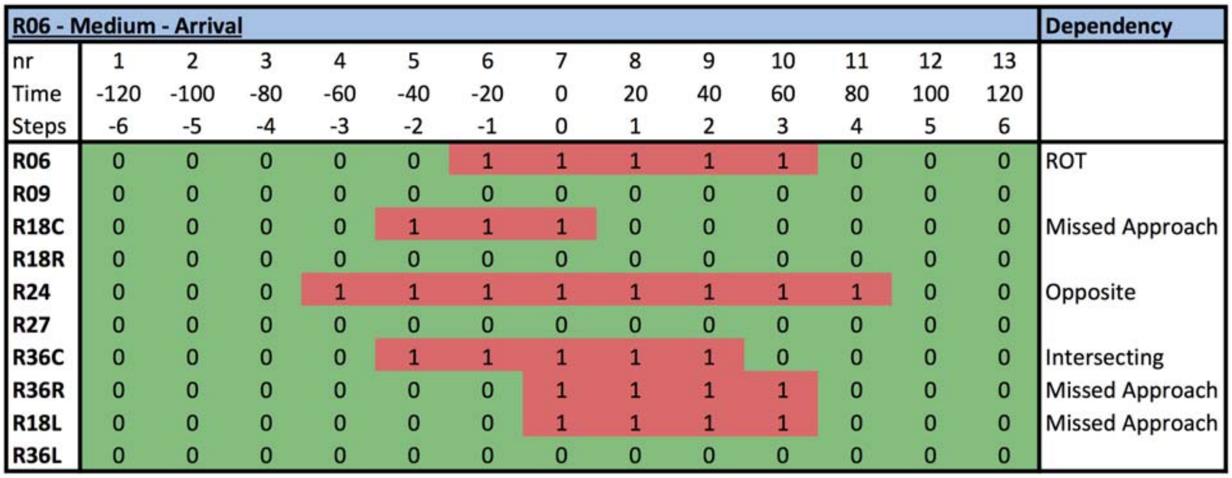
Table 3: IAF to runway times in seconds

B. Runway dependencies

Runway layout is an important factor in determining capacity. Runway dependencies are the results of this layout, since correlation may exists between runways. It is possible that aircraft are constrained in their operations due to these factors. Multiple dependencies can exist, depending on the runway layout. Based on previous work five different categories of dependencies are identified:

- Converging and diverging runways
- Intersecting runways
- Mixed mode
- Parallel runways
- Ground restrictions

Two capture these dependencies, the model uses a set of matrices that indicate per operation and weight class type on each runway, which other runway will be blocked at a time difference of Δt . An example of a dependency matrix form AMS is shown in Figure 3. It can be seen that switching from runway end 06 to the opposite runway end 24, means a time penalty of 160 seconds is assumed. A current limitation is that the weight class of conflicting aircraft is taken into account, as this significantly increases the amount of dependencies in the model.



R06 - Medium - Arrival														Dependency
nr	1	2	3	4	5	6	7	8	9	10	11	12	13	
Time	-120	-100	-80	-60	-40	-20	0	20	40	60	80	100	120	
Steps	-6	-5	-4	-3	-2	-1	0	1	2	3	4	5	6	
R06	0	0	0	0	0	1	1	1	1	1	0	0	0	ROT
R09	0	0	0	0	0	0	0	0	0	0	0	0	0	
R18C	0	0	0	0	1	1	1	0	0	0	0	0	0	Missed Approach
R18R	0	0	0	0	0	0	0	0	0	0	0	0	0	
R24	0	0	0	1	1	1	1	1	1	1	1	0	0	Opposite
R27	0	0	0	0	0	0	0	0	0	0	0	0	0	
R36C	0	0	0	0	1	1	1	1	1	0	0	0	0	Intersecting
R36R	0	0	0	0	0	0	1	1	1	1	0	0	0	Missed Approach
R18L	0	0	0	0	0	0	1	1	1	1	0	0	0	Missed Approach
R36L	0	0	0	0	0	0	0	0	0	0	0	0	0	

Figure 3: Runway dependancy matrix example for AMS

C. Noise

The noise modeling is done by calculating the Sound Exposure Level (SEL) for every possible aircraft, track and procedural profile in the Integrated Noise Model (INM). To save time, all medium sized aircraft where represented by a 737-800 and all heavies by a 777-200ER. The noise grid area for which these calculations are done, is shown in Figure 4.

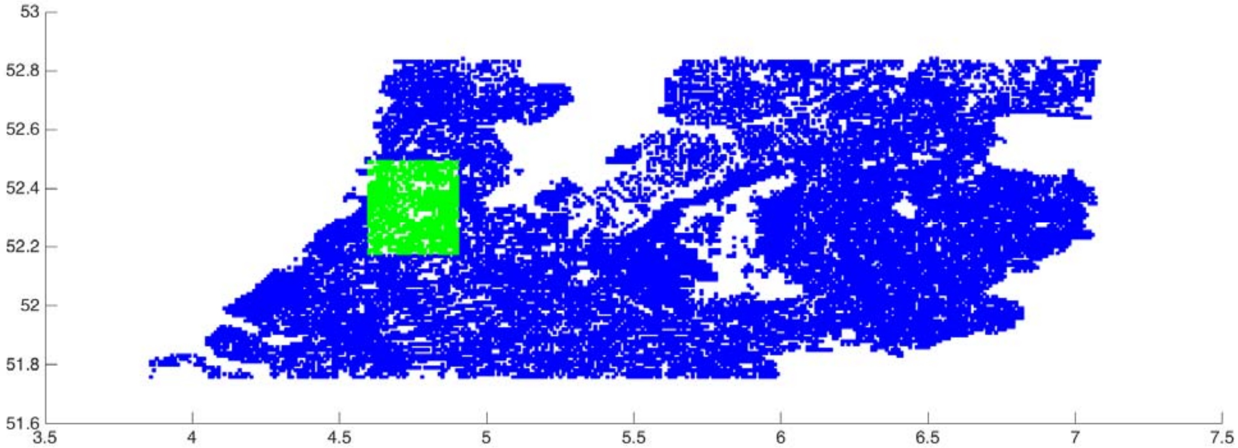


Figure 4: Noise grid lat/long coordinates: Blue dots indicate population points, green dots indicate the scope for which the runway allocation model calculates and optimizes noise.

This produces a Sound Exposure Level (SEL) grid. As the relationship between SEL and Acoustic Energy Level (AEL) is given by:

$AEL = 10^{\frac{SEL}{10}}$,we can rewrite the equation for L_{den} to $\sum_{n=1}^{N_{flights}} w_n AEL = \frac{\tau}{T_{den}} 10^{\frac{L_{den,\max}}{10}} = N_{\lim}$, where w_n is the evening (3.16) and night (10) penalty factor, τ is a reference time of 1 second and T_{den} is the timespan in seconds. As this AEL is linear with the number of flights, we can use these values in out linear programming model, where the limit is given by recalculating the L_{den} limit to the AEL limit for the relevant period of time.

D. Fuel consumption

Fuel computations play a crucial role in this study on flexible arrival and departure runway allocation. If a trade-off is anticipated between fuel and noise, computations in these areas have major impact on the final outcome. Fuel usage is expressed as kilogram of kerosene used for a particular operation.

Flight segments indicate the track distance and time an aircraft will be situated on a certain segment. Since in every segment different thrust settings are applied, the engine fuel flow will similarly differ per segment. The methodology discussed here is under an assumption; per segment a fixed fuel flow rate can be identified. Per segment fuel flow or fuel burn characteristics are extrapolated using Base of Aircraft Data (BADA 3.12) from EUROCONTROL. From this database aircraft performance specifics can be extracted. By inserting different criteria as variables in BADA, segments can be plotted. From this data the fuel flow per segment, including taxi time, and condition can be evaluated.

If an aircraft experiences delay on a certain flight segment, this results in a longer distance flown at equal airspeed. Although total fuel usage is therefore increased, the assumption is made that it has no effect on the flight path in terms of noise calculations. In other words, fuel use is increased during delay, noise exposure remains constant.

III. Mixed Integer Linear Programming model

The model uses a binary application of Mixed-Integer Linear Programming (MILP) in order to optimize the value for fuel burn and noise. Specifics of the linear programming problem are explained in this section

E. Decision variables

The model uses two types of binary decision variables:

- $x_{f,r,d}$, which indicates whether flight f is assigned to runway end r with delay d.
- G_{xy} , which indicates if the noise energy level at grid point at x,y is exceeded (1) or not (0).

F. Objective Function

The optimization model for runway allocation tries to find an optimum value for fuel and noise, in this case a minimum. The total objective function is $Z = \alpha n_u Z_u + \left(1-\alpha\right) n_n Z_n$, where α is the weighing factor for fuel vs. noise, which has a value between 0 and 1. The other parts of the equation are explained below.

1. Fuel

The objective function for fuel only is $Z_f = \sum_{f\in F}\sum_{r\in R}\sum_{d\in D} C^U_{f,r,d}.x_{f,r,d}$, where $C^U_{f,r,d}$ is the fuel costs associated with flight f operating on runway r with delay d.

2. Noise

The objective function for noise only is $Z_n = \sum_{xy\in G} C^P_{xy}.G_{xy}$, where C^P_{xy} is the number of houses or population living at grid point x, y.

3. Weighing

To obtain a weighed objective between fuel and noise, we need to normalize both objectives.

The normalization factor for fuel is $n_u = \dfrac{1}{Z^n_u - Z^f_u}$, where Z^n_u is the value of the fuel objective function for the noise optimal solution and Z^u_u is the value of the fuel objective function for the fuel optimal solution.

The normalization factor for noise is $n_n = \dfrac{1}{Z^u_n - Z^n_n}$, where Z^u_n is the value of the noise objective function for the fuel optimal solution and Z^n_n is the value of the noise objective function for the noise optimal solution.

The total objective function is $Z = \alpha n_u Z_u + \left(1-\alpha\right) n_n Z_n$, where α is the weighing factor for fuel vs. noise, which has a value between 0 and 1. A pareto front is created by re-optimizing for a range of α .

G. Constraints

The following constraints are used in the model

1. *Flight assignment*

$$F_f : \sum_{r\in R}\sum_{d\in D} x_{f,r,d},\ f \in F$$

Flight assignment assigns each flight to one runway with a single amount of delay.

2. *Runway occupation*

$$R_r : \sum_{r^*\in R}\sum_{f\in F}\sum_{d\in D} n_{f,r^*,r,t-d}\, x_{f,r,d} \le 1, r \in R$$

Runway occupation enforces that only one aircraft can block each runway at a time. To do this, it utilizes a dependency matrix, which allows the pre-processor to look up all the $n_{f,r,t-d}$ values, which indicate where a flight operating on runway r^* at time t with a delay d will block runway r.

3. *Noise limit*

$$N_{xy} : \sum_{f\in F}\sum_{r\in R}\sum_{d\in D} C^N_{f,r,d,xy}.x_{f,r,d} - M.G_{xy} <= N_{\lim}$$

The noise limit constraint uses $C^N_{f,r,d,xy}$, which represents the noise energy level a flight f operating at runway r produces at location x,y, including evening and night penalty factors. For all flight operations added at point x, y the sum must be lower than $N_{\lim}$. If the sum of all flight contributions is higher, G_{xy} will have to be 1 for that location. M should be equal or higher than the sum of the highest possible noise level $C^N_{f,r,d,xy}$ for all flights (thus the noisiest runway choice) at location x,y. It should be noted that while d is in the summation, delay does not affect noise.

Results

The model will try to optimize fuel burn during the arrival, departure and taxi-phase of aircraft operating on Schiphol Airport. This is done by smartly and flexibly allocating aircraft on runways, resulting in shorter flight routes and potentially reduced delay. The fuel burn is compared to the currently applied situation in which aircraft follow a strict runway preference list, focusing on reducing noise exposure on surroundings. In order to display the workings of the Runway Allocation model several scenarios are tested. Two scenario days of Airport Schiphol operations are discussed in which a reference scenario is run in tandem with the scenario as computed by the allocation tool. In this paper we will show only the results of the full day scenarios, indicated in Table 4.

Scenario	Time start	Time end	
Scenario 1	Full day run	06:00	00:00
	Morning run	06:00	12:00
	Afternoon run	12:00	18:00
	Evening run	18:00	00:00
Scenario 2	Full day run	06:00	00:00
	Morning run	06:00	12:00
	Afternoon run	12:00	18:00
	Evening run	18:00	00:00

Table 4: Scenario's

A. Scenario 1

The first scenario which will be discussed is based on actual data of operations at Amsterdam Airport Schiphol. Full day operations and aircraft data has been collected for June 18th, 2013. On this day winds speeds where at an hourly average of 4.0 m/s from the North-North east, meaning that all runways where available.

Figure 5 shows that whilst the fuel optimal solution will allocate flights to runways which are closes to their IAF, the noise optimal solution will put arrivals mostly on runway 36R and departures on runway 36L.

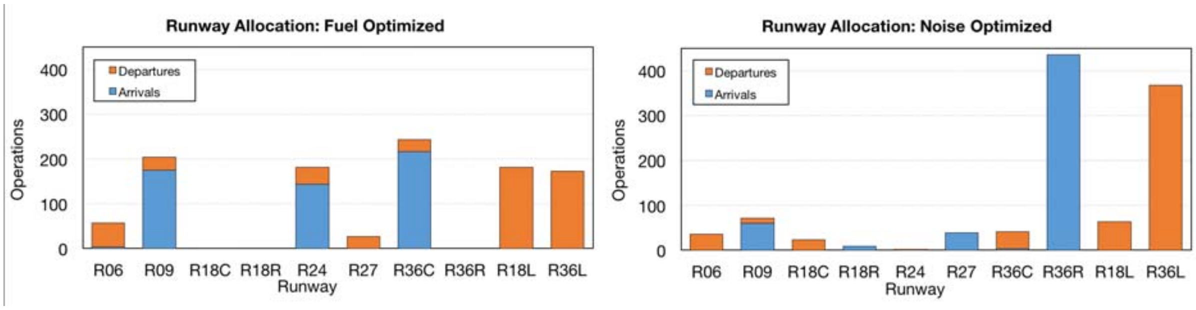


Figure 5: Fuel optimal (left) and noise optimal (right) solutions for scenario 1

Figure 6 shows that for the fuel optimal solution, noise limits at many grid points are exceeded whilst for the noise optimal solution, only those under the flightpaths from 36L and to 36R. The other runways are only used up to the allowed noise limit.

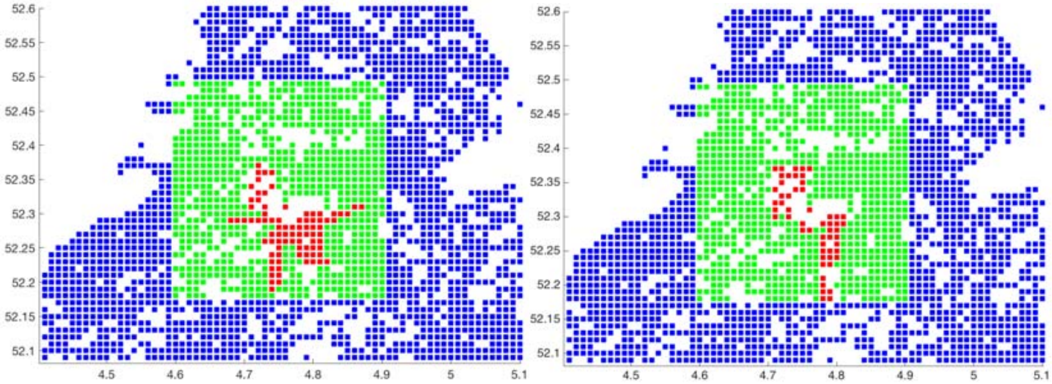


Figure 6: Grid points exceeding L_{den} limits for fuel optimal (left) and noise optimal (right) solution for scenario 1

The scenario is also run for a range of different weights between fuel and noise. It is important to note that not all solutions where fully converged to an optimum and thus outside the optimal region. To get a Pareto front, a selection is made based on identifying if a point has a better solution for either fuel or noise in comparison to its peer points. Figure 7 shows the resulting Pareto front with one of the most likely trade off solutions. The orange dotted line indicates the currently applied annual average day limit for 12,800 houses exposed to the given L_{den} noise limit. The green dotted line indicates the houses exposed for the reference simulation. It lies above the orange dotted line, showing that the annual average limit is slightly crossed under the actual runway allocation. This is compensated for if on other days the limit value is not exceeding the annual average limit. The fuel usage is represented by the grey line, at 1460 tons. Figure 8 shows the reference scenario, as the runways would normally be used and the Pareto trade off scenario, indicated with a red dot in Figure 7.

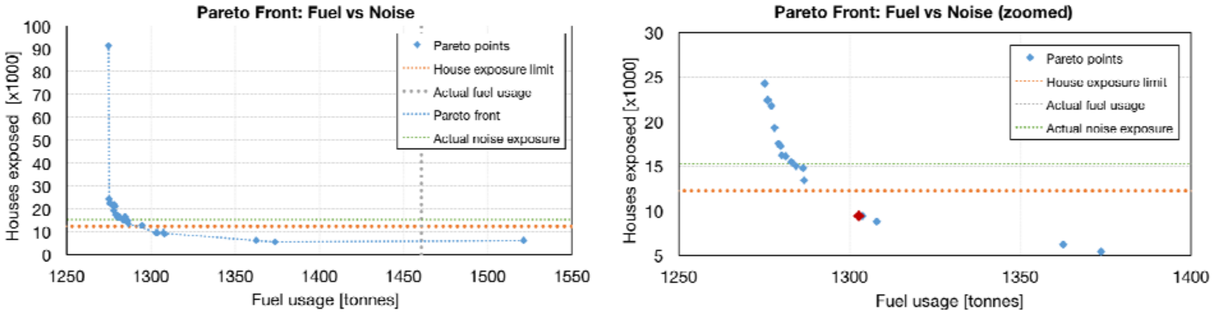


Figure 7: Pareto front for full day scenario 1

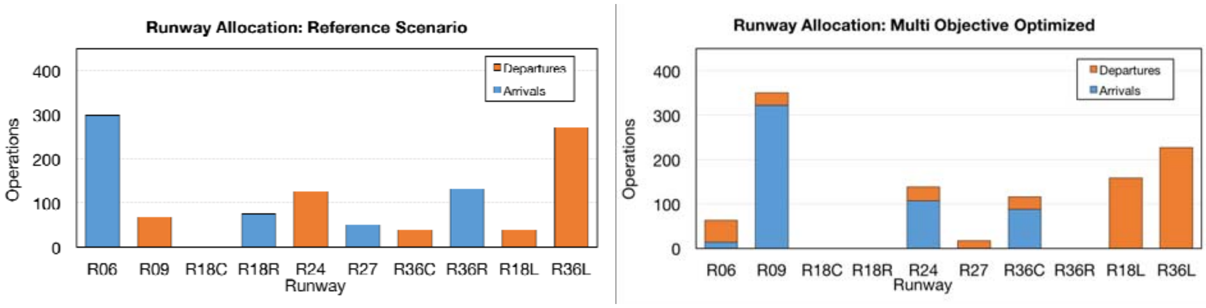


Figure 8: Reference (left) scenario and pareto trade off (right).

B. Scenario 2

For scenario 2 data is used for June 21th 2013 operations, as they occurred at AAS. A strong south-westerly wind and limited visibility settings leads to a change in runway availability. Due to the crosswind and tailwind limits, no arrivals and departures are allowed on R06, R09, R36C, R36R and R36L.

Figure 9 shows the results for the fuel optimal and noise optimal solutions. As can be seen, only five runway ends are available now. While the difference between the options is much smaller than for scenario 1, it can be seen that allocating all departures on R18L and distributing the arrives over the other 4 is much more noise optimal, as the noise level stay below the threshold for the most important areas, as can be seen in figure 10. Using only 18R and 24 for arrivals is much more fuel optimal, as these result in the shortest flight paths from all directions.

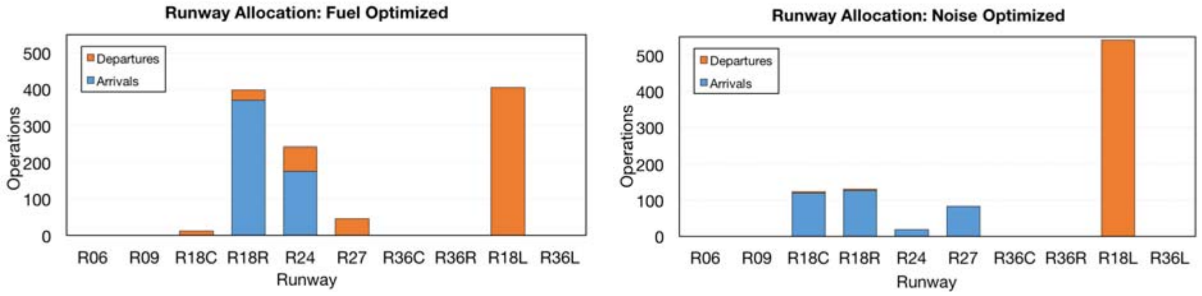


Figure 9: Fuel optimal (left) and noise optimal (right) solutions for scenario 2

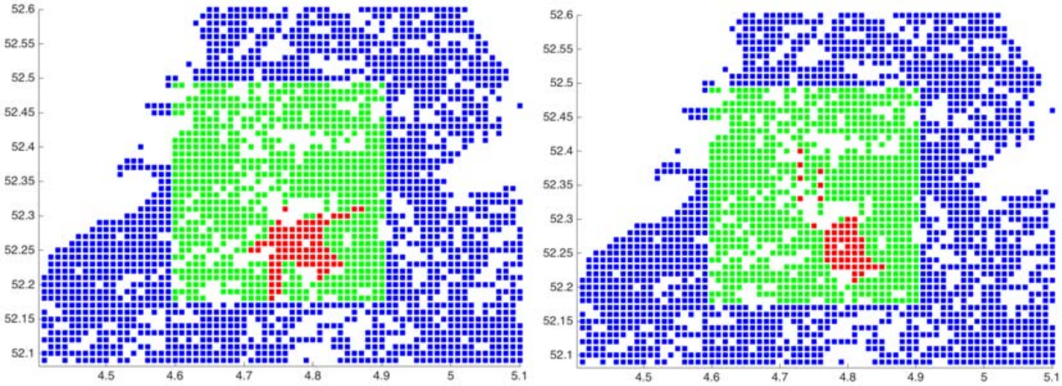


Figure 10: Grid points exceeding L_{den} limits for fuel optimal (left) and noise optimal (right) solution for scenario 2

Figure 11 shows the Pareto optimal solutions for scenario 2. Especially the fuel consumption range starts much higher than in scenario 1, as the flight routes from the south are much longer. As the options for distributions flights over different areas are much more limited, also the range for houses exposed starts at a higher level. Due to this, even the noise optimal solution results in a too high number of houses exposed. In reality, this needs to be compensated by staying well below the threshold on other days. The reference and Pareto trade off solutions are shown in figure 11.

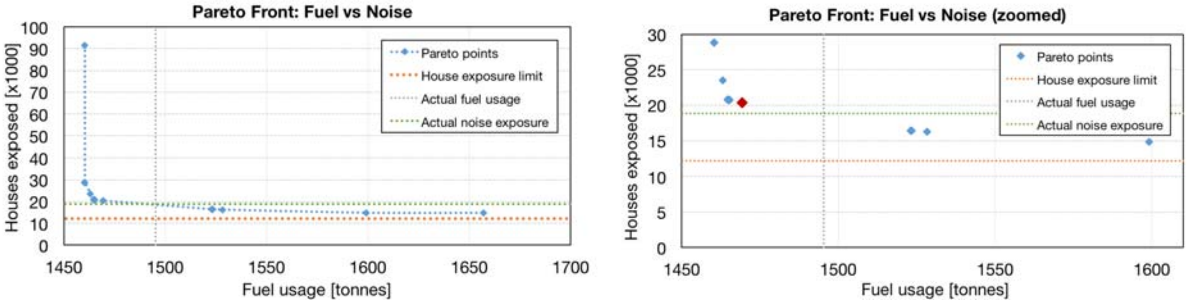


Figure 11: Pareto front for full day scenario 2

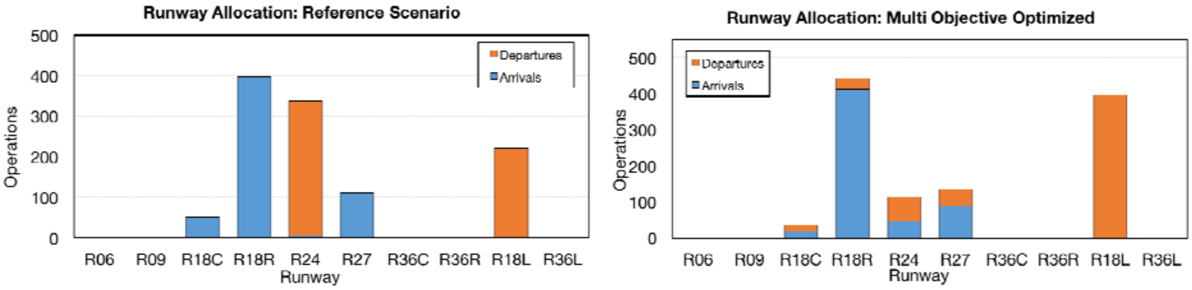


Figure 12: Reference (left) scenario and pareto trade off (right).

Conclusions and recommendations

Fuel usage can be significantly reduced by flexible runway allocation. For a full day simulation of a low wind scenario a potential fuel increase for multi-objective optimization corresponds to a saving of 157 ton kerosene (9.2%) in fuel consumption, while still resulting in a lower number of affected households. Also for a high wind day some saving can be achieved, though these are considerably lower.

For a fuel optimized case, often delay is reduced to a minimum in order to put aircraft on the ground as early as possible, hence reducing total fuel consumption. Nevertheless, in some cases the optimization selects a delay, so that an aircraft can hold for a more beneficial runway to become available, hence reducing total flight/taxiing time.

A range of optimal noise to fuel ratios can be calculated using a multi-objective optimization. From comparison of several scenarios it can be observed that certain optimization settings indicate an optimal noise to fuel ratio range. The established ratio is subject to discussion, but gives an interesting look on the potential savings in airport operations using allocation optimization.

The model should be expanded by implementing aircraft specific characteristics for a large set of aircraft, hence increasing fleet mix characteristics. This research assumed only two types of aircraft MTOW classes, whereas a more realistic allocation model could include a wide variety of aircraft types. For future research, the impact of wake vortex class grouping can then be simulated more accurately. Additionally, the effect on noise and fuel of old aircraft versus a new fleet can be researched.

It is recommended to further investigate the potential risks of flexible arrival and departure allocation. Not only should runway dependencies factors be further validated, also the human aspect of e.g. ATC workload should be researched. An interesting research area arises if systems are indeed able to flexibly allocate aircraft to runways and to what extend is human interaction desirable.

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