Nationaal Lucht- en Ruimtevaartlaboratorium

National Aerospace Laboratory NLR

Executive summary

Impact of Environmentally Optimized Departures on Runway Capacity

Problem area
This report presents a runway capacity study in relation to the use of advanced noise abatement departure procedures. The departure procedures in question are based on a previously presented concept of custom optimized departure profiles, a form of aircraft trajectory optimization geared towards reducing noise impact near airports. One of the observations made during a previous study is that aircraft flying these profiles exhibit a speed behavior that deviates significantly from what is observed when flying today's standard procedures. This means that effects on runway capacity can be expected. This study looks into these capacity effects

Description of work
The first activity has been the generation of a collection of optimized departure profiles. This collection is obtained by varying aircraft type, take-off mass, and departure route. Several subsets are created by also varying the optimization objectives. Trajectories based on the current departure procedure at Amsterdam Airport Schiphol form a separate subset as well.
The next step is the generation of random departure sequences from one or more of the subsets. For each of these sequences, the theoretical capacity is calculated for different separation criteria. Finally, the relative effects on runway capacity are obtained by comparing the results from the different subsets.

Results and conclusions
The capacity results show that the optimized profiles do have an influence on capacity. When using optimized profiles exclusively, runway capacity can be increased while maintaining the same minima for horizontal separation between consecutive flights. The actual increase is dependent on the definition of the separation criteria, but for the tested criteria, the average increase is 10-30% compared to the baseline. Runway capacity was studied as well for the situation where some of the departing aircraft perform a traditional departure procedure and the rest use an optimized procedure. In this situation, it is theoretically still possible to obtain a higher runway capacity compared to the baseline of traditional departures only. However, with more variation in the procedures, runway capacity becomes more sensitive to the actual departure sequence.

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Impact of Environmentally Optimized Departures on Runway Capacity

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Summary

This report presents a runway capacity study in relation to the use of advanced noise abatement departure procedures. The departure procedures under investigation are based on a previously presented concept of custom optimized departure profiles. This is basically an application of aircraft trajectory optimization geared towards reducing noise impact near airports. Under this concept aircraft are fixed along standard departure routes, but the speed and altitude profiles are optimized for each specific flight. One of the observations made during a previous study into this concept is that aircraft flying these profiles may exhibit a speed behavior that deviates significantly from what is observed when flying today's standard procedures. This means that effects on runway capacity can be expected and this study looks into these capacity effects. First of all, runway capacity is compared for the two situations, one where all aircraft use the standard (ICAO-A) departure procedure and one where all aircraft use their own optimized procedure. Finally, this study also looks into the effects of mixing both procedures for departures from a single runway.

Contents

Abbreviations

FAA	Federal Aviation Administration
FICAN	Federal Interagency Committee on Aviation Noise
ICAO	International Civil Aviation Organization
INM	Integrated Noise Model
NADP	Noise Abatement Departure Procedures
NLP	Nonlinear Programming
RNAV	Area Navigation
SID	Standard Instrument Departure

1 Introduction

The noise resulting from flight operations at major airports is a continuing source of annoyance in nearby residential communities. Different efforts are geared towards reducing the noise impact. A very common operational measure is the use of noise abatement procedures (*Ref. 1*). For example, two well known types of noise abatement departure procedures (NADP) are the so-called distant and close-in NADP's (*Ref. 2*). Procedures that belong to one of these types are designed to bring noise relief either close to or somewhat more distant from the airport.
A characteristic that is shared among these types of procedures is that they are generic in nature, i.e. they are not optimized with respect to the local situation. This means that although they have been optimized for a particular shift in noise load, they do not take the actual population distribution around the airport into consideration. Among previous research projects that do follow this approach are trajectory optimization studies, in which the trajectory optimization is applied to a specific arrival or departure (*Ref. 3, Ref. 4, Ref. 5*). Such studies have been performed for arrivals as well as for departures and the results with respect to noise exposure reduction are impressive.
Although these fully optimized trajectories can offer substantial benefits with respect to environmental impact, several problems arise with respect to a potential implementation. For example, the proposed trajectories are definitely more complex from the pilot's point of view, and are not directly compatible with today's navigation and guidance principles. A second problem that can be identified is a considerable increase in airspace complexity (*Ref. 6*) and the resulting challenges for air traffic controllers and their support systems. When assuming that the navigation and guidance difficulties can be overcome by near-future levels of flight deck automation, the airspace complexity remains the dominating problem. A previous publication presents a concept that does not suffer from the increase in complexity, but is still able to significantly reduce environmental impact by means of trajectory optimization (Ref. 7). This concept is based on fixed (published) Area Navigation (RNAV) departure routes, combined with individually optimized, let's say custom-made, or tailored departure profiles for each flight.
One of the observations made with respect to these optimized profiles is that the speed profile in the first few thousand feet of the climb differs significantly from the current situation. Since the velocity and acceleration behavior determines the resulting spacing between consecutives departures, this difference is expected to influence the runway departure capacity. This report looks into these capacity effects, including those of what can be expected when mixing both types of departure procedures.
First, chapter 2 provides an overview of the concept of custom optimized departure profiles by presenting the optimization tool, the departure procedure constraints and an example. Chapter 3

presents the runway capacity analysis method that has been used to identify the expected capacity effects. The results of the actual capacity study can be found in chapter 4. Finally, the concluding remarks are presented in chapter 5.

2 Custom Optimized Departure Profiles

This section gives a short overview with respect to the concept of custom optimized departure profiles. It first introduces the trajectory optimization tool that has been used. The next subsection then describes the applied constraints for these procedures, and finally, an example of a fuel-optimized trajectory is compared to a traditional departure.

2.1 The NOISHHH optimization tool

To facilitate the design of advanced noise abatement procedures, a tool called NOISHHH is being developed at the Delft University of Technology. The tool can generate routings and flight-paths for both arrivals and departures for which the single event environmental impact in the residential communities surrounding the airport is minimized, while satisfying all imposed operational and safety constraints. To perform this task, the tool combines an implementation of the Integrated Noise Model (INM), a dose-response relationship, a geographic information system and a dynamic trajectory optimization algorithm.

The numerical optimization method employed to solve the dynamic trajectory optimization problem is the direct optimization technique of collocation with nonlinear programming (NLP). The collocation method essentially transforms an optimal control problem into a NLP formulation by discretising the trajectory dynamics. To this end, the time interval of an optimal trajectory solution is divided into a number of subintervals. The individual time points delimiting the subintervals are called nodes. The values of the states and the controls at the nodes are then treated as a set of NLP variables. The system differential equations are discretised and transformed into algebraic equations (implicit integration). The path and control constraints imposed in the original optimal control problem are treated as algebraic inequalities in the NLP formulation.

To evaluate aircraft flyover noise, a model has been developed that essentially implements the basic methodology employed within the Integrated Noise Model (INM) (Ref. 8) . This model computes the sound exposure levels at specified observer locations. Based on the calculated results and population density data from the geographic information system the noise performance index is computed using dose-response relationships. For NOISHHH, the relationship most commonly used is the noise-awakenings relationship as proposed by the Federal Interagency Committee on Aviation Noise (FICAN) in 1997. This particular

relationship provides the percentage of the population exposed expected to be awakened (%Awakenings) as a function of the single event indoor sound exposure level (Ref. 9). Indoor levels are obtained from the computed outdoor levels, assuming an average sound transmission loss of 20.5 dB(A) for a typical home.
The performance index usually employed for this problem is a composite function. Depending on the actual application the performance function can be changed, but is typically the weighted sum of the fuel burn and the number of awakenings:

$$J = m \cdot \int_{t_0}^{t_f} \sigma_{fuel}\, dt + k \cdot A \qquad (1)$$

Where the integral from the initial time (t_0) to the final time (t_f) over the fuel flow σ_{fuel} represents the total fuel burn, A is the number of awakenings and k and m are user-defined multiplication factors ($k,m \geq 0$).

NOISHHH itself is capable of optimization in all dimensions. In other words, it usually determines routing (horizontal plane) as well as speed and altitude profiles (vertical plane) simultaneously. However, as mentioned in the introduction, the concept of custom optimized departure profiles is based on fixed RNAV departure routes because of airspace complexity considerations. This means that for this particular application, only the speed and altitude profiles are optimized along a specified RNAV Standard Instrument Departure (SID) track. Please note that this does not mean that this concept itself is incompatible with using optimized routing. As long as there is a single acceptable result for all traffic destined for a specific SID and the published departure routes are updated accordingly, it would still be possible to use this optimized route.

2.2 Departure procedure description

The optimized departure profiles used in this study are based on the description as provided by a FAA advisory circular (Ref. 2). Based on this description related to the so-called close-in community NADPs, the primary constraints for the optimization problem statement are:

- Acceleration for configuration cleanup should be commenced before thrust cutback is initiated.
- Thrust cutback should not take place before reaching an altitude of 800 ft.
- Acceleration for configuration cleanup is not allowed before reaching an altitude of 400 ft (not mentioned in the circular, but added for reasons of safety).

For reasons of simplicity, the model is not able to simulate the take-off roll phase of the departure. In light of the above mentioned constraints, this does not influence the result: optimization is not started before an altitude of 400ft is reached. However, it does mean that the tool needs to be provided with non-trivial initial conditions. The initial conditions that are chosen are those that correspond to the situation where the aircraft reaches an altitude of 50 ft, shortly after take-off, as provided by INM. The velocity and position down the runway provided at this point for the optimized procedures do not differ in any way from the normal take-off procedures.

Apart from the freely optimized profiles, a standard ICAO-A departure can be replicated by the optimization tool as well. When using this procedure, the aircraft performs the initial climb at V2 plus 10 knots (Ref. 10). At 1,500 ft, the thrust setting is reduced from take-off thrust to climb-thrust, while maintaining the same calibrated airspeed. At 3,000 ft and still at climb thrust, the aircraft is accelerated and the transition towards the clean configuration is initiated. This procedure is also optimized using NOISHHH. However, the detailed specification of the procedure precludes most optimization opportunities. Basically, NOISHHH will only determine the fuel optimal trade-off between a steeper climb and a quicker acceleration after reaching 3000 ft.

The main advantage of having NOISHHH to generate the standard departure procedure is that the comparison of the results of both types of procedures is more reliable. When using this approach, initial conditions, final conditions, the flight mechanics model, the fuel burn model, and the noise model are all the same. This means that any differences in the results can be attributed to the differences in the departure procedures.

A final remark with respect to the procedure: NOISHHH is able to take wind fields into consideration when computing the optimal departure trajectory. For this study however, the wind model was disabled for both the optimized procedure as well as for the ICAO-A procedure.

2.3 Example result: fuel optimized versus ICAO-A

To show the capabilities of the optimization tool, this section presents a comparison between the traditional ICAO-A procedure and a procedure that was optimized for minimum fuel burn, both computed with NOISHHH. The results presented are for a runway 24 ARNEM1S departure from Amsterdam Airport Schiphol, using a Boeing 737-300 model. Initial conditions are identical and final conditions are equal with respect to position, altitude and speed. The final time however is free, and as will be shown, differs for both solutions because of differences in speed behavior. Aircraft weight is kept constant during the simulation and equal for both examples. Figure 1 presents the speed profiles of both procedures and Figure 2 provides the two corresponding altitude profiles.

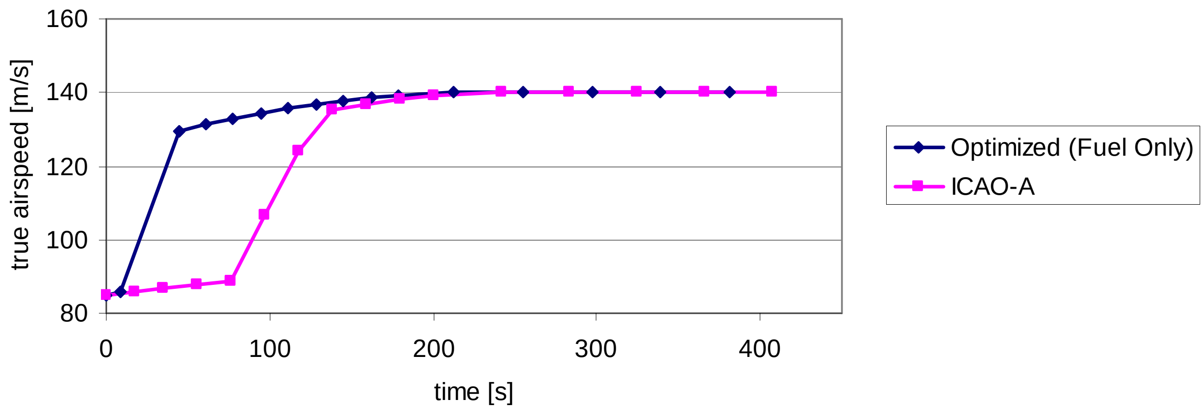

Figure 1 Speed profile example

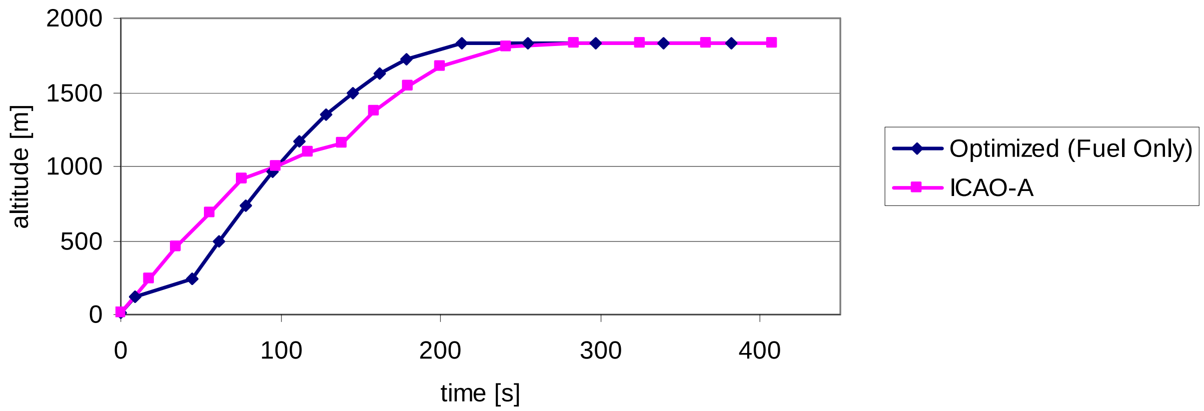

Figure 2 Altitude profile example

When analyzing the speed behavior, it is evident that the fuel optimized procedure starts to accelerate in an early stage whereas the ICAO-A departure is still maintaining a constant calibrated airspeed. This means that for the optimized procedure, the aircraft goes to clean configuration early in the departure. Acceleration continues until the imposed speed limit of 250 kts (129 m/s) calibrated airspeed is reached. In the figure, the true airspeed than still rises slowly with altitude until the final altitude of 6000 ft (1829 m) is reached. As already mentioned, the ICAO-A departure maintains a constant calibrated airspeed until an altitude of 3000 ft (914 m). At that point, the aircraft is accelerated, goes to clean configuration, and also reaches the speed limit, shortly before reaching the final altitude.

The altitude profile for the optimized case in Figure 2 is as expected: as soon as the aircraft starts to accelerate, this results in reduced climb performance compared to the ICAO-A result. However, when the acceleration is complete, the clean configuration helps in achieving an efficient climb. This results in a situation where the optimized profile reaches the final altitude

first. The ICAO-A result clearly shows the steep climb to 3000ft (914 m), than a part with a reduced flight path angle because of the acceleration towards a higher speed and finally another climb segment towards the final altitude.
Apart from the differences in speed and altitude, both trajectories give different results regarding fuel burn and estimated awakenings based on the FICAN relationship. The departure based on ICAO-A burns 467 kg of fuel, compared to 429 kg for the fuel-optimal procedure, a reduction of 8 percent. And although the optimized profile is not optimized for awakenings, it performs better in that area as well. The total number of awakenings is 3146 for the ICAO-A procedure versus 2347 for the fuel-optimized one, a reduction of 25 percent. Of course, the awakenings results depend on the actual population distribution under the calculated departure route.
As mentioned, the above result is optimized for minimum fuel burn only, corresponding to a k-factor of zero in Equation 1. When using a nonzero value for k, the number of awakenings can be reduced even further, at the cost of a small increase in fuel burn. When using for example a k/m-ratio of 0.05, the number of awakenings for the same situation is further reduced to 2167. This is more than a 30% reduction and clearly shows the rationale for optimizing departure procedures for noise abatement purposes.
However, what the results above also show is the significant difference in speed behavior between the two procedures during the first few thousand feet of the climb. As already mentioned, since the velocity and acceleration behavior determines the resulting spacing between two consecutive departures, this difference is expected to influence the runway departure capacity. The remainder of this report looks into these capacity effects, including those of what can be expected when mixing both types of departure procedures.

3 Capacity simulation method

This section discusses the design of the capacity simulation model. This model is used to determine the theoretical runway capacity based on the departure profiles that are being used. First, the general method for determining departure capacity is discussed. Then the different subsection will provide more detail. The actual results of the capacity simulation are not presented in this section, but can be found in chapter 4.

3.1 General method description

Runway departure capacity is ultimately a function of the required separation distance between different flights. In practice however, separation standards between two consecutive departing flights are usually not distance-based but time-based, provided in minutes and wake-class dependent (Ref. 11). Counting down is indeed also more practical than to aim for a certain spatial separation. However, the objective of this capacity simulation is to identify changes in runway capacity due to the changes in aircraft operation procedures, particularly due to the changes observed in speed behavior. This means that simply using the time-based intervals will not work, because then capacity is only dependent on the aircraft mix. Any resulting changes in spatial separation (and possibly even loss of separation) because of altered velocity profiles will not show in the capacity numbers. Therefore, time-based separation is not suitable for this study.

Instead, the capacity analysis method to study the effects of the optimized departures will use the resulting separation distance between consecutive flights. Provided with a separation requirement, a search algorithm is used to find the minimum interval that is required between specific flights in order not to violate the separation requirement. This interval is than used to calculate the ultimate runway capacity. It is important to realize that because of the unusual definition of separation employed herein, the results of the capacity analysis results should not be compared to current capacity calculations or declarations. This means that the numbers should only be used for a relative assessment of the different cases that are presented here.

Beforehand, it was expected that variations in parameters such as aircraft type, weight and routing may influence the runway capacity, especially in conjunction with the departure sequence. A wide range of capacity simulations has been performed to identify the main drivers and the extent of the variation in departure capacity. A Monte Carlo approach was used to generate the input for all of these experiments. The overall process is depicted in Fig. 3.

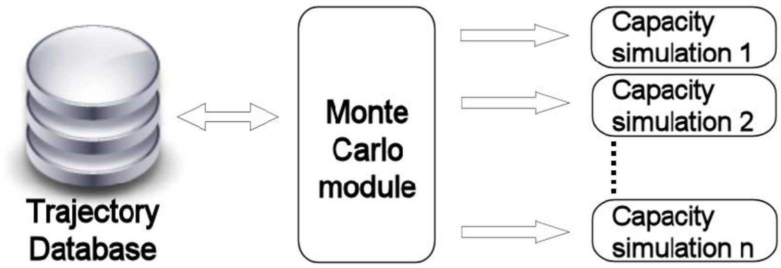

Figure 3 Monte Carlo procedure for calculating departure capacity

First the Monte Carlo module selects a number of eligible trajectories from a database of departure trajectories. These trajectories are provided to the search algorithm in a random order, to form a departure sequence. The capacity simulation uses a search algorithm to determine the minimum interval between each of the flights and calculates the resulting runway capacity for that specific situation. This process is repeated as often as desired.

The next three subsections provide more detail on the three elements used for this capacity simulation. First, more details are provided on the database of departure trajectories, followed by a discussion on the Monte Carlo module. The last subsection presents the search algorithm that determines the minimum safe interval and calculates runway capacity.

3.2 Database of departure trajectories

NOISHHH was used to generate a database of optimized departure trajectories. Several parameters were varied to obtain the set of distinct solutions. However, to keep the number of unique combinations in check, the variation in the parameters was restricted. First of all, three different aircraft types were used: the B747-400, B737-300, and the B737-800. For each of these aircraft types, between 5 and 7 different take-off weights were selected, loosely based on the available take-off weight of the respective types in the INM database. Next, the departure routes were varied based on six different SID's from runway 24 at Schiphol airport in The Netherlands. Finally, four different sets of optimization criteria have been used, as indicated in table 1. For this experiment, the mixing of aircraft types, weight, and SID resulted in 42 unique combinations. All 42 have been computed for each of the four optimization criteria sets, resulting in a database of 168 distinct trajectories for the runway under consideration.

Table 1 Sets of optimization criteria

Set	**Fuel factor *m***	**Noise factor *k***	**ICAO-A constraints**
1: ICAO-A	**1.0**	**0.0**	**Yes**
2: Fuel optimized	**1.0**	**0.0**	**No**
3: Noise low	**1.0**	**0.02**	**No**
4: Noise high	**1.0**	**0.05**	**No**

The results as generated by NOISHHH are unfortunately not directly suitable for usage in the capacity simulations. One of the incompatibilities is that the optimization tool generates trajectories that do not include the take-off roll. As mentioned before, all NOISHHH trajectories start at an altitude of 50 ft (15 m). Because it is desirable for the traffic simulation to simulate the ground run part as well, all optimized trajectories are extended with a ground run and initial climb-out. This extension is based on the assumption of linear acceleration during the missing initial part of the trajectory. Using this assumption and given the location of the brake-release point on the runway and the location and the velocity of the start of the optimized trajectory, the duration of take-off roll and the corresponding acceleration can be computed.

A second problem with the results generated by NOISHHH is that they only provide the aircraft states at a limited number of nodes, as can been seen in the figures from the previous section. Some of the nodes can be large distances apart and this was considered inconvenient for use with the search algorithm. Therefore the database was populated with computed trajectory data giving the interpolated state of the aircraft in 1-second intervals, based on the original trajectory data as provided by NOISHHH.

3.3 Monte Carlo Experiments

Because it is expected that the runway capacity is dependent on the chosen subset of trajectories from the database and their actual sequence, a Monte Carlo experiment is designed to study the runway capacity under these varying conditions. On a high level, the Monte Carlo experiment first selects a number of trajectories (typically 20) from the database and generates a random take-off sequence as input for the capacity simulation. Next, it runs the capacity simulation, saves the capacity results, and repeats the whole process as often as specified, typically a hundred times.

The Monte Carlo algorithm can be instructed to use only a subset of the database of solutions. This property is used to compare the results based on the different sets of optimization criteria. For example, it can be specified that the algorithm should only select ICAO-A departures (set 1) from the database. Multiple subsets can also be made eligible. One of the results in the next subsection, for example, will be based on traffic from only set 1 and 2.

The algorithm also uses subsets of the database to make a distinction based on the wake vortex categories of the different flights. This property is used to get a certain traffic mix between medium and heavy aircraft for each of the capacity runs. The specified mix however is not enforced, but it is used as a probability in the drawing process. In the results presented here a 30-70 percent heavy-medium ratio was used. For the typical capacity run using 20 flights, this means that there is an expectancy of six out of twenty being heavy. The actual mix for a certain run may of course vary and the number of heavies observed during all of the experiments varied between none and as much as fourteen.

3.4 Capacity simulation method

The departure capacity simulation is based on a very simple conflict search method. First of all the departure sequence is provided by the Monte Carlo algorithm, using an id for each departure. The corresponding trajectory data is than retrieved from the database. The first aircraft in this sequence is assumed to start the take-off at time t=0. The next aircraft (number two in the sequence) is positioned a short while behind the first one (e.g. take-off roll starting at t=20s.) and a conflict search is initiated along their tracks. If at some point in time a horizontal loss of separation is detected, the latter aircraft (number two) is delayed for one second and the conflict search is repeated, until all possible conflicts are eliminated. When the first two are conflict free, the time of take-off for the second departure is frozen and the third departure is positioned shortly behind the second one. Once again, delay is added until all conflicts are resolved. This process is continued for all remaining aircraft in the sequence.

Some of the potential conflicts may be resolved naturally when two consecutive departures have different and quickly diverging departure routes. Although this is fine, this introduces a small chance that a departure two positions behind another one may gain too much on the first one. For example, if the last of three aircraft is allowed to commence the take-off roll when separated from the middle one because of route divergence, it could theoretically still catch up with the leading one if these two aircraft are on the same route. This situation should be prevented. Therefore, starting from the third aircraft in the sequence it is made sure that aircraft n is not only conflict free with aircraft n-1, but also with aircraft n-2.
When the last aircraft in the sequence has been positioned, the average inter-departure interval is calculated as the departure time of the last aircraft divided by the number of aircraft in the sequence minus one. Finally, the runway capacity in departures per hour is obtained by dividing 3600 seconds by the calculated inter-departure interval.
One final issue that has not been discussed is the separation standard to be used for the conflict search. As already mentioned, the commonly used time-based criteria cannot be used for this method. This means that distance-based criteria have to be defined for this experiment, but their choice may have a significant influence on the results. To reduce this sensitivity, three different sets of separation standards have been used for the experiments, as presented in table 2.

Table 2 Sets of separation standards

	Separation during take-off roll	Horizontal separation
Set 1: Airborne only	Not required	3 nm
Set 2: Strict	Required	3 nm
Set 3: Wake dependent	Not required	3 nm or wake class dependent

As can be seen, the first two sets use a standard separation distance of 3 nm, with the difference the required separation during the take-off roll. Set 2 uses a strict definition and does not allow the take-off roll to commence, before the preceding aircraft is already 3 nm down from that point. This minimum separation is also maintained for as long as both aircraft are on their departure route. The strict definition of separation however results in a considerable head start for the preceding aircraft, so actively maintaining separation by delaying departure time of the follower is usually not required. Separation set 1 allows for anticipation and make sure that the required separation is available before the trailing aircraft becomes airborne. In this situation, maintaining separation during the remainder of the trajectory is more of an issue. Set 3 also does not require separation between airborne and rolling aircraft, but in addition uses wake vortex class dependent separation distances typically used for arrivals (Ref. 11). This means 5 nm for a medium trailing a heavy, 4 nm for a heavy trailing a heavy and 3 nm for the two remaining combinations.

4 Results of the capacity simulations

This section presents the results of the Monte Carlo experiments. For each of the experiments, the Monte Carlo algorithm was instructed to select trajectories from a different subset in the trajectories database. These six experiments were defined:

- A: ICAO-A (also provides the baseline capacity)
- B: Fuel optimized (noise factor k set to zero)
- C: Low noise (a combination of fuel and noise with a k/m-ratio of 0.02)
- D: High noise (a combination of fuel and noise with a k/m-ratio of 0.05)
- E: Mix of ICAO-A and Fuel (a combination of A and B)
- F: Mix of all (a combination of A,B,C, and D)

For each experiment, the MC-algorithm generated 100 departure sequences of twenty aircraft based on the active subset of trajectories and all experiments were performed three times to allow for the three different definitions of separation. This means that in total 1800 runway capacity runs have been performed and all of them are shown in the next six figures. Fig. 4 first presents the results for experiment A. The vertical axis shows the departure capacity, and the horizontal axis shows the ratio of heavy aircraft. Each capacity run result is shown using a single marker, based on the capacity result and the fraction of heavies of that run. Marker style and colour variation is used to make a distinction between the three different definitions of separation standards. The figure next to it shows the same, but then for experiment B.
When analyzing the baseline results from experiment A in figure 4, a number of observations can be made. Clearly, the first set of separation standards (airborne only) results, as expected, in a much higher capacity than the second one (strict). For both results, the actual mix between medium and heavy aircraft does not seem to influence capacity. Because of the definition of separation, the wake turbulence class is not a factor here and apparently, the differences in speed profiles between the heavies and the mediums are not sufficient to cause a significant influence on the runway capacity. For the third set of separation standards, however, traffic mix is important. Again, this is not unexpected, as the separation distances are influenced by the composition of the traffic. There is clearly a negative relation between the fraction of heavies and the runway capacity. At a low number of heavies, the capacity approaches that of set one, and for a high fraction of heavy aircraft, the capacity even falls off to levels below that of set two. Apart from the (average) capacity, the spread in results is important as well, as this influences the reliability and predictability of the runway capacity. The standard deviations (μ) and averages (σ) for experiment A and all other experiments are provided in Table 3.

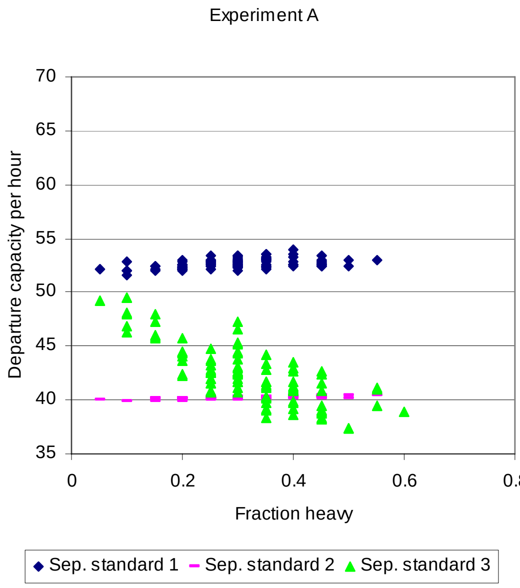

Figure 4 Capacity results for "ICAO-A"

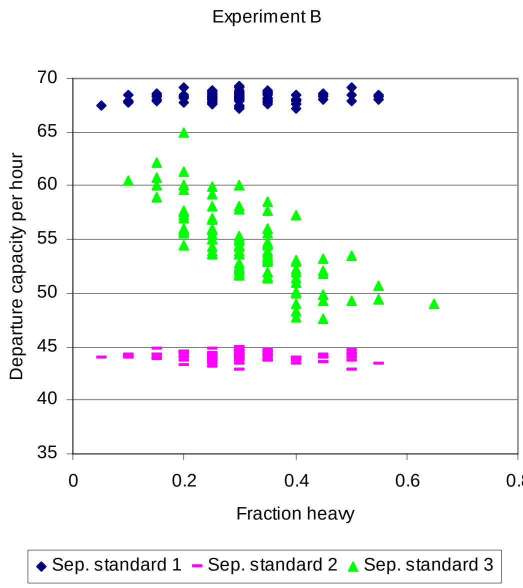

Figure 5 Capacity results for "Fuel optimized"

As was already clear from Fig. 4, the variation in capacity for set 2 is extremely low. The individual data points for the capacity runs can hardly be distinguished. It can be concluded that traffic composition, departure sequence, nor route selection results in significant capacity variations. Apparently, the large initial separation as caused by the strict definition prevents any conceivable conflict during the remainder of the trajectory. This means that it is not necessary to add further delay even if, for example, the following aircraft is faster than is predecessor. This means that the actual departure sequence is therefore not really important and the variation becomes very small.

Table 3 Capacity results for all experiments

Experiment	Separation standards					
	Set 1		Set 2		Set 3	
	μ	σ	μ	σ	μ	σ
A: ICAO-A only (baseline)	52.7	0.42	40.2	0.12	42.5	2.73
B: Fuel optimized	68.2	0.42	44.1	0.39	54.5	3.43
C: Noise low	68.2	0.45	44.1	0.47	55.2	3.72
D: Noise high	68.1	0.42	44.0	0.41	54.5	3.69
E: Mix: ICAO-A and Fuel	60.3	2.00	42.4	0.54	49.5	2.85
F: Mix: All available	62.4	2.03	43.1	0.54	51.2	3.33

For set one the standard deviation increases to 0.42, still a reasonably low number. The actual departure sequence and route choice becomes somewhat more important, especially if there are

trajectories with speed profiles with substantial differences. For set three, the situation is completely different and the standard deviation increases to 2.73. For this set, the departure sequence becomes a major factor. Of course, the actual sequences in combination with speed profile incompatibilities still may have some influence, but in this case the departure sequence also influences the required average separation because of the wake vortex considerations.
The results for experiment B (fuel optimized trajectories) are provided in Fig. 5. At first sight, the results show a similar pattern. Set one shows a horizontal group of high capacity numbers, set two shows an also horizontal group of much lower capacity, and finally group three is again in between and clearly a function of the fraction of heavy aircraft. However, if the results of experiment A and B are compared, it is readily clear that the overall capacity is much higher for experiment B. For set two, the difference in average capacity is only about 4 departures per hour, but for set one and three this increases to 15 and 12 respectively. This can only be explained by looking at the speed profile as discussed in chapter 2. All departures in experiment B start the acceleration as soon as possible, whereas all departures in experiment A remain at constant calibrated airspeed until reaching 3000ft. Higher speeds lead to covering the same distances in less time, so the earlier acceleration for the fuel optimized trajectories also reduces the inter-departure intervals.
Figure 6 and 7 show the results for experiments C and D, both optimized for fuel burn as well as for noise impact, using two different weighting factors in the objective function.

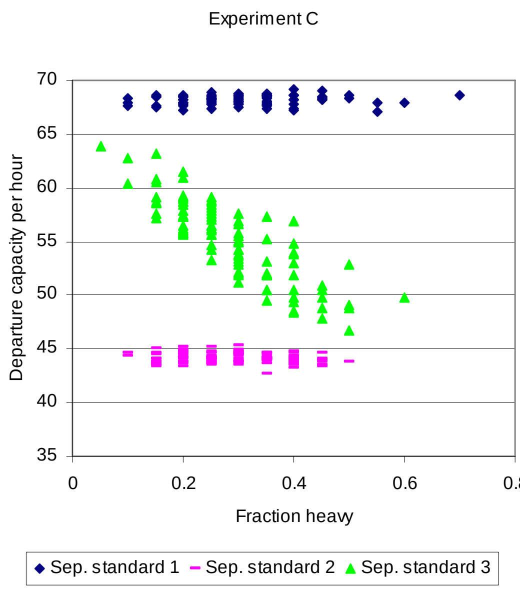

Figure 6 Capacity results for "Low noise"

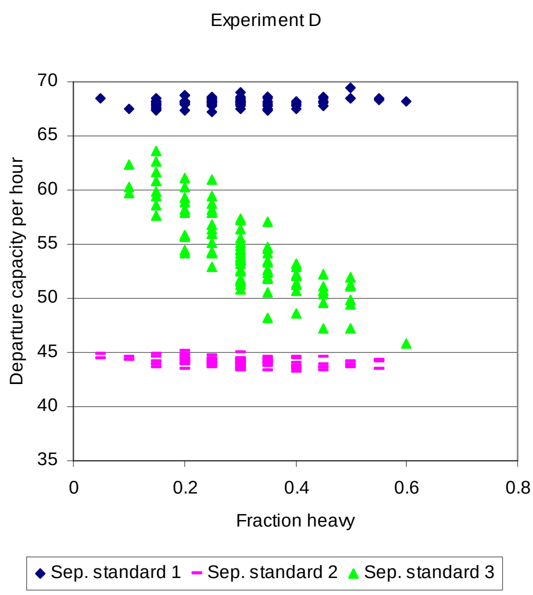

Figure 7 Capacity results for "High noise"

Both figures do not only look very familiar; they are also almost identical. Even more so, both results are also similar to those of experiment B. This is also confirmed when looking at the

averages and standard deviations. Differences can be identified, but these are very small. This means that increasing the *k*/*m*-ratio for the optimization problem does not result in differences in speed behavior that have a significant influence on the runway capacity. This observation is valid for all three definitions of separation.
Based on the results until now it can be concluded that the optimized trajectories result in a higher runway departure capacity than the ICAO-A departures and that the choice between fuel-optimized and noise-optimized trajectories does not have a significant influence on departure capacity. This conclusion is advantageous for the concept of custom optimized departure trajectories. However, these results are only valid for a situation in which all aircraft use the optimized profiles. Since the execution of these profiles will probably have to rely on onboard automation systems, this may not be very realistic, or at least not for the near future. Therefore, more experiments have been performed, in which a part of the aircraft still uses the ICAO-A departure and the rest uses the optimized departures. The results are provided in figures 8 and 9.

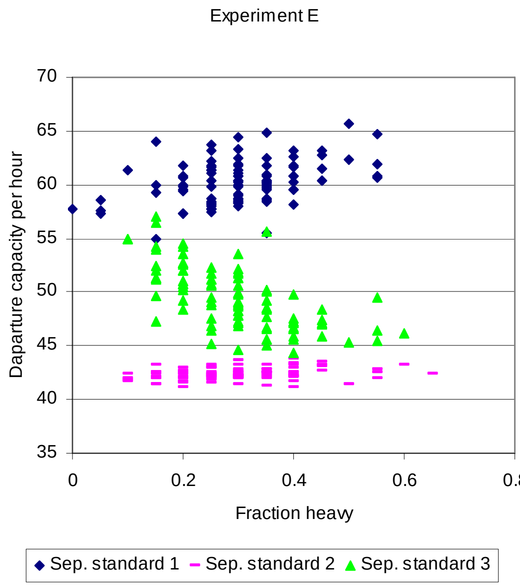

Figure 8 Cap. results for "Mix ICAO-A and Fuel"

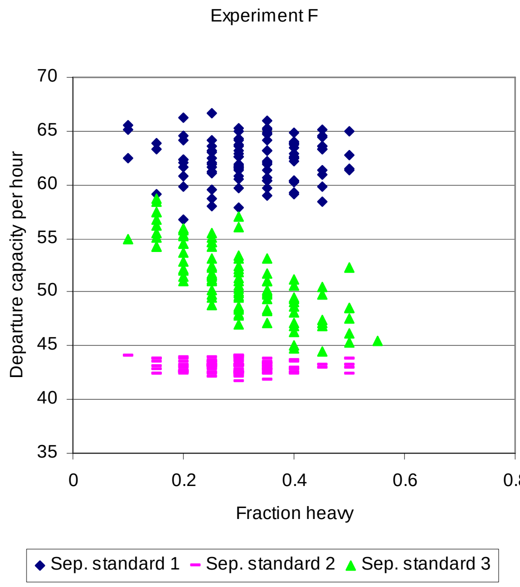

Figure 9 Cap. results for "Mix of all"

For experiment E, the Monte Carlo algorithm selects at random from the ICAO-A and the fuel optimized results. This means that the average ratio between the two types should be 50-50, but again this may vary for a specific capacity run. For experiment F, all four subsets are available, so the average percentage of traditional departures should be 25% and 75% for the remaining three groups.
Generally speaking, the capacity for the two experiments that involve mixing is in between that of experiment A and the three optimized ones. For all three sets of separation standards, experiment F scores better than experiment E. Apparently the ICAO-A departures are indeed the limiting factor. The variation in results for the last two experiments is evidently higher than for the previous four, at least for the first two sets of separation standards. This is already clear from

the figures, but it can also be confirmed when inspecting the standard deviation. This can most likely be explained from the presence of the two different types of procedures. First of all the actual ratio between ICAO-A and optimized departures for a particular capacity run may differ, but on top of that the departure sequence with respect to procedure type becomes important as well.

Probably the most important conclusion from these results should be that switching to optimized departures or mixing traditional and optimized departures procedures does not lead to a reduction in runway capacity when compared to the baseline situation. This means that the concept of custom optimized departure profiles does not exhibit a disadvantage in this area. Based on the observed required separation times, it could even lead to a higher runway capacity if this is desired. A second main conclusion should be that when using a mix of traditional and optimized departures, the process of optimizing the actual departure sequence becomes even more advantageous than it is today for situations were runway capacity is of critical importance.

5 Conclusions

Previous research has shown that custom optimized departure profiles can outperform the standard ICAO-A procedure in terms of fuel burn and noise exposure. One of the observations made at that time was a clear difference in speed and acceleration shortly after take-off when compared to traditional departure procedures. Based on this observation, an impact on the runway departure capacity was expected.

This research reveals that there is indeed an impact on the departure capacity. When using optimized profiles exclusively, runway capacity can be increased while maintaining the same minima for horizontal separation between consecutive flights. The actual increase is dependent on the definition of the separation criteria, but for the tested criteria, the average increase is 10-30% compared to the baseline. Runway capacity was studied as well for the situation where some of the departing aircraft perform a traditional departure procedure and the rest use an optimized procedure. In this situation, it is still possible to obtain a higher runway capacity compared to the baseline of traditional departures only. However, with more variation in the procedures, runway capacity becomes more sensitive to the actual departure sequence. This means that optimizing the departure sequence would be even more important for capacity critical situations.

The impact of the optimized departures on the runway capacity was only one of remaining issues with respect to this concept. For example, the required avionics functionality has not been studied at this point in time and the same holds for pilot and controller acceptability. This means that future research will need to be conducted with respect to these remaining areas.

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