Air Traffic Control Decision Support for Integrated Community Noise Management

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1. Introduction

The noise resulting from flight operations at major airports is a continuing source of annoyance in nearby residential communities. This being recognized by the industry, new aircraft generations continue to be less noisy than their predecessors, but this development in itself does not solve the problem in a fast growing market. Therefore a range of mitigation measures has been implemented at airports located close to sensitive communities. Some of these measures, like (night) curfews, restrictions on flight numbers and noise pricing tend to control and/or shape the demand from the airport's point of view. A second range of measures, including the use of noise preferential runways, noise abatement routes and the use of low noise procedures aims at a reduction of noise impact without interfering with the supply of airport capacity or the demand for air traffic.

The implementation of noise abatement procedures at the side of Air Traffic Control (ATC) authorities is not always straight forward, as it may interfere with respect to safety and efficiency requirements. This can be observed when considering the current implementation of the Continuous Descent Approach (CDA). The trade-off for this procedure is either to accept a less than ideal continuous descent, or to accept a reduced arrival capacity (Davison Reynolds et al., 2006; Kershaw et al., 2000; Weitz et al., 2005). However, contradictory requirements are not the only problem that air traffic controllers face with respect to reducing community noise impact. Taking noise beneficial decisions can also be difficult because of a lack of noise-related information. Usually, controllers have access to 'static' information, like the preferred use of certain routes and runways. However, they are not provided with information on the continuously developing situation with respect to community noise exposure. This means for example that they cannot respond to developments in the noise exposure in the past or expected developments in the near future. Nor can they evaluate the environmental effects of a tactical or operational decision they are about to take.

This paper presents a concept for integrated community noise management in the form of a decision support system (DSS) for air traffic controllers. It should assist controllers in guiding arriving and departing traffic near airports in a safe and efficient matter, making use of the future concept of four-dimensional trajectory-based operations and future technology currently under development. The system should be able to create conflict-free or de-conflicted, individually customized and optimized trajectories for all arrivals and departures. While doing so, the system minimizes the negative environmental effects of the flight operations and manages their spatial allocation, both for individual movements and cumulative exposure.

2. Towards trajectory based operations

Trajectory based planning is a relatively novel concept. Both the European Single European Sky ATM Research (SESAR) program, as well as the US Next Generation Air Transportation System (NextGen) program envision the transition to trajectory-based operations (TBO), based on the four-dimensional trajectories (4DT) of the aircraft. The TBO concept, including digital data exchange between aircraft and the Air Navigation Service Provider (ANSP) is expected to replace the current way of operating based on flight plans, resulting in a greatly reduced uncertainty with respect to the future (forecasted) position of an aircraft in flight (Joint Planning and Development Office, 2007). This is not only true for the spatial position in three dimensions, but also for the expected time along the different positions of the trajectory. For the NextGen program, this is achieved through the concept of Controlled Time of Arrival (CTA), a time window in which the aircraft is expected to cross a certain waypoint.

The NextGen Concept of Operations identifies that there will be different types of operations in TBO airspace. For example, oceanic airspace operations are managed in a different way than operations into or out of an airport. The airspace around the airports is expected to be managed by the ANSP, taking responsibility for both trajectory management as well as separation management. Ideally, arriving aircraft are assigned a 4DT trajectory at the top of descent that does not employ the current practice of low-altitude path stretching and holding.

The primary reason for shifting towards TBO is to increase efficiency and airspace and airport capacity. This can be achieved because it allows for removing additional separation that is the result of the current lack of control precision and behaviour predictability. The result of the increased predictability is that the tasks of the air traffic controllers can shift from a more controlling or operating task to a more supervisory, planning-oriented task, supported by sophisticated automation tools. Together, the accurate position forecasting possibility and the planning-oriented task of the air traffic controller will also greatly improve the possibility to manage the geographical allocation of environmental effects with respect to individual movements. This means that the already foreseen transition towards TBO will provide a unique opportunity to combine environmental management with the traditional responsibilities of air traffic control. Especially if such a system would enable aircraft to fly individually customized and optimized trajectories, multiple benefits can be identified, as discussed in the next section.

3. Concept and benefits of integrated environmental management

In the concept of integrated environmental management, the meaning of the phrase 'integrated' is twofold. First, it is used to indicate that all efforts towards environmental impact reduction are managed concurrently and consistently, yielding a more effective approach (Clairbois, 2005). Second, it refers to the integration of environmental management into the air traffic control processes through the use of advanced decision support systems. Both concepts and their advantages are discussed in this section.

Noise mitigation efforts can be categorized into different levels of aggregation. The design of noise preferential routes and/or procedures is at a lower level than the actual use of them in an operational environment. Even higher are activities in the strategic range such as noise allocation efforts in relation to noise zoning and land use planning, for example through changing runway use preferences (Hebly & Wijnen, 2005; Galis et al., 2004). Currently, these efforts do not always take place simultaneously and are often not managed by a single party. For example, departure procedure design is largely an international affair, aimed at the development of standardized operating procedures, such as the ICAO-A and ICAO-B departures. Subsequently, it is the ANSP that is responsible for selecting one of the procedures to be used for a particular airport. However, if the chosen procedure is aimed at reducing community noise exposure, it should match the land use planning policy, which is governmental responsibility. For this specific example, it turns out that three different stakeholder groups are involved, which may each have different objectives. Second, although the reasoning behind standardization is clear in today's operational environment, it also means that these procedures are not optimized with respect to the local demographic situation.

In the ideal situation, all environmental impact mitigation efforts at all levels should be managed concurrently. When using such a form of integrated environmental management, it can be ensured that all actions taken to minimize the nuisance caused by aircraft noise and emissions will be consistent, complement each other, and make use of synergy benefits. At the same time, it helps avoiding that a certain decision (partly) reduces the effectiveness of another measure at a different level or made by a different stakeholder.

When making use of a DSS for consistent environmental management, the basis for all decisions involving trade-offs with respect to noise and emissions should be the actual situation around the airport. This requires a detailed model of the surrounding areas, preferably not limited to static population density only. A more dynamic representation of the location and activities of people should be used, as a lot of people do not spend their day at home. If desired, this information can be combined with building data, also including (estimated) sound transfer loss, allowing for a much more accurate estimation of actual noise exposure. Sound proofing programs directly influence the indoor noise exposure and can in turn influence noise allocation considerations. The model should keep track of previous noise exposure allowing it to take this into consideration during future noise allocation decisions, and it should be aware of current local air quality. Optionally, noise from other sources (other traffic modes and industry) could be regarded as well, if this is desired.

On top of the model of the surrounding areas, the responsible governmental body should set the policies with respect to their environmental objectives. Without such objectives, decision making is often hampered by occurring conflicting interests. For example, changes in aircraft routings can be beneficial for a lot of people if a certain residential area is avoided. However, such a change typically comes at the cost of increased exposure in other areas. Even if the area experiencing increased exposure would be completely uninhabited, still conflicts may arise because of the commercial, recreational or wildlife preservation functions that that area may have. The government imposed policies are required to settle the conflict in these situations.

Together, the airport surroundings model and the government policy model function as an additional input for the trajectory synthesis process. This leads to the situation where environmental considerations are directly present at the operational level of air traffic control. The trajectory synthesis process should eventually be capable of handling both arrival and departure traffic simultaneously, while applying a multi-objective trajectory optimization algorithm searching for conflict-free trajectories, optimized with respect to efficiency, fuel burn, environmental and possibly other objectives. At the same time, the system is also responsible for sequencing of traffic, runway assignment and managing cumulative noise exposure in the area around the airport.

The use of TBO alone, thus without an interrelated environmental management system, can also provide several environmental benefits. For example, it should enable the possibility to perform high navigation precision, Continuous Descent Approaches (CDA) during all traffic demand situations. However, integrating the environmental management into TBO air traffic management also gives several benefits on top of the advantages that can be accredited to TBO alone. Most of the advantages stem from the possibility to decrease uniformity and increase flexibility by designing a trajectory for each individual flight.

Different aircraft have different performances, not only concerning flight performance, but also concerning noise and emissions. Even two aircraft of the same type and with the same systems installed may show different behaviour, mostly because of different instantaneous weights and atmospheric conditions. This is inevitable and does not have to be a problem, but it currently results in two disadvantages. First of all, for most airports, the procedures for arriving and departing traffic are designed such that at least the great majority of visiting aircraft should be able to adhere to the procedures under a wide range of weather and wind conditions. Basically, this means uniform design for the weakest link, possibly inhibiting better performing aircraft (in any sense) to exploit their capabilities. Second, differences in flight performance may reduce airport capacity. This is most evident when considering two consecutive aircraft flying the same trajectory with a different speed profile. The difference in speed will at some point result in an unnecessary large gap, which is basically a waste of capacity. A situation where each aircraft would be flying its own customized and optimized trajectory can eliminate both disadvantages (Vormer et al., 2006). It allows for optimizing for individual performance, and it can prevent aircraft with different speed behaviour to fly the same trajectory. This may not be necessary and/or desirable all of the time, but could be employed during peak hours if capacity is critical for the airport under consideration

Flexible use of airspace (FUA) is currently being implemented in ECAC states, including sharing airspace between civil and military users. When used, segregation of traffic is temporary, based on real-time usage within a specific time period. The concept of individually designed and assigned trajectories matches very well with the concept of flexible use of airspace. Areas can be closed down on a rather short notice by no longer issuing trajectories through that area, or even updating already issued trajectories to clear an area as fast as possible. Although this is in fact again an advantage of TBO itself and has nothing to do with environmental considerations, the same principle can be used in that sense. In the Netherlands, several temporary restricted areas exist in order not to disturb memorial ceremonies with loud aircraft noise. Since the proposed DSS can perform trajectory synthesis with access to noise information, it can easily take such temporary restrictions into account. Please note that also offers the opportunity to transforms the current spatial restriction into real noise restrictions, which means that individual noise performance can be taken into consideration.

When addressing both departing and approaching traffic simultaneously in the trajectory planning process, it should be possible to apply a less strict procedural segregation between these two flows. Based on previous research, it is expected that this results in fewer altitude restrictions for departing traffic (Jung & Isaacson, 2002). This can in turn reduce noise exposure, emissions and fuel burn, which is not only beneficial for the residential community, but of course also for the airline itself.

With respect to gaseous emissions, the actual spatial allocation currently receives less attention than total airport related emissions. However, from a health perspective, local air quality is far more important than total airport related emissions. When using flexible routing, this also offers the possibility to influence the air quality to some extent. Although one should consider that aviation as a source only has a limited share in the resulting air quality, it may for example be possible to avoid certain areas in the trajectory synthesis process if that area is experiencing air quality problems at that time. Similarly, departure procedures can be chosen such that the emission of a particular substance is minimized if the concentration of that substance if critical at that time. Both options are dynamic air quality measures and are comparable to concepts such as adapting highway speed limits based on actual measured or predicted air quality (Spit & Sluis, 2006).

Finally, depending on the development of new noise models and the availability of more accurate real-time atmospheric condition information, it might be possible in the future to take current conditions such as wind and temperature gradient into consideration in the noise propagation modelling, resulting in more accurate noise predictions. If it is possible to perform such calculations in a timely manner in an operational environment, this would allow for a trajectory synthesis process based on more realistic noise modelling. In other words, trajectories may be adjusted not only for actual atmospheric conditions with respect to flight performance of the aircraft, but also with respect to the actual weather related noise propagation properties.

4. Arrival management as interim concept

It is important to realize that the ideal environment for the DSS is currently not in place. First of all, high accuracy 4D navigation needs to be available to all or at least the great majority of aircraft. The same is true for the required 4DT exchange functionality. There are, however, research projects that look into elements of the proposed system without relying on the 4D technology. These projects look into modifying currently existing or planned automation tools for arrival management. These tools help controllers in creating an efficient flow of aircraft towards the runway, eliminating delay as much as possible. Often, the resulting trajectories from these tools are basically small variations to existing arrival patterns, in order to achieve a certain amount of delay required for a safe and efficient flow.

The Center-TRACON Automation System (CTAS) terminal area tools used at some airports in the US include tools used for arrival management. These tools are capable of generating advisories that respect separation requirements and minimize delay. A suggestion has been made to inject noise related information into the current constraint resolution and scheduling logic, to create a system that is capable of generating advisories with respect to both delay and noise (Capozzi et al., 2002, 2003). The resulting concept is called the Noise

Avoidance Planner (NAP). However, because of the current CTAS constraint resolution architecture, noise considerations and efficiency cannot be addressed simultaneously.
Although only altering arrival management tools cannot offer all of the benefits as previously identified, it can be seen as a step in the right direction in the absence of the technology required for 4DT. The remainder of this paper will focus on research done concerning an arrival management model where noise and efficiency are considered simultaneously (Hebly, 2007). Please note that it is not designed or build to function as an operational arrival manager, but purely to study the effects of adding noise objectives to the otherwise delay driven support tools for sequencing and scheduling, and to identify the interaction between the noise and efficiency objectives.

4.1 Arriving traffic concept

As long as trajectory exchange is not a possibility, the method of issuing vectors or defining a limited number of fixed arrival trajectories are the two remaining options for controlling the lateral part of the trajectories of arriving aircraft. Fixed routes have the advantage that they can be designed as noise optimal routes, can be flown with high navigation precision and at the same time allow for more optimal CDA procedures. The downside of fixed routes is that the controller looses the path stretching possibility. This means that any required delay should be absorbed before aircraft start their assigned fixed arrival route, apart from the fine tuning that might be achieved using speed control.
The arrival management model used here can deal with multiple fixed routes to a single runway of an airport. The configuration presented in this paper is based on three routes towards one of the runways of Amsterdam Airport Schiphol. This is depicted in figure 1.

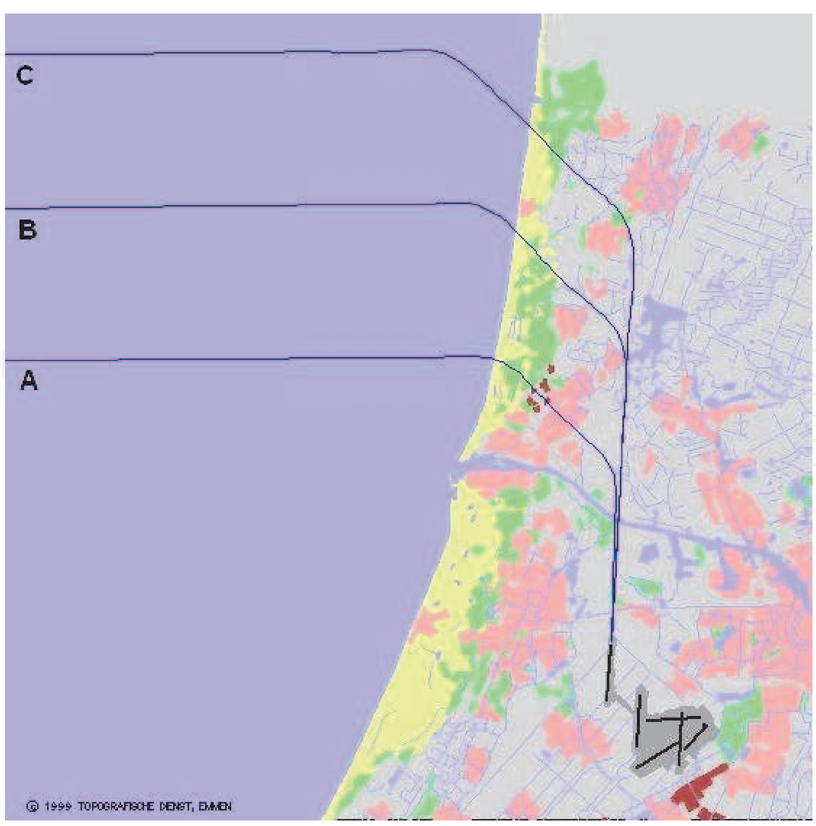

Fig. 1. The three arrival routes used

For this scenario, it is assumed that all traffic from the West is guided to this runway. Traffic from the East is not modelled, but is assumed to land at another runway independent of the modelled part. Of the three routes, the last part of the center route (labelled B) is very similar to the current night-time CDA for this runway. The two outer routes (A and C) are variants of the route in the sense that they cross the coastline either further away or closer to the runway. Please note that in reality, these routes do not exist and the use of fixed arrival routes is currently limited. For the model, all approaches are assumed to be CDA procedures, from the points where the fixed routes start. As a result, the three different routes cross the more densely populated areas close to the coastline at different altitudes, before turning towards the runway over a less populated area. This is expected to result in different noise exposure, except for the final part, where all three routes are equal.

Before a flight movement starts on one of the three depicted fixed approach routes, it is assumed that it crosses one of two available metering fixes, situated north-west and south-west of the starting points of the fixed approach routes, see figure 2. Since all three routes can be used from both fixes, this may lead to crossing traffic. The model does not regard separation before traffic is on the depicted routes. Therefore, possible conflicts in the area between the gates and the approach routes must be solved using altitude constraints.

The arrival model is provided with a traffic sample. The sample specifies aircraft type, metering fix and expected, (undelayed) time of crossing time of the metering fix. Furthermore, the model is aware of the (undelayed) transit times from both fixes to the runway threshold via the three different routes. These transit times have been determined using the NLR ATC simulator (NARSIM) for different aircraft types.

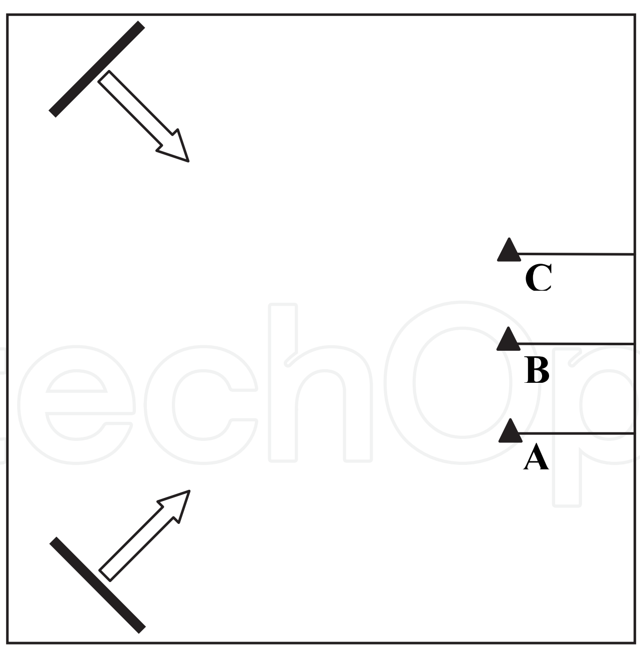

Fig. 2. Metering fixes and starting points for the CDA approaches

4.2 Noise metrics and indicators

In order to allow the model to perform routing selection based on noise criteria, it requires information on the noise exposure resulting from the selection of a route. The single event noise exposure of flying the three different trajectories can be expressed using several metrics or indicators based on those metrics. Noise levels are typically computed at a large number of points within the area of interest. Although this type of result is suitable to compare different results graphically, it is not fit for a numerical comparison. Indicators that are derived from the metrics however can be seen as an aggregate of the result, often expressing the result using a single number. This enables easy comparison between the results of the different routes and aircraft types, but as with all aggregated data, a part of the original data is lost. Checking for consistency among multiple indicators is therefore always a safe option. Four different single event indicators based on two different metrics will be presented here.

The World Health Organization (WHO) recommends to limit the number of maximum A-weighted indoor peak level (LA_{max}) events of 45 dB(A) or more during night-time in the bedrooms (Berglund, 2000). This corresponds to a 60 dB(A) level outdoors, when assuming a sound transmission loss of 15 dB, a modest value that allows for people to sleep with the windows open. Based on this recommendation, the number of people exposed to higher peak levels during an aircraft flyover is a suitable single-number indicator for undesirable night-time noise events. This number is used as the first indicator. For day-time noise, there is no similar recommended or often applied limit. However one could argue that, based on the 10 dB penalty that is often applied to night-time events for the cumulative metrics, a daytime 70 dB(A) LA_{max} limit is equivalent to a 60 dB(A) night time limit. Therefore, the number of people exposed to peak levels higher than 70 dB(A) is used as the second indicator.

Another option is to use dose-response relations to estimate the effects of noise exposure. Therefore, the third indicator is based on the relationship as proposed by the Federal Interagency Committee on Aviation Noise (FICAN) in 1997 (Federal Interagency Committee on Aviation Noise, 1997). It represents an upper bound on the percentage of people likely to awake due to a flyover, where the percentage of awakenings is a function of the indoor Sound Exposure Level (SEL, L_{AE}), see figure 3. For this function, a sound transmission loss value of 20.5 dB is used, as an average value for a typical home.

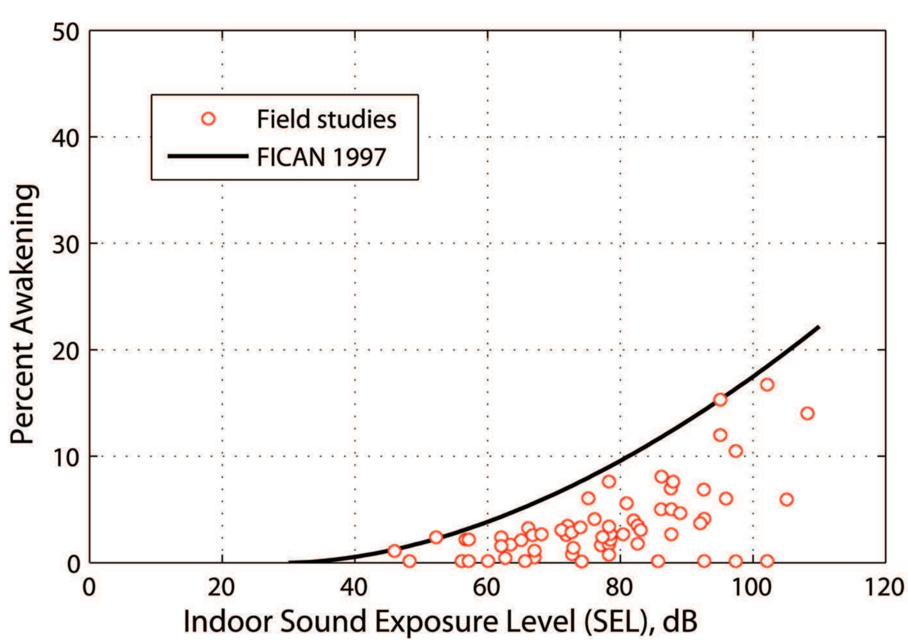

Fig. 3. FICAN proposed sleep disturbance dose-response relationship (Federal Interagency Committee on Aviation Noise, 1997)

As a fourth and final indicator, an estimation of the number of complaints will be used. This relation is based on Dutch research that relates the number of complaints concerning a flyover to its (computed) maximum noise level (Lieshout, 2006). It turned out that the different communities around the airport show different complaint rates. However, because the study was performed for a limited number of communities, here the complaint rates for the most sensitive community are used for the complete study area. Therefore, the number should be interpreted as a worst bound on the expected number of complaints due to an aircraft noise event. The resulting dose-response relationship is given in table 1.

LA_{max} dB(A)	Complaint rate (per 1000 inhabitants)
$x < 50$	None
$50 \leq x < 60$	0.130
$60 \leq x < 70$	0.437
$x \geq 70$	1.269

Table 1. Exposure-response relationship for expected complaints

Using the Dutch noise computation model, the results for different aircraft types and the three different routes have been computed for the four single event indicators. The results are presented in table 2 for a limited number of aircraft types. Please note that aircraft types are categorized in the Dutch noise model based on their noise performance. This may lead to the same results for different types, like for the Airbus A320 and the Boeing 737-800.

Indicator	Route	Aircraft type				
		CRJ700 Dash 8-400	A320-200 B737-800	A330-300 B767-400	B777-300	B747-400
1 60 dB(A) LA_{max}	A	228	545	30350	24030	50335
	B	178	1045	7108	4845	24655
	C	178	1045	8448	6945	25480
2 70 dB(A) LA_{max}	A	35	73	298	348	700
	B	35	78	308	345	1095
	C	35	78	308	345	1093
3 FICAN awakenings	A	445	773	1860	1672	2756
	B	287	470	1896	1560	2929
	C	321	501	2483	1946	3909
4 Expected complaints	A	3.22	5.83	18.82	16.33	26.86
	B	0.97	2.66	11.84	9.55	21.72
	C	1.29	2.78	13.18	10.42	26.78

Table 2. Single event noise indicators for the three approach routes

When analyzing the different results, the first observation is that the 'inhabitants within the 70 dB(A) contour' metric can hardly make a distinction between the three different approach routes, except maybe for the Boeing 747. This means that it is not fit for our purpose and is

further discarded. Not very surprising, the remaining indicators show that exposure increases with aircraft size, with the exception of the B777-300 category performing slightly better than the smaller A330-300 / B767-400 category. Concerning choice of routing, the B-route generally performs best, with a second place for the C-route. Again some exceptions can be observed, especially for the B747-400.
Instead of selecting one of the single event metrics for the arrival management model, it is also possible to use a composite function of the three remaining indicators, by summing them up. However, because of the very large differences in absolute number, some sort scaling is required to prevent one indicator from dominating the other ones.

4.3 Optimization model description

The scheduling problem is stated as a Mixed Integer Linear Programming (MILP) problem. This approach allows the problem to be formulated in generic form using (algebraic) constraint equations instead of designing a dedicated algorithm. Apart from the clarity of using equations, it also allows for easy changes or additions to the model, such as changing the goal function.
The sequencing is based on the existing principle of Constrained Position Shift (CPS), where an aircraft is allowed a difference of n positions between First Come First Serve (FCFS) order and the actual landing order (Balakrishnan & Chandran, 2006). When using FCFS, all aircraft land in order of their scheduled arrival times at the runway. When using CPS, an aircraft that is for example fourth in the FCFS sequence, is allowed to take the landing positions 3, 4 and 5 when n = 1. For a sequence of four aircraft, this leads to a decision tree as depicted in figure 4. Aircraft 1 and 6 do not join the sequencing process. Aircraft 1 can be thought of as the last aircraft that already has a fixed or frozen landing position and time. It prevents the aircraft taking position 2 from landing earlier than possible, based on the landing time of aircraft 1 and the required separation. The last aircraft, number 6 in this example is not necessarily a real (future) aircraft, but is mainly used to prevent the scheduler to push heavy aircraft to the back of sequence. Without this additional aircraft, the scheduler might do so because it does not regard the required separation behind the last aircraft in the sequence. Adding the dummy aircraft automatically adds the required separation behind the last real aircraft

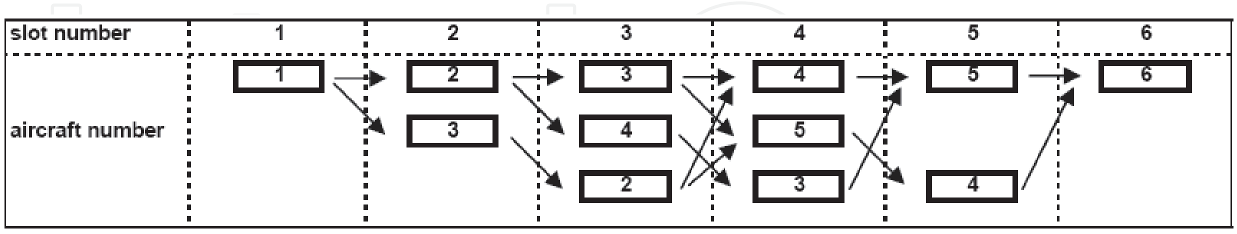

Fig. 4. Decision tree for the example problem

Next to the scheduling, there is also the route selection process. The scheduler is forced to choose exactly one of the three offered approach routes for each flight. The route selection determines the noise score for a specific flight as discussed in the previous section, as well as the earliest possibility to land. For example, a Boeing 737-800 approaching via the southern metering fix cannot land earlier than the time required to reach the fix plus 737 seconds when using route A, 807 seconds when using route B or 867 seconds when using route C.

Aircraft are prohibited to land earlier than their predecessor in the sequence and are also required to respect a minimum separation time based on the wake vortex category of the pair under consideration. The separation values used are 95 seconds minimum following a medium aircraft, 125 seconds minimum for a heavy aircraft following a heavy one and 155 seconds minimum for a medium following a heavy.
Due to the constraints described above, it is very likely that an aircraft is scheduled to land later than its earliest possible landing time. The difference - that is the delay - needs to be absorbed at some point. The model does not look into how the delay is absorbed; it only calculates the required amount. In practice, delay can probably best be accommodated before crossing the metering fix.
Finally, the objective function for this problem is defined as:

$$\text{Min}: \sum_{j=1}^{m} LT_j + k \sum_{j=1}^{m-1} NE_j \tag{1}$$

where LT_j is the landing time of the jth aircraft, k is the noise cost multiplier and NE_j is the noise exposure of the jth aircraft. The landing time is expressed in seconds from the instant the schedule is created, and is used as a proxy for delay. The noise exposure itself is formulated as:.

$$NE_j = a_j \cdot NE_{j,r=A} + b_j \cdot NE_{j,r=B} + c_j \cdot NE_{j,r=C} \tag{2}$$

$$\begin{aligned} a_j + b_j + c_j = 1 \\ a_j, b_j, c_j \in \{0,1\} \end{aligned} \tag{3}$$

where $NE_{j,r=A}$ is the noise exposure of aircraft j when using approach route A, etc. As can be seen, the noise cost for the last aircraft is excluded from objective function, since this is not a real aircraft to be scheduled. Its flying time is included on the other hand, because of the reason the aircraft was added in the first place. The noise cost and flying time for the first aircraft are taken into consideration, although the scheduler will not be able to optimize for these values, since they are already fixed. Noise cost multiplier k determines the importance of the noise related performance relative to the delay related performance. When k equals zero, noise exposure is not regarded at all, turning the optimizer into a traditional, delay driven only tool. When k is very large, the optimizer will still generate an optimal landing schedule, but the routing process is completely dominated by noise considerations.
The problem itself is generated by a script that reads the input variables, and writes the mathematical formulation for the problem. This can than be solved by a solver such as ILOG CPLEX (commercial) or LP_SOLVE (open source). Finally, the solution as returned by the solver is post-processed for ease of interpretation. In the post processing, the solution is also converted to a traffic file for NARSIM. Using this file, NARSIM can be instructed to 'playback' the solution on a radar screen, making it very easy to visualize, check and interpret the results.

4.4 Scheduler results

Scheduler results and the trade-off between average delay and noise exposure are shown in figures 5, 6 and 7 for 20 arrivals in a mix of 30% heavy and 70% medium aircraft. Figure 5 is based on an arrival rate of 45 aircraft per hour, which is higher than the runway capacity. Figure 6 is based on the same traffic sample of 20 aircraft, but arriving at a rate of 36 aircraft per hour and figure 7 is based on an arrival rate of 30 aircraft per hour. All figures show the average delay per operation and the resulting (combined) noise exposure index (NEI), both against the noise cost multiplier k. This multiplier is varied between 0 and 200. The average delay can also be compared to the average delay that is achieved when using FCFS. The FCFS solution is based on time optimal routing only, so it does not regard noise exposure at all.

From the results, it can be concluded that adding noise considerations to the model does indeed reduce the noise exposure indicator. Furthermore, increasing the importance of the noise objectives relative to the efficiency objectives, the noise indicator value can be reduced further, at the cost of increased delay, possibly leading to a solution that is worse than the reference FCFS solution. Of course, in such a situation, the noise exposure of the optimized solution is lower than that of the FCFS solution. Interesting to note is that a (small) noise improvement can be achieved without an increase in delay. This can be seen in all three figures by looking at the differences in solutions resulting from k = 0 and k =1. Apparently, routing can sometimes be changed in favour of noise without affecting the sequence and the schedule.

When comparing the three figures, the effect of the arrival rate can be seen. In the situation where the arrival rate is below the runway capacity, it can be seen that reducing the noise exposure indicator easily leads to solutions that are worse than the FCFS solution in terms of efficiency. At arrival rates higher than the runway capacity, the situation is clearly different. In this situation, all aircraft need to be delayed. For efficiency, it does not matter whether the required amount of delay is absorbed before the metering fix or during the approach by using a different route. This allows the scheduler to assign longer, but noise optimal routes without effecting landing times and runway throughput.

Apart from the results shown here, which are based on the expected complaints indicator, additional results have been generated for the other optimization criteria. Similar results are obtained when using the other two indicators, as well as with an indicator based on a combination of the three. More results have also been generated using higher and lower arrival rates and different traffic samples, all showing different results of course, but similar trends.

4.5 Cumulative noise exposure

Instead of single event metrics or indicators, true community noise exposure is often based on cumulative exposure metric, such as the day-night level (L_{dn}) or the day-evening-night level (L_{den}). Both metrics describe weighted average noise levels, where both apply a 10 dB(A) penalty for night time events, but only L_{den} applies a 5 dB(A) penalty for evening noise as well. However, when assigning routes to aircraft based on the single event noise indicators only using a scheduling, sequencing and routing method as showed above, it is likely that one route is used exclusively, especially when the noise cost multiplier is high. When only using single event indicators, a route that is optimal for a certain flight, is still optimal 50 flights later. This can easily lead to an extremely high exposure for the area under that specific route, resulting in a situation that is considered unacceptable.

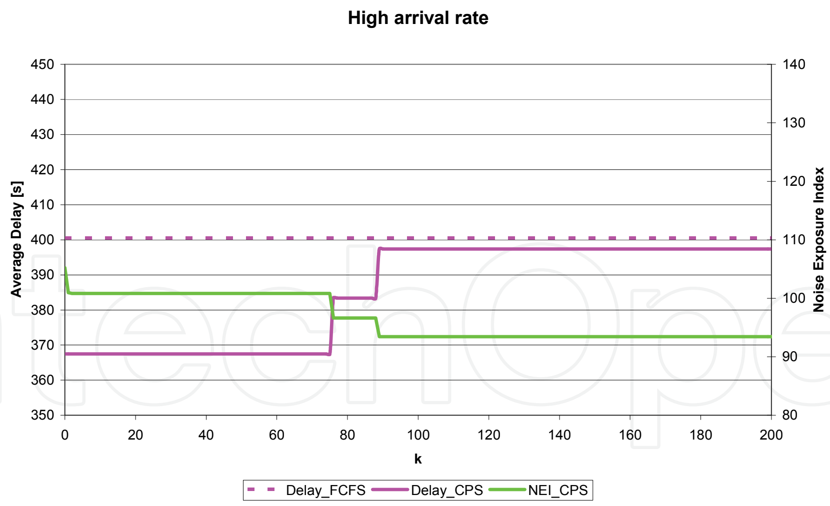

Fig. 5. Scheduler results for an arrival rate higher than the runway capacity

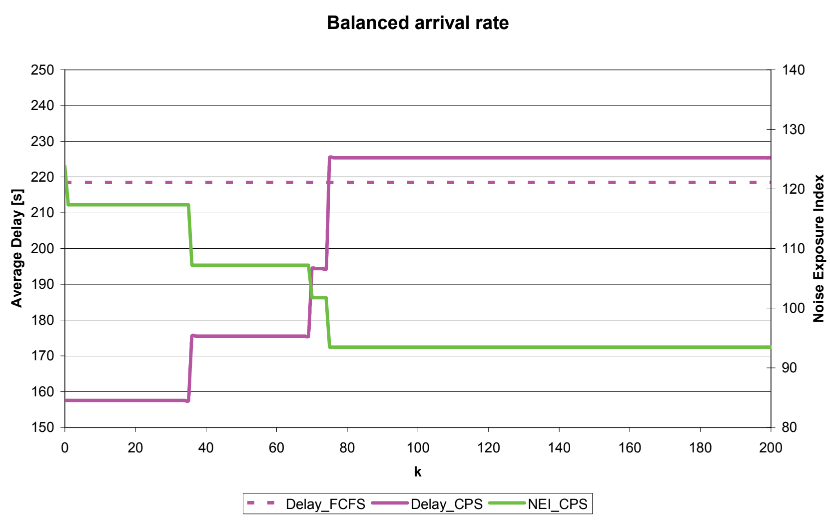

Fig. 6. Scheduler results for an arrival rate near the runway capacity

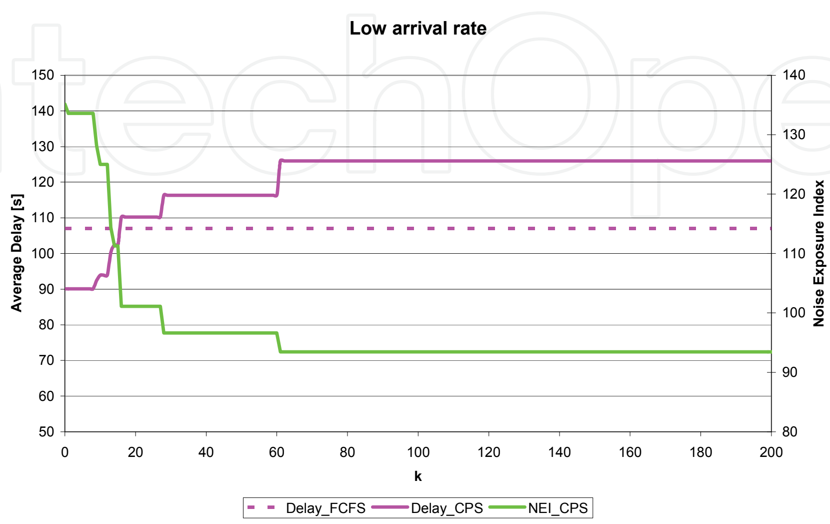

Fig. 7. Scheduler results for an arrival rate lower than the runway capacity

An obvious solution is to add a cumulative exposure indicator to the problem. A well-known indicator based on either L_{dn} or L_{den} is the number of people annoyed by aircraft noise, based on the relations as established by Miedema (Miedema & Oudshoorn, (2001). These dose-response relationships predict the long term average percentage of people annoyed by aircraft noise, based on the L_{dn} or L_{den} levels. Combining this information with population data, this leads to the single number annoyance indicator.

Whether using a single event or cumulative exposure metric, the scheduler will still need to make decisions on a per flight basis. A possible setup is to use the cumulative exposure of a past period of certain duration, and calculate the increase in exposure due to the flight currently under consideration. Based on the difference, the rise in total population annoyance can be computed, resulting from the marginal contribution of that movement. The first problem with this approach is that the dose-response relations have been established for long term average and stabilized exposure. As such, the additional annoyance calculated from a single flight, is certainly not guaranteed to be near the actual increased annoyance due to single flyover, if such increase could be quantified in the first place. However, when aware of this limitation, it can still be used to compare different alternatives.

A more fundamental problem lies in the behaviour of the dose-response relation itself. This is illustrated in figure 8. The annoyance percentage is a function of L_{dn} or L_{den} in dB(A) and is plotted against decibels on a linear scale, as in the left part of the figure. Plotted like this, the function appears to be convex. This would be desirable for our course, because when minimizing for annoyance, the increasing slope would result in traffic being directed away from the areas were exposure is already high. However, the function can also be plotted against a number of noise events, say the number of annual noise events of 90 dB(A) SEL each, as indicated in the right part of the figure. Here the function turns out to be concave, resulting in exactly the opposite behaviour: as soon as a certain area is experiencing high noise levels, annoyance is hardly increased by adding more flights. This cannot only be observed when examining this particular dose-response relation. When plotting other dose-response relations - like the one as established by Schultz (Federal Interagency Committee on Aviation Noise, 1997) - against the number of noise events, the same observation can be made. Apparently, total community annoyance can be minimized by maximizing exposure in the least sensitive area.

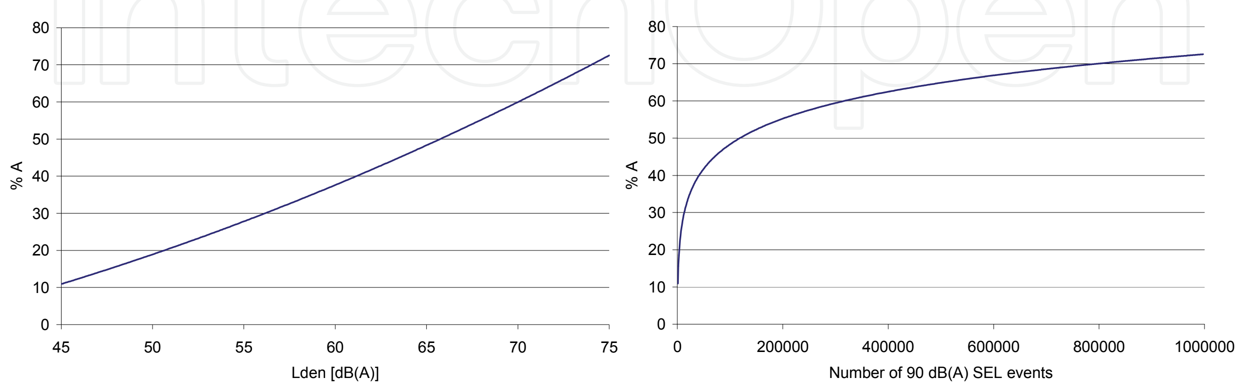

Fig. 8. The Miedema dose-response relation plotted against Lden in dB(A) as well as against a number of annual 90 dB(A) SEL events

Summarizing, when flight movement concentration results in unacceptable (or 'unfair') cumulative noise levels, adding indicators based on cumulative exposure annoyance does not solve the problem. An alternative is to set maximum allowable levels. When enforcing these maximum level limits by adding constraints to the scheduling problem, traffic will be redistributed in order not to break the limits. If cumulative level limits are defined as annual maxima, it can be desirable to derive a daily or hourly allowance, based on the year-to-date exposure. This can prevent very high exposure in one part of the year compared to a very low exposure in the remaining part, or vice versa.

5. Conclusions and future work

The foreseen transition towards TBO offers a unique possibility to integrate environmental management into the actual ATC process. When using such a form of integrated environmental management, it can be ensured that all actions taken to minimize the nuisance caused are consistent. At the same time, this concept allows all aircraft to fly trajectories that are optimized with respect to several objectives, including airport and airline efficiency and environmental ones.

Since the envisioned concept is years or even decades away from realization, adding noise considerations to the objective function of current or near future arrival managers appears to be an attractive interim solution. Based on the results of a model using the concept of fixed arrival routes in combination with CDA procedures, a small improvement in noise exposure can be achieved even without sacrificing efficiency. The noise indicators can be reduced further, but only when allowing increased delay. For low traffic situations, this can easily lead to situations that are worse than the FCFS solution in term of delay, but for heavy traffic situations, the trade-off is more advantageous.

Based on these results, it appears advisable to incorporate noise information in the arriving traffic scheduling process, even when sacrificing efficiency is deemed unacceptable. Further research will be conducted to look into the possibility of adding noise information to the performance indicator of a real arrival manager, as well as the effect of incorporating annual cumulative noise exposure limits.

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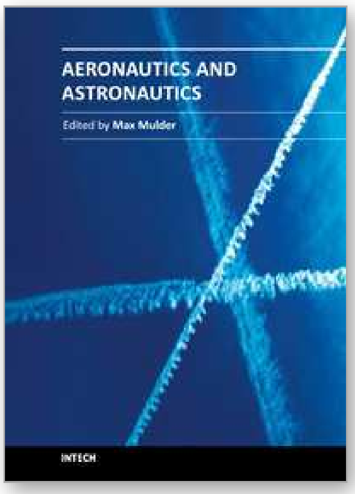

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In its first centennial, aerospace has matured from a pioneering activity to an indispensable enabler of our daily life activities. In the next twenty to thirty years, aerospace will face a tremendous challenge - the development of flying objects that do not depend on fossil fuels. The twenty-three chapters in this book capture some of the new technologies and methods that are currently being developed to enable sustainable air transport and space flight. It clearly illustrates the multi-disciplinary character of aerospace engineering, and the fact that the challenges of air transportation and space missions continue to call for the most innovative solutions and daring concepts.

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