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Simultaneous design of different aircraft departure routes taking community noise exposure events into account

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ABSTRACT

At many airports, ground track segments may be shared by different departure routes, and the population living underneath these segments is exposed to all aircraft movements which are sent to these routes. This may cause negative community reaction to authorities and policymakers, leading to objections against the expansion of airport and aircraft operations. To take into account this concern in the design of optimal departure routes, a new multi-objective optimization formulation is developed and solved in this study. Besides two conventional objectives, i.e., annoyance and fuel consumption, a new objective is considered in the problem formulation which aims to split a ground track segment shared by two different departure routes into two different parts corresponding to each route. As a consequence, the number of people exposed to all flights operating on these routes is decreased considerably. An optimization problem with three objectives is formed, and solved by a multi-objective evolutionary algorithm based on decomposition (MOEA/D). The reliability and applicability of the developed model are demonstrated through a case study at Amsterdam Airport Schiphol. The obtained simulation results reveal that the proposed approach can offer solutions which can more effectively balance between the considered objectives.

Keywords: Noise, Environment, Annoyance
I-INCE Classification of Subject Number: 30

1. INTRODUCTION

Despite having a positive influence on economic growth and job creation, air transport also has some negative impacts causing a significant amount of noise and pollutant emissions that directly influences on the quality of life of communities

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surrounding airports. As a result, the extension of airport and aircraft operations is often faced with the opposition from the communities surrounding airports. This opposition may become more serious as the aviation industry is predicted to rapidly grow in the coming years [1]. Basically, in order to make the operations of aircraft and airports more sustainable as well as to protect the communities from noise emission zones, noise regulations such as the European Environmental Noise Directive 2002/49/EC [2], and the Night Noise Guidelines for Europe [3] are applied. In addition, research on noise mitigation has been quite extensive and attracting much attention from researchers over the years.

Among different research directions, the design of optimal departure and arrival routes appears as a potential approach [4]. In this field, the selection and formulation of optimization criteria are quite important. There are two common objectives that are often considered in previous studies, notably noise annoyance and fuel consumption. Regarding noise criteria, research can be classified into two groups: single-event and cumulative noise criteria. In the first group, only a single aircraft noise event is considered, and hence the obtained route is optimized only for one specific aircraft type [5–11]. Meanwhile, the second group takes into account multiple aircraft noise events concurrently, and the obtained result is therefore optimized for all considered aircraft types [12–14]. Nevertheless, because of the limitation on computational cost, this approach often designs only one route which is applied to all aircraft types. It therefore cannot take full advantage of the characteristics of each individual aircraft type. From an operational perspective, however, this approach may be more realistic, as it is easier to handle all aircraft types on the same route compared to managing separate routes for different aircraft types.

By looking at the studies in the second group, it is recognized that the noise criteria used in this group are often related to noise annoyance (e.g., the number of people annoyed), which is derived from L_{den} or L_{night} metrics [12,13,15]. However, recent studies have indicated that these metrics entail certain shortcomings such as a lack of transparency and difficulties for the general public to understand them [16,17]. Furthermore, these metrics do not sufficiently consider the influence of the frequency of noise events, which has recently been recognized as one of the emerging concerns that should be investigated and taken into account in noise regulations and policies [18–20].

With the consideration of the above issues, it can be imagined that the increase in the number of aircraft movements could lead to serious issues at busy hub airports such as Amsterdam Airport Schiphol (AMS), where the different departure routes often share the same ground tracks during a certain time of departure operation. In an effort to address this concern in the design of optimal routes, a new multi-objective optimization formulation is developed in this study. In the problem formulation, a new objective that aims to reduce the number of people living underneath a flight path shared by two different departure routes is introduced. The purpose of considering this objective is to reduce the number of people exposed to all noise events (and hence the frequency of these events) as much as possible by allocating aircraft to two different departure routes as soon as possible. In addition, to keep optimal solutions in a balanced trade-off with other conventional concerns such as overall noise annoyance and fuel consumption, the total number of people annoyed and fuel burn are also considered as objective functions and optimized concurrently. As a result, a three-objective optimization problem is formulated and then solved by a new version of a multi-objective evolutionary algorithm based on decomposition (MOEA/D) developed recently in [10]. A case study at AMS is used to exemplify the reliability and the applicability of the developed model. Moreover, to estimate the influence of the new objective on the obtained solutions, the conventional optimization model that considers only the number of people annoyed and fuel burn as objectives is also applied to the case study. The obtained solutions of both approaches are analyzed and compared with the reference case.

2. OPTIMIZATION PROBLEM FORMULATION

In order to get a better insight into the problem formulation a case study at AMS is introduced, in which two standard instrument departures (SID), namely LEKKO and LUNIX, are considered.

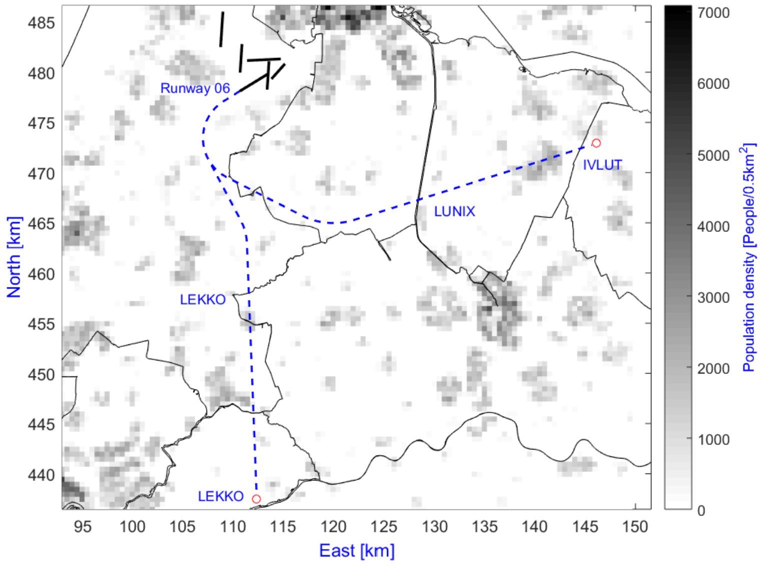


Figure 1. Illustration of LUNIX and LEKKO SIDs.

As seen in Figure 1, these SIDs share the same ground track at the start of the departure routes, and the people living underneath this flight path will be exposed to all aircraft movements operating on these routes. As mentioned earlier, the main purpose of this study is to design new routes which lead to a reduction of the number of people exposed to all flight movements departing from these routes. To achieve this objective, therefore, it is obvious that the routes should be split up as soon as possible. However, this aim may make the optimal routes worse for other criteria, such as the total number of people annoyed and fuel burn, due to the spread of noise and longer routes. Thus, to make the optimal solutions well-balanced between concerned criteria, all these criteria are considered as objective functions. Consequently, a multi-objective optimization problem with three objectives is formulated and stated as follows:

$$\underset{\mathbf{d}\in\Omega}{\text{Minimize}} \qquad \left\{ f_1(\mathbf{d});\, f_2(\mathbf{d});\, f_3(\mathbf{d}) \right\} \tag{1}$$

where $\mathbf{d} = \{\mathbf{g}, \mathbf{p}\}$ is the decision variable vector of the optimization problem, in which $\mathbf{g}$ and $\mathbf{p}$ are the variable vectors defining the horizontal and vertical parts of the routes, respectively. The symbol $\mathbf{\Omega}$ is the feasible design space of the optimization problem, which is determined based on the intersection of boundary constraints of design variables $\mathbf{d}$ and aircraft performance constraints.

In Equation 1, the first objective $f_1(\mathbf{d})$ is the total number of people exposed to all noise events operating on both routes, and its formulation is given in Equation 2.

$$f_1(\mathbf{d}) = \sum_{j=1}^{2} \bigcap_{i=1;\ \mathrm{N65}}^{N_{\mathrm{at}}} N_{\mathrm{p}_j} \tag{2}$$

where the indices j and i are, respectively, the number of routes and the number of aircraft types. The parameter N_{at} is the number of aircraft types, and the term $\bigcap_{i=1;\ \mathrm{N65}}^{N_{at}} N_{p_j}$ is the total number of people enclosed in the intersection of 65 dBA $L_{A,max}$ (so-called N65) contours caused by all aircraft types on route j. Essentially, this metric counts the number of people exposed to at least 65 dBA $L_{A,max}$ by all departing aircraft. It should be noted that the reason for choosing N65 to estimate $f_1(\mathbf{d})$ is because this metric has been widely used as a noise indicator to evaluate noise events in many countries such as Australia [21], Austria, Sweden and the United Kingdom [17]. The second objective $f_2(\mathbf{d})$ is the total number of people annoyed, which is estimated based on the criterion determined by the European Union [15]. According to the regulation in [15], the percentage of people annoyed (%PA) caused by a certain L_{den} value, is determined as follows:

$$\%PA(\mathbf{s},\mathbf{d}) = 8.588\times10^{-6}(L_{den}(\mathbf{s},\mathbf{d})-37)^3 + 1.777\times10^{-2}(L_{den}(\mathbf{s},\mathbf{d})-37)^2 + 1.221\,(L_{den}(\mathbf{s},\mathbf{d})-37) \quad (3)$$

in which, $L_{den}(\mathbf{s},\mathbf{d})$ is the day-evening-night noise level defined by

$$L_{den}(\mathbf{s},\mathbf{d}) = 10\log_{10}\left[\sum_{j=1}^{2}\sum_{i=1}^{N_{at}} a_{ij}10^{\frac{SEL_{ij}(\mathbf{s},\mathbf{d})+w_{den}}{10}}\right] - 10\log_{10}T \text{ (dBA)}, \quad (4)$$

where $\mathbf{s} = (x, y)$ is the vector of centre coordinates of a grid cell in the investigated area. The variable a_{ij} is the number of aircraft type i on route j. The parameter $w_{den} = \{0,5,10\}$ is the weighting factor for day, evening and night time operations. The metric $SEL_{ij}(\mathbf{s},\mathbf{d})$ is the sound exposure level caused by aircraft type i on route j at the grid cells, which is computed by using a replication of the noise model described in the technical manual of the Integrated Noise Model (INM) [22]. By using a Geographic Information System (GIS), the objective $f_2(\mathbf{d})$ can be estimated by getting the sum of the multiplication of %PA in each grid cell with the population in that cell. The last objective $f_3(\mathbf{d})$ is the total fuel burn which aircraft utilize during departure and denoted as follows:

$$f_3(\mathbf{d}) = \sum_{j=1}^{2}\sum_{i=1}^{N_{at}} a_{ij}\, fuel_{ij}(\mathbf{d}), \quad (5)$$

where a_{ij} is the number of aircraft type i on route j and $fuel_{ij}(\mathbf{d})$ is the fuel burn of aircraft type i on route j.

3. METHODOLOGY

3.1 Trajectory modelling

As mentioned earlier in Section II, the design variable vector of a route includes two parts: horizontal and vertical. By applying the trajectory parameterization technique described in [22], the horizontal part is constructed by employing navigation based on required navigation performance (RNP), in which two common leg types, i.e., track-to-a-fix (TF) and radius-to-a-fix (RF) are used. An example of using these leg types for creating routes is given in Figure 2. It can be observed from the figure that the route consists of four straight legs and three turns. The design variable vector **g** of this route includes L_1, L_2, L_3, R_1, R_2, R_3, $\Delta\chi_1$ and $\Delta\chi_2$, whereas L_4 and $\Delta\chi_3$ are determined through the geometric relationship, where the initial and final position are fixed. For the vertical part, in this paper, the vertical profile is assumed to be fixed and follows the published Noise Abatement Departure Procedures (NADP 1 or NADP 2) in [23]. To exploit the advantage of these procedures, the selection of one of them for each aircraft type on each route is considered as a design variable for this part, which is defined by the design vector **p**.

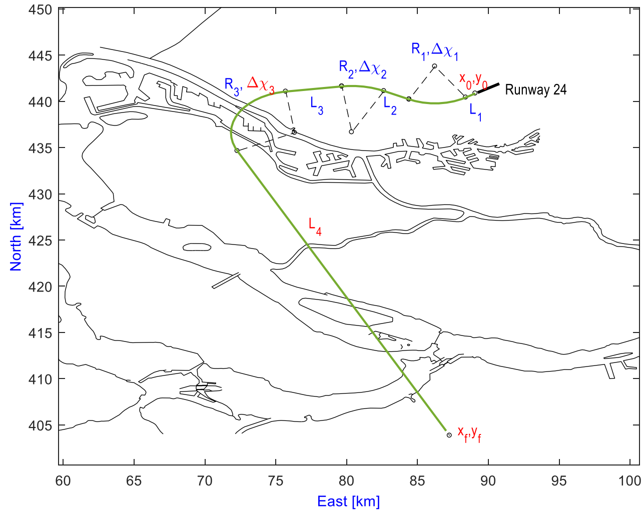


Figure 2. Illustration of ground track parameterization.

3.2 Aircraft performance modelling

The performance of aircraft is evaluated based on an intermediate point-mass model [22]. This model is built based on some assumptions: 1) no wind is present, 2) the Earth is flat and non-rotating, 3) flight is coordinated, and 4) the flight path angle is sufficiently small ($\gamma < 15^0$). The equations of motion are written as follows:

$$\begin{aligned} \dot{V}_{\mathrm{T}} &= g_0\left(\frac{T-D}{W}-\sin\gamma\right), \\ \dot{s} &= V_{\mathrm{T}}\cos\gamma, \\ \dot{h} &= V_{\mathrm{T}}\sin\gamma, \\ \dot{W} &= -ff\, g_0, \end{aligned} \tag{6}$$

in which, g_0, V_T, s, h, and W are the gravitational acceleration, true airspeed, ground distance flown, altitude and aircraft weight, respectively. The parameters T, D, and ff are, respectively, thrust, drag and fuel flow.

In case of low altitudes and airspeeds, the indicated airspeed can be approximated by the equivalent airspeed V_E, and expressed as:

$$V_{\mathrm{E}} = V_{\mathrm{T}}\sqrt{\rho/\rho_0}, \tag{7}$$

where ρ is the ambient air density, and ρ_0 is the air density at sea level.

Based on the relationship in Equation 7(7, the equations of motion in Equation 6 can be rewritten as follows:

$$\begin{aligned} \dot{V}_{\mathrm{E}} &= \left[g_0\left(\frac{T-D}{W}-\sin\gamma\right)+\frac{1}{2\rho^2}\frac{\partial\rho}{\partial h}V_{\mathrm{E}}^2\rho_0\sin\gamma\right]\sqrt{\rho/\rho_0}, \\ \dot{s} &= V_{\mathrm{E}}\sqrt{\rho_0/\rho}\cos\gamma, \\ \dot{h} &= V_{\mathrm{E}}\sqrt{\rho_0/\rho}\sin\gamma, \\ \dot{W} &= -ff\, g_0, \end{aligned} \tag{8}$$

where $\frac{\partial\rho}{\partial h}$ is the derivative of the ambient air density with respect to altitude.

By integrating Equation 8 along the trajectory defined in Section A, the input parameters for the calculation of *SEL* and $L_{A,max}$ are acquired. By using INM, the values of $SEL_{ij}(\mathbf{s},\mathbf{d})$ and $L_{A,max}(\mathbf{s},\mathbf{d})$ at each grid cell are defined.

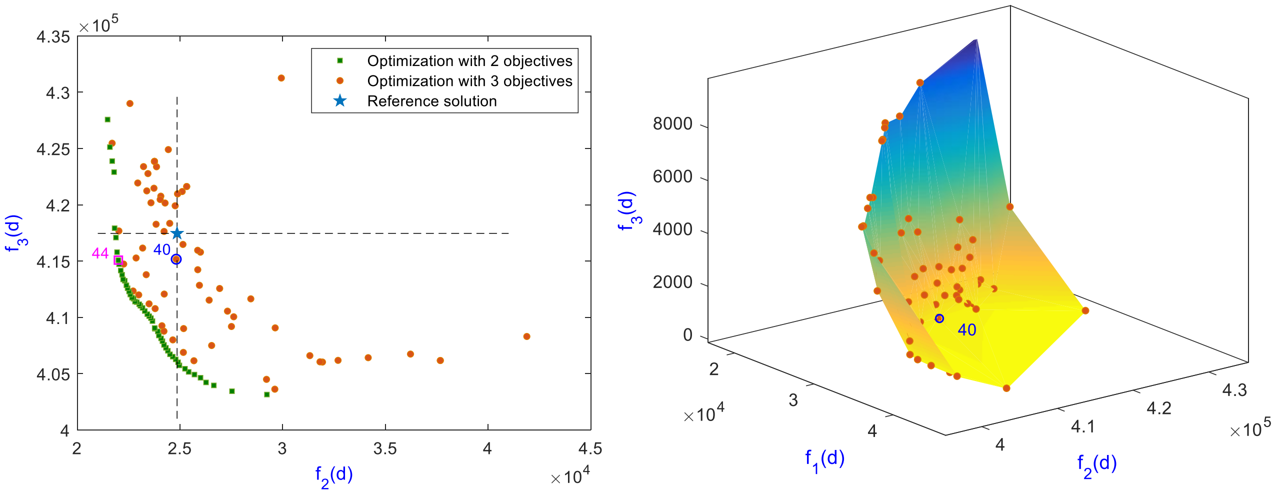
3.3 Optimization method

To solve the optimization established in Equation 1, a new version of an optimization method called the multi-objective evolutionary algorithm based on decomposition (MOEA/D) developed recently in [10] is employed. The MOEA/D method was originally proposed by Zhang and Li [24] and has been recognized as one of the most effective multi-objective evolutionary algorithms in recent years [25]. In MOEA/D, decomposition approaches, such as Tchebycheff decomposition, are utilized to transform a multi-objective optimization problem into a set of scalar optimization sub-problems. Then, evolutionary algorithms, such as differential evolution (DE) and genetic algorithm (GA), are employed to solve these sub-problems concurrently. The performance of MOEA/D for the design of optimal aircraft departure and arrival routes has been demonstrated in [10,26]. Since details of the algorithm have been given in [10,24,27], interested readers are encouraged to refer to these references.

4. NUMERICAL RESULTS AND DISCUSSION

In this section, a case study at AMS is used to evaluate the reliability and the applicability of the proposed approach. Two departure routes called LUNIX and LEKKO, as depicted in Figure 1, are considered. The data of aircraft movements on 22 October 2010, is used [28]. On this day, there were 100 flights operating on route LUNIX (including 66 day, 3 evening and 31 night flights), and 63 flights operating on route LEKKO (including 37 day and 26 night flights). Although many different aircraft types were operated on these routes, for the sake of simplicity all flights are represented by either of two aircraft types, namely the Boeing 777-300 (B773) and Boeing 737-800 (B738). It is assumed that the B773 represents heavy aircraft which account for 20% of the total number of flights, whereas the B738 represents small and medium aircraft which account for the remaining 80%. These aircraft are modelled based on the Base of Aircraft Data (BADA) [29]. Two different problems (approaches) are considered here. The first problem is the conventional problem which only considers the number of people annoyed and fuel burn as the objectives, and the second problem is as established in Equation 1. A region of 51x42 km with a population grid cell size of 500x500 m obtained from the Dutch Central Bureau of Statistics (CBS) is investigated. The MOEA/D algorithm with a population size of 50 is used to solve both problems.

The comparison of Pareto solutions in terms of the number of people annoyed and fuel burn obtained by both approaches are presented in Figure 3a, in which the reference solution that is evaluated based on the standard SIDs, is also provided. The Pareto surface obtained by the second problem is shown in Figure 3b. All solutions select NADP 2 as an optimal solution for the vertical part. From Figure 3a, it can be seen that some of the solutions of the second problem are quite close to those of the first one, while most of the other solutions are dominated by those of the first problem. Nonetheless, the solutions obtained in the first problem perform quite poorly with respect to the first objective, i.e., the number of people exposed to all flights. This is because the solutions obtained by the first approach only balance between two objectives, i.e., the number of people annoyed and fuel burn, while those obtained by the second approach have to balance all three objectives. In comparison with the reference solution, it is also observed that both approaches offer better solutions regarding both the number of annoyed people and fuel burn.

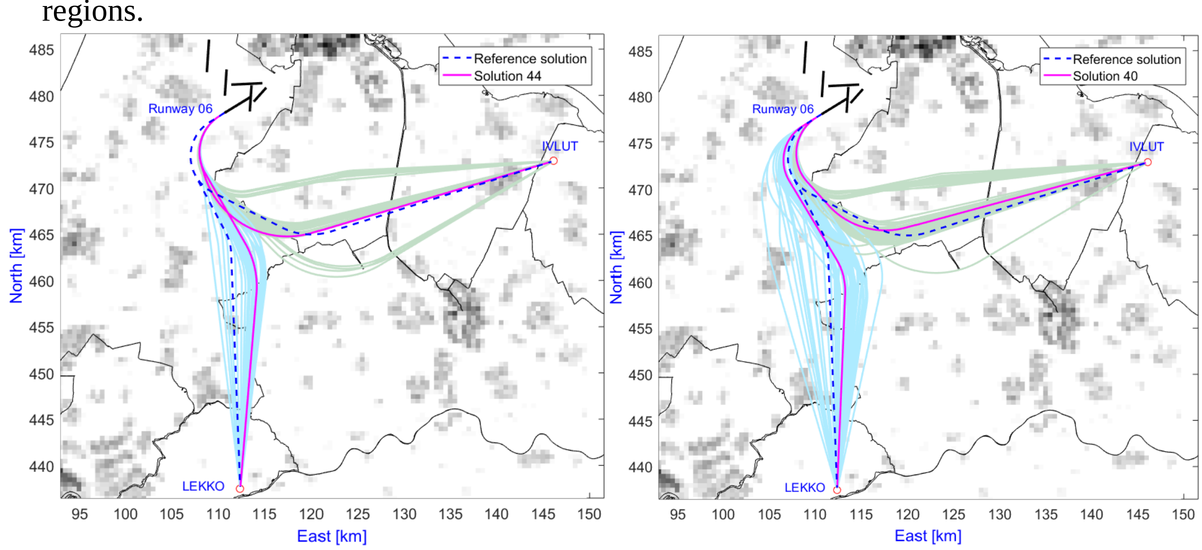


a) Comparison of Pareto fronts obtained by the first and second problems and the reference case.

b) Pareto fronts obtained by the second problem.

Figure 3. Illustration of optimal solutions.

The ground tracks corresponding to the results given in Figure 3 are visualized in Figure 4. As can be seen from the figures, all solutions obtained by the first approach share the same flight path at the start of the routes, while those obtained by the second approach try to split the flight paths as soon as possible. This explains why the solutions obtained by the first problem perform quite poorly with respect to the first objective. Also, it is recognized that all solutions obtained by both approaches try to avoid populated regions.



a) The first problem.

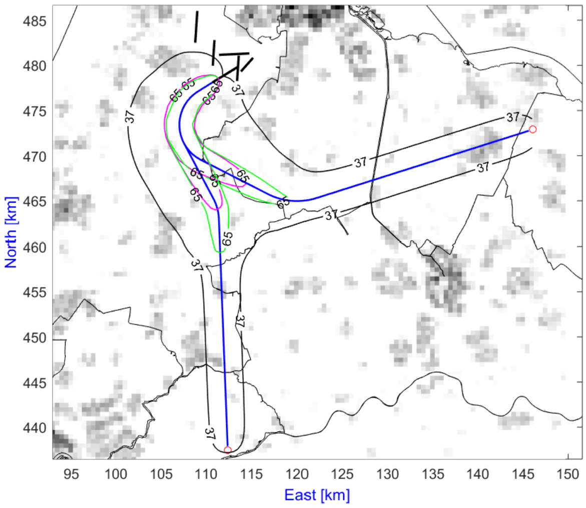
b) The second problem.

Figure 4. Illustration of optimal ground tracks.

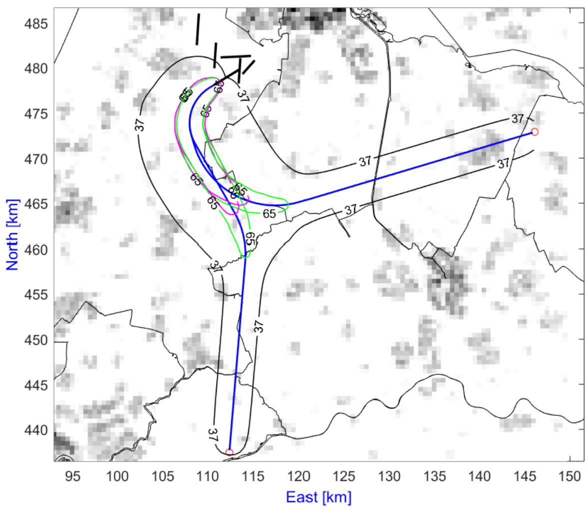
For a comparison of specific values, two solutions, *viz.* solution 44 representing the first approach and solution 40 representing the second approach, are selected and highlighted as in Figure 3 and Figure 4. It should be noted that the reason for selecting these solutions is based on the purpose to identify solutions that have a good trade-off between all the considered objectives, whilst they still have better performance compared with the reference case. A comparison of the objectives of these solutions is given in Table 1. In terms of the number of people annoyed, it can be seen from the table that the first approach gives a reduction of 11.5% compared to the reference case, while that of the second approach has almost the same performance. Regarding fuel burn, both approaches result in almost the same amount as the reference case. There is, however, a large difference associated with the number of people exposed to all noise events. Specifically, solution 40 shows a significant reduction of 41.2%, while solution 44 features a huge increase of 105.5%. The reason for this difference can be readily understood from the noise contours of these solutions in Figure 5, where the N65 pink contour is caused by aircraft type B738, while the N65 green contour is caused by aircraft type B773, and the blue one is the 37 dBA L_{den} contour evaluated by Equation 3.

Table 1. Comparison of the criteria of the representative solutions and the reference case.

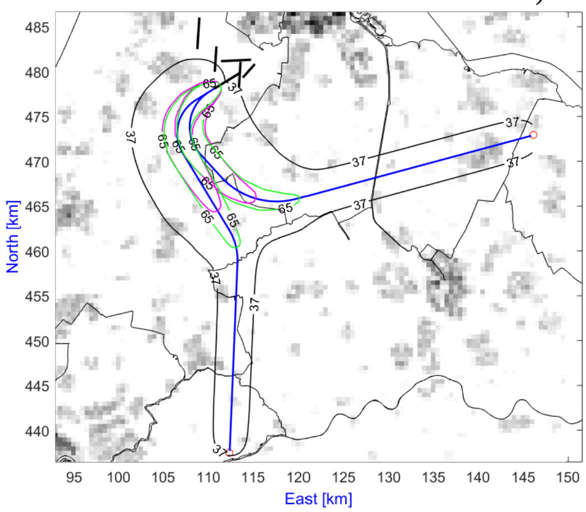
Optimization approaches	Case number	No. of people annoyed	Fuel burn (kg)	No. of people living within N65 and exposed to all flights
2 objectives	Solution 44	22002	415085	7790
	% reduction	-11.5	-0.6	105.5
3 objectives	Solution 40	24818	415167	2230
	% reduction	-0.2	-0.5	-41.2
Reference solution		24859	417461	3790



a) Reference solution



b) Solution 44



c) Solution 40

Figure 5. Illustration of noise contour levels.

5. CONCLUSIONS

A new multi-objective optimization formulation for the design of optimal departure routes has been presented in this study, based on the assumption that in future noise regulations flight frequency – and hence noise exposure frequency – will play an increasingly important role. In the problem formulation, besides two traditional objectives, i.e., noise annoyance and fuel consumption, a new objective is considered that aims to reduce the number of people living underneath a flight path shared by two different departure routes. This objective aims to reduce the number of people exposed to all aircraft movements operating these routes as much as possible. A case study at AMS has been conducted to demonstrate the reliability and applicability of the proposed model. The influence of considering the new objective on the conventional approach has also been investigated. The simulation results indicate that the proposed model is capable of providing solutions that can balance effectively between the considered objectives.

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