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Strategic Planning of Aircraft Movements with a Three-Cost Objective

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Europe's public airports and its aviation industries face the transport challenge of working toward sustainable development, a concept that incorporates both the effective functioning and protection of the environment. This paper addresses how a decision tool is applied toward aviation community noise and could be used to assist in airport management and environmental policies in their overall reduction of noise at lowest global costs. A coupled cost/noise approach is based on the integrated noise model simulation software and a geographic information system. Both models are combined and accessed via a Web-based scheduling tool; aviation noise and related costs are fed to an intermediate database and then used in a minimal-cost-objective problem. The calculation is done in the context of the air freight company Cargolux Airlines International S.A., based at Findel Airport (Luxembourg). The minimization problem is formulated as a linear program. The optimal solution represents the best arrangement of the carrier's daily scheduling, approach/departures routes, operational procedures, and fleet composition, which minimizes the overall cost. Simulated night-level noise is used to estimate numbers of habitations that would require noise insulation at a cost to the state. Depreciation levels for private residences are also modeled. Combined company, state, and private costs are used in one objective function. The methodology is based on current aircraft movements and reasonable growth parameters that allow for a case study in sustainable (International Air Transport Association) air transportation and a balanced approach.

Nomenclature

$\mathbf{A}$ = all combinations of numbers of aircraft type
$\mathcal{C}$ = summed total costs
$\tilde{\mathcal{C}}$ = linear approximations to cost
$\mathcal{C}_C$ = company costs
$\mathcal{C}_{\text{fc}}$ = local in-flight fuel expenditures
$\mathcal{C}_{\text{lc}}$ = landing fees
$\mathcal{C}_{\text{pc}}$ = night-flight penalty charges
$\mathcal{C}_S$ = state costs
$\mathcal{C}_{\text{tc}}$ = ground fuel (taxiing) expenditures
$\mathcal{C}^*$ = summed company costs
$\mathrm{d}s$ = differential space step
h = weighted mean cost for a habitation
i = index for day (0700–1900 hrs)
j = index for evening (1900–2300 hrs)
k = index for night (2300–0700 hrs)
L_{eq} = single-event continuous sound pressure level
L_N = average level of noise at night
m = index for lower-limit night threshold level
N_M = number of flight movements
N_{nig} = number of night flights
$\underline{\mathbf{N}}_\ell^{\mathbf{AC}}$ = minimum number of aircraft, type ℓ
$\bar{\mathbf{N}}_\ell^{\mathbf{AC}}$ = maximum number of aircraft, type ℓ
$\underline{\mathbf{N}}_\ell^{\mathbf{AP}}$ = minimum number of approaches, type ℓ
$\bar{\mathbf{N}}_\ell^{\mathbf{AP}}$ = maximum number of approaches, type ℓ
$\underline{\mathbf{N}}_\ell^{\mathbf{OP}}$ = minimum number of operational procedures, type ℓ
$\bar{\mathbf{N}}_\ell^{\mathbf{OP}}$ = maximum number of operational procedures, type ℓ
$\underline{\mathbf{N}}_\ell^{\mathbf{SH}}$ = minimum number of schedule possibilities, type ℓ
$\bar{\mathbf{N}}_\ell^{\mathbf{SH}}$ = maximum number of schedule possibilities, type ℓ
$\underline{\mathbf{N}}_\ell^{\mathbf{TO}}$ = minimum number of takeoffs, type ℓ
$\bar{\mathbf{N}}_\ell^{\mathbf{TO}}$ = maximum number of takeoffs, type ℓ
n_ℓ = general element in combination sets
$\mathcal{P}$ = planning period
p_S = number of inhabitants in region
p_Z = scenario-dependent noise factor linked to citizen costs
R^2 = regression value
s = general space coordinate
s_1, s_2 = Cartesian coordinates to localized surface
$\mathbf{T}^{\mathbf{AP}}$ = all combinations of other combinations of approach routes
$\mathbf{T}^{\mathbf{TO}}$ = all combinations of other combinations of takeoff routes
α = average number of habitations per inhabitant in the study area
β = average costs of noise insulation
Γ = set of all night threshold levels
γ_C = company growth rates
δ = growth rate for habitations
δ_P = population density
$\mathbf{\Theta}$ = all combinations of other operational procedures
μ = mean noise depreciation index
Ξ^S = reduced-noise area
$\mathbf{\Pi}$ = all combinations of schedules
$\tau_\bullet$ = lower-limit night threshold level
Υ = deviations in the selection of takeoffs and landings, operational procedures, and scheduling
Υ_{AC} = deviations in the selection of aircraft type
Ω = set of all combinations of aircraft type, takeoff, approach routes, operational procedures, and schedules
ω = element of Ω

I. Introduction

NOISE originating from air carriers and freight traffic represents one of the most important environmental impact concerns in the European urban environment. Community noise [1] is the noise that is perceived by habitants surrounding the modern metropolitan airport. According to the International Civil Aviation Organization (ICAO), despite significant noise reductions achieved in the last 40 years through the evolution of quieter aircraft and engine technology,

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flight frequencies have increased and populations have grown and expanded into the relatively confined spaces around some airports [2]. The management of aircraft noise is a key issue in the attempt toward sustainable aviation growth, an activity that incorporates the combined notion of effective administration of airport functioning and protection of the environment.

The challenge can be achieved in the framework of a balanced approach acting between the needs of the community (minimizing noise and improving air quality) and the need for commercial activity. These needs are competitive and intertwined; commercial activity is essential for the wellbeing of the community. This very activity potentially generates adverse community noise. These needs have given rise to the general theme of common transport policy of sustainable transportation development, the concepts of which are reviewed by the International Air Transport Association [3].

A summarizing statement from the International Air Transport Association incorporates this balance:

"The aviation industry relies on a rational, stable, and international harmonized regulatory framework adapted to its long development cycles and long product life. The development of noise reduction technologies is driven by a broad long-term vision of the worldwide future environmental requirements."

The ICAO vision consists of identifying the noise problem at an airport and then analyzing the various measures available to reduce noise using four principal elements: reduction at the source, land-use planning and management, noise-abatement operational procedures, and aircraft operating restrictions.

The four measures describe the necessity for a balance between environmental benefits, technological feasibility, and economic viability described in European noise directives.

The first part of the balanced approach works toward environmental improvement. Globally, environmental impact from carriers can be reduced by one of three methods: reducing the number of carriers or aircraft movements, rearranging the movement so that the impact is minimized, or lowering the noise at the source with quieter aircraft. Historically, the first method has been frequently used; direct economic instruments (charges, taxes, and penalties) have been used to curb airports activities and reduce noise [4,5].

The rearranging of air movements requires an augmented level of planning sophistication. Several airport pilot projects have been launched, including studies of noise-abatement procedures [6,7] and modified operational procedures, for example, at London's Heathrow Airport [8]. Others have explored the role of air traffic controllers, whereby using their global knowledge of the situation had reduced aviation noise by directing appropriate procedures such as continuous descent [9] when appropriate. Still others, outside of the European Union, have been prompted by Federal Aviation Administration [10] criteria in order to explore alternative flight patterns under appropriate conditions, minimizing aviation-related noise to the surrounding community [11]. Other work along these lines includes environmental noise and gas abatement using optimization tools [12].

The question then arises of who should pay for such improvement and how much should one pay. Will it be the airlines and airports [13], or the citizen [14], or the government [15]? Attempts have been made to connect costs for noise, air pollution, and accident risks using data on aircraft emissions, exposure-response parameters, and economic valuation of environmental goods [15]. Such studies show that the environmental costs represent only a small fraction (2.5%) of the internal cost of aviation as measured by the average ticket price; three-quarters of this cost addresses noise abatement.

We explore the cost/noise relationship with Cargolux Airlines International S.A. (hereby referred to as Cargolux) air freight's activities. The company is located at Findel Airport, located 6 km from the Luxembourg city center. The single-runway airfield is at an altitude of 376 m and is home to both Luxair International Airlines and Cargolux. The runway has a length of 4 km with headings of 60 and 240 (60 and 240° from the north). Figure 1 gives an overhead view of the runway, departure, and approach routes, the fix station measurement locations (not used in this study) and the surrounding area. Figure 2 gives examples of the operational procedures.

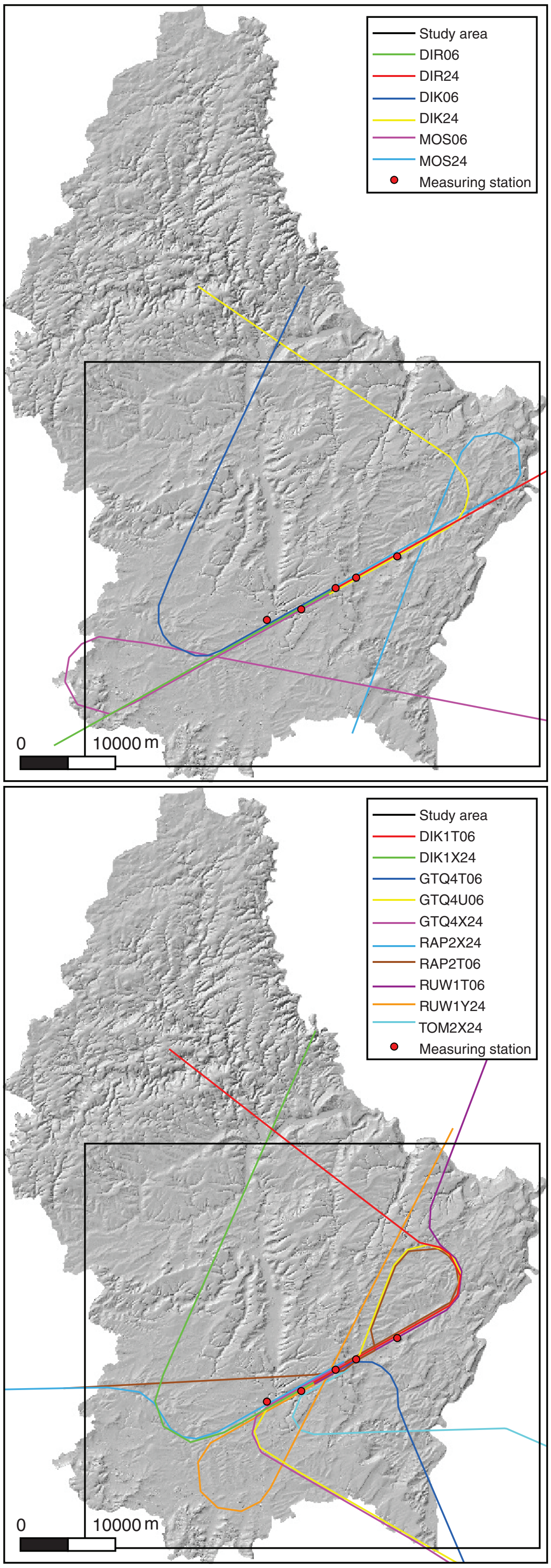

Fig. 1 Overview of the study area: six arrival (top) and 10 departure (bottom) routes and the five noise-measuring stations.

II. Methodology

A. Noise Metrics

Our study is based on a single-event exposure level (SEL) based on the single-event continuous sound pressure level L_{eq}. The SEL is the L_{eq} normalized to 1 s. $SEL_{i,j,k}$, can be evaluated during different times of the day [i for day (0700–1900 hrs), j for evening (1900–

Table 1 Descriptions of scenarios and major set symbols

Scenarios and major set symbols	Description
Base	Cargolux base settings for Dec. 2002
Routes T	
TRD[a] 1-10	All flights forced to be one of these 10 takeoff routes
TRA[b] 1-6	All flights forced to be one of these six approach routes
Scheduling Π	
Day	All flights forced to be in day
Evening	All flights forced to be in evening
Night	All flights forced to be in night
Operational settings Θ	
CDA	Approach continuous descent
ALF	Approach landing flaps
LAC	Departure lower-altitude cutback
DTT	Departure displaced threshold takeoff
DTA	Approach displaced threshold
MTOF	Departure minimum takeoff flap setting
PTDC	Departure performance takeoff deep cutback
Aircraft type A	
CURRF	Current fleet (747-400)
≡ base Dash 8	Quieter new fleet (747-8)

[a]TRD is trajectory departure. [b]TRA is trajectory arrival.

2300 hrs), and k for night (2300–0700 hrs)] and is typically evaluated for air craft noise using simulation tools. In this study, we focus only on the night period (2300–0700 hrs). We use the 3-D spatial and temporal calculator, the integrated noise model, INM 7.0 [10]. The multi-event night metric L_N is determined in a space $\mathbf{s} = (s_1, s_2)$. Noise is added only during the night period and represents noise that is the most problematic to the surrounding community. The metric is developed in a Cartesian coordinate system†,

$$L_N(\mathbf{s}) = \log_{10} \sum_{k=1}^{N_{\text{nig}}} 10^{\text{SEL}_k(\mathbf{s})/10} \tag{1}$$

where L_N is the average level of noise at night.

B. Scenario Development

We explore a set of aircraft movements that are distributed over the 24 h day and are composed of various aircraft flight settings, including: flight scheduling, movement route vectors, operational procedures (e.g., time profiles of turbine power levels at takeoff and climb, flap settings in takeoffs and approaches, altitude variations in climb and approaches, takeoff/landing runway displacements), and fleet composition. We consider $N_M = 400$ movements (200 arrivals and 200 departures) for Cargolux over a period of December 2002, yet add the potential modifications for 747-8 aircraft. We inventoried five major sets that are separable and tunable.

As an example, for all combinations of numbers of aircraft type, $\mathbf{A} = \bigcup_{\ell \in 1,2} n_\ell^{\text{AC}}$ ($n_\ell^{\text{AC}} \in [\underline{N}_\ell^{\text{AC}}, \bar{N}_\ell^{\text{AC}}]$ and $\mathbf{A} \subset \mathbf{Z}^{2+}$) and represents the number of 747-400 and 747-8 aircraft, respectively, with minimum and maximum limits. We refer the reader to [16] to describe the other combinations of takeoff routes $\mathbf{T}^{\text{TO}}$, approach routes $\mathbf{T}^{\text{AP}}$, operational $\mathbf{\Theta}$, and scheduling combinations $\mathbf{\Pi}$. A decision vector ω, $\omega \in \Omega := \{\mathbf{A}, \mathbf{T}^{\text{TO}}, \mathbf{T}^{\text{AP}}, \Theta, \Pi\} \subset \mathbf{Z}^{28+}$, is created by concatenation of n_ℓ from the above combinations, and the vector is used in a nonlinear integer programming (NLIP) problem. We rewrite the static noise metrics using the decision variable $\text{SEL}(\mathbf{s}, \omega)$ and $L_N(\mathbf{s}, \omega)$. Short scenario descriptions are given in Table 1.

C. Cost Calculations

The noise cost function is composed of three parts: the company, state, and private citizen (habitation owner). In the comparison of these disparate cost sources, we build the calculation first on a short-term one-year perspective (for the company), then combine it with a longer-term period for the state and private citizen costs.

1. Cost to the Company

Company costs are determined by a combination of local in-flight fuel expenditures $\mathcal{C}_{\text{fc}}$, ground fuel (taxiing) expenditures $\mathcal{C}_{\text{tc}}$, night-flight penalty charges $\mathcal{C}_{\text{pc}}$, and landing fees $\mathcal{C}_{\text{lc}}$.

The fuel expenditures in this calculation include only those costs that are required by the aircraft in a takeoff or as it approaches the airport. We do not include fuel used by the aircraft above 915 m. The full journey links represent cruising altitudes (outside of INM range) and are also scenario-independent. The expenditures are predicted with linear regression. Candidate variables are true airspeed, barometric altitude, operation (approach or departure), thrust, and engine type. Stepwise-backward regressions suggested taking all variables into account.

The regression analysis reveals an R^2 of 0.6, suggesting an error of 40%. The fairly large error results from outliers in fuel flow measurements and nonlinear behavior of some of the predictors. Using a linearized approach results in the current R^2. A nonlinear approach might lead to a slightly better result, but was out of the main focus of this paper.

Taxiing costs $\mathcal{C}_{\text{tc}}$ include the fuel needed to move an aircraft to/from the hangar and to/from the ends of either runway 06 or 24 (Fig. 1). Landing charges $\mathcal{C}_{\text{lc}}$ depend on the weight of the aircraft and the period of the day. Values are summarized in Table 2.

Considering costs for a 12-month operation, the scenario-dependent total company costs are built from the one-month fuel expenditures:

$$\mathcal{C}^*(\omega) = \mathcal{C}_{\text{fc}}(\omega) + \mathcal{C}_{\text{tc}}(\omega) + \mathcal{C}_{\text{lc}}(\omega) + \mathcal{C}_{\text{pc}}(\omega) \tag{2}$$

$$\mathcal{C}_C(\omega) = 12\mathcal{C}^*(\omega)(1 + \gamma_C) \tag{3}$$

where $\gamma_C = 0.058$ is the expected growth of Cargolux movements. We do not consider the full origin-destination links and the fuel expended in these routes.

2. Cost to the State

State costs in this example are to finance (100% level) the insulation for habitations in regions above night threshold levels. The cost is based on the contour footprint of $L_N(\mathbf{s}, \omega)$ and the number of inhabitants in the same region. A night-level indicator, based on a tuning parameter threshold level for night, is constructed using a lower limit: $\tau_\bullet \in \Gamma := \{50, 55, 60\}$. Integrating over a reduced area, $\Xi_\bullet^S(\omega) := \{\Xi^S \mid \omega, \tau_\bullet \leq L_N(\mathbf{s}, \omega)\}$,

$$p_S(\omega) = \int_{\Xi_\bullet^S(\omega)} \delta_P(\mathbf{s})\,\mathrm{d}s \tag{4}$$

where $\delta_P(\mathbf{s})$ is the population density and $p_S(\omega)$ is the number of inhabitants in region $\Xi_\bullet^S(\omega)$, The cost associated with the state is

$$\mathcal{C}_S(\omega) = p_S(\omega)\alpha\beta(1 + \gamma) \tag{5}$$

The average number of habitations per inhabitant in the study area is $\alpha = 0.32$. We consider habitation to include apartments and houses. We base this value on the number of habitations in a commune (Sandweiler) adjacent to Findel Airport. The average costs of noise insulation is ($\beta = €20,000$/habitation) based on a average of several sources. The value of €20,000 is roughly equivalent to the cost for insulation in a study at Anchorage International Airport [17], as well as general U.S.,‡ Belgium [18], and U.K. costs. The growth rate for habitations is $\delta = 0.038$ (2005 value) [19] and the flight growth γ_C, combining $\gamma = \gamma_C + \delta$, represents the combined growth of the population and the company.

†Considering the problematic night noise, we focus only on the L_{DEN} subset-night metric, whereas [16] also covers the full day–evening–night metric L_{DEN}.

‡Data available online at http://www.nonoise.org/library.htm [retrieved July 2010].

Table 2 Ground cost calculations: landing fees calculated based on maximum takeoff weights

	Day/evening (0600–2300 hrs)	Night (2300–0600 hrs)
	Landing fees	
747-400	€6.45 × 396.890 t = €2560	2 × €2560
747-8	€6.45 × 439.985 t = €2837	2 × €2837
	Takeoff (penalty)	
747-400	€0.0	1 × €2560
747-8	€0.0	1 × €2837
	Taxiing costs (arrivals)	
747-400		
Runway 06	3 min × 45 kg/min × €0.6/kg = €81	——
Runway 24	7 min × 45 kg/min × €0.6/kg = €189	——
747-8[a]		
Runway 06	3 min × 50 kg/min × €0.6/kg = €90	——
Runway 24	7 min × 50 kg/min × €0.6/kg = €210	——
	Taxiing costs (unit fees)	
Findel landing fee per ton	6.45€	——
Night factor	2×	——
2010 fuel cost per kg	€0.6/kg	——

[a]The 747-8 kg/min used in taxiing is calculated by scaling the maximum takeoff weights.

D. Cost to the Citizen

A cost model to citizens arises from the depreciation of habitation value due to aviation noise. We necessarily omit the complexities of individual habitation costs (for example, size and/or quality of houses or apartments and particularities of the neighborhood that might include distances to schools and shops) and other noise considerations from road and rail. Our interest is to examine only the scenario-dependent factors: namely, habitation location with respect to noise levels. The cost to the citizen is based on the average hedonic cost of noise impact. Depreciation models have been developed in a wide set of literature [5,14,20]. We use the mean noise depreciation index from Schipper [15] of $\mu_o = 0.81\%$ dB, representing the decrease in price per decibel increase. This value is based on earlier survey work [20,21]. The depreciation is conditioned on the fact that people's perception of value of habitation is connected to the actual measured level of noise and a preestablished noise-value system.

We convert this depreciation level by considering the average habitation cost in $\Xi^S_\bullet(\mathbf{s},\omega)$. Expanding the concept of threshold limits from the previous section, we integrate over a reduced area:

$$\Xi^S_{\bullet,m}(\omega) := \{\Xi^S \mid \tau_{\bullet,m} \le L_N(\mathbf{s},\omega) \bigcap L_N(\mathbf{s},\omega) < \tau_{\bullet,m+1}\}$$
$$\tau_{\bullet,m} \in \Gamma, \qquad \tau_{\bullet,m} < \tau_{\bullet,m+1} \tag{6}$$

A scenario-dependent noise factor is the sum for all sound bands from 50 to 60 dB,

$$p_Z(\omega) = \sum_{m=m_{\min}}^{5} \mu_o m \int_{\Xi^S_{\bullet,m}(\omega)} \delta_P(\mathbf{s})\,\mathrm{d}s \tag{7}$$

and a cost of

$$\mathcal{C}_Z(\omega) = h\alpha p_Z(\omega)(1+\gamma) \tag{8}$$

where $h =$ €381,000 is the weighted mean cost for a habitation, based on a 2006 estimate of 27,941 apartment sale announcements with an average price of €330,000/apartment. The house sale announcements numbered 22,089, with an average price of €549,000/house [22]. This value is an estimate of those habitation costs that fall in the noise footprint of this study, yet are based on the national averages.

E. Minimum-Cost Model

Equations (4), (5), and (8) are combined. Our planning period of $\mathcal{P} = 20$ years represents a moderate period of time where population and flight movement evolution are generally understood. We now combine the three cost terms in a minimization problem:

$$\mathcal{C}(\omega) = \mathcal{P}\cdot\mathcal{C}_C(\omega) + \mathcal{C}_S(\omega) + \mathcal{C}_Z(\omega) \tag{9}$$

The number of aircraft, different flight operations, and schedules are constrained in predefined limits. The sum of all flights is equal to the maximum number of flights, and the optimal solution to the decision is ω^*:

$$\omega^* = \arg\min(\mathcal{C}) \tag{10}$$

$$\text{subject to } \omega \in \Omega \subset \mathbf{Z}^5 \tag{11}$$

$$\underline{N}^{AC}_\ell \le \omega^{AC}_\ell \le \bar{N}^{AC}_\ell, \qquad \ell = \{1,2\} \tag{12}$$

$$\underline{N}^{TO}_\ell \le \omega^{TO}_\ell \le \bar{N}^{TO}_\ell, \qquad \ell \in \{1,\ldots,10\} \tag{13}$$

$$\underline{N}^{AP}_\ell \le \omega^{AP}_\ell \le \bar{N}^{AP}_\ell, \qquad \ell \in \{1,\ldots,6\} \tag{14}$$

$$\underline{N}^{OP}_\ell \le \omega^{OP}_\ell \le \bar{N}^{OP}_\ell, \qquad \ell \in \{1,\ldots,7\} \tag{15}$$

$$\underline{N}^{SH}_\ell \le \omega^{SH}_\ell \le \bar{N}^{SH}_\ell, \qquad \ell \in \{1,2,3\} \tag{16}$$

$$\omega^{AC}_1 + \omega^{AC}_2 = N_M \tag{17}$$

$$\sum_{\ell\in 1,\ldots 10} \omega^{TO}_\ell = N_M/2 \tag{18}$$

$$\sum_{\ell\in 1,\ldots 6} \omega^{AP}_\ell = N_M/2 \tag{19}$$

$$\sum_{\ell\in 1,2,3} \omega^{SH}_\ell = N_M \tag{20}$$

To construct a well-bounded problem, we use minimum and maximum values based on reasonable operational limits, company structure, and fleet evolution. Our strategy is to allow for deviations in the selection of takeoffs and landings, operational procedures, and scheduling by no more than $\Upsilon = 25\%$ from the base values. We chose these values so that they are consistent with strong environmental abatement policies, as suggested by the European Union

Table 3 Incremental cost changes for TRD 1–10 departures (part 2: operations, schedules, and aircraft), $\Lambda_C(\omega) = \mathrm{d}\mathcal{C}_C/\mathrm{d}\omega_{X,\ell}|_{\tau_\bullet}$ €/unit change

		State			Citizen		
Name scheduling	Company	50 dB	55 dB	60 dB	50 dB	55 dB	60 dB
Day	−4,713	−93,670	−8,821	−20	−1,718,529	−136,729	−308
Evening	−4,713	−93,670	−8,821	−20	−1,718,529	−136,729	−308
Night	47,128	1,052,497	354,204	42,265	29,128,164	6,769,889	652,174
Operational settings							
ALF	−169	−8,484	−182	0	−136,518	−2,803	0
CDA	−4,190	0	0	7	308	206	103
DTA	0	−22,037	−1,629	0	−390,309	−25,132	0
DTT	−291	−2,224	−1,190	33	−69,504	−17,339	514
LAC	−393	−3,909	3,012	13	33,255	46,888	206
MTOF	−172	−6,709	−43	0	−104,864	−671	0
PTDC	−3,291	−17,520	2,359	637	−168,036	56,066	9,833
Aircraft type							
CURRF ≡ BASE	——	——	——	——	——	——	——
Dash 8	644	−62,672	−8,047	−20	−1,216,326	−124,790	−308

directives 2002/30/EC [23] and 2002/49/EC [24]. Bounds are also set for new and quieter aircraft replacements (747-8) that are currently zero but are expected to reach $\Upsilon_{\mathrm{AC}} = 33\%$ of the fleet capacity. The minimum bounds are defined in terms of N_M, the base (B), and the current values $n^B_{X,\ell}$. The maximum values are also based on modest increases to takeoff/landing above the current number in the base using $\Upsilon = 25\%$.

We solve Eq. (10) subject to the constraints via a linear solver (GMPL with mixed-integer programming). We also assume that the five sets [Eqs. (11–20)] have been arranged and can be solved independently (a change in one set will not affect the behavior of another set), similar to the approach used in [16]. As an example, the replacement of one or more 747-400 aircraft by a 747-8 in the aircraft set will not affect takeoff or approach routes or operational or scheduling procedures. All other changes in other sets can be treated in a similar fashion. Empirical tests have included adding flights on individual scenarios and observing the small or nonexistent effects in other tunable sets as mentioned above, validating this assumption. This assumption allows the solving of the five individual problems and simultaneously solves the original problem.

We also assume that objective (10) can be approximated by a linear approximation:

$$\tilde{\mathcal{C}}_{C,\tau_\bullet}(\omega) = \sum_{\ell=1,\ldots,\omega_X} \left(\frac{\mathrm{d}\mathcal{C}_C}{\mathrm{d}\omega_{X,\ell}}\right)_{\tau_\bullet} \cdot \omega_{X,\ell} \tag{21}$$

$$\tilde{\mathcal{C}}_{S,\tau_\bullet}(\omega) = \sum_{\ell=1,\ldots,\omega_X} \left(\frac{\mathrm{d}\mathcal{C}_S}{\mathrm{d}\omega_{X,\ell}}\right)_{\tau_\bullet} \cdot \omega_{X,\ell} \tag{22}$$

$$\tilde{\mathcal{C}}_{Z,\tau_\bullet}(\omega) = \sum_{\ell=1,\ldots,\omega_X} \left(\frac{\mathrm{d}\mathcal{C}_Z}{\mathrm{d}\omega_{X,\ell}}\right)_{\tau_\bullet} \cdot \omega_{X,\ell} \tag{23}$$

where X represents AC (aircraft), TO (takeoffs), AP (approaches), OP (operations), and SH (schedules) at threshold $\tau_\bullet$. These hypotheses imply that the NLIP problem of Eq. (10) is converted to a set of five separate integer programming problems. The results are given in Tables 3 and 4. For a resolution of 100×100 m^2 and area 2500 km^2, INM 7.0 requires 8–15 min for one flight and 2 h to produce a map for an entire scenario (real time) on a UNIX HP Proliant DL 580 server using a dual-core 64-bit 3.2 GHz Xeon processor.

III. Case Study: Cargolux at Findel Airport

Simulations are designed around the Cargolux air freight company. The base scenario is composed of N_M movements representing December 2002. The base L_N contours in the region around the airport are given in Fig. 3. The base L_N contours also give $p_S(\omega) = 2671, 252$, and 1 persons, respectively, for $\tau_\bullet = 50, 55$, and 60 dB thresholds [see Eq. (4)]. In terms of costs, the base company costs (€1.2 million) are composed of fuel costs $C_{\mathrm{fc}} = €354,505$, taxiing costs $C_{\mathrm{tc}} = €109,380$, landing fees $C_{\mathrm{lc}} = €512,000$, and night-penalty charges $C_{\mathrm{pc}} = €233,473$, representing charges (over one month).

A prototype of a Web-based graphical user interface (GUI) for the Luxembourg Aviation Noise (LAN) project has been developed in order to allow a user to readily inspect the stored flight scenario information and visualize the most important LAN calculator results of a scenario. A second part of the application allows the user to create new custom scenarios and to run the LAN calculation in order to compare results with any other stored scenarios. The main components used on the application server side are given in Fig. 4 (top). On the client side a Web browser is all that is needed to access the application. A secured access via a virtual private network limits the access to users coming from an identified network and using

Table 4 Solution to Eq. (10) and comparison with base

	Percent		
	50–55 dB	60 dB	Base
Scenario departures			
DIK1T06	15.8	9.5	12.7
DIK1X24	32.7	54.6	43.7
GTQ4T06	7.6	4.5	6.09
GTQ4U06	0.63	.38	0.51
GTQ4X24	4.5	7.5	6.60
RAP2T06	3.8	2.2	3.04
RAP2X24	3.4	5.7	4.57
RUW1T06	24.6	14.7	19.7
RUW1Y24	1.8	3.1	2.53
TOM2X24	0.40	.63	0.51
Scenario approaches			
DIK06	9.2	9.2	12.3
DIK24	18.7	18.7	18.7
MOS06	1.6	1.6	2.95
MOS24	9.0	9.0	5.91
DIR06	12.9	12.9	23.6
DIR24	55.6	55.6	36.4
OP approaches			
CDA	100	100	0.0
ALF	100	100	35
DTA	100	100	6.09
OP. departures			
LAC	0	0	10.5
DTT	100	100	0.0
MTOF	100	100	83.5
PTDC	100	100	0.0
Scheduling			
Day	75.2	75.2	60.2
Evening	21.2	21.2	17
Night	17.1	17.1	22.8
Aircraft			
747-400	67	67	100
747-8	33	33	0.0

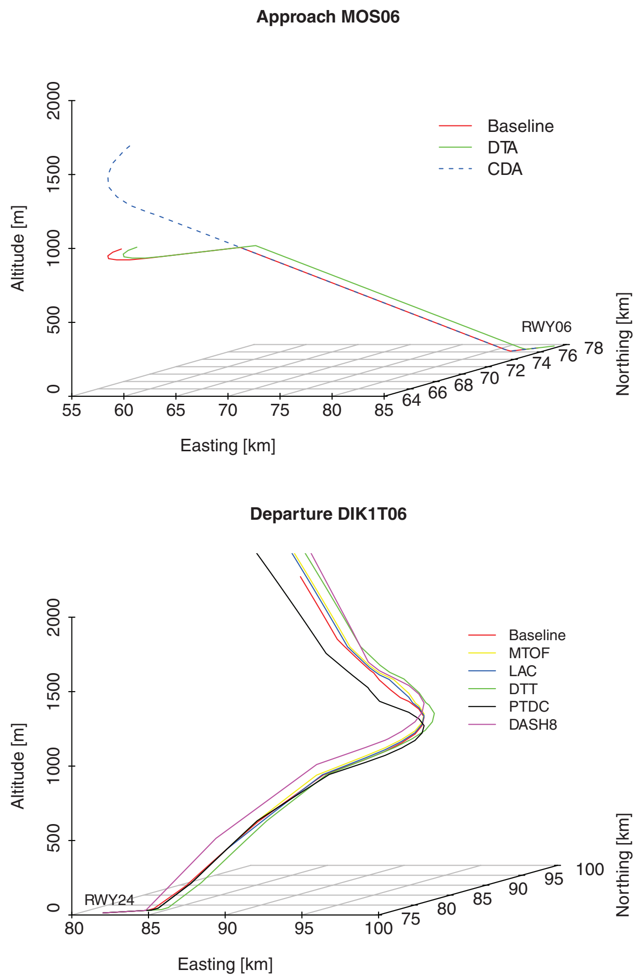

Fig. 2 Examples of approach and departure trajectories for the operational procedures. Further details on the operational descriptions in Table 1.

specific Internet Protocol addresses. The image in Fig. 4 (bottom) represents the main result page of the LAN Web GUI. It shows impact results in the form of maps and values as well as cost information an basic flight scenario information. An adjustable OpenLayers map viewer allows the user to zoom and pan over the study area. The represented result map can be exchanged by the user and general mapping data including national roads, highways (default), residential areas, and the runway of the airport are available as overlays for a better orientation.

IV. Results and Discussion

The present study shows improvement and worsening in terms of abatement cost, either to the company, state, or citizen. Results are also scenario-dependent, and a number of distinct improvements and worsened situations are identified. The positive values in Tables 3 and 4 show worsening, and negative numbers show improvement.

Both state and citizen values $\mathcal{C}_S$ and $\mathcal{C}_Z$ are costs (either negative or positive) for low threshold levels of 50 dB and, with few exceptions, drop to very low levels at the 60 dB threshold level. State and citizen costs for thresholds of 50 and 55 dB are typically much larger than values for the company; this difference is accounted for by the short time period for the company (one year) and a longer period (20 years) for the former two. The difference in time horizons has been treated via a coefficient in the optimization problem (10), and results are given in Table 4. The three-cost results of Table 4 complement those of [16], whereby results are based only on environmental impact. Overall results differ only on the 10% due to the constraints of the problem. Optimization results for departures/arrivals are the same for 50 and 55 dB settings.

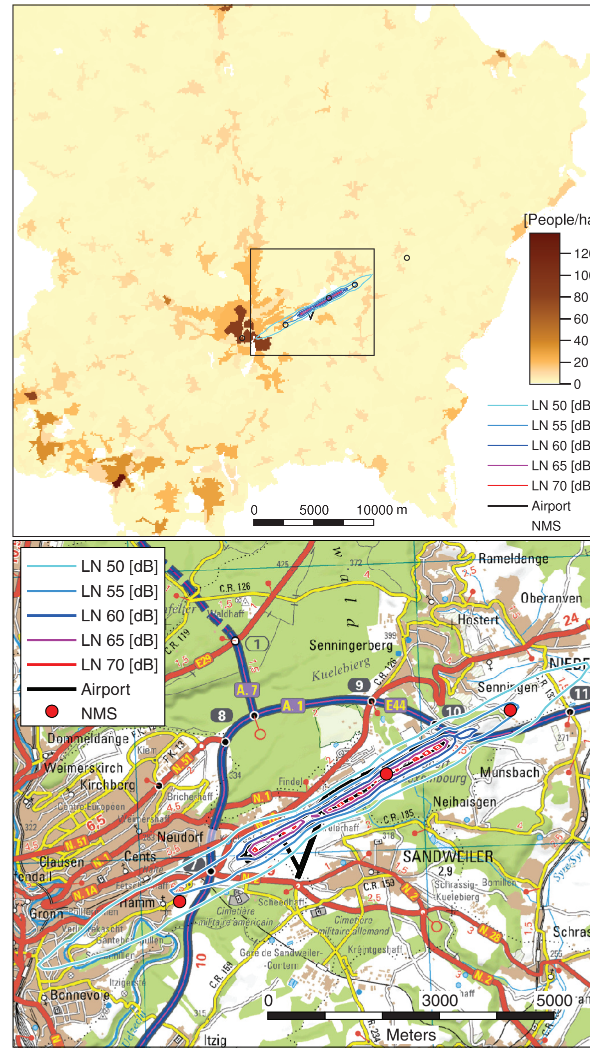

Fig. 3 L_N contours around Findel airport superimposed on the population density in the study area Ξ^S (top) and close-up of the region around the airport (bottom).

A. Aircraft Scenarios

Dash 8 scenarios show considerable improvement in state and citizen costs, but increased costs toward the company. The increased company costs reflect the fact that 747-8 aircraft are heavier than the 747-400. The 747-8 carry more cargo, and thus the benefit of the new aircraft is seen in the number of kilograms of cargo carried per liter of fuel expenditure, but this aspect is not reflected in the study. Should the 747-8 carry the same amount of cargo as the 747-400, the improvement (lessening in state and citizen costs) would be greater.

B. Departure and Arrival Scenarios

Generally speaking, shorter routes give lowered costs for the company. Both departure and approach scenarios show improvement for paths that are away from the city center and worsening for paths that are directed over the city center. The company cost for departure/approach are clearly dependent on the length of taxi travel (runway 06 takeoffs require longer taxiing trips).

The lowered 60 dB values for $\mathcal{C}_S$ and $\mathcal{C}_C$ result in flipped optimization results in the departure route scenarios. For example, departure DiK1T06[§] is increased to 15.8% of the total departures for the 50 and 55 dB settings, as compared with the base, where the choice of DiK1T06 represents only 12.7% of the total takeoffs. The lowest possible solution for this setting is 9.5% at the 60 dB setting.

[§]Takeoff on runway 06, turning toward the north, and flying over Diekirch, 36 km north of Luxembourg city.

Fig. 4 Main functionalities of the scenario interface and LAN calculator (top) and main result page of the GUI (bottom).

This behavior is repeated for all departures. The small footprint for the 60 dB results overlaps very little habitation and is the reason for this behavior.

The overall reduced costs, for example, can be obtained by favoring eastward-bound routes (approaches and departures to and from the east) whenever possible. These routes tend to be shorter and fly over less populated areas. If administered, this practice could only be done at night, where flight frequencies are low and impact is large. Safety and regulatory considerations would, of course, have to be respected for these procedures. If significant tail winds (greater than 10 kt) are present, for example, certain departures (or approaches) could not be used. Certain routes are also subject to other restrictions (e.g., airport instructions and air traffic regulations).

C. Operational Scenarios

Operational scenarios ALF, CDA, DTA, DTT, MTOF, and PTDC (see Table 1) all show improvement for threshold settings $\tau_{\bullet} = 50$ and 55 dB but worsening (costly) abatement at 60 dB settings, as found with the departure and arrival scenarios. Again, the small 60 dB footprint, the size of the airport, and the distance of the habitations contribute to this result. With the exception of the LAC procedure, the generally positive results of the operational scenarios would suggest the implementation of these operations. Furthermore, these operations could show much promise at other airports sharing configurations similar to those of Findel.

D. Scheduling Scenarios

As expected, flights in the day and evening are dramatically better than night flights. Left unconstrained, the optimized result would, of course, place all flights during the day. Placing the $\Upsilon = 25\%$ allows for some evening and night flights.

E. Web Interface

The LAN Web GUI is a prototype interface and allows for an easy interaction with the LAN calculator and the management of flight scenarios stored on the server side. The user can browse and analyze stored flight scenarios and visualize the main LAN calculator results. Custom scenarios can be created starting from the base and adding, subtracting, or modifying flights or creating combinations of any of the major scenario sets. The tool allows for combinations of route, flight scheduling, operational possibilities, and fleet composition. Before storing new custom scenarios, a consistency check is performed in order to guarantee that the LAN calculator is able to handle the specified flight scenario schedule. Results can be viewed and compared via maps and numbers on the Web browser. As the LAN Web GUI is a prototype, the implementation of some features can be seen as an example of feasibility. For example, comparing the results of different scenarios could be enhanced by a more interactive interface.

V. Conclusions

The integer programming method proposed in this paper proves to be a viable technique in the selection of optimal scenarios. The results are consistent with environmental impact results explored in early work on noise impact around Findel Airport, Luxembourg. This application has been designed for a small airport and one carrier, yet apart from computational costs, there are no limits to the size of the target application to which the cost model can be applied. In principle, this application can be exported to larger airports handling several freight carriers and commuter airlines, each with their own operational restrictions and possibilities, multiple runways, and population distributions. Future airport applications of this tool will treat different aircraft. It would be necessary to account for routes that are consistent with these different aircraft.

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