Aircraft Annoyance Minimization Around Urban Airports Based On Fuzzy Logic

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Abstract— **This paper presents a strategy based on fuzzy logic and lexicographic multi-objective optimization for designing noise abatement procedures aimed at reducing the noise exposure of the population living around the airports. A non-linear multi-objective optimal control problem is formally written and identified. A lexicographic optimization technique is presented for establishing a hierarchical order among the optimization objectives which are the noise at several different sensitive locations and fuel or time consumption criteria. A fuzzy logic set has been established to represent the noise annoyance in four different sensitive locations around the airport. A model for departure procedures has been used and the solution for a hypothetical scenario with four different noise sensitive locations is presented.**

Index Terms— **Acoustic noise, acoustic annoyance, fuzzy logic lexicographic multi-objective, optimization of aircraft trajectories.**

I. INTRODUCTION

Currently, the design of noise abatement procedures aimed at reducing the noise exposure of the population around airports is one of the main issues that airport authorities and national navigation services providers have to address.

A departure procedure specifies the trajectory that an aircraft has to follow, starting from the runway until a final location, in which the aircraft joins the en-route airway structure. The national navigation services provider is responsible for designing these kinds of procedures, taking into account several factors such as obstacle clearance, airport and air traffic management issues, separation criteria etc ... In addition, the aforementioned procedures could be designed to mitigate the aircraft noise over sensitive locations around the airports. In this context, the horizontal flight path or the vertical climb profile may be modified.

Some research in theoretical optimum trajectories minimizing the noise impact in depart/approach procedures is found in the literature. For instance, in [1] a tool combining a noise model with a Geographical Information System (GIS) and a dynamic trajectory optimization algorithm is presented aimed at obtaining optimal noise depart and approach procedures. A similar methodology is proposed in [2], and an adaptive algorithm for noise abatement can be found in [3]. Another study, see [4], emphasizes that most current noise abatement procedures are local adaptations of generic procedures trying to minimize the noise footprint and do not generally take into account the actual population density and distribution. In the same work, a noise performance trade-off between arrival trajectories that are optimized according to different types of noise abatement criteria is presented. Typically, these different criteria are not compatible and the variables that optimize one objective may be far from optimal for the others, pointing out the difficulty to properly identify the absolute minimal trajectory among all the local minimal ones. In order to deal with this kind of multi-objective problems in a better way, this work presents an optimization strategy which uses goal hierarchical or lexicographic techniques.

Due to the fact that the selection of the best trajectories depends on the noise annoyance generated by the aircraft, we present in Section 2, a fuzzy model of the acoustic annoyance and in Section 3, we describe an interesting lexicographic method to deal with our multi-objective optimization problem. Section 4 shows the results obtained for different scenarios with four specific zones: a school, a hospital, a residential zone and a market around the airport. Finally, Section 5 will show the main conclusions of this work.

II. ANNOYANCE MODEL OF ACOUSTIC NOISE

A. Acoustic noise model

The acoustic noise is measured in decibels (dB) as the real perception level of the acoustic pressure in the human ear. Usually, when measuring the environmental noise it is quite common to weight the pressure value by a factor depending of the fundamental frequencies of the noise. This weighting (or filter) is known as the *A-weighting*, and it is related with the sensitivity of the human ear respect to all the range of the frequency spectrum of the acoustic noise. The measured unity of this kind of pondered acoustic noise is usually named dBA or dB(A). A common metric of the aircraft acoustic noise is the *Maximum Sound Level (Lmax),* that measures in dBA the maximum noise produced by an event, such as the flight of an aircraft. There are others possible acoustic noise metrics, as the *Sound Exposure Level (SEL)* or the *Day and Night Average Sound Level (DNL)* defined properly in [5] but the *Lmax* metrics has been selected in this work as the basis of acoustic noise model necessary to build further an annoyance model based on fuzzy logic.

B. Annoyance model based on fuzzy logic

The annoyance or perception of the acoustic noise describes a relation between a given acoustic situation and a given individual or set of persons affected by the noise and cognitively or emotionally must evaluate this situation.

The acoustic annoyance of the aircraft flights around an urban airport depends logically of the acoustic behaviour produced in the interest points (using, as an example, the Lmax metric) but it is not a sufficient measurement to define completely the annoyance behaviour of a noise. For example, a list of non acoustic elements to take into account to define the annoyance behaviour is as follows:

- Types of affected zones (rural zone, residential zone, industrial zone, hospitals, schools, markets,…)
- Time interval during the noise event (day, evening, night)
- Period of time between two consecutive flights
- Personal elements (emotional, apprehension to the noise, personal healthy, age,…)
- Cultural aspects (young or aged people habits, activities, holidays,…)

In conclusion, the annoyance is a subjective and a complex concept which can be studied as a qualitative form using fuzzy logic sets, as previous similar works in this area have been done [6], [7]. In this paper, the annoyance generated by the aircraft trajectories will be represented by fuzzy logic sets from the fuzzification of the maximum sound level (Lmax) and from the flight time regarding 4 typical zones around an urban airport (Fig. 1): a residential zone, a hospital, a market and a school.

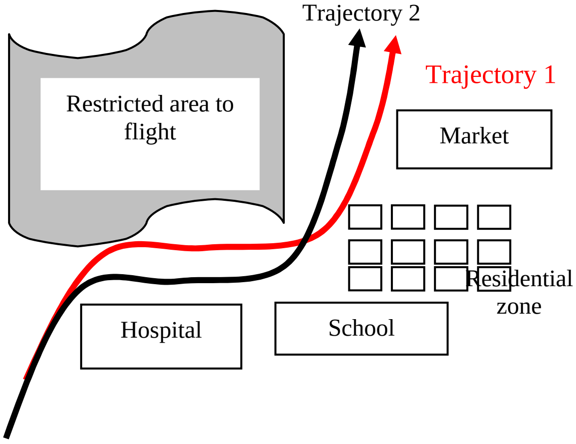

Fig. 1. Example of a possible configuration of the typical zones around an urban airport

Two sets of membership functions have been defined. A first set is related with the maximum sound level (Lmax) and 5 linguistic terms have been selected to define the noise: very high (VH), high (HH), medium (ME), Low (LL) and very low (VL) following a similar structure of fuzzy sets proposed by [7] from the Lmax metrics in dBA (Fig. 2). A second set is related with the flight time, establishing three crisp linguistic terms: morning (MR), afternoon (AF) and night (NG) to indicate the moment of the day for a given aircraft flight (Fig. 3).

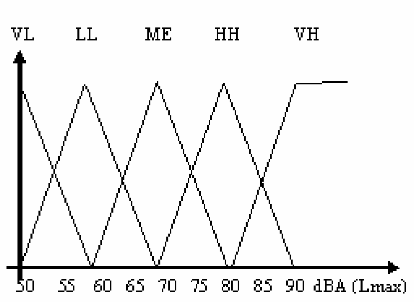

Fig. 2. Membership functions of the maximum sound level fuzzy set.

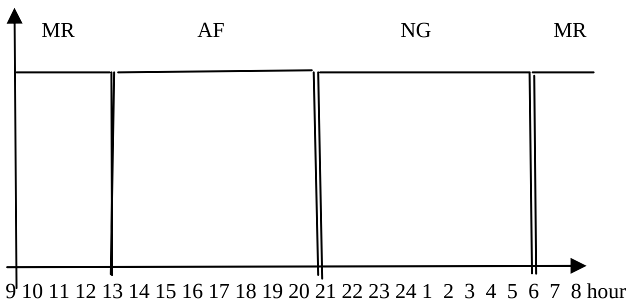

Fig. 3. Membership functions of the flight time

Afterwards, a rule base has been designed to represent the annoyance of an event defined by the two fuzzy logic sets for each of the 4 zones considered in this work. The annoyance concept has been represented by the following linguistic terms: extreme (EX), high (HI), moderated (MO), small (SM) and null (NL).

To build the rule base, one initial selection has been considered for a “standard” situation, consisting in considering the terms of the annoyance set (EX, HI, MO, SM and NL) equivalent to the terms of the sound level (VH, HH, ME, LL and VL). The residential zone, during the evening has been considered as the “standard” situation for this zone. On the other hand, the residential zone during the night is more sensible to noise and, consequently, the annoyance terms have been shifted one higher position in the linguistic terms of the Lmax. In the same way in the residential zone, during the morning, it is worth to suppose that less people are living in the zone. In addition, environmental noise is higher during the morning than in the evening or night, thence the annoyance terms have been shifted to one lower position (Table 1).

Similarly, in the school the standard situation has been considered during the lecture period of the evening, meanwhile in the morning period a higher position has been considered because usually there is more people than afternoon and because the activities of the morning need to pay more attention than these of the evening. Finally, the annoyance at the school during the night is practically null because there is no activity in this zone (Table 2).

In the hospital a standard situation has not been considered, because sick people are more sensible to the noise. Therefore, morning and afternoon annoyance have been shifted one position higher than the Standard situation, while the night period has been shifted two positions (Table 3).

Finally, the standard situation for the market has been considered in the afternoon, meanwhile in the morning usually the environmental noise is higher than the afternoon and for this reason the morning in the market has been considered one point lower than the standard situation. During the night, the annoyance is insignificant because there is a very small activity (Table 4). Based on this simple reasoning the four rule bases have been designed for this study.

Table 1. The rule base of the annoyance in the residential zone

RESIDENTIAL ZONE	*Morning*	*Afternoon*	*Night*
Very Low	**NL**	**NL**	**SM**
Low	**NL**	**SM**	**MO**
Medium	**SM**	**MO**	**HI**
High	**MO**	**HI**	**EX**
Very High	**HI**	**EX**	**EX**

Table 2. The rule base of the annoyance in the school

HOSPITAL	*Morning*	*Afternoon*	*Night*
Very low	**SM**	**SM**	**MO**
Low	**MO**	**MO**	**HI**
Medium	**HI**	**HI**	**EX**
High	**EX**	**EX**	**EX**
Very High	**EX**	**EX**	**EX**

Table 3. The rule base of the annoyance in the hospital

MARKET	*Morning*	*Afternoon*	*Night*
Very Low	**NL**	**NL**	**NL**
Low	**NL**	**SM**	**NL**
Medium	**SM**	**MO**	**NL**
High	**MO**	**HI**	**SM**
Very high	**HI**	**EX**	**MO**

Table 4. The rule base of the annoyance in the market

SCHOOL	Morning	Afternoon	night
Very low	**SM**	**NL**	**NL**
Low	**MO**	**SM**	**NL**
Medium	**HI**	**MO**	**NL**
High	**EX**	**HI**	**SM**
Very high	**EX**	**EX**	**MO**

For the sake of simplicity, the fuzzy set of the annoyance has been defined as a crisp set to derive the normalized degree of annoyance (Fig. 4). In this work a "max-min" inference method has been applied and the common centre of gravity technique has been considered as the method for the defuzzification process.

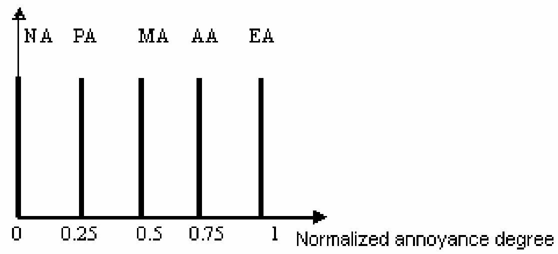

Fig. 4. Membership function of the annoyance degree set.

Fig. 5 represents, for each of the three flight time terms the relation between the normalized annoyance degree and the maximum sound level (Lmax) in a given zone (residential zone in this case) after a process of fuzzification and defuzzification of all possible values of Lmax. Fig. 6 shows, for a given flight time term (night in this case) the normalized annoyance degree of all 4 zones for all the possible values of Lmax.

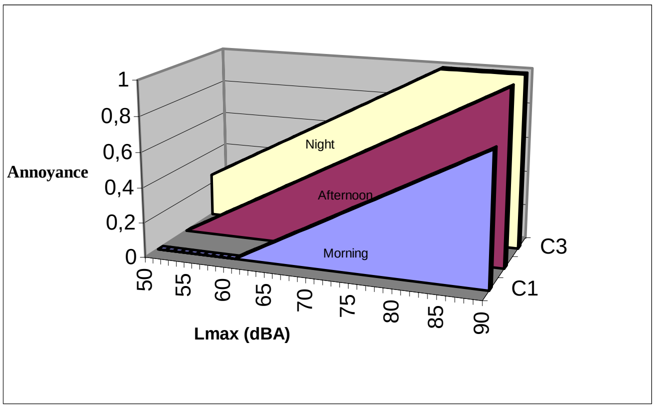

Fig. 5. Annoyance degree in the residence zone as a function of Lmax for the set of flight time

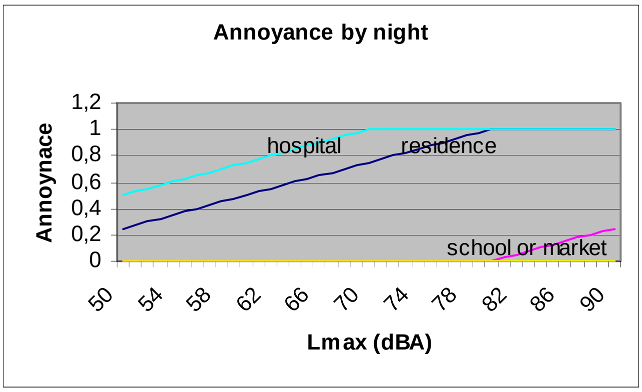

Fig. 6. Annoyance degree by night as a function of the Lmax for the 4 zones of this study

III. MULTI-OBJECTIVE OPTIMIZATION

A. Multi-objective optimization

The solution of the optimization problem associated with the computation of the trajectory that minimizes noise (or noise nuisances) is a multi-objective optimization problem since additionally to fuel and time minimization used in the trajectory, nuisance minimization in several zones at the same time should be considered.

Let $\vec{x}(t)=[x(t),y(t),z(t),t]$ be an aircraft trajectory described by the three spatial components in a particular time slot during the day. The considered optimization problem takes into account 6 criteria evaluated through the corresponding objective functions that will be denoted in the following as:

$f_r(\vec{x})$	noise nuisance in residential zone
$f_h(\vec{x})$	noise nuisance in hospital zone
$f_m(\vec{x})$	noise nuisance in market zone
$f_e(\vec{x})$	noise nuisance in school zone
$f_c(\vec{x})$	Fuel consumed during the trajectory

The aim is to find an optimal aircraft trajectory $\vec{x}^*(t)$ within the set of all possible trajectories χ that minimizes each of the previously defined criteria by solving the following multi-optimization problem

$$\begin{aligned} &\min_{\vec{x}} \quad f_r, f_h, f_m, f_e, f_c \\ &\text{subject to}: \quad \vec{x} \in \chi \end{aligned} \qquad (1)$$

where the domain χ is defined through a set of restrictions: $g_j(x) \le 0, j=1,...,m$ that comes from aircraft dynamics and operating limits in actuators and state variables.

A solution $x^* \in X$ of (1) is said to be *Pareto optimal* if and only if there does not exist a $x \in X$ and an a i such that $f(x) \le f(x^*)$ and $f_i(x) \le f_i(x^*)$. In other words, a solution is (global) Pareto optimal if and only if an objective f_i can be reduced at the expense of increasing at least one of the other objectives.

There are several methods to solve multi-optimization problems [8]. In general, in these methods, multi-objective optimization problems are solved by scaling. This means converting the problem into a single or a family of single objective optimization problems with a real-valued objective function. This objective function is called the scaling function and it may be a function of some parameters. This enables the use of the theory and the methods of scalar optimization.

B. Lexicographic method

One of the most well known multi-objective techniques is the linearly weighted sum, where the vector objective function is scaled in such a way that the value judgment of the decision making can be incorporated. The drawback of this method is that weights should be tuned by "trial and error". On the other hand, if a hierarchy between objectives can be defined "a priori" according to their absolute importance, the lexicographic method can be used [8]. Let the objective functions be arranged according to the lexicographic order from the most important f_1 to the least important f_k. We can write the lexicographic problem as:

$$\begin{aligned} &\operatorname{lex}\min_{x} \quad f_r, f_h, f_m, f_e, f_c \\ &\text{subject to}: \; x \in \chi \end{aligned} \qquad (2)$$

A standard method for finding a lexicographic solution is to solve a sequential order of single objective constrained optimization problems. After ordering, the most important objective function is minimized subject to the original constraints. If this problem has a unique solution, it is the solution of the whole multi-objective optimization problem. Otherwise, the second most important objective function is minimized. Now, in addition to the original constraints, a new constraint is added. This new constraint is there to guarantee that the most important objective function preserves its optimal value. If this problem has a unique solution, it is the solution of the original problem. Otherwise, the process goes on as above.

More formally, $f^* := [f_1^*, \cdots, f_r^*]$ is the lexicographic minimum of (2) iff

$$f_1^* = \min_{x \in \chi} f_1(x) \qquad (3)$$

for all $i \in \{2, \cdots, r\}$

$$f_i^* = \min\{ f_i(x) | f_j(x) \le f_j^*, j = 1, \cdots, i-1 \} \qquad (4)$$

On the other hand, a given $x^* \in X$ is a lexicographic solution of (4) iff

$$x^* \in \{ x \in \chi | f_j(x) \le f_j^*, j = 1, \cdots, r \} \qquad (5)$$

C. Determining the lexicographic order using "max-min" approach

The aim of this paper is to obtain the minimization lexicographic order of the different objectives by considering the nuisance of each trajectory computed using fuzzification/defuzzification process on each of the considered zones (hospital, school, residential and market), taking into account the day time and the noise perception level. However, the noise perception level depends of the considered optimal trajectory that only can be obtained once the order of minimization of each particular objective has been established. This means that in this case no "*a priori*" order can be obtained. This is why in this paper what is proposed, is to obtain the minimisation order by solving 4 mono-objective problems, one for each zone under study and select the optimal trajectory that produces the biggest nuisance in one of the considered zones that is marked as of the highest priority. Then, a new set of 3 mono-objective problems are solved for the other non-considered zones. A new restriction is added in order to guarantee that the obtained optimal trajectories produces a nuisance in the first considered zone less or equal than the one obtained in previous phase of optimization. From the result of this second phase of optimizations, again the trajectory that is selected, is the one that produces the biggest nuisance. The zone where the biggest nuisance appears will be the second in the order of minimization. This process is repeated until all considered zones are ordered. Finally, the minimization of fuel consumed and time elapsed during the trajectory will be added as last objectives in the lexicographic minimization process.

This method is inspired from the "*min-max*" approach used in predictive control where a set of possible disturbances should be considered and the objective is the minimisation of the one that produces the worst-effect [9]. However, this approach is used here to determine the minimization lexicographic order by obtaining at each phase the zone to be minimised first in order that the whole set of nuisances in the different zones is minimized. So, this method can be considered as an extension of the lexicographic method where the order is determined dynamically by using a "*min-max*" criterion.

IV. RESULTS

This section presents a practical example concerning three hypothetical scenarios, where the optimum take off trajectories for a given airport should be computed by the morning, afternoon and night periods The urban environment of the airport consists in four different zones: market, school, hospital and residential zone. For each time period the acoustic annoyance in these sensible zones must be minimized. The optimal control problem described in Section III is firstly transformed into a non linear programming (NLP) problem by parameterizing the control and state variables. This technique, see for instance [10] and [11], allows for an easy use of commercial optimization software which copes with these kinds of problems. In the following simulations the General Algebraic Modeling System (GAMS)[1] has been used to code the problem for the NLP solver CONOPT[2] . In this example the aircraft is supposed to take off eastwards and, for the sake of simplicity, the origin of coordinates (0,0) is taken at the point where the initial straight trajectory of the aircraft reaches 400ft in height above the runway. From this point on, the trajectory optimization takes place under aircraft's dynamic constraints, which are described in detail in [12], and some airspace restrictions, defining an usable area of airspace, as it can be seen by dashed lines in figures 7, 8 and 9. Finally the final coordinates of the trajectory are fixed at point (20000 km,10000 km) and the altitude must be equal or higher than 3000 ft passing this point.

Table 5 shows the results of max-min lexicographic optimisation method applied to the 4 sensible zones during the morning period. As it can be seen, after the four mono-objective optimizations, the school is the most annoyed location and therefore becomes the most important objective. Subsequent optimizations give the rest of priorities as Hospital, Market and Residential zone.

Table 5. Numerical results for the 4 phases of the optimization trajectories during the morning

MORNING	Annoyance Residential	Annoyance Hospital	Annoyance Market	Annoyance School
1ª Optimization (R,H,M,S)	0,23	0,45	0,00	**0,53**
2ª Optimization (R,H,M)	0,23	**0,45**	0,35	
3ª Optimization (R,M)	0,23		**0,58**	
4ª Optimization (R)	**0,23**			

Figure 7 shows the resulting trajectories at each partial step of the optimization process. A fifth lexicographic optimization is also done, where burned fuel is minimized. The obtained trajectory maintains the same level of annoyance at all locations but fuel consumption is reduced by a 14.8% with regards to the trajectory resulting from the fourth optimization.

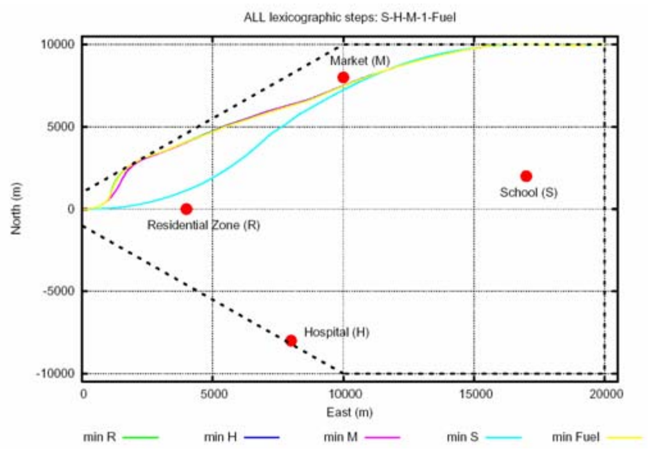

Fig. 7. Refined trajectories of the aircraft during the morning

Table 6 shows the results of max-min lexicographic optimisation method applied to the 4 zones during the afternoon period, giving a situation where the hospital is the most important objective followed by the residential zone, the market and the school.

Table 6. Numerical results of the 4 phases of the optimization trajectories during the afternoon

AFTERNOON	Annoyance Residential	Annoyance Hospital	Annoyance Market	Annoyance School
1ª Optimization (R,H,M,S)	0,48	**0,45**	0,23	0,28
2ª Optimization (R,M,S)	**0,48**		0,38	0,28
3ª Optimization (M,S)			**0,40**	0,28
4ª Optimization (S)				**0,40**

Figure 8 gives the plot corresponding to these trajectories and in this case, fuel reduction in a fifth optimization is only improved by a 2.3%.

[1]GAMS: The General Algebraic Modeling System is a high-level modeling system for mathematical programming and optimization (www.gams.com).
[2]CONOPT is a solver for large-scale nonlinear optimization (NLP) based on a improved version of the GRG method and it is fully integrated within the GAMS system (www.conopt.com).

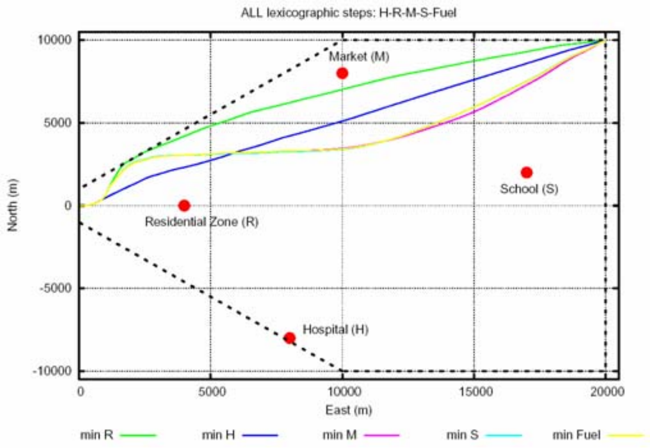

Fig. 8. Refined trajectories of the aircraft during the afternoon

Finally, Table 7 shows the results of max-min lexicographic optimisation method applied to the 4 zones during the night period. In this case the priority is given as: Residential Zone, Hospital, School and Market.

Table 7. .Numerical results of the 4 phases of the optimization trajectories during the night

NIGHT	Annoyance Residential	Annoyance Hospital	Annoyance Market	Annoyance School
1ª Optimization (R,H,M,S)	**0,73**	0,70	0,00	0,00
2ª Optimization (H,M,S)		**0,70**	0,00	0,00
3ª Optimization (M,S)			0,00	**0,00**
4ª Optimization (M)			**0,00**	

On the other hand, Figure 9 shows the trajectories of this refined optimization, where the fuel improvement in last optimization reaches a 4.2%..

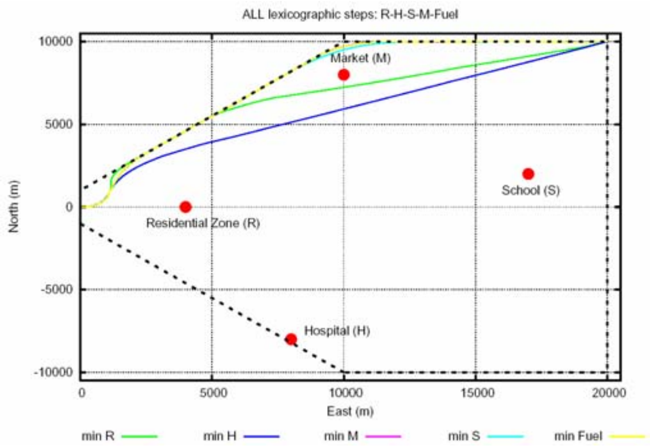

Fig. 9. Refined trajectories of the aircraft during the night

V. CONCLUSIONS

This work deals with aircraft noise annoyance modelling and trajectory optimisation for noise abatement in surrounding areas close to airports.

The applicability of a numerical tool for calculating noise-optimized trajectories has been demonstrated in a hypothetical scenario that involves four typical zones around an urban airport at different time of the day.

The paper proposes the use of fuzzy logic to express qualitatively the acoustic annoyance in the different sensitive zones with regards to the perceived maximum sound level (Lmax) and the moment of the day. In this context, a fuzzy logic set has been established to represent the noise annoyance in four different sensitive zones around the airport.

In order to solve the problem of multicriterion optimization, a lexicographic solution has been applied, where the partial goals (noise at different locations and fuel consumption) are ordered in a sequential form and the previous optimization result is added as a restriction to the new optimization.

Some results show the viability of the proposed solution where completely different take-off trajectories are obtained depending on the time period that are supposed to be flown.

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