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AIR TRAFFIC ASSIGNMENT TO REDUCE POPULATION NOISE EXPOSURE AND FUEL CONSUMPTION USING MULTI-CRITERIA OPTIMISATION

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Abstract - *Air traffic assignment to departure and arrival routes has a major impact on the population noise exposure in the vicinity of the airport. In some cases, by choosing the suitable air traffic assignment it is possible to avoid overflying populated areas and reduce number of people affected by noise. However, such an approach almost always leads to an increase in route length, and therefore an increase in fuel consumption and CO_2 emissions. Although aircraft noise and fuel consumption reduction are conflicting goals, they both represent pivotal aspects of air transport sustainable development. In this paper, the methods of multi-criteria optimisation are applied, which are generally used when it is necessary to make an optimal decision that requires a compromise (trade-off) solution between two or more conflicting goals. The aim of this research is to develop a mathematical model and to propose an algorithm for air traffic assignment to departure and arrival routes that will, through the Pareto optimality concept, find the approximation of a set of nondominated solutions that minimize population noise exposure and fuel consumption. The approach was demonstrated on Belgrade airport to show the benefits of the proposed model on a real data example. Since all Pareto optimal solutions are considered equally good, from all obtained air traffic assignments the three representative solutions were compared to the actual air traffic assignment (Base case). The obtained results indicate that the proposed approach can provide solutions which offer a good trade-off between the concerned metrics.*

1. INTRODUCTION

Major commercial airports generate benefits to their neighbouring communities, providing more investment and employment, increasing mobility, as well as providing a strong stimulus to the globalization of the industry, business and long distance tourism. However, external costs are associated with these benefits and any increase in aircraft movement causes adverse environmental impacts. It is widely accepted that the most significant environmental impacts related to the operation of airports arise from the noise generated by aircraft and fuel consumption leading to global CO_2 emissions increase.

Considerable efforts have been invested in order to alleviate the noise nuisance and reduce fuel consumption. On the European level, the Environmental Noise Directive 2002/49/EC (END) relating to the assessment and management of environmental noise has been introduced [1]. In the framework of implementing the requirements set in this Directive, many airports have developed strategic noise maps and noise action plans [2]–[4]. Numerous initiatives to reduce fuel consumption and emissions have been launched in recent years including Atlantic Interoperability Initiative to Reduce Emissions (AIRE), Asia and South Pacific Initiative to Reduce Emissions (ASPIRE), ACI Airport Carbon Accreditation, The European Advanced Biofuels Flightpath.

In addition to these initiatives that require enormous budgets and are more focused on the strategical level, on a practical level it was observed that the variation of aircraft/airport operational procedures could bring short-term improvements and could be less costly in comparison with the other options [5].

The literature shows that efforts to design optimal departure and arrival routes with less noise and fuel burn have been well studied over the past decades, and various strategies have been proposed. Besides the attempts to design environmentally friendly departure/arrival routes, the allocation of aircraft and operational procedures to specific routes could also help to considerably diminish the environmental impacts. For instance, Frair [6] proposed a nonlinear integer programming model to minimize community annoyance at an airport by allocating aircraft to the existing arrival and departure trajectories. Zachary et al. [7] investigated the optimization problem which aims at finding an optimal combination of approach and departure routes, operational procedures and fleet composition to optimize noise and pollutant emissions. Kim et al. [8] built an optimization model to minimize the total emissions on the airport surface and in the terminal area by allotting aircraft to runways and scheduling the arrival and departure operations on these runways concurrently.

Several air traffic assignment strategies have been proposed in order to allocate noise more wisely. Netjasov suggested the model that was based on the categorization of aircraft according to engine type and wake turbulence category and the assignment of specific runways for take-off and landing for each aircraft category [9]. Heblij et al. developed the Noise Allocation Planning Tool that maintained an equal noise level over a wider area, effectively reducing peak levels [10]. Zaporozhets and Tokarev formulated and solved several problems related to minimisation of aircraft noise impact, including a selection of optimum operations around an airport by distributing the aircraft between the routes [11]. On a tactical level, Nibourg et al. have developed Runway Allocation Advice System (RAAS) which is currently in

operation at Amsterdam Airport Schiphol (AAS) and Basel Euro Airport and which allows controllers to choose the optimal runway (combination) in any given situation with respect to noise preferential runway system in place [12]. Kuiper et al. proposed an optimization approach that aims to minimize the risk of exceeding the limit at any predefined location in the vicinity of the airport by distributing flights over different runways [13].

Each decision regarding the assignment of aircraft to routes should consider the number of people who will be exposed to adverse noise levels. Due to population daily migrations, number of people in some residential areas could significantly differ from census data. Ott was one of the first researchers to spot the drawback when relying to census data since it leads to overlooking the fact that some residents spend a long time far from the area, which is supposed to represent their exposure [14]. Ganić et al. [15] incorporated population daily migrations into air traffic assignment optimisation model with the aim to reduce the number of people exposed to noise but without taking into account fuel consumption. Although the importance of analysis of daily migrations has been recognized in many transportation studies [16]–[21], to the best of the authors' knowledge, none of the air traffic assignment strategies addressed trade-off between population noise exposure and fuel consumption in combination with temporal and spatial variations in population in an airport's vicinity.

The idea presented in this paper is to tailor air traffic assignment of aircraft to departure and arrival routes taking into account temporal and spatial variations in population in an airport's vicinity in order to reduce the number of people exposed to noise as well as fuel consumption. The approach was demonstrated on Belgrade airport to show the benefits of the proposed model on a real data example. The obtained results indicate that the proposed approach can provide solutions which offer a good trade-off between the concerned metrics.

The rest of the paper is organised as follows. Section 2 presents the formulation of the multi-objective optimization problem by defining the mathematical model, explaining the necessary input data as well as the proposed (used) NSGA-II algorithm. Section 3 describes the Belgrade airport case study which is used to assess the capability of the proposed air traffic assignment model. The results are presented in Section 4. Finally, Section 5 provides the conclusion and ideas for further research.

2. MULTI-OBJECTIVE OPTIMIZATION PROBLEM FORMULATION

To generate optimal air traffic assignment with respect to population daily migrations, the mathematical model of an optimization problem with two objectives is developed. As a continuation of the research done by Ganić et al. [15], besides population noise exposure, this research takes into account fuel consumption as the second objective.

2.1. Input data

Description of proposed air traffic assignment model requires following input data:

- air traffic data,
- departure and arrival routes for each runway,
- noise data for each location produced by each aircraft flying over routes,
- fuel consumption data for each aircraft flying over each route,
- population data,
- human mobility patterns based on daily migrations.

Air traffic data includes information about origin and destination, aircraft type, actual take-off time (ATOT), arrival time, runway in use, operation type (take-off or landing) and can be obtained from Air Traffic Control. Real radar data could be used to represent departure and arrival routes or they could be obtained from Aeronautical Information Publication (AIP).

Noise level for each location produced by each aircraft flying over routes could be either measured or calculated. In the first case, noise levels are measured at noise monitoring stations which represent locations. In the second case, noise levels are calculated using some noise prediction and mapping software, such as Predictor-LimA, SoundPlan, Integrated Noise Model (INM), etc. Even though the first approach gives the opportunity to work with real-time data, the second approach seems more appealing since there are no limitations regarding the number of locations and their position.

Selection of locations for which noise levels will be assessed together with the actual number of people exposed to those noise levels during the observed periods is crucial for the population noise exposure assessment. Low level of detail required for this research allows each settlement to be represented by a single point, i.e. location instead of observing each housing unit in particular.

Fuel consumption was calculated using the EMEP/EEA air pollutant emission inventory guidebook – 2016 [22]. Fuel burn for Landing and Take-Off (LTO) flight phases was assessed using information about origin and destination airports, aircraft type (engine type, number of engines), duration for each LTO phase (taxi, take off, climb out, approach) and rate of fuel burn (kg/s/engine). For Climb/Cruise/Descent (CCD) flight phases fuel consumption was calculated based on CCD stage length and aircraft type.

Population data are collected for each location which implies gathering the number of people living in each settlement based on census data. During some period of the day, especially when employees go to work and pupils and students go to schools and faculties, number of people at some residential areas could significantly differ from census data due to population daily migrations. Having that in mind, assessment of human mobility patterns based on daily migration gives an estimation of how many people will actually be present at some location during a defined period of time. Daily migrations presented in this paper include a special form of spatial mobility of economically active population performing an occupation, of pupils and students. This data can be obtained from the National Statistical Office for each municipality around the airport [23].

2.2. Mathematical model

To formulate this model, the following notations are used:

Parameters:

P is the set of periods, $t \in P$

O_t is the set of operations during period t, $i \in O_t$, $t \in P$

L is the set of locations, $k \in L$

S_i is the set of feasible operational options of operation i, $i \in O_t$

T_t is the duration of period t, $t \in P$

p_{kt} is the number of population living at a location k during period t

k_{kt} is the legal noise limit at a location k during period t

$fuel(xi)$ is the fuel consumption that operation i costs when option x is selected

$nl(x_i)$ is the noise level that operation i cause when option x is selected

Design variables:

$\boldsymbol{x} = \{x_i, i \in O_t\}$ is the vector of optimal assignment of all operations to routes.

x_i: is an optimal option of operation i, which is selected from set of all feasible operational options S_i, ($x_i \in S_i$).

The set of operational options $S_i = \{1,2,\dots,M\}$ is defined based on its operational type (departure/arrival) and navigation point, in which $1,2,\dots,M$ is the number of options that can be derived for aircraft operation i. For each option, noise level ($nl(x_i)$) and fuel consumption ($fuel(x_i)$) are predefined.

Objective functions:

$$min\left(T_{fuel}(x), N_{pa}(x)\right) \tag{1}$$

- *Fuel consumption*:

$$T_{fuel}(x) = \sum_{\mathrm{i}\in \mathrm{O_t}} fuel(x_i) \tag{2}$$

- *Number of people affected by noise*:

$$N_{pa}(x) = \sum_{\mathrm{k}\in \mathrm{L}} \mathrm{p_k} \cdot \mathrm{S_k}(x) \tag{3}$$

$$\mathrm{S_k}(x) = 2^{0.1\cdot(\mathrm{N_k}(x)-\mathrm{k_k})}, \forall k \tag{4}$$

$$N_k(x) = 10\log\left(\frac{1}{\mathrm{t}}\cdot\sum_{\mathrm{i}\in \mathrm{O_t}} 10^{0.1\cdot \mathrm{nl}(x_i)}\right), \forall k \tag{5}$$

It should be noted that besides the introduction of a new objective, i.e., fuel consumption, this model also contains a new promising feature in comparison with the model proposed in [15]. Particularly, in the model [15], for each operation, all feasible options it can be assigned to are considered as binary design variables, which means that only one of these options is equal to 1 if it is selected, and the rest of them will be equal to 0. Consequently, the size of optimization problem will be extremely enlarged when the number of operations increases. This may make the problem more difficult to solve by using evolutionary algorithms or even integer nonlinear programming models. On the contrary, in the paper, each operation is considered as a design variable, and all its feasible assignments will serve as its design space. As a result, the number of design variables of the problem will dramatically decrease, and hence the problem can be effectively solved by using evolutionary algorithms.

2.3. NSGA-II algorithm

As described in Section 2.2, the formulated problem is an integer nonlinear optimization problem with two objective functions, which is hard to be solved by gradient-based optimization methods or linear/nonlinear programming models. Fortunately, in recent years, many evolutionary algorithms have been proposed that are capable of effectively solving such kind of problems. Among them, nondominated sorting genetic algorithm II (NSGA-II) proposed by K. Deb et al. [24] emerged as one of the most powerful methods, which has been widely used in many different engineering applications. In this paper, it is therefore utilized to deal with the optimization problem stated above. Since the details of the algorithm have been given in [24], interested readers are encouraged to refer to this reference.

3. BELGRADE AIRPORT CASE STUDY

To demonstrate the reliability and applicability of the proposed approach, a case study is carried out in this section. Belgrade airport Nikola Tesla (ANT), the largest and busiest international airport in Serbia, situated 18 km west of downtown Belgrade, has been chosen as the case study. In 2017, the airport handled more than 5 million passengers and approximately 60 thousand aircraft operations with single runway 3400 m long (direction 12/30).

The first step in this case study was to obtain detailed air traffic data for one day. September 16th, 2016 has been chosen since it was a summer day with relatively heavy traffic and some of the data was already available from the previous study [25] which also included measured noise levels at one location near Belgrade airport.

Daily traffic consisted of 220 operations, including 109 departures and 111 arrivals. Distribution of operations between runways was slightly in favour of runway 12 which handled 128 operations (58.2%), while the runway 30 was used for 92 operations (41.8%).

Departure and arrival routes for each runway were obtained from radar data since Standard Instrument Departure (SID) and Standard Arrival Routes (STAR) could not be considered accurate due to aircraft vectoring mostly in place at ANT. Taking into account that aircraft vectoring at ANT is usually done in a similar way, radar data could be regarded as constant since changes in departure/arrival routes derived from radar data from one day to another are minor.

From a bundle of radar tracks presented in Fig. 1a, a 27 different routes were selected to represent actual SID/STAR routes. There are seven departure routes and seven arrival routes from runway 12 (Fig. 1b) and six departure routes and seven arrival routes from runway 30 (Fig. 1c). Departure routes are marked in blue while red colour corresponds to arrival routes.

Noise and fuel data are in function of aircraft type. For the observed day, fleet mix consisted of 25 different aircraft types. However, for the purpose of simplifying the calculations, they were classified into 11 groups based on the similarity of aircraft types. In this way, 85% of the operations were presented by the aircraft types that were actually flown that day, while the remaining 15% were presented by aircraft

types that have approximately the same level of noise exposure and fuel consumption as their representative.

Table 1 shows the number of departure and arrival operations per each period per each aircraft type categorised as per the INM [26] and AzB [27] databases.

Before calculating the noise data, it is pivotal to choose the optimal number and position of locations for which the noise and population data will be obtained. Since ANT is surrounded by populated areas, 23 different municipalities were considered to be affected by aircraft noise: 17 Belgrade municipalities and the municipalities of Stara Pazova, Indjija, Irig, Ruma, Pecinci and Pancevo. In order to be certain that adequate locations would be selected, the conservative approach of calculating noise exposure of each location around the airport was applied in the following way: the most unfavourable case for a certain selected location is when all operations are assigned to departure and arrival routes that are closest to that location and when the noisiest aircraft type is overflying the location (in this study it is "Airbus A330-200"). From 306 locations (settlements) for which the noise exposure was calculated using a conservative approach, only 17 locations were selected since the noise levels at these locations were above legal noise limit values (above 55dB L_{den} and/or 45dB L_{night}). Table 2 shows legal noise limits and population data for each selected location.

As it can be seen from Table 2, population data are presented in four different columns. Data in the first column represents 2011 census data [23]. In order to take into account human mobility patterns and to simulate the three-8h working shifts the day has been divided into three-8h periods: Period 1 from 8 am to 4 pm (90 operations), Period 2 from 4 pm to12 am (79 operations) and Period 3 from 12 am to 8 am (51 operations). In order to obtain data on daily migrations of economically active persons who perform an occupation, pupils and students for each of the 23 municipalities around the airport it was necessary to make private request for special processing of data collected in the 2011 census to the Statistical Office of the Republic of Serbia since this data was not available publicly. Definition provided in 2011 Census methodology describes daily migrants as persons who work or go to school/university outside the place of their usual residence, but who return on a daily basis or several times a week [23]. Data on daily migrations was the key to calculate the total daily inflow and outflow of inhabitants for each municipality. Based on that, the approximation of total daily inflows and outflows of the inhabitants for each settlement within the municipality was done in proportion to the number of inhabitants in the settlement.

Having in mind that in this way, human mobility patterns are obtained for the whole day only, and not for the separate periods of the day, some assumptions were needed to be made in order to assess how many people would actually be present at each location during a defined period of time. It was assumed that 50% of employees work first shift, 40% work second shift, and 10% work night shift, while pupils and students go to school in two shifts (Period 1 and 2) equally. In this way, for each period population data were calculated based on the census and daily migration data showing the difference in the number of people at the locations between periods. The total number of residents living near these 17 locations based on census data was 238,741.

Legal noise limit values for day, evening and night, given in Table 2, represent the limit values for EU common noise indicators L_{den} and L_{night} in the Republic of Serbia, for residential areas (see [28]). For Period 1 and 2, representing the day and evening, legal noise limit values in dB (A) were set to 55dB, while for Period 3 representing the night noise limit value of 45dB was used.

INM software was used to calculate the sound exposure levels (SEL) for each aircraft type in the fleet mix, flying over each route, for each location separately. This data was used as input for noise objective in optimization model. For each operation, standard INM profile settings were used taking into account the fact that different aircraft types overfly locations at different altitudes and thrust settings. In addition, different profile parameters for each aircraft type were assigned including take-off and landing masses, thrust and flaps settings, climb rate, descent angle,...

Table 1 *Flight statistics and aircraft classifications*

Aircraft type	Assigned AzB class	INM airplane code	Departure			Arrival		
			Period 1	Period 2	Period 3	Period 1	Period 2	Period 3
Boeing 737-300	S 5.2	737300	4	1	3	5	3	1
Boeing 737-800	S 5.2	737800	2	2	1	3	1	0
Airbus A319	S 5.2	A319-131	10	9	9	11	15	3
Airbus A320	S 5.2	A320-211	11	4	6	12	5	5
Airbus A330-200	S 6.1	A330-301	1	1	0	0	1	1
BE20	P 1.4	CNA441	1	0	1	1	0	0
Cessna 560 XL	S 5.1	CNA560XL	1	1	2	2	1	1
SW4	P 2.1	DHC6	1	2	1	3	1	0
ATR 42	P 2.1	DHC8	1	3	0	1	3	0
ATR 72	P 2.1	DO328	7	8	10	6	14	6
Embraer 190	S 5.2	EMB190	4	2	0	3	2	1
		Total	43	33	33	47	46	18

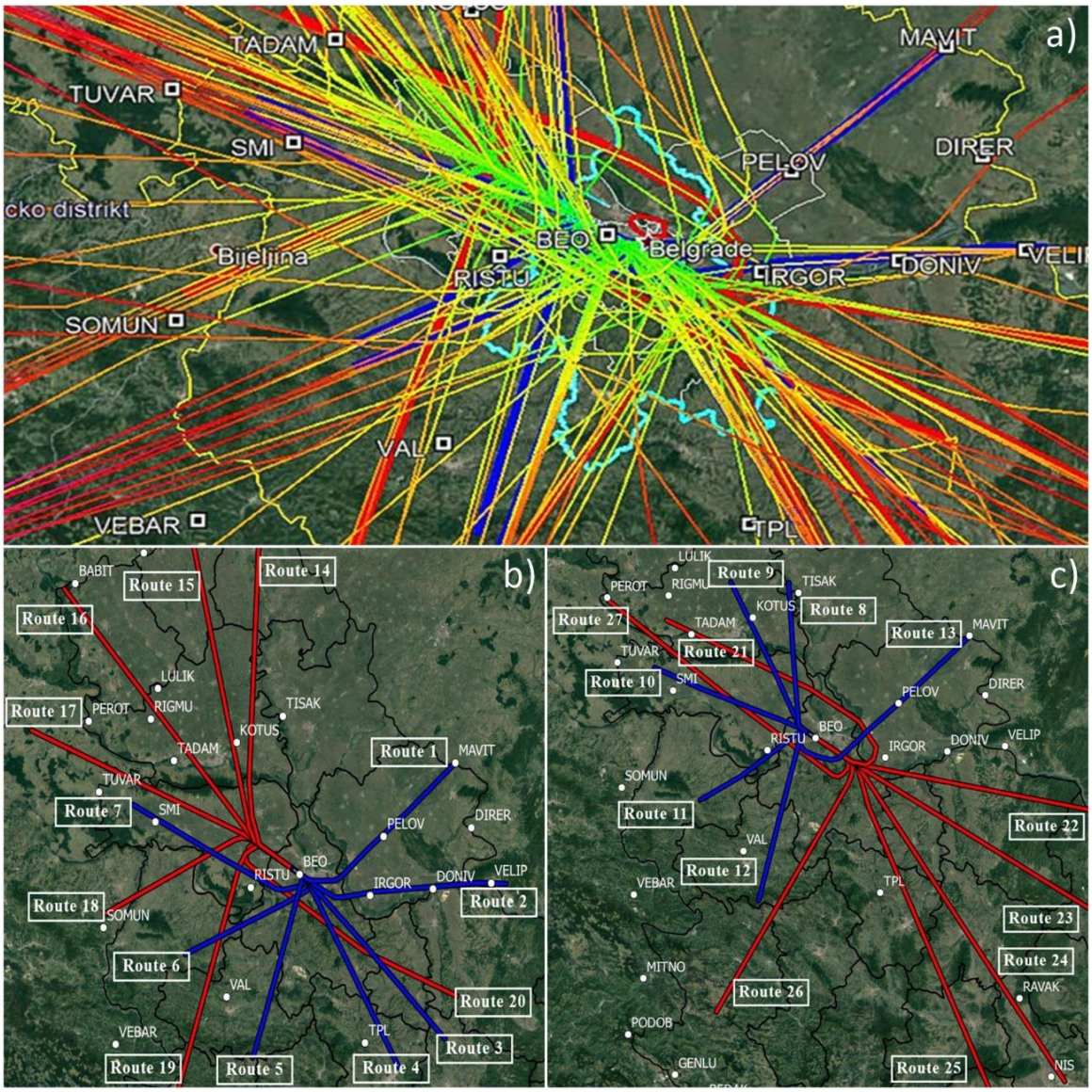


Fig. 1 *Radar data and departure and arrival routes (source: Flightradar24.com, using Google Earth)*

Table 2 *Location and population data*

No.	Municipality	Settlement	Legal noise limit (dB)		Population			
			Day and Evening	Night	2011 Census	Period 1	Period 2	Period 3
1	Cukarica	Banovo Brdo	55	45	44669	40098	40790	43978
2	Cukarica	Cerak	55	45	43993	39492	40172	43312
3	Cukarica	Zarkovo	55	45	30979	27809	28289	30500
4	Novi Beograd	Bezanijski blokovi	55	45	22455	22725	22610	22570
5	Novi Beograd	Ledine	55	45	6813	6895	6860	6848
6	Novi Beograd	Sava	55	45	18899	19126	19029	18996
7	Rakovica	Kanarevo Brdo	55	45	11389	9975	10194	11170
8	Rakovica	Kosutnjak	55	45	4944	4330	4425	4849
9	Rakovica	Miljakovac	55	45	7622	6676	6822	7476
10	Rakovica	Skojevska	55	45	4739	4151	4242	4648
11	Surcin	Dobanovci	55	45	8503	8055	8089	8469
12	Vozdovac	Jajinci	55	45	8876	8672	8733	8815
13	Vozdovac	Kumodraz	55	45	6064	5924	5966	6022
14	Vozdovac	Kumodraz 1	55	45	3852	3763	3790	3826
15	Vozdovac	Rakovica	55	45	3292	3216	3239	3269
16	Zemun	Ugrinovci	55	45	10807	10585	10616	10776
17	Stara Pazova	Krnjesevci	55	45	845	809	813	841
	Total				238741	222301	224679	236365

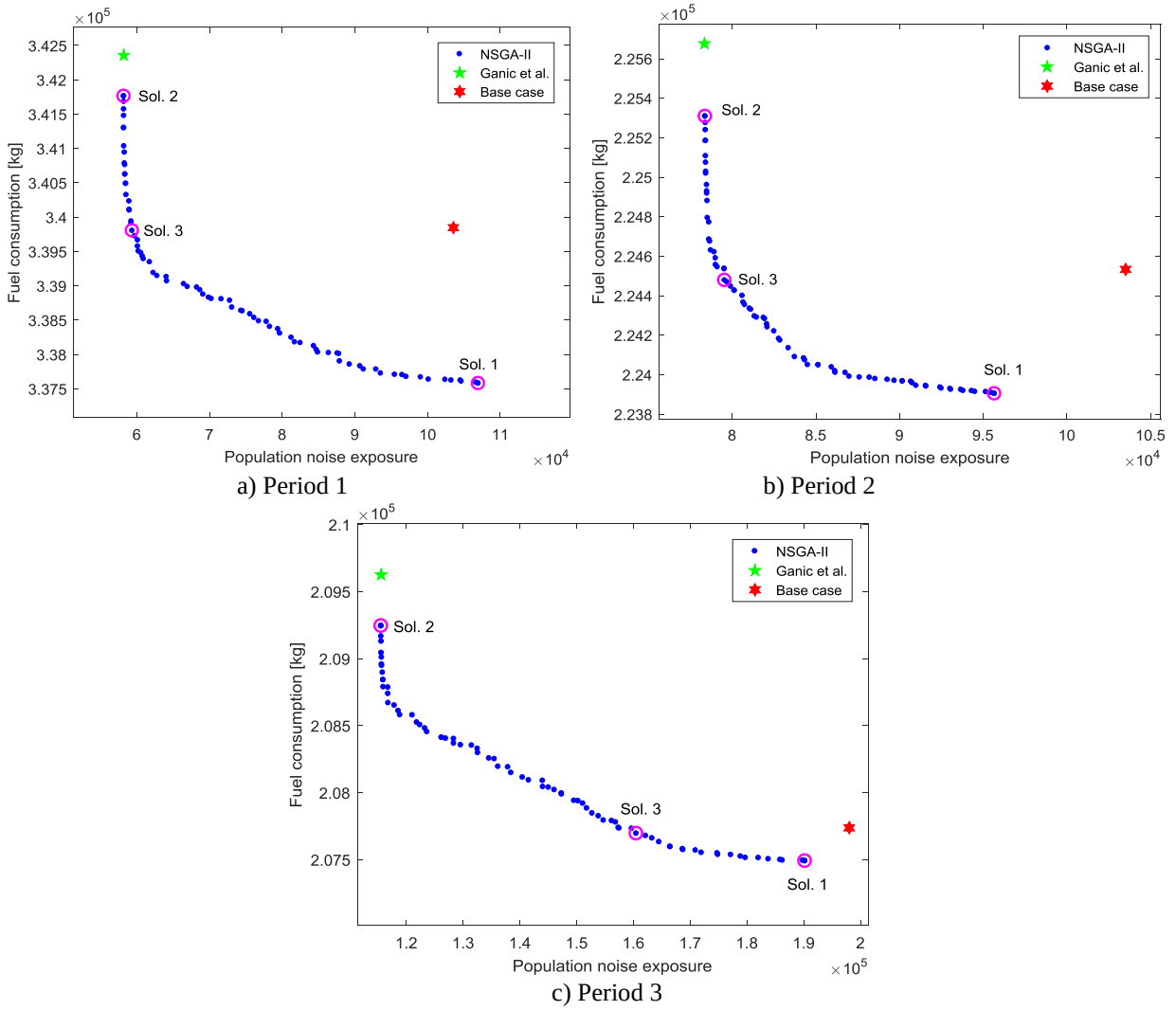
4. RESULTS AND DISCUSSION

The results obtained by the proposed approach for three different periods in comparison with those acquired by the base case and the model in [15] are depicted in Fig. 2. At first glance, it can be seen from Fig. 2 that the present approach offers a wide range of solutions (denoted as Pareto front), which try to make a good trade-off between the population noise exposure and fuel consumption. Another observation is that, for all three periods, the proposed model can provide solutions that dominate the base case, while compared with those obtained by [15], they are worse in terms of noise criterion and better regarding fuel burn.

In order to make the comparison more apparent, for each period, three different solutions are selected and highlighted, as shown in Fig. 2. With this selection, solution 1 represents for fuel optimization, solution 3 prefers to noise criterion, whereas solution 2 is one of solutions from the Pareto fronts which is close to the base case. All the metrics derived from these solutions are given in Table 3, where those obtained by the base case and the model in [15] are also provided.

From the table, a common trend for all the periods can be observed. Specifically, compared to base case, solution 1 offers a better performance in fuel burn, solution 2 performs better in noise criterion, while with almost the same amount of fuel consumption, solution 3 achieves a significant reduction in population noise exposure. For example, in Period 1, solution 1 has a reduction of 0.7% and 0.5% in fuel burn and route length, respectively, and an increase of 3.3% in population noise exposure, compared with the base case. Solution 2 has a very good performance in noise criterion with a considerable decrease of 43.8% in comparison with the base case, which is almost the same with that of the model in [15]. However, it is worse than the base case in term of fuel burn and route length. For solution 3, there is a good trade-off between all the concerned metrics to be found. With the same amount of fuel burn, it gains a great reduction of 42.7% in noise metric, while the one acquired by Ganic et al. [15] has a reduction of 43.8%, but causes a significant increase up to 0.7% in fuel burn.

From the results obtained above, it can be concluded that the proposed approach is reliable and quite effective. It not only provides reliable solutions, but also offers a variety of options for interested users to choose with only one single run. This feature has made the proposed approach dominating other single objective approaches in previous studies. Moreover, with the new form of the optimization problem given in Section 2.2, the problem size is reduced significantly, which allows the proposed model to be capable of solving large scale problems.



a) Period 1 b) Period 2

c) Period 3

Fig. 2 *Pareto front obtained by the NSGA-II algorithm*

Table 3 *Comparison of the metrics of the representative solutions and the reference case*

Period	Metrics	Base case	Ganić et al. [15]		Solution 1		Solution 2		Solution 3	
			Absolute value	% reduction	Absolute value	% reduction	Absolute value	% reduction	Absolute value	% reduction
1	Population noise exposure	103541	58187	-43.8%	106974	3.3%	58211	-43.8%	59359	-42.7%
	Fuel consumption (kg)	339844	342358	0.7%	337567	-0.7%	341761	0.6%	339798	0.0%
	Route length (NM)	51459	52065	1.2%	51227	-0.5%	51923	0.9%	51647	0.4%
2	Population noise exposure	103506	78332	-24.3%	95643	-7.6%	78356	-24.3%	79518	-23.2%
	Fuel consumption (kg)	224527	225682	0.5%	223897	-0.3%	225315	0.4%	224477	0.0%
	Route length (NM)	38664	38924	0.7%	38515	-0.4%	38833	0.4%	38644	-0.1%
3	Population noise exposure	197999	115514	-41.7%	190204	-3.9%	115539	-41.6%	160493	-18.9%
	Fuel consumption (kg)	207735	209631	0.9%	207488	-0.1%	209248	0.7%	207695	0.0%
	Route length (NM)	33713	34279	1.7%	33639	-0.2%	34191	1.4%	33700	0.0%

5. CONCLUSION

In this paper, a new approach for air traffic assignment is developed. The proposed model is based on a new form of the optimization problem, in which two conflicting objective functions, including noise and fuel criteria, are taken into account simultaneously. The formulated problem is then solved by the well-known multi-objective optimization method, named NSGA-II. The reliability and applicability of the proposed approach are demonstrated through a case study at Belgrade Airport in Serbia. Through the evaluation and comparison of the obtained results with those of the base case and the model in [15], it reveals that the proposed method is reliable and quite effective. It does not only provide reliable solutions but also gives a wide range of solutions – featuring a good trade-off between the considered two objectives – which can be a good reference base for users to refer to before making decisions.

Furthermore, thanks to the new ways of formulating the optimization problem, the proposed approach is promising to be extended for solving large problems in busy airports.

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