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Benefits of Proactive Planning of High-Performance Aircraft Training Operations in Flexible Airspace Structures for Pollution Reduction

Nikola Mostarac[1], Tomislav Mihetec[2], Andrea Reščić[2]
[1]*Faculty of Transport and Traffic Sciences, University of Zagreb, Vukelićeve 4, Zagreb 10000, Croatia.*
[2]*Croatia Control Ltd, Rudolfa Fizira 2, Velika Gorica 10410, Croatia.*

Abstract

The flexibility of airspace use is at odds with its predictability. The extent of unplanned military activity, although a second-order factor relative to traffic variability, directly influences civil traffic and its pollution footprint. In this research, the assessment of the benefits of proactive planning of high-performance aircraft training operations in flexible airspace structures is performed to examine the possibility of reducing the pollution footprint and the improvement of environmental protection issues by shifting the operational time-frame. Assessment has been performed through a series of simulations on the actual traffic samples using the EUROCONTROL NEST - Network Strategic Tool. The initial impact scenario with flexible airspace structures available without restrictions proved the traffic sample validity. On top of the initial scenario, the reference scenario and the modified activation scenario were simulated, with flexible airspace structures not available in the periods reserved for military high-performance aircraft. Several civil-military ATM performance indicators were developed to compare the reference results and the modified activation scenarios. Specific findings of the research indicate the possible quantitative benefits of proactive planning of high-performance aircraft training operations in flexible airspace structures as well as the constraints of the process.

Keywords*:* civil-military ATM performance indicators, flexible airspace structures, high-performance aircraft training operations, improvement of environmental protection.

1. Introduction

Aviation causes 3–5% of total global warming by carbon dioxide (CO_2) emissions, nitrogen oxide (NOX) emissions, water vapor emissions, aerosols, and persistent contrail and contrail-cirrus formation [1]. Ground delay fuel consumption is six times lower than airborne delay fuel consumption [2]. Aviation negative impact on the environment was reduced at Madrid-Barajas Airport through a modified arrival sequence that resulted in up to 4,5% reduced overall fuel consumption [3]. The research described in [4] revealed that the introduction of the highly dynamic approach and landing procedures demonstrated the ability to reduce ground noise and decrease landing distance as well as to decrease the fuel burn by up to 56% compared to the "published transition route".

Major degradation of operational efficiency regarding fuel consumption, flight time, and flight distance is created due to non-optimal altitude, trajectories, and speed [5]. The cruise flight phase contributes to the climate impact proportionally to its duration and has the highest potential in terms of altitude and speed adjustments [6], [7]. The higher altitude of a cruise increases radiative forcing and induces long-term temperature change [8]. The cruise phase of flights performed at high altitudes represents approximately 80% of the flight time. This airspace originates the greatest

Corresponding author: Nikola Mostarac (nmostarac@fpz.unizg.hr)
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share of total fuel consumption and pollutant emissions, which contribute to the changes in the atmosphere and amplify climate change [9]. Potential fuel savings data resulting from research presented in [10] for modified cruise altitudes vary between 1,75% and 1,96%.

The benefit of an hourly in-flight trajectory re-optimization considering hourly weather forecasts is researched in [11]. The research was conducted for the cruise part of the A320 flights from Seattle to New York simulated for 93 days with five hourly weather forecasts per day. The fuel savings of re-optimized flights compared to the former modeled flights fluctuate between 0,5% and 7% per flight [11]. The study of trajectory optimization of single trajectories within the corridor based on the variability of weather parameter uncertainties indicates possible fuel savings of up to 1,1%, if compared to the initially filed flight [12].

Temporary military activities, as well as airspace congestion or any other airspace restriction such as adverse weather conditions, impact the actual flight trajectory of aircraft. It causes deviation from the planned route, reduces the predictability of air traffic and degrades the efficiency of the air traffic management system [13]. Airspace restrictions lead to either laterally or vertically non-optimized trajectories. A trajectory optimization comparison of the Chinese and European airspaces indicates that prohibited areas might have a prominent impact on flight efficiency during the cruise phase [14]. Similarly, in Japan, airspace is mainly restricted for military reasons [5]. Therefore, even though military activity uncertainty is a second-order factor compared to the variability of traffic, the military aircraft's use of flexible airspace structures needs to be examined in order to increase the predictability and flexibility of airspace use [15].

Fragmented European airspace and its inefficient air traffic management (ATM) system emphasize the necessity of a flexible use of airspace (FUA) concept. FUA should ensure the temporary segregation of users based on real-time needs and actual use of airspace by military and civil users. The key enabler for FUA is reliable and accurate information regarding the actual use of airspace by military users [16]. The International Civil Aviation Organization (ICAO) recognized problems that needed to be mitigated in inadequate coordination among stakeholders as well as inadequate coordination at the local, regional, and global levels due to a fragmented operational approach [17].

The impact of flexible airspace structure on flight efficiency was elaborated and described in [18]. Flight efficiency was defined as the difference between the distance of the actual flight path and the possible distance of the direct flight path, which connects the entry and exit points for the selected airport. The parameters used to measure its value were: additional mileage, additional travel time, additional fuel consumption and further increase in the cost of airline operators. Research scenarios included a scenario of modification of vertical limits of flexible airspace structure and a scenario of modification of activation period. Redesign of the flexible airspace was also researched. The research was performed on 15-minute shifts of activation times, 45 minutes in total both beforehand and after the original activation time. Modification of activation period scenarios every week created an overall increase of the flight efficiency of 29,98% if the best solution for each simulated day was used.

The research on high-performance aircraft pilots' flight training syllabus structure and its specific impact on proactive planning of training operations in flexible airspace structures was performed [19]. The research was performed on flexible airspace structures in Zagreb FIR due to its significant diversity in the hourly distribution of civil traffic demand. Research was performed on three fixed periods in daytime flying operations and three fixed periods in nighttime flying operations with fixed intervals between periods. The simulation of proactive planning was performed during a period of 529 days. The relative share of civil traffic for daytime flying operations had an average minimal value of 25.59%, an average median value of 33,63%, and an average maximal value of 40,78% of total traffic in all three periods. Proactive planning of the use of the one daily interval with minimal value of civil traffic at critical flight levels reduced the number of impacted civil aircraft by 15,29%. For the nighttime operations, there was an average minimal value of 21,21%, an average median value of 33,38% and an average maximal value of 45,41% of total traffic in all three periods. Proactive planning of the use of the intervals with minimal value of civil traffic reduced the number of impacted civil aircraft by 24,2%. Meanwhile, the proactive planning created a longer duration of total pilot training. For the original syllabus there was an increase of 12% and for the optimized syllabus structure there was an increase of 4% [19].

More interestingly, there was a reduction of impact on civil traffic compared to non-proactive planning of the use of the flexible airspace structures. For the original syllabus case, fuel consumption decreased by 23%, as well as CO_2 emissions, NOx emissions decreased by 22% and fuel consumption decreased by 29%. For the optimized syllabus, fuel consumption decreased by 28%, as well as CO_2 emissions, NOx emissions decreased by 26% and fuel consumption decreased by 41% [19].

Previously discussed existing studies have left certain issues that need to be addressed to complement existing knowledge regarding the pollution reduction capacity of proactive planning of high-performance aircraft training operations in flexible airspace structures. Functioning of a high-performance aircraft training operations requires a daily routine without daily micro-irritations by slot shifting. That directs the area of interest to the approach in which daily slots are permanently assigned. The aim of this paper is to investigate the impact of such proactive planning of high-performance aircraft training operations in flexible airspace structures on actual traffic samples.

Unlike previous studies, this paper focuses on environmental performance assessment of the proactive planning of high-performance aircraft training operations in flexible airspace structures. The research is focused on coupled slot-shifting logic applicable under operational constraints that do not allow the reduction of turn-around time due to flight safety standards. This will enable decision-making and development of a locally-developed priority system. In total, the knowledge gained in this research will help enable the reduction of military activities' impact on civil aircraft operations.

2. Materials and Methods

This section provides the rationale of the simulations' assumptions and basis regarding the high-performance aircraft, operational time, and flight time intervals. Airspace structure and traffic demand chosen for the simulations are described and their suitability to provide answers for research questions under research assumptions. Finally, simulation setup scenarios as well as the simulation software are explained.

2.1. Research Assumptions and Questions

In peacetime, one of the high-performance military aircraft primary missions-training flights have to be performed as close as possible to the standards of the real ones they are training and preparing for. These training flights are performed daily [20]. Based on the fact that the majority of the fighter aircraft fleet in Europe consists of high-performance aircraft, this category of aircraft is chosen for this research. Uniformity and overlapping of the way they use airspace for the same type of sortie makes it irrelevant which particular type of aircraft operates inside the airspace as long as it is either of high-performance aircraft.

Peculiarities of aircraft maintenance regarding aircraft preparation and apron services influence the organization of daily flying operations [21]. Slots in which military high-performance aircraft flights are performed daily during the operational interval are separated by intervals that contain the turnaround time between two successive slots, as shown in Figure 1.

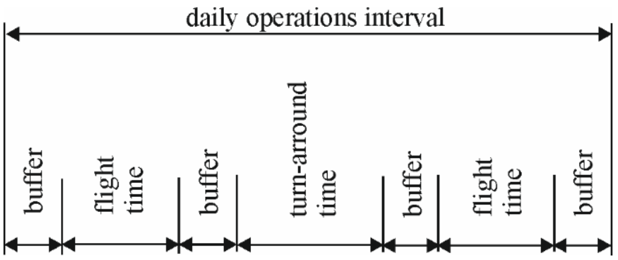

Figure 1. Daily operational time and flight time intervals.

Shrinking the time between flights requires intervention on time available for maintenance procedures performed between flights—turnaround time. Such an intervention would directly influence flight safety. Therefore, the intervention regarding time between slots does not represent the rational long-term daily routine, and it is not the subject of the research. The real-world restrictions of operational time affect the possibility of flight time modification. These, closely related to the simulation scenarios, unaddressed in previous studies, are incorporated into research scenarios.

Training activities of high-performance aircraft in flexible airspace structures in this research are performed daily in two two-hour slots. This arrangement corresponds to the real-life modus operandi. The arrangement secures mission time inside flexible airspace structures and buffer times before and after the mission. The buffer intervals are necessary for civil flights to leave the airspace before the mission inside airspace commences and, after the mission is completed, for regular traffic flow to be established. Time between two-hour slots, the turn-around time, remained unchanged due to operational reasons. To enable a continuous stable operational environment, two sets of two-hour mission flight time slots are contained in daily operations intervals.

Optimization of the design of flexible airspace structures chosen for research regarding dimensions, volume and modularity is performed in previously explained research [18]. For this research, these structures are presumed as optimized and therefore suitable for the experimentation regarding modification of activation period(s). This paper's research is performed on a smaller scale of distribution of civil traffic than in [19] and [22] to examine the more detailed peculiarities of civil-military aircraft operations and consequent interactions.

Zagreb AoR airspace and its appurtenant flexible airspace structures used for military high-performance aircraft training emerge as suitable for this article's topic research for several reasons. Their peculiar dimensions and volume practically fit AoR boundaries. When activated, these structures not only interfere with the civil aircraft flights from the European airspace management point of view but also completely obstruct the Zagreb AoR traffic flow in the corresponding North sector of the AoR airspace. Volume and dimensions of the flexible airspace structures leave no possibility for either vertical nor lateral adjustments of the airspace. Once activated, these flexible airspace structures divert the civil air traffic flow to alternative routes.

Types of training sorties inside the flexible airspace structures performed by either of the high-performance aircraft types do influence neither the structures' dimensions nor the activation times.

Furthermore, prevailing meteorological conditions in the research interval, from 22 July 2024 to 2 August 2024 represent the ideal environment to secure undisturbed performance of sorties to eliminate the influence of meteorological conditions on high-performance aircraft flight operations.

High-performance aircraft training activities have continuous demand for flexible airspace structures use throughout the year regardless of the civil traffic distribution. Therefore, seasonal rescheduling of high-performance aircraft training is operationally insignificant, although comprehensive research for a longer period could be deemed necessary.

There are Civil-military ATM performance indicators defined in [23]:

- SUA (Special Use Airspace) Capacity Requested,
- CoTT (Transit Cost),
- ACoT (Average cost of Transit,
- AvsO (Allocated SUA Dimensions vs Optimum SUA Dimensions),
- AvT (Average Transit Time),
- AAE (AUP Allocation Efficiency),
- UoA (Use of Allocated SUA),
- tPvtU (Time Planned vs time Used by GAT in Available SUA),
- rStU (Released SUA Time Used by GAT),
- ASMx (Proportion of SUAs to which ASM Level X Applies),
- SASn (SUA Allocation at Short Notice),
- tGAT (SUA Released to GAT prior to Scheduled Start).

Although useful for airspace allocation and coordination performance measurement these performance indicators are not suitable for this study's assessment of the environmental effects. These do not directly measure fuel consumption, CO_2 emissions, NOx emissions, flight distance, or flight time.

This research is designed to provide data for the calculation of the following performance indicators defined in [23].

nA/C_{rel} – relative number of civil aircraft flights representing the ratio of the number of civil aircraft affected by zones activation during modified activation slots – nA/C_{mod} and the number of civil aircraft affected by zones activation during reference slots - nA/C_{ref}, - presented in Eq. 1;

$$nA/Crel = \frac{nA/Cmod}{nA/Cref} x100 \tag{1}$$

C_{nsmrel} – relative fuel consumption representing the ratio of the increase of fuel consumption of civil aircraft affected by zones activation during modified activation slots – C_{nsmmod} and the increase of fuel consumption of civil aircraft affected by zones activation during reference slots – C_{nsmref} - presented in Eq. 2;

$$Cnsmrel = \frac{Cnsmmod}{Cnsmref} x100 \qquad (2)$$

CO_2r_{el} – relative CO_2 emission – relative CO_2 emission representing the ratio of the increase of CO_2 emission of civil aircraft affected by zones activation during modified activation slots – CO_{2mod} and the increase of CO_2 emission of civil aircraft affected by zones activation during reference slots – CO_{2ref} - presented in Eq. 3;

$$CO2rel = \frac{CO2mod}{CO2ref} x100 \qquad (3)$$

NOX_{rel} - relative NOX emission representing the ratio of the increase of NOX emission of civil aircraft affected by zones activation during modified activation slots – NOX_{mod} and the increase of NOX emission of civil aircraft affected by zones activation during reference slots – NOX_{ref} - presented in Eq. 4;

$$NOXrel = \frac{NOXmod}{NOXref} x100 \qquad (4)$$

FNM_{rel} - relative flight distance representing the ratio of the increase of flight distance of civil aircraft affected by zones activation during modified activation slots – FNM_{mod} and the increase of flight distance of civil aircraft affected by zones activation during reference slots – FNM_{ref} - presented in Eq. 5;

$$FNMrel = \frac{FNMmod}{FNMref} x100 \qquad (5)$$

and an additional one,

FT_{rel} – relative flight time of civil aircraft flights representing the ratio of flight time of civil aircraft affected by zones activation during modified activation slots – FT_{mod} and the flight time of civil aircraft affected by zones activation during reference slots - FT_{ref}, - presented in Eq. 6.

$$FTrel = \frac{FTmod}{FTref} x100 \qquad (6)$$

2.2. Airspace Structure and Traffic Demand

Flexible airspace structures LDTR24, LDTR25, LDTR26, and LDTR27 in the eastern part of the Zagreb AoR are used in this paper's research.

The impact of LDTR24, LDTR25, LDTR26, and LDTR27 activation on civil air traffic during two-hour periods (26.7.2024, 7-9 UTC and 11-13 UTC) at FL325-FL660 is shown in Figure 2.

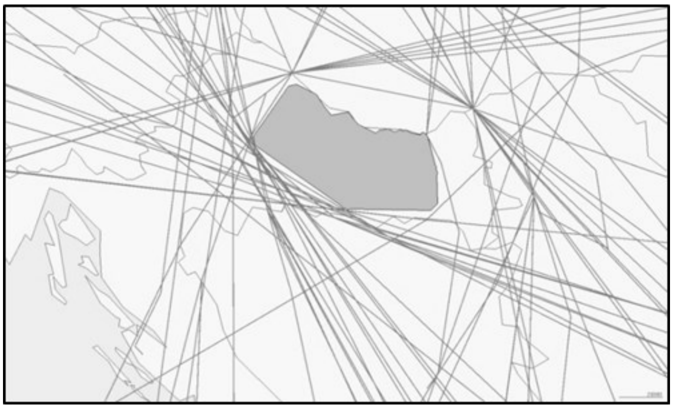

Figure 2. Civil air traffic trajectories in the case of LDTR24-27 activated at FL325-FL660.

Civil air traffic in the same airspace during the same period without LDTR activation is shown in Figure 3. Rerouted civil flights not only outside these flexible airspace structures but also outside Zagreb AoR as well (Zagreb AoR boundaries include Croatian borders) are noticeable.

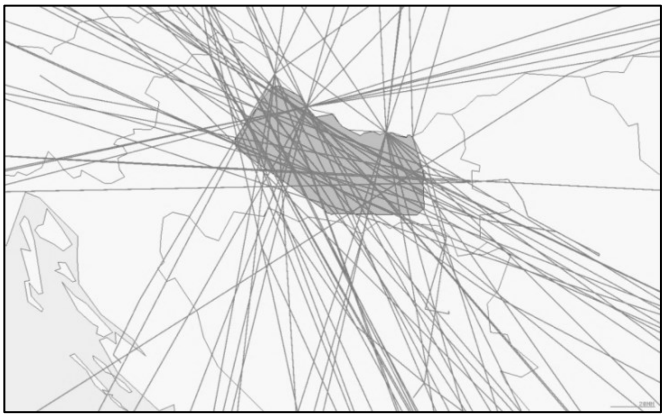

Figure 3. Civil air traffic trajectories in the case of LDTR24-27 were not activated.

LDTR24, LDTR25, LDTR26, and LDTR27 activation affected 348 civil aircraft during a two-hour period

(26.7.2024, 7-9 UTC and 11-13 UTC) at FL325-FL660 as shown in Figures 2 and 3. There was an increase in civil flights length by 507,32 NM, an increase in flight time of 49,83 minutes, an increase in civil aircraft CO_2 emission of 3266,56 kg and an increase in civil aircraft NOX emission of 10291,18 kg.

There is a distribution of the number of civil flights through these flexible airspace structures during the day. Periods of reservation of flexible airspace structures by the high-performance aircraft in the research period, for the paper's research purpose, 22 July 2024 to 2 August 2024, are shown in Table 1.

Table 1. Periods of use of flexible airspace structures.

Date	2024-07-22 – 2024-08-02*
Reference Slot 1 (UTC)	06.00 – 08.00
Modified Slot 1' (UTC)	07.00 – 09.00
Reference Slot 2 (UTC)	10.00 – 12.00
Modified Slot 2' (UTC)	11.00 – 13.00
* 27 and 28 July excluded – weekend days	

2.3. Simulation setup scenario

Using the data regarding the number of civil aircraft affected by flexible airspace structures LDTR24-27 use at FL325-FL660, three sets of simulations were performed. For simulation purposes, EUROCONTROL NEST (Network Strategic Tool) was used with its' specific simulation settings, routing assumptions, conflict resolution logic, trajectory generation settings, and configuration parameters. NEST is a stand-alone desktop application used by the Network Manager (EUROCONTROL) and ANSPs (Air Navigation Service Providers) for airspace structure design and development, capacity planning and post-operations analysis, strategic traffic flow organization, scenario preparation for fast and real-time simulations and ad-hoc studies at the local and network level.

For the purposes of the simulations, the Simulate Trajectory function was used with the Use Rerouting option, which defines the air spaces (Exclusion Area) through which flying is prohibited. The Simulate Trajectory function for a defined traffic pattern "searches" for the shortest available routes, respecting the route restrictions defined in the Environment, and at the same time bypassing the airspace defined in the Exclusion Area. The shortest available route when bypassing the airspace may have a maximum extension of the shortest route by up to 50NM or 15%.

NEST uses various algorithms for the analysis of the traffic input data that are actual flight plans in the research periods. Simulation results regarding the fuel burn, NOX and CO_2 emissions were obtained by NEST tool, specifically the Advanced Emission Model (AEM) [24].

The Advanced Emission Model (AEM) is a standalone application developed and maintained by EUROCONTROL Innovation Hub in Brétigny. It is designed to estimate aircraft emissions and fuel consumption. Additionally, AEM analyzes flight profile data on a per-flight basis, supporting air traffic scenarios of various scales, from localized airport studies to global aircraft emissions assessments. AEM can calculate:

- The amount of fuel burned by the main engines of a specific aircraft type with a given engine model following a defined 4D trajectory,
- The corresponding quantities of certain gaseous and particulate emissions produced by fuel combustion.

The estimated emissions include carbon dioxide (CO_2), water vapor (H_2O), nitrogen oxides (NOx), sulfur oxides (SOx), unburnt hydrocarbons (HC), carbon monoxide (CO), volatile organic compounds (VOCs), and other organic gases (OGs).

The ICAO Advanced Emission Model (AEM) estimates CO_2 emissions based on the mass of fuel burned, using a standard emission index for carbon dioxide. The formula for calculating CO_2 emissions is presented in Eq. 7.

$$CO2 = Fuel\ Burnt\ x\ EICO2 \qquad (7)$$

Where:

- CO_2 = Mass of carbon dioxide emitted (kg)
- Fuel Burn = Mass of fuel consumed (kg)
- EI_CO_2 = Emission index of CO_2 (kg of CO_2 per kg of fuel burned).

For Jet-A1 fuel, the typical ICAO CO_2 emission index (EI_CO_2) is 3,16 kg of CO_2 per kg of fuel burned. This value is based on the carbon content of aviation fuel and the stoichiometric combustion process. The sequence of simulations is shown in Figure 4.

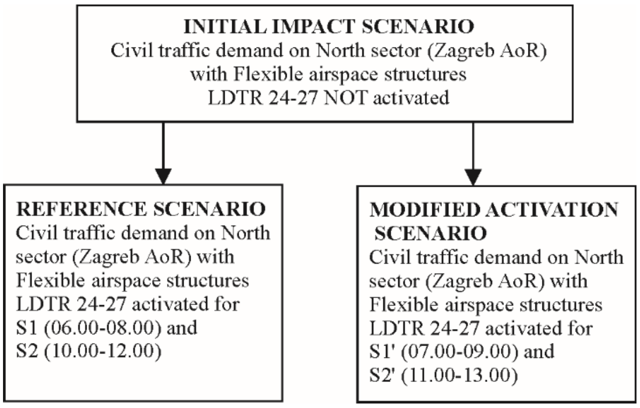

Figure 4. Sequence of simulations.

The first set of simulations for the initial impact scenario was performed with flexible airspace structures available without restrictions.

The second set of simulations, the reference scenario, was performed with flexible airspace structures not available in the periods with flexible airspace structures reserved for military high-performance aircraft, namely Slot 1 and Slot 2. The impact of military flights related to the difference between civil traffic without and with flexible airspace structures used for military high-performance aircraft is examined regarding absolute and relative changes in flight time, fuel consumption, CO_2, and NOX emissions.

As the planning of high-performance aircraft training operations in flexible airspace structures is performed a day in advance, the adjacent time intervals with lower civil traffic demand on the following day are chosen based on data in Table 1.

The third set of simulations, the modified activation scenario, was performed with flexible airspace structures not available in the periods with flexible airspace structures reserved for military high-performance aircraft, namely Slot 1' and Slot 2'.

3. Results

For days of use of flexible airspace structures for the research period as shown in Table 1, civil traffic demand on Sector North Zagreb AoR, defined by using the NEST tool, with flexible airspace structures LDTR24, LDTR25, LDTR26, and LDTR27 not activated – initial scenario, is presented in Table 2 and visualized in Figure 5.

Table 2. Civil traffic demand on Sector North Zagreb AoR with flexible airspace structures LDTR24, LDTR25, LDTR26, and LDTR27 not activated.

Date	nA/C_{ref} - Slot 1 and Slot 2	nA/C_{mod} - Slot 1' and Slot 2'	nA/C_{mod} - nA/C_{ref}
2024-07-22	308	328	20
2024-07-23	310	293	-17
2024-07-24	302	335	33
2024-07-25	324	324	0
2024-07-26	348	348	0
2024-07-29	320	321	1
2024-07-30	327	300	-27
2024-07-31	317	316	-1
2024-08-01	331	328	-3
2024-08-02	308	328	20
Total	3.238	3.238	/

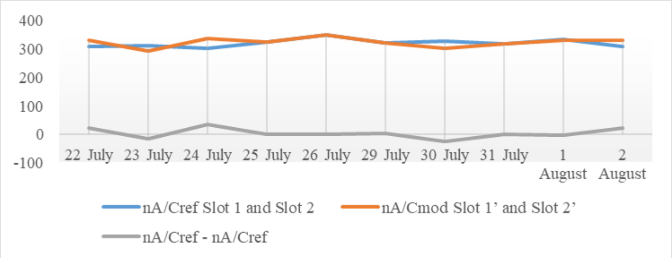

Figure 5. Civil traffic demand on Sector North Zagreb AoR with flexible airspace structures LDTR24, LDTR25, LDTR26, and LDTR27 not activated.

Data contained in Table 2. show differences between traffic demand in slots 1' and 2' and traffic demand in slots 1 and 2 daily. The average increase in traffic demand on the sampled days was one flight, which represents a negligible relative difference.

Performance indicator nA/C_{rel} - relative number of civil aircraft flights calculated from the Table 2. data is presented in Table 3 and visualized in Figure 6.

Table 3. Performance indicator nA/C_{rel}.

Date	**nA/Cr_{el}**
2024-07-22	106,49
2024-07-23	94,52
2024-07-24	110,93
2024-07-25	100,00
2024-07-26	100,00
2024-07-29	100,31
2024-07-30	91,74
2024-07-31	99,68
2024-08-01	99,09
2024-08-02	95,44

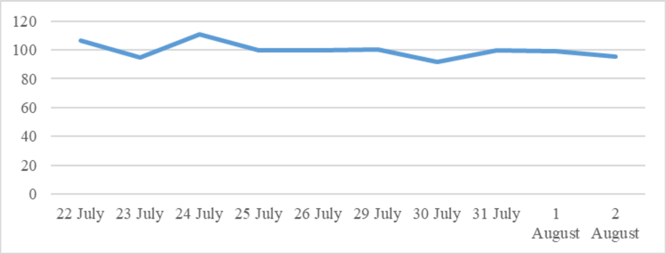

Figure 6. Performance indicator nA/C_{rel}.

Performance indicator - nA/C_{rel} values presented in Table 3 has a minimal value of 91,74% and a maximal value 110,93%? The median value of 99,82% is closely correlated with the average increase in traffic demand on sampled days.

The difference between the results of the first set of simulations 2 and the results of the second set of simulations, regarding affected civil flights' length, flight time, fuel consumption, CO_2, and NOX emissions is presented in Table 4 and visualized in Figure 7, and Figure 8.

Table 4. Difference between simulation results of the first and the second scenario in Slot 1 and Slot 2.

Date	FNM_{ref} (NM)	FT_{ref} (min)	C_{nsmref} (kg)	$CO2_{ref}$ (kg)	NOX_{ref} (kg)
2024-07-22	420,53	54,13	4307,74	13576,37	65,95
2024-07-23	550,04	71,93	5830,57	18371,09	93,27
2024-07-24	369,14	52,69	4102,70	12927,14	66,73
2024-07-25	418,79	51,82	4439,42	13991,85	69,56
2024-07-26	520,17	70,34	4706,28	14831,58	72,67
2024-07-29	416,04	55,54	4342,65	13684,18	65,92
2024-07-30	536,27	73,99	5001,47	15758,21	81,87
2024-07-31	407,9	57,82	4563,38	14378,01	69,90
2024-08-01	437,05	57,57	4320,25	13615,91	69,43
2024-08-02	539,36	67,9	5091,24	16045,7	80,48

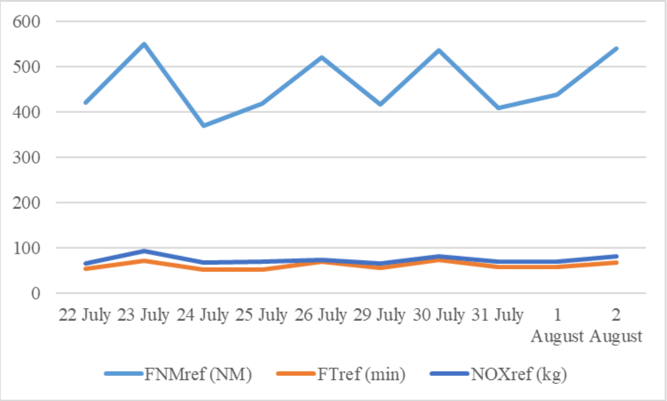

Figure 7. Difference between simulation results of the first and the second scenario in Slot 1 and Slot 2 - FNM_{ref} (NM), FT_{ref} (min) and NOX_{ref} (kg).

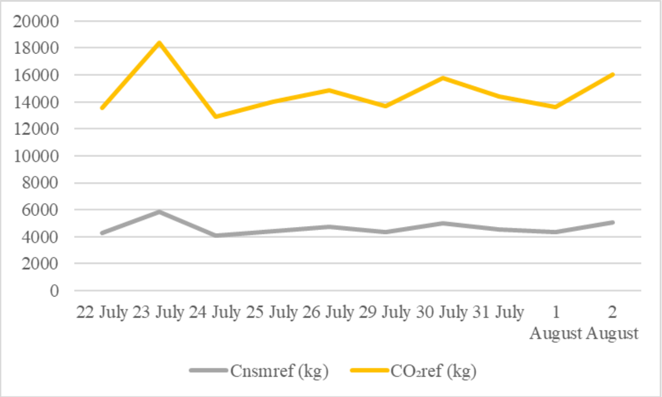

Figure 8. Difference between simulation results of the first and the second scenario in Slot 1 and Slot 2 - CO_{2ref}(kg) and C_{nsmref} (kg).

All parameters show an increase compared to parameters of flights with flexible airspace structures in-active. Minimal and maximal values, as well as average values for FNM_{ref}, FT_{ref}, NOX_{ref}, $CO2_{ref}$ and C_{nsmref} are presented in Table 5.

Table 5. Average, minimal and maximal values for FNM_{ref}, FT_{ref}, NOX_{ref}, $CO2_{ref}$ and C_{nsmref} emissions simulation results of the first and the second scenario in Slot 1 and Slot 2.

Date	FNM_{ref} (NM)	FT_{ref} (min)	C_{nsmref} (kg)	CO_{2ref} (kg)	NOX_{ref} (kg)
AVER	461,53	61,37	4670,57	14718,00	73,58
MIN	369,14	51,82	4102,70	12927,14	65,92
MAX	550,04	73,99	5830,57	18371,09	93,27

The difference between the results of the first set of simulations and the results of the third set of simulations, regarding affected civil flights' length, flight time, fuel consumption, CO_2, and NOX emissions are presented in Table 6 and visualized in Figure 9 and Figure 10.

Table 6. Difference between simulation results of the first and the third scenario in Slot 1' and Slot 2'.

Date	FNM_{mod} (NM)	FT_{mod} (min)	C_{nsmmod} (kg)	CO_{2mod} (kg)	NOX_{mod} (kg)
2024-07-22	392,28	32,56	3205,82	10099,84	48,66
2024-07-23	519,17	49,6	3488,77	10994,62	47,25
2024-07-24	385,34	40,79	3010,34	9483,50	45,86
2024-07-25	427,82	40,11	3745,49	11798,96	61,07
2024-07-26	507,32	49,83	3266,56	10291,18	46,94
2024-07-29	389,13	35,64	3192,98	10060,33	48,47
2024-07-30	482,40	51,25	2827,82	8909,91	41,73
2024-07-31	395,22	42,88	3036,71	9567,11	42,37
2024-08-01	402,75	43,59	3156,33	9942,46	51,48
2024-08-02	479,98	43,63	3508,31	11054,21	53,41

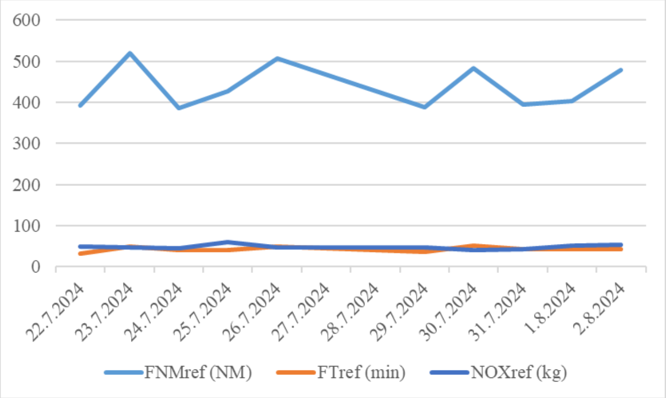

Figure 9. Difference between simulation results of the first and the third scenario in Slot 1' and Slot 2' – FNM_{mod} (NM), FT_{mod} (min) and NOX_{mod} (kg).

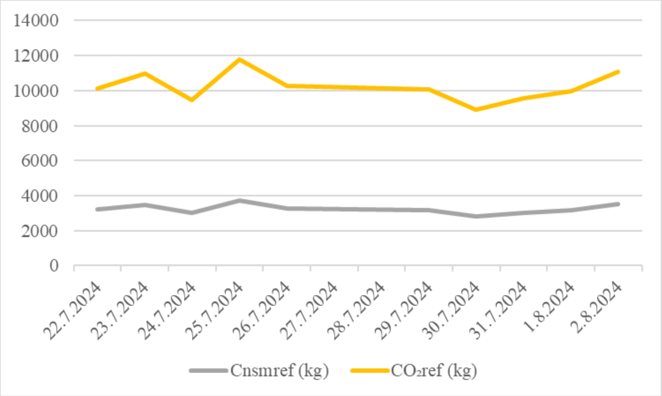

Figure 10. Difference between simulation results of the first and the third scenario in Slot 1' and Slot 2' - CO_{2mod}(kg) and C_{nsmmod} (kg).

Similarly, to the previous case, there is an increase of all parameters in the case of the activation of flexible airspace structures in slot 1' and slot 2' presented in Table 6. Minimal and maximal values as well as average values for FNM_{mod}, FT_{mod}, NOX_{mod}, $CO2_{mod}$ and C_{nsmmod} are presented in Table 7.

Table 7. Average, minimal and maximal values for FNM_{mod}, FT_{mod}, NOX_{mod}, $CO2_{mod}$ and C_{nsmmod} emissions simulation results of the first and the third scenario in Slot 1' and Slot 2'.

Date	FNM_{mod} (NM)	FT_{mod} (min)	C_{nsmmod} (kg)	CO_{2mod} (kg)	NOX_{mod} (kg)
AVER	438,14	42,99	3243,91	10220,21	48,72
MIN	385,34	32,56	2827,82	8909,91	41,73
MAX	519,17	51,25	3745,49	11798,96	61,07

Performance indicators: nA/C_{rel}, FNM_{rel}, FT_{rel}, C_{nsmrel}, CO_{2rel}, and NOX_{rel}, values are presented in Table 8 and visualized in Figure 11.

Table 8. Performance indicators values.

Date	nA/C_{rel}	FNM_{rel}	FT_{rel}	C_{nsmrel}	CO_{2rel}	NOX_{rel}
2024-07-22	106,49	93,28	60,16	74,42	74,39	1,36
2024-07-23	94,52	94,39	68,95	59,84	59,85	1,97
2024-07-24	110,93	104,39	77,42	73,37	73,36	1,46
2024-07-25	100,00	102,16	77,42	84,37	84,33	1,14
2024-07-26	100,00	97,53	70,84	69,41	69,39	1,55
2024-07-29	100,31	93,53	64,16	73,53	73,52	1,36
2024-07-30	91,74	89,95	69,27	56,54	56,54	1,96
2024-07-31	99,68	96,89	74,16	66,55	66,54	1,65
2024-08-01	99,09	92,15	75,71	73,06	73,02	1,35
2024-08-02	95,44	88,99	64,26	68,91	68,89	1,51

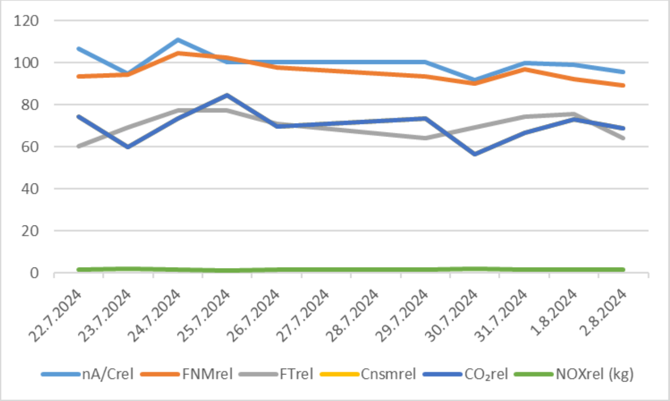

Figure 11. Performance indicators values.

4. Discussion

The initial research on proactive planning of training operations of high-performance aircraft in flexible airspace structures was performed on civil traffic demand with significant distribution. The research examined the restrictive impact of flight training syllabus structure on the diversified use of different operating flight levels in flexible airspace structures. Proactive planning based on the original syllabus enabled an increase of 12% in the total training duration, but civil aircraft' fuel consumption decreased by 23%, as well as CO_2 emissions, NOx emissions decreased by 22% and fuel consumption decreased by 29%. If the original syllabus structure was optimized, proactive planning enabled a fuel consumption decrease of 28%, as well as CO_2 emissions, NOx emissions decrease of 26% and fuel consumption decrease of 41% with an increase of 4% of the total training duration.

Further research of the potential benefits of proactive planning of high-performance aircraft training operations in flexible airspace structures for pollution reduction is focused on the peculiarities of potential shifting of flight slots as a response to local variation of civil traffic demand. As contemporary high-performance aircraft training operations show negligible potential for a single flight slot shift, but rather as a coupled pair of slots, the research approach is constructed in such a manner. Distribution of civil traffic demand in targeted flexible airspace structures coupled with maintenance demands imposed the simulation scenario with a one-hour shift of total operating time. This one-hour shift stems from the limitations of the practical implementation of the concept. It is not just the mere limitation of civil-military cooperation but the necessity to establish and maintain viable and sustainable modus operandi for military entities. Flight training operations need to be performed in an orderly manner due to the complexity and interdependence of the system. Therefore, the reliable operational schedule and daily routine stand as *conditio sine qua non.*

Unlike previous studies, this paper recognizes the operational constraints of high-performance aircraft training operations' daily working schedule structure. Previous research's findings are extended in this novel study's approach focused on operationally imposed slot-shifting logic. The specific contribution of this paper lies in the environmental indicators of the benefits of such proactive planning of high-performance aircraft training operations.

As expected, nA/C_{rel} (relative number of civil aircraft flights) performance indicator values for a one-hour shift of flight slots during the research period demonstrated significantly less distribution than the distribution of civil traffic demand throughout the day. Simulations results create values of monitored performance indicators: nA/C_{rel} (relative number of civil aircraft), FNM_{rel} (relative flight distance), FT_{rel} (relative flight time), C_{nsmrel} (relative fuel consumption), CO_{2rel} (relative CO_2 emission) and NOX_{rel} (relative NOX emission). The resulting values of these performance indicators are not in distinct correlation with nA/C_{rel} (relative number of civil aircraft flights) performance indicator.

Results change under alternative activation schedules and traffic demand conditions. Noticeably, results vary on a day-to-day basis but there are examples, such as day 4 and day 5 of the simulation, when the traffic demands of the same number of civil aircraft creates different results. These results are related to traffic characteristics and its' structure. Not only the aircraft count influences the results, but their trajectory distribution in rerouting patterns does. Aircraft performance differences significantly influence the total results.

Nevertheless, these indicate the potential benefits of proactive planning of high-performance aircraft training operations in flexible airspace structures regarding pollution reduction.

5. Conclusion

No direct correlation of a relative number of civil aircraft and other performance indicators of small-scale distribution of traffic demand can be drawn, but the results presented in this paper indicate that:

- Benefits of proactive planning have the potential to significantly contribute to pollution reduction;
- The very mix of civil aircraft in the chosen traffic sample related to their technical specifications, as well as their flight trajectories, and the impact of the flexible airspace activation on the civil traffic in the broader picture, has to be examined to predict the influence of small-scale distribution of

traffic demand on benefits of proactive planning for pollution reduction;
- Small-scale distribution of traffic demand needs to be tracked for a prolonged period to create a reliable basis for decisions regarding profitable justification for the shift of operating time and therefore the flight time.

It is to be assumed that certain differences in airspace organization, regulatory frameworks, and operational practices lead to different performances in individual states or FIRs. Therefore, these peculiarities require separate case studies for each different setup of conditions as a possible direction for future research into the efficiency of the concept.

A conclusion could be drawn from this research regarding the representativeness and limitations of the selected limited 10-day traffic sample. Although the sample is sufficient for general conclusions regarding proactive planning benefits and environmental performance indicators, it would be beneficial for future case studies to be performed over a prolonged period of observation. The more prolonged sample period would bring to bear data that would reinforce the significance and impact of the proactive planning approach. The single-FIR nature of this simulation-based research could be altered in future studies if the multi-FIR point of view, effects and consequences were examined. Future implementation-oriented research should challenge the stakeholder coordination issues, particularly regarding operational limitations for collaborative decision-making.

Practical civil-military coordination could support standing operational priorities and informed decision-making, within regulatory framework, that could bring to bear stakeholder acceptance if the continuous benefits for a prolonged period of time are likely. On the other hand, frequent slot shifting on a day-to-day basis is not likely to be nourished by the stakeholders. Not only due to practicality but due to flight safety issues that could arise from such an approach. Furthermore, solutions valuable and beneficial in one FIR could be the trigger for research but don't necessarily need to bring about benefits for the other FIR. The position of the flexible airspace structure within the FIR and the associated civil traffic could make this approach more or less reasonable or even irrelevant.

Competing Interests Statement

The authors declare no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

Data Availability Statement

Supplementary materials and data used in this research are available upon request. To obtain access, please contact the corresponding author via email at nmostarac@fpz.unizg.hr.

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