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DATA-BASED FLIGHT OPTIMIZATION MODEL FOR SCHEDULING: NOISE MANAGEMENT APPROACH

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Abstract. Civil aviation noise remains a key challenge that limits the industry's growth. With the rise in global air traffic, aviation noise pollution is becoming an increasingly pressing concern. This research develops a data-driven flight optimization model to mitigate noise levels at Vilnius Airport. The research is conducted in three stages: first, existing noise reduction strategies and the potential of scheduling optimization tools are reviewed. Next, EUROCONTROL's integrated aircraft noise and emissions modelling platform is used to assess noise levels for each flight operation under relevant atmospheric conditions. Finally, a flight schedule optimization model is developed by considering key variables, constraints, and assumptions affecting airport noise, followed by an evaluation of its performance and efficiency. The findings suggest that effective noise management requires a comprehensive approach, integrating operational adjustments with a detailed understanding of industry factors.

Keywords: noise assessment, flight schedule optimization, data-driven model, genetic algorithm, 4D trajectories, civil aviation.

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1. Introduction

Air travel is in demand, driven by various factors such as globalization, business travel, tourism, and convenience of air travel. Looking to the future, demand for air travel is expected to double by 2040, growing at an average annual rate of 3.4% (International Air Transport Association [IATA], 2023). As global air travel increases, development of efficient noise reduction technologies becomes crucial to mitigate negative impact of airport-related noise pollution. Addressing this challenge is not only a question of social responsibility but is also crucial to maintain sustainable community relations and regulatory compliance standards (Grampella et al., 2017). The problem arises from the significant and adverse effects of airport noise pollution on surrounding communities (Mohamed et al., 2021; Al-Harthy et al., 2021; Fajersztajn et al., 2019): chronic exposure to high noise levels is linked to cardiovascular diseases, cognitive disorders, increased stress and sleep disturbances, while also causing impairment of quality of life for people living near airports (Mohamed et al., 2021). As Vilnius Airport (VNO), located in Lithuania, is situated close to the city, it is under increasing pressure to adopt noise abatement measures, to reduce the overall impact of environmental noise pollution.

Various noise mitigation strategies, including operational restrictions, noise abatement procedures and land-use planning, have been implemented globally (Alonso et al., 2017; Rodríguez-Díaz et al., 2017). However, assessing their effectiveness remains challenging due to the combined application of multiple regulations, making it difficult to isolate individual impacts (Alonso et al., 2017). Furthermore, the effectiveness of noise abatement strategies depends on multiple factors, such as airport layout, flight trajectories, meteorological conditions and community demographics, necessitating a multidisciplinary approach to evaluation (Orikpete et al., 2024). As air traffic continues to grow, airports must balance capacity expansion with community noise concerns, making it imperative to assess mitigation strategies under dynamic operational conditions (Pretto et al., 2020). Additionally, community engagement and transparent communication are essential, as active involvement in decision-making can significantly influence noise management strategies (Heyes et al., 2021). While airports and local governments continue to analyze and implement noise mitigation strategies while increasing capacity (Rodríguez-Díaz et al., 2017), there is a need for more comprehensive evaluations to understand their effectiveness under varying operational conditions (Ehmer et al., 2023). Without a holistic, data-driven approach that integrates technological, regulatory and social aspects, achieving sustainable noise reduction in aviation will remain a challenge, particularly as air traffic volumes continue to rise.

Flight scheduling is usually focused on balancing efficiency and demand, however, environmental considerations, particularly noise reduction, have received limited attention (Zeng et al., 2021; Ribeiro et al., 2018; Zografos et al., 2017; Pang et al., 2024). Given that noise impact varies throughout the day – with the same noise level having different social and environmental effects depending on whether it occurs during the daytime, evening, or nighttime (Smith et al., 2022), flight scheduling could play a crucial role in mitigating aviation noise, especially during noise sensitive periods. By strategically adjusting flight schedule, airports can reduce overall noise exposure while maintaining operational efficiency.

The objective of this research is to create a data-based flight optimization model with the purpose to minimize the noise levels during sensitive hours (22 PM – 06 AM) at VNO. The research is carried out in three stages. First, a review of current noise reduction measures and potential of scheduling optimization tools is conducted. Subsequently, EUROCONTROL's integrated aircraft noise and emissions modelling platform (IMPACT) is used to gather noise assessment for each flight operation under relevant atmospheric conditions. Thirdly, considering the assumptions, constraints and various variables impacting airport noise, a flight schedule optimization model is created and evaluated for performance and efficiency.

2. Balanced approach to noise management: international standards and airport applications

The International Civil Aviation Organization (ICAO) has established international standards for noise management in ICAO Document Nr. 9829 (International Civil Aviation Organization [ICAO], 2020) which sets out a mandatory provision for all Member States of the organization to adopt a balanced approach to aircraft noise management based on 4 key principles:

- Reducing noise emissions directly from the source by enhancing aircraft technologies and introducing new ones.
- Focusing on land use planning and management on detailed policy recommendations related to planning and land use around airports.
- Designing flight procedures to incorporate considerations to reduce noise emissions around airports, including adjustments to flight paths.
- Implementing operating restrictions to reduce or limit access for the noisiest aircraft at the observed airport.

VNO has implemented a comprehensive noise abatement strategy that includes operational procedures, spatial planning, and continuous monitoring to minimize noise impact on surrounding communities (Table 1).

The data such as airport data, flight schedules, noise monitoring station positions, collected from VNO, along with understanding of the existing noise mitigation procedures, provide key base for the flight schedule optimization model development. The potential practical implication of the developed flight optimization model is the incorporation of new noise abatement operational procedures for VNO. By applying data-driven optimization and making operational adjustments, this proposed solution seeks to align with the ICAO's balanced approach.

Worldwide Airport Slot Guidelines (WASG) categorizes airports into three levels of congestion and capacity, which directly influences the method through which scheduling decisions are made (IATA, 2024). VNO is classified as a Level 2 schedule-facilitated airport by the Republic of Lithuania's Ministry of Transport and Communications (Lithuanian Airports, 2023). Typically, this level airport can have some periods of the day, week, or season where congestion could occur, but may be prevented by schedule adjustments mutually agreed between airlines and with assistance of an airport facilitator (Figure 1) (IATA, 2024).

VNO is a schedule-facilitated airport which provides greater flexibility in managing congestion and peak

Table 1. VNO noise abatement procedures (source: compiled by the authors, based on VNO expert interview results obtained on 2024–01-17)

Operations	Spatial planning	Monitoring
Development of Noise Preferred Routes RWY 01	Noise maps	Noise Monitoring System
Continuous Descent Operations (CDO)		Mobile Noise Monitoring
Continuous Climb Operations (CCO)	Noise protection zones	Annual Noise Report
Delayed Deceleration Operations		Monitor 01 Standard Instrument Departure (SID) Compliance

Figure 1. Airport scheduling process (source: compiled by authors)

Table 2. Optimization models of flight scheduling (source: compiled by the authors)

Study & Year	Noise Reduction
Frair (1984)	up to 40% reduction in total noise impact
Feng et al. (2023)	maximum noise reduction of 4.906 dB
Feng et al. (2023)	2.649 dB reduction (take-off direction) + 1.415 dB (schedule displacement)
Rodríguez-Díaz et al. (2019)	up to 43% of reduction in total noise impact

periods. This flexibility allows for more adaptable scheduling adjustments, making the optimization process smoother when aiming to reduce noise.

Considering the complications of managing the flight schedule, different research has been focusing on managing airport demand and capacity or addressing growing concerns, for instance noise pollution. In view of the rapid growth of aviation, various perspectives were analyzed to optimize flight schedule and reduce their negative noise impact. Strategies for noise reduction are presented in scientific literature through temporal scheduling and prioritization of sensitive areas (Table 2).

The limitations of previous research include several key factors that affect its overall effectiveness. First, the accuracy of noise assessment is restricted by the lack of real-time atmospheric condition data, which influences how noise propagates and impacts surrounding areas. Second, it does not consider all flight trajectories, limiting ability to provide a complete noise distribution assessment. Additionally, the optimization process treats all flights equally, without incorporating priority-based noise reduction, which helps to balance operational and environmental constraints. Some of the research did not compare seasonal changes. Overall, addressing these limitations by integrating real-time atmospheric data, considering all flight trajectories, incorporating priority-based noise reduction, and analyzing seasonal variations would enhance the accuracy and effectiveness of noise assessment and optimization strategies.

3. Methodology

Research framework outlines a structured approach to optimize flight schedule with the goal of minimizing aircraft noise impact (Figure 2). It utilizes noise reduction strategies and genetic optimization algorithm to develop a feasible schedule that balance operational efficiency and noise mitigation.

Process begins with data collection, where relevant flight data, meteorological conditions, and airport-specific parameters are gathered. This dataset includes detailed information on flight operations such as destinations, aircraft types, aircraft registrations, schedule of arrivals and departures, airline companies, and maximum takeoff

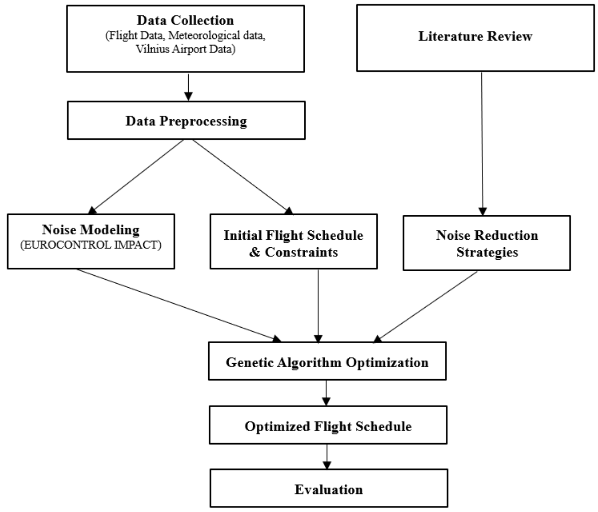

Figure 2. Framework of the flight schedule optimization model (source: compiled by the authors)

weights for all calendar year of 2023. The research examines three specific days – Peak day, Standard Day, Off-Peak Day representing different traffic conditions.

EUROCONTROL IMPACT tool, which in this research is used for noise modeling, is based on ECAC noise model is a best-practice segmentation model proposed by the European Civil Aviation Conference for assessing aviation noise around airports (EUROCONTROL, 2025). EUROCONTROL IMPACT tool assessment process involves preparation of comprehensive dataset on several matters (Table 3).

VNO airport and runway layout values were obtained from the Lithuanian Aeronautical Information Publication (AIP), published by Oro Navigacija, and were converted into a Cartesian system based on the ARP for accurate mapping and analysis of airport infrastructure. 4D trajectory data is obtained from Flightradar, which provides historical flight data through a subscription service. This data is collected using Automatic Dependent Surveillance–Broadcast (ADS-B) technology, capturing key flight parameters such as the aircraft's geographical position, altitude,

Table 3. IMPACT tool's noise assessment dataset (source: compiled by author based on IMPACT user guidelines)

Dataset	Description
Airport	Airport's layout associated with Aerodrome Reference Point (ARP) and elevation, pressure, temperature, headwind, relative humidity.
Operations	Aircraft identification, operation type, runway, complete flight operation details and departure and arrival dates and times.
Runway	Data on runway usage and their characteristics associated with the Cartesian system aligned with ARP.
4D Trajectory	Flight path information, capturing latitude, longitude, altitude, time, date, true speed and corrected net thrust.

time, and velocity. However, the recorded 4D trajectory data may contain errors, including missing data points and duplicated entries, which can affect the accuracy of subsequent analyses. To address these issues, a thorough data preprocessing process is conducted to clean and refine the dataset. Additionally, spline interpolation is applied to reconstruct and capture trajectory conditions at 10-second intervals, ensuring a smooth and continuous representation of flight movements for further analysis (Puechmorel & Delahaye, 2007).

Calculating engine thrust for approach and departure flights must be considered separately (Zhu et al., 2024). The corrected net thrust for departure and approach was calculated using the ECAC methodology (European Civil Aviation Conference [ECAC], 2016). Corrected net thrust for departure follows a formula that incorporates engine-specific coefficients, calibrated airspeed, altitude, and temperature corrections. The corrected net thrust is determined using the Equation (1):

$$\frac{F_N}{\delta} = E + F \cdot V_{CAS} + G_A \cdot h + G_B \cdot h^2 + H \cdot T, \quad (1)$$

where: $\frac{F_N}{\delta}$ is corrected net thrust per engine; δ is ratio of ambient air pressure at the aeroplane to the standard air pressure at mean sea level; h is altitude**,** taken from flight trajectory data; T is ambient temperature, sourced from METAR data; E , F, G_A, G_B, H are engine thrust constants or coefficients, obtained from the ANP data; V_{CAS} is airspeed corrected for compressibility effects, converted from true airspeed or groundspeed.

The corrected net thrust for approach is determined by considering the aircraft weight, drag-to-lift ratio and glide angle which is derived from the rate of descent and groundspeed. The Equation:

$$\frac{F_N}{\delta} = W \frac{R_a \cdot \cos\gamma + \sin\gamma + \dfrac{a}{g}}{n\delta}, \quad (2)$$

where: $\frac{F_N}{\delta}$ is corrected net thrust per engine; δ is ratio of ambient air pressure at the aeroplane to the standard air pressure at mean sea level; W is the aircraft weight; R_a is the ratio of the aircraft drag coefficient for a given flap setting to its lift coefficient; γ is the descent angle, standard glide slope of 3°; n is the number of engines.

Aircraft use pressure at mean sea level (QNH) during departures to ensure that altimeter readings reflect altitude above mean sea level relative to local atmospheric pressure till the transition altitude. During arrivals, aircraft use the standard pressure setting until reaching the transition level, at which point they switch to the local QNH for accurate altitude readings. The transition altitude is fixed, while the transition level varies depending on the local QNH. Noise assessment is conducted up to the transition altitude for departures and from the transition level down to the runway threshold for arrivals.

The Sound Exposure Level (SEL) value is used to assess the noise of each flight operation and identify the noisiest flights for rescheduling. Noise impact is assessed with respect to its proximity to a noise monitoring station. Two monitoring stations, located in Vilnius at Birbynių St. 11D which is called TMS 02 and Molynės St. 18 which is called TMS 03, serve as focal points for evaluating operational noise levels, providing a location-specific assessment of noise exposure. The corresponding SEL value is extracted from the grid data, which is provided as one of the outputs of the EUROCONTROL IMPACT tool after noise assessment was conducted. Each SEL value is used for flight schedule optimization model.

Research proposed model aims to optimize the schedule facilitation by minimizing schedule displacement and environmental noise impacts during noise-sensitive period from 22 PM–06 AM. Figure 3 provides a percentage of flights operating throughout the night, revealing two distinct peak periods – one in the evening and in the early morning.

The flight schedule optimization model is designed to account for two peak periods observed in the graph, as these are the times when flight activity is highest. The scheduling strategy primarily aims to minimize noise impact in the direction of noise monitoring station TMS 02, which is located near the city and residential neighborhoods. Since compliance with runway 01 SIDs has already been ensured, further noise reduction is focused on minimizing nighttime noise in that area. As shown in the Figure 4, TMS 02 is positioned along the extended flight path, where noise-sensitive zones are most affected.

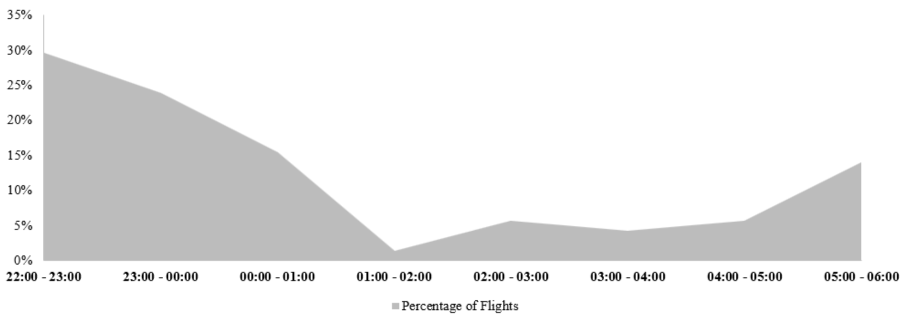

Figure 3. Flights frequency through the nighttime (source: compiled by the authors)

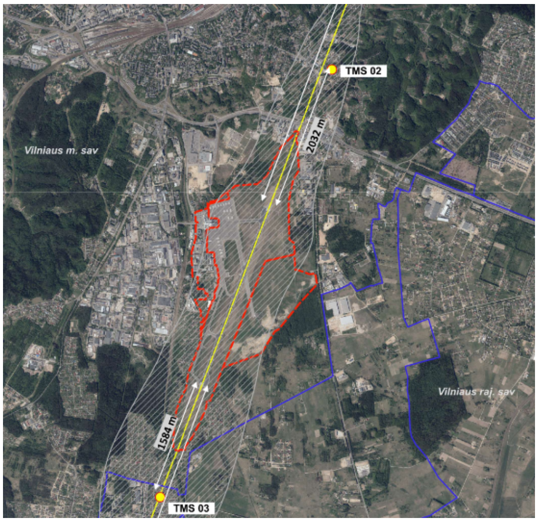

Figure 4. Noise monitoring stations positions at VNO (source: VNO expert interview results obtained on 2024-01-17)

By implementing flight rescheduling and displacement for operations impacting TMS 02, noise exposure in the city and surrounding residential areas can be reduced. By integrating ICAO chapter compliance for aircraft noise standards, turnaround time constraints, and airport capacity limits, the model ensures that rescheduling decision remain both operationally feasible and environmentally beneficial. Table 4 presents three noise minimization strategies aimed for optimizing flight schedule while reducing nighttime noise at VNO.

The proposed flight optimization model aims to achieve the highest possible noise reduction, with targets set at 1 dB, 2 dB, and 3 dB minimization. However, since the algorithm is based on constraints rather than unrestricted changes, it may not always reach the maximum target and instead stops at the best possible solution within the given limitations. The 1 dB noise minimization strategy makes small adjustments (15–30 minutes) to minimize noise level. The 2 dB strategy introduces greater flexibility (30–60 minutes) for non-hub and cargo flights, prioritizing the redistribution of noisier aircraft. Finally, the 3 dB strategy applies a rescheduling approach, restricting nighttime slots to ICAO Chapter 4 and 14 non-compliant aircraft.

In accordance with the WASG, flight rescheduling must follow a clear prioritization hierarchy to maintain operational efficiency and minimize disruptions. Schedules effective for a longer period within the same season take precedence, ensuring stability (IATA, 2024). Regularly planned operations are prioritized over ad hoc operations, and flights constrained by operational factors, such as slots or curfews at the destination airport, are given preference over those with flexible timing. Regular flights, which connect regional airports to major international hubs, are the most critical due to their role in facilitating passenger transfers across global networks. These flights are granted the highest protection, with rescheduling adjustments restricted in the first case a maximum of 15 minutes in the second case of 30 minutes, and only when necessary to comply with noise regulations and turnaround times. Non regular, charter and cargo flights, essential for maintaining

Table 4. Flight rescheduling strategies (source: compiled by authors)

Rescheduling Strategy	Noise Minimization Target	Displacement Limits	Aircraft Restrictions
1st strategy – prioritize shifting noisier aircraft	~1 dB Noise Minimization	Apply small displacements (15 and 30 min) to flights that significantly impact cumulative noise.	Limited adjustments
2nd strategy – prioritize shifting noisier aircraft	~2 dB Noise Minimization	Allow greater flexibility (30 and 60 min) to flights that significantly impact cumulative noise.	Limited adjustments
3rd strategy – encourage future fleet	~3 dB Noise Minimization	Ensure that only Chapter 4 and 14 aircraft operate in nighttime slots.	Shift non-Chapter 14 and 4 aircraft to non-sensitive hours

Table 5. Table of constraints (source: compiled by authors)

Constraint Type	Description
Non-overlap	A single rescheduled time is assigned to each flight, either for its departure or arrival, depending on operational requirements.
Turnaround Time	Ensures that there is a minimum time between the arrival and departure of an aircraft. This varies by airline: 30 minutes for low-cost carriers, 60 minutes for legacy carriers.
Operational Capacity	The airport can handle a maximum of 26 operations per hour (takeoffs and landings). While the airport's maximum capacity is set at 26 aircraft operations per hour, actual operations may not approach this limit during peak periods. This capacity limit serves as a reference point for future modelling and operational adjustments.
Flight Separation	Requires a minimum separation between flights.
Max Displacement	Limits the amount of time a flight can be rescheduled, ensuring that the flight stays close to its original time to minimize disruptions to the overall schedule.

airport efficiency, are prioritized after regular flights and offer greater flexibility. They can be rescheduled by maximum of 30 minutes in the second case of 60 minutes.

Aircraft certification follows the ICAO Annex 16 noise standards, with Chapter 4 introduced in 2006 and Chapter 14 in 2018. Given this timeline, an aircraft's production age can serve as a key indicator of its original certification (European Union Aviation Safety Agency [EASA], 2025). Unless modifications or recertifications are documented, the aircraft is considered compliant with the standards applicable at the time of approval. In this research, an assumption is made based on registration details, production timeline, and ICAO regulations to determine compliance.

To ensure efficient and feasible flight schedule optimization, several operational constraints must be considered (Table 5). These constraints help balance airport capacity, operational efficiency, and noise reduction while minimizing disruptions.

The Genetic Algorithm (GA) is selected as an optimization technique which is capable to solve complex problems efficiently by iteratively improving solutions (Figure 5). GA works by maintaining a population of possible solutions, evaluating their quality using a fitness function, and then applying processes such as selection, crossover, and mutation to generate better solutions over multiple generations.

The initial population consists of a set of possible flight schedules, where each schedule represents a chromosome. Each chromosome is a list of flights with assigned shift values, determining their rescheduled departure times. The initial population is generated randomly, respecting the maximum displacement and constraints for each flight:

$$t_{new} = t_{original} + \Delta t, \Delta t \in \left\{ -D_{max,} -D_{max,} + 5, \ldots, D_{max} \right\}, \quad (3)$$

where: t_{new} is the new departure time; D_{max} – is the maximum allowed rescheduling displacement.

Formula calculates L_{night} by summing the energy contributions from all events (flights) (World Health Organization, 2019). The logarithmic nature of the formula accounts for the fact that louder events contribute more to the overall noise exposure. This metric is derived from the SEL of flights operating during the nighttime period (22:00–06:00):

$$L_{night} = 10 \log_{10} \left(\sum_{i=1}^{N} 10^{\frac{SEL_i}{10}} \right) - 10 \log_{10} (T), \quad (4)$$

where: L_{night} – average long-term A-weighted sound level, determined for the nighttime period (from 22:00 to 6:00); SEL is the for each noise event (e.g., aircraft flight); N is the number of events; T is the total duration of the night period.

The pure fitness function evaluates each candidate's schedule by calculating the nighttime noise level.

The GA model selection process determines which candidate schedule proceeds to the next generation. The algorithm employs tournament selection, where a subset of candidate schedules is randomly chosen, and the schedule with the lowest L_{night} is selected. This selection mechanism ensures that flights with nigher SEL value are rescheduled. The crossover function combines elements of two schedules to produce new candidate solutions. Mathematically, if P_k is defined as set of k randomly selected candidates, the chosen schedule is:

$$S_{best} = \min_{S \in P_k} L_{night} (S), \quad (5)$$

where: S_{best} represents the selected schedule with the lowest nighttime noise impact; P_k is the subset of schedules randomly chosen from the population during tournament selection, $L_{night}(S)$ is the nighttime noise impact function evaluated for schedule S.

This process follows a one-point crossover method, where a random position k is selected within the schedule. Flights before this position remain unchanged from the original sequence, while flights after this point are replaced with corresponding values from an alternative schedule.

$$S_{new}[i] = \left\{ \begin{matrix} S_{first}[i], i < k \\ S_{second}[i], i < k \end{matrix} \right\}, \quad (6)$$

where: S_{new} is the resulting schedule after crossover; S_{first} is the initial schedule for contributing the first segment; S_{second} provides the remaining portion; k is the randomly chosen crossover point.

This ensures that the new schedule incorporates different characteristics, combining elements from both schedules to explore potentially improved solutions.

The mutation function introduces random variations in the schedule to prevent premature convergence to sub-

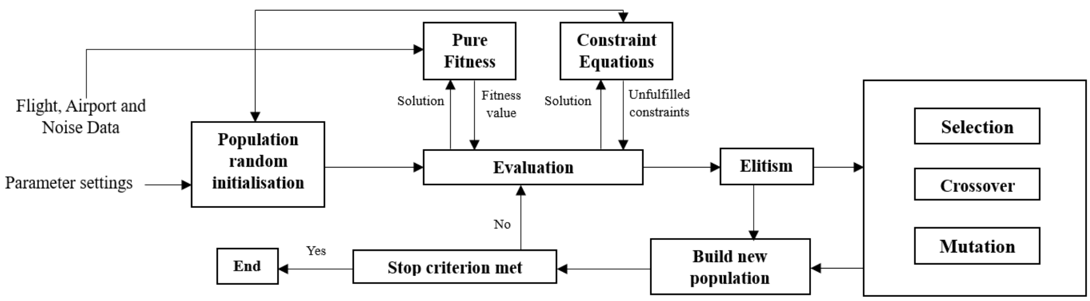

Figure 5. Genetic algorithm framework (source: Guedan-Pecker & Ramirez-Atencia, 2024)

optimal solutions. Each flight in a schedule has a predefined probability of being mutated, which results in a new shift value being randomly assigned within the allowed displacement range. The flight time is then recalculated as:

$$t_{mutated} = t_{new} + \Delta t_{mutate}, \quad (7)$$

where: $t_{mutated}$ is time shift value.

In order to perform the optimization, a Python-based genetic algorithm was developed utilizing relevant libraries for evolutionary computation. The implementation was structured using NumPy for numerical operations, random for stochastic processes, and math for fitness evaluations. Additionally, OpenPyXL was used for reading and writing Excel files containing flight schedules. The optimization process followed the principles of genetic algorithms, incorporating selection, crossover, and mutation to iteratively refine flight schedules and achieve noise reduction objectives.

In order to evaluate how different input parameters influence the output of an optimization model, sensitivity analysis was performed. In this research, it is applied to assess the impact of various GA parameters on noise reduction. The goal was to determine which parameter values lead to the most efficient optimization and identify the point at which additional increases in parameters cause performance degradation. The four key GA parameters analysed were:

1. Mutation rate (controls randomness in genetic variations);
2. Population size (number of solutions evaluated per generation);
3. Tournament selection size (influences selection pressure);
4. Number of generations (iterations before stopping).

The logarithmic transformation was applied to scale the impact of GA parameters in the sensitivity analysis. This method ensures that earlier improvements have a stronger effect, while adjustments beyond an optimal range contribute progressively less to optimization results. The reason for using a logarithmic transformation is that GA optimization typically follows a diminishing returns pattern – where initial improvements are significant, but after a certain point, further increases in parameter values yield smaller improvements or performance degradation (Mills et al., 2015).

The mutation rate influences the diversity of solutions in GA by introducing small, random variations in flight rescheduling. Increasing the mutation rate from 0.05 to 0.1 provides substantial noise reduction. Peak optimization is reached at 0.15–0.2, where noise reduction is maximized, beyond 0.2, additional mutation does not significantly improve results and can introduce instability in scheduling (Figure 6).

The population size determines the number of schedules (solutions) evaluated per generation. Larger populations increase the chances of finding better solutions but also require more computational resources. Increasing the

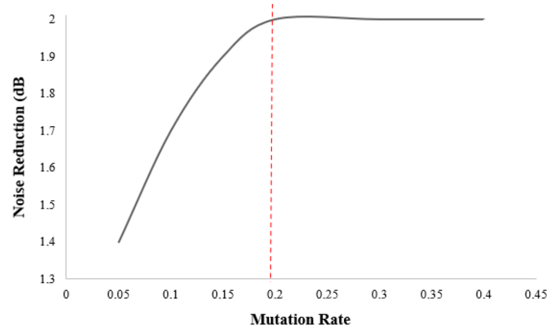

Figure 6. Mutation rate vs noise reduction (source: compiled by authors)

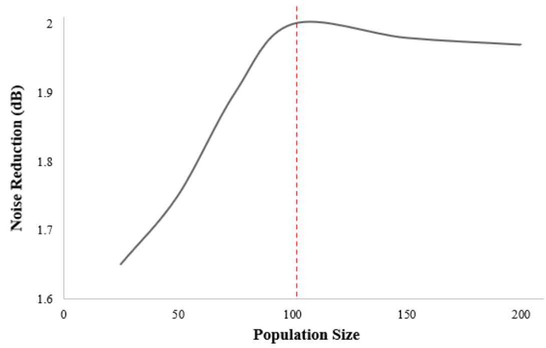

Figure 7. Population size vs noise reduction (source: compiled by authors)

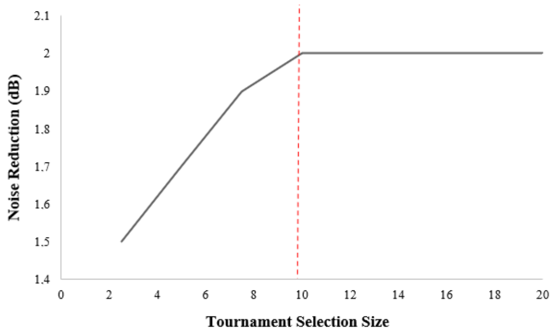

Figure 8. Tournament selection size vs noise reduction (source: compiled by authors)

population size from 25 to 100 significantly improves noise reduction. Beyond the 100, additional population members do not provide further improvements. At 200, noise reduction slightly decreases, likely due to longer optimization times without meaningful improvement (Figure 7).

Tournament selection controls the selection process in GA. Higher values mean stronger selection of high-quality solutions, but too large values can reduce diversity. Small tournament sizes (2–5) maintain diversity but slow down optimization. The optimal range for tournament size is between 5 and 10, allowing for both diversity and convergence (Figure 8).

The number of generations represents how many iterations the GA runs before stopping. More generations

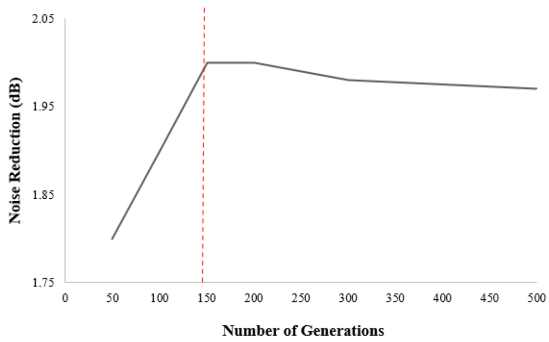

Figure 9. Number of generations vs noise reduction (source: compiled by authors)

allow the algorithm to explore more solutions and refine scheduling, but there is a point where improvements stop. Increasing generations from 50 to 150 results in significant noise reduction. After 200 generations, improvements slow down, showing diminishing returns (Figure 9).

The optimal solutions identified in this sensitivity analysis are specific to the tested dataset and the given optimization constraints. While these parameter values provide the best results within this range of data, the optimal settings may vary for different datasets, constraints, or problem-specific conditions. Therefore, further testing and tuning would be required when applying this approach to other scenarios. This sensitivity analysis confirms that GA parameters must be carefully chosen to balance efficiency and optimization quality.

4. Results

The suggested model successfully optimized the flight schedule by applying different noise minimization strategies. Based on these strategies, the suggested model adjusted departure and arrival times to reduce nighttime noise exposure while maintaining operational feasibility. The results in Table 6 show noise reduction achieved under different minimization levels across peak, standard, and off-peak days.

Table 6. Noise reduction in TMS 02 (source: compiled by authors)

Rescheduling Strategy	Peak day	Standard Day	Off-Peak Day
1st strategy	1.09 dB	1.24 dB	1.52 dB
2nd strategy	2.10 dB	2.05 dB	3.86 dB
3rd strategy	1.21 dB	2.38 dB	`3.86 dB

The 1st rescheduling strategy results in noise reduction ranging from 1.09 dB on peak days to 1.52 dB on off-peak days, indicating slightly better performance in lower traffic periods, since there are less noise events. The 2nd rescheduling strategy provides more substantial noise reductions, particularly on off-peak days – 3.86 dB. The 3rd rescheduling strategy shows variability in noise mitigation results, with a peak of 3.86 dB on off-peak days but more modest reductions on peak and standard days – 1.21 dB and 2.38 dB, respectively. The flights that were rescheduled under the 2nd strategy of off-peak day were also those that required rescheduling under the 3rd strategy, highlighting a notable alignment between the two approaches. This unexpected coincidence suggests that the flights identified as non-compliant with ICAO chapter 4 and 14, were already operating within time frames that allowed for adjustments under the 2nd strategy. As a result, when the 3 dB strategy was applied, the same flights were naturally prioritized for rescheduling.

Noise reduction achieved under TMS 03 differs significantly from TMS 02, indicating a lower effectiveness of this strategy in reducing noise (Table 7). This is not primarily the target area, as the number of noise events in this position is already lower.

Table 7. Noise reduction in TMS 03 (source: compiled by authors)

Rescheduling Strategy	Peak day	Standard Day	Off-Peak Day
1st strategy	0.004 dB	0.001 dB	0.1 dB
2nd strategy	0.007 dB	0.002 dB	0.1 dB
3rd strategy	0.40 dB	0.97 dB	0.1 dB

When flights are rescheduled, they do not provide a significant noise reduction at TMS 03, as the overall noise impact in this area is inherently less affected by departure noise. The adjustments primarily influence departure flights with higher initial noise exposure, particularly with respect to TMS 02. However, the third noise minimization strategy differs from the first two by not only targeting the loudest individual events but also modifying the overall aircraft compliance, ensuring that only Chapter 4 and 14-compliant aircraft operate in nighttime slots. This broader approach impacts on the entire flight schedule, including arrivals, not just departures. TMS 03 lies under the arrival flight path when runway 01 is in use, meaning its noise exposure is primarily influenced by arriving aircraft rather than departing ones. Since arrival flights tend to generate louder noise events at TMS 03, this strategy indirectly contributes to noise reduction in that area as well. By limiting noisier aircraft types across all operations, rather than focusing solely on rescheduling departures, the third strategy provides a more comprehensive noise reduction effect, extending benefits beyond just TMS 02.

Schedule displacement refers to the average shift in flight times due to noise minimization efforts and is calculated only based on the flights that had their times adjusted. This means that the displacement value reflects the average rescheduling impact on the modified flights, rather than considering all flights in the schedule (Table 8).

Table 8. Average schedule displacement (source: compiled by authors)

Rescheduling Strategy	Peak day	Standard Day	Off-Peak Day
1st strategy	11.7 min	15 min	10 min
2nd strategy	11.7 min	17.5 min	17.5 min
3rd strategy	59 min	102 min	17.5 min

For the 1st strategy, the shifts remain relatively low, ranging from 10 minutes (off-peak) to 15 minutes (standard days). However, at the 2nd strategy, the displacements increase to around 17.5 minutes for standard and off-peak days, while remaining at 11.7 minutes for peak days. The most significant shifts occur during the 3rd strategy, where scheduled displacements reach 59 minutes on peak days and 102 minutes on standard days, while off-peak days maintain a much lower 17.5-minute average. The 3rd strategy affects the entire flight schedule and without displacement limitations, the average value increases. This happens because rescheduling some flights for noise reduction also leads to adjustments in other flights to maintain operational feasibility, such as ensuring proper turnaround times.

The percentage of flights rescheduled during night hours varies depending on the amount of traffic (Table 9).

Table 9. Percentage of night rescheduled flights (source: compiled by authors)

Rescheduling Strategy	Peak day	Standard Day	Off-Peak Day
1st strategy	10.0%	9.1%	7.7%
2nd strategy	20.0%	18.2%	15.4%
3rd strategy	16.7%	22.7%	15.4%

The results indicate that a greater percentage of flights required rescheduling as noise minimization targets increased, particularly during peak and standard days, when airport traffic is highest. This trend highlights the direct correlation between traffic volume and the necessity for flight displacement to achieve significant noise reduction.

The results demonstrate that rescheduling strategies for noise minimization can reduce noise levels while maintaining operational feasibility. The best noise minimization strategy depends on traffic conditions and the balance between noise reduction and operational feasibility. On peak days, the 2nd strategy is the preferable choice, achieving 2.10 dB reduction with only 11.7 minutes of schedule displacement, while the 3rd strategy requires excessive shifts (59 minutes) for minimal additional benefit. On standard days, the 3rd strategy is optimal, providing the highest noise reduction (2.38 dB), though requiring 102 minutes of displacement, which is manageable due to greater scheduling flexibility. On off-peak days, the 2nd strategy is again the most effective, achieving 3.86 dB reduction with only 17.5 minutes of displacement, making it the best option with minimal disruption.

5. Conclusions

In this research, a data-driven flight optimization model was developed to mitigate nighttime noise pollution at VNO while maintaining operational feasibility. By integrating EUROCONTROL's IMPACT tool, historical flight data, and a GA based schedule optimization, the research results demonstrated that strategic rescheduling effectively reduces noise levels with minimal disruption. The GA sensitivity analysis captured diminishing returns, proving that certain thresholds, increasing mutation rates, population sizes, and generations had negligible or even negative effects on noise reduction. The 2nd rescheduling strategy proved to be the most efficient trade-off in noise minimization, achieving up to 3.86 dB reduction, while the 3rd strategy is stricter, requires excessive shifts (up to 102 minutes), making it impractical during peak periods.

However, several key limitations and areas for improvement remain. The model primarily focuses on departures affecting TMS 02, but VNO runway 19 arrivals, which would also impact TMS 02 and surrounding areas, require further analysis. While landings are generally quieter than takeoffs, factors such as reverse thrust, flap deployment, and touchdown noise still contribute significantly to urban noise exposure. Implementing grid-based noise analysis using spatial models could provide a more accurate, area-wide noise impact assessment, enabling targeted mitigation strategies for high-density residential areas. Another crucial factor is feasibility with airlines while the noise optimization model demonstrates theoretical effectiveness, its practical adoption depends on airline willingness, regulatory incentives, and operational constraints. Airlines may be reluctant to alter established schedules. A cost-benefit analysis should be conducted to assess how rescheduling affects airport revenue, airline logistics, and passenger convenience, ensuring that noise reduction strategies are both environmentally and commercially viable.

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