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Hybrid Approach for Minimizing Departure Air Traffic Delays Following Standard Instrument Departures

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Abstract The efficient scheduling of departure air traffic persists as one of the most challenging aspects of air traffic management in recent years. A proper sequencing enhances airport operations, minimises delay, and improves airspace capacity and traffic forecasting. This paper proposes a sequential hybridisation algorithm designed to assist air traffic controllers in determining the optimal departure sequence complying with the standard instrument departures (SIDs).
The level of complexity increases when taking into account the departure runway constraints, the configuration of flight paths after takeoff, and the aircraft's operational limits during the takeoff phase. Another challenging aspect is the wide diversity in aircraft types.
The suggested approach proposes a Genetic algorithm (GA) strengthened with the Partially Mixed Crossover technique (PMX). The initial population of the GA is enhanced with the Shortest Job First (SJF) method. This sequential hybridisation algorithm dynamically arranges the departure traffic sequence based on their performances and the complexity of the followed SIDs.

Keywords Departure sequencing, Standard Instrument Departure, Genetic Algorithm, Partially Matched Crossover, Shortest Job First, Sequential Hybridization Optimization, Delay Minimization

AMS 2010 subject classifications ???, ???

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1. Introduction

Departure aircraft sequencing is a crucial component of air traffic management. It has important consequences for safety, operational efficiency [1], and the environment [2] [3]. In terms of safety, appropriate sequencing ensures safe spacing between aircraft and regulates traffic while respecting the wake turbulence, which reduces the risk of collisions. From an operational standpoint, adequate sequencing minimizes departure delays and optimizes the use of available runways. It also helps absorb the waiting times in parking areas before engines start and contributes to significant fuel savings. Furthermore, it lowers airline expenses, provides better airspace use, and prevents congestion and bottlenecks [4]. In the environmental aspect, efficient departure sequencing reduces the periods during which aircraft remain idling on the ground and at holding points, which reduces greenhouse gas emissions.

Efficient management of departure traffic is considered a complex task due to several operational, environmental, and technological constraints. Nowadays, the main challenges include increasing traffic volumes, airspace capacity and restrictions [5], weather conditions and forecasts, coordination and communication between multiple stakeholders, technological limitations, ...etc. To address these challenges, it is possible to implement

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advanced technologies like those recommended by the research projects NextGen [6] and SESAR [7], as well as other decision-making supports to help Air Traffic Controllers (ATCos) manage air traffic. Moreover, improving coordination through collaborative decision-making and integrated systems would certainly contribute to optimizing air traffic scheduling and sequencing [8]. Additionally, dynamic air traffic management like predictive analytics can be used to maintain safety, optimize efficiency, and promote sustainability in air traffic operations.

This study is an extension of prior research papers [2] [9] [10] that handled air traffic scheduling and taxing from parking positions to departure holding points. This study proposes novel decision-making support to assist air traffic controllers in sequencing departure traffic following multiple and non-separated standard instrument departure routes. This tool is developed using a sequential hybridization of the short Job First (SJF) and the Genetic Algorithm reinforced by the Partially Matched Crossover (PMX) technique.

The SJF, when employed to sequence departure traffic, can be adapted to prioritize aircraft that require the shortest time to complete the taxi and take-off processes. This helps decrease total departure delays while taxiing. However, the SJF algorithm may prioritize certain aircraft according to their types or parking positions (short process [11]) which might be considered unfair to other aircraft.

On the other hand, applying genetic algorithms (GAs) to sequence departure traffic is an innovative method for optimizing sophisticated scheduling problems. GAs are search heuristics that get their inspiration from the natural selection process. They excel at tackling problems that include wide search spaces and various restrictions [12][13]. Nevertheless, GAs can be challenging in terms of processing resources, parameter optimization, convergence, and integration with pre-existing systems. And the final proposed solutions are not necessarily the best ones.

The limitations and constraints of the SJF and GA algorithms, when applied individually, highlight the need to use a hybrid solution for sequencing the departure traffic. The fast performance of the SJF offers a good initial population for the GA to start with. Additionally, integrating the PMX technique into the process enhances the efficiency of the GA for complex sequencing tasks such as sequencing departure traffic in air traffic management.

The remainder of this paper is organized as follows

2. Literature review

Departure aircraft sequencing is a complex issue; it is classified as an NP-hard problem characterized by a wide range of diverse constraints. Therefore, it is challenging to successfully find the ideal solution. Conventional optimization methods struggle with air traffic sequencing problems due to their rigidity and time-consuming nature. Meta-heuristic algorithms, such as Genetic Algorithms, Simulated Annealing, Particle Swarm Optimization, and Ant Colony Optimization, are very adaptable and flexible, efficiently navigating search space and escaping local optima to find near-optimal solutions within a reasonable time frame [21].

2.1. Short Job First in departure air traffic sequencing

The implementation of the SJF concept in air traffic management meets notable difficulties, including the challenges of correctly predicting tasks duration (i.e., flight times and delays) and the dynamic nature of air traffic, which may result in inefficiencies and possible fairness concerns. The aircraft taxiing and sequencing problem was handled in [2] by incorporating an algorithm that takes into account aircraft categories, taxiing and take-off times, and the respected standard departure trajectories. This method, using the SJF theory, seeks to enhance the efficiency of departure trajectories and minimize ground time. The SJF algorithm was compared to the First Come First Served (FCFS) algorithm in a traffic simulation, and the results were satisfying. But it still needs further enhancements since it only privileges aircraft with the shortest jobs to taxi first and considers that all aircraft will follow the same Standard Instrument Departure after takeoff. The paper [10] addresses the same issue using the GA. The results were outstanding in comparison with the FCFS model.

2.2. Various applications of Genetic Algorithms in decision-support systems for air traffic control

Genetic algorithms (GAs) have proven to be efficient in tackling the departure aircraft sequencing problem due to their multi-objective optimization, adaptability, and customization capabilities. Various studies have investigated how GAs can improve aircraft sequencing. [14][15][16] [17][18][19][20]. The following papers focus on developing decision support tools for different aircraft sequencing phases. Using GAs,[15] implemented a ground traffic simulation tool at Roissy Charles De Gaulle airport, which minimized taxing time while respecting separation and runway capabilities. In [22], the authors set up a mathematical model to handle multiple runways and multiple aircraft. The strategy in [16] is to incorporate departure aircraft into the sequence, establish an evolving model, and construct a particular genetic algorithm that resolves the aircraft-sequencing issue. Paper [23] builds a mathematical model to solve the aircraft departure sequencing problem. It establishes a genetic algorithm based on two types of codes with related implementation techniques. In [24], they used a GA approach to tackle the aircraft arrival sequencing and scheduling problem. The GA in [25] constructs chromosomes using a binary representation of the neighboring connection between aircraft, rather than relying on arrival time order. The authors in [26] suggested and built an improved GA to optimize the departure sequencing problem. The objective of study [27] is to provide a solution method using a genetic local search algorithm to solve the aircraft landing problem with runway-dependent features. One of the models introduced in [28] aims to enhance the departure manager using a GA. It can manage traffic automatically and minimize the flight delay. The implemented GA in [18] addressed the problem of aircraft sequencing on a runway and was compared to a tabu search algorithm. The suggested approach made an encouraging difference and seems suitable for adoption. The research [29] presents a hybrid algorithm that combines indirect and direct encoding methods to optimize the flow of air traffic. The system uses a heuristic algorithm and chromosomal representation, surpassing direct encoding in terms of efficiency for both artificial problems and real-world data. In [30] the gate assignment problem was transformed to a non-dominated sorting GA problem. The study focuses on issues such as passenger walking distances, resilience, and conventional expenses. The suggested approach demonstrated superior performance compared to the BAT, PSO, ACO, and ABC algorithms. [19] presents a novel approach for optimizing flight trajectories by splitting flight plans into separate lateral and vertical sections. The approach uses a GA to discover the optimal flight plan that minimizes the overall cost. A comprehensive method is suggested in [31] to get an approximate solution to the aircraft sequence and landing problem. Initially, a GA is used to acquire an initial solution. Subsequently, this technique is enhanced using a heuristic algorithm. The departure manager program in [20] was improved with a GA to determine the target take-off times and the target startup approval time for departure traffic.

2.3. Genetic Algorithms operators' enhancement

Additional researches have improved certain genetic algorithm operators while addressing the problem of aircraft sequencing. The following section discusses numerous articles related to the topic. Paper [23] presents enhanced adaptive probabilities for crossover and mutation in the GA. The proposed algorithm is efficient in terms of departure consumption. The GA in [24] employed a particular connection between aircraft to produce chromosomes, allowing the implementation of a very efficient "uniform crossover" operator. It demonstrated efficacy and efficiency in finding, inheriting, and safeguarding shared sub-traffic sequences while preserving variety. [25] applied a powerful uniform crossover operator provided by the binary representation of the chromosomes. The GA in [26] applied symbolic coding, with a type of total probability crossover and big probability mutation. Research [32] explored the role of crossover operators in competitive GAs and their use for tackling the Travelling Salesman Problem. Tests demonstrated that the OX operator outperforms other operators that were examined. [33] determined both relative and absolute position in aircraft permutation according to its distribution of the used cluster method. This data could assist in constructing novel crossover and mutation operators that can effectively minimize infeasible permutations and enhance convergence time.

2.4. Hybridization of Genetic Algorithms

Hybridizing genetic algorithms with other optimization techniques like local search, RHC, PSO, SA, Dijkstra, Greedy algorithms and ant colony optimization has shown to be a successful approach for tackling the aircraft sequencing issue. Hybrid techniques improve the performance of GAs by merging their ability to search globally with the local optimization strengths of other algorithms. This results in solutions that are stronger, efficient, and of higher quality. These are some works that hybridize the GA with other metaheuristics to solve the aircraft sequencing problem. An integrated strategy is offered in [31] to provide an approximate solution. A GA is employed at first to get an initial solution, which is subsequently enhanced using a heuristic algorithm. Papers [34] [24] [25] introduce the integration of Receding Horizon Control (RHC) into GA to address the issue of arrival scheduling and sequencing at highly congested hub airports. Research has shown that the RHC-based GA outperforms a pure GA in terms of performance in much less computing time. [24] indicates it was intended for real-time implementation. While [25] handles the dynamic aircraft sequencing and scheduling problem. Study [26] developed an optimization framework for the departure air traffic. Simulation results show that incorporating Particle Swarm Optimization (PSO) into GA increases efficiency and minimizes complexity. A hybrid algorithm in [33] combines bee evolutionary GAs with a modified clustering approach. Experiments indicate that the hybrid algorithm achieves the optimum landing sequence and times in a short time. Paper [35] presents a novel GA for combinatorial problems, which includes a ripple-spreading (RS) model. This model converts the original landing sequence to values using a deterministic technique inspired by RS. The new algorithm enables existing GAs to develop variables to discover an optimum sequence, showing its benefits in combinatorial issues. The proposed GA in [36], which used a hybrid encoding technique, was capable of adaptive searching. It produced a better answer than previous GAs with inbuilt greedy heuristics. The latter is employed for sequence initialization and reinitialization. The hybrid GA in [29] employed the Dijkstra algorithm to generate multiple forms of shortest paths on a graph while modifying the weights on each arc. The Dijkstra initiation with a novel chromosomes' strategy in the hybrid GA gave impressive results on synthetic data.

3. Problem statement

The management of departure aircraft raises considerable issues due to the coordination and allocation of tasks between air traffic control organisations, particularly approach control and control tower. The latter is responsible for maintaining a safe altitude between aircraft after departure, up to a certain defined altitude. Above that altitude, the approach control assumes responsibility. Nevertheless, the control tower's limited capacity to handle an expanded range of altitudes amplifies the complexity for approach management. This problem becomes increasingly noticeable when dealing with aircraft of different performance characteristics, making it more difficult to ensure safe altitude between them, particularly during the crucial time of control transfer.

Delegating certain authorisations to the control tower, even if it is not entirely responsible for the corresponding airspace for these authorisations, increases the potential risks. Particularly throughout the transfer process, there is no guarantee of constant separation. The lack of precise information on the exact altitude at which separation is still maintained worsens the issue. Furthermore, safety concerns arise during a departure aircraft sequence, especially when managing aircraft with significantly varied performance capabilities.

Given these challenges, it is essential to develop a methodology that improves the visualisation of projected aircraft patterns and provides the ideal scenario for runway spacing. The main goal of this procedure is to optimise the departure aircraft sequence in order to minimise the risk of aircraft crossing paths while also guaranteeing a safe altitude between them at all times. Implementing this strategy can reduce the associated complications with approach control and improve overall safety and efficiency.

Our contribution in this article is to propose such a process, which will help air traffic controllers better visualize the projected traffic scenario and determine the best sequence for departures. This will optimize runway separation, reduce the risk of aircraft overtaking each other, and ultimately enhance the safety and efficiency of aircraft departures.

The purpose of this article is to provide an approach that assists air traffic controllers in visualising the predicted air traffic scenario and determining the best aircraft departure sequence following the standard instrument departures (SIDs). The proposed method will dynamically sparate departure traffic according to their performance (the ability to reach certain altitudes after takeoff) and the followed SID.

The Standard Instrument Departures (SIDs) are established Air Traffic Service (ATS) routes outlined in instrument departure procedures that aircraft must comply with after takeoff to transit into the en-route phase. They are designed to provide pilots with a standard procedure for taking off from an airport. These SIDs may be accessed in the Chart Supplement and the Aeronautical Information Manuals. The SIDs description includes details such as the direction and angle of the followed path, as well as the minimum altitude requirements. The guidelines are crucial for ensuring consistent and secure airport operations. [10] [38].

4. Methodology and modelization

The aircraft-sequencing problem (ASP) is a complex NP-hard problem with several constraints, making it challenging to come up with a feasible solution in practice. Compared to other algorithms with exact solutions, meta-heuristic algorithms have proven effective in tackling and solving this problem in short time frames, but they do not necessarily lead to good results [37].

In a busy airport, sequencing the departure traffic can be as difficult as sequencing an arrival sequence. As mentioned in the previous section, the hybridization of the GA with other algorithms not only reinforced their convergence, but also gave much better results than using only the GA.

This work hybridizes the GA with the SJF using the PMX technique. This combination leverages the strengths of both algorithms with the efficient PMX crossover mechanism to optimize the departure air traffic sequence following standard instrument departure routes.

4.1. Advantages of employing the SJF in the proposed hybrid GA

The SJF algorithm is a scheduling strategy that selects the next job with the shortest execution time. In the context of aircraft sequencing, it prioritizes aircraft with the shortest taxiing periods, potentially reducing overall waiting time and improving runway utilization.

By prioritizing aircraft that can taxi quickly, the SJF can increase the number of departures within a given time frame. It also decreases efficiently aircraft numbers in the taxiways, which reduces congestion and improves the maneuvering area traffic flow. This results in minimized aircraft waiting time, improved punctuality for traffic schedules, fuel savings, and respectively less greenhouse gas emissions.

The conventional GA may take a long time and does not necessarily help in obtaining good final results. A resilient hybrid strategy is formed by combining the deterministic efficiency of SJF with the explorative capability of GA. The SJF algorithm offers a solid starting solution that may be further refined by the GA, possibly resulting in superior overall performance compared to employing either approach alone.

4.2. The partially matched crossover (PMX) mechanism

The PMX is a crossover approach used in GAs that guarantees that the offspring inherit both ordering and positional information from their parents. This technique is especially beneficial for tasks that include permutations, such as departure air traffic sequencing. PMX preserves the relative order and locations of genes, hence maintaining crucial sequence information. Including PMX in the GA for this particular application adds an innovative crossover mechanism that improves the GA's capacity to efficiently recombine and optimize sequences. PMX preserves critical positioning data, which is essential for minimizing delays in departure sequences.

4.3. The proposed hybrid GA parameters

When implementing the hybrid GA to sequence the departure aircraft, careful parameter selection is critical to getting the best possible sequence. In this section, we define the essential GA parameters and explain the logic behind their choice.

1. **Population size**: We choose a moderate population size of 50 to balance the variety of solutions and computational efficiency. A larger population increases genetic diversity and the chances of finding the general optimum, but it also needs more computational resources. A smaller population may converge quickly, but it also risks premature convergence to a local optimum.
2. **Number of Generations**: Running the GA for 100 generations provides sufficient iterations for the algorithm to explore and refine solutions. This value is a compromise between giving the GA enough time for

Table 1. The proposed hybrid genetic algorithm parameters summary

Parameter	**Value**	**Reason**
Population Size	50	Balances diversity and computational efficiency
Number of Generations	100	Sufficient iterations for optimization
Crossover Rate	0.8 (80%)	Promotes recombination and exploration
Mutation Rate	0.1 (10%)	Maintains diversity, prevents premature convergence
Selection Method	Tournament (size 5)	Balances selection pressure and diversity
Crossover Operator	PMX	Suitable for permutation problems, maintains sequence quality
Mutation Operator	Swap Mutation	Simple and effective for small changes in permutations
Initialization	SJF sequence + random	Ensures high-quality start and population diversity
Termination Criteria	100 generations or convergence	Limits computation time, ensures convergence

optimizing and ensuring that computation times remain acceptable. Preliminary testing can help adjust this parameter based on the problem's complexity and available computational resources.

3. **Crossover Rate**: The rate of 0.8 indicates that 80% of the population participates in the crossover, leading to the production of offspring in each generation. This high rate ensures that genetic material from parents is frequently recombined, promoting the discovery of new solutions while maintaining their diversity.
4. **Mutation Rate** : 0.1 (10%)
   A mutation rate of 10% (0.1) triggers variability in the population, which prevents premature convergence and preserves genetic diversity. We choose this rate to be low enough to prevent the disruption of good solutions, yet sufficiently elevated to explore new ones.
5. **Selection Method**: Tournament selection (size 5) is a robust and easy method to implement. Fitter individuals have a greater chance of selection while preserving some diversity. The size 5 offers a satisfactory balance between selection pressure and diversity.
6. **Crossover Operator**:
   The PMX operator is particularly well-suited for permutation problems, such as aircraft sequencing. The algorithm assures the preservation of solutions' quality through generations by maintaining valid permutations and ensuring that offspring inherit excellent sub-sequences from their parents.
7. **Swap Mutation Operator**:
   The process involves switching two elements in the sequence. It is basic and effective for solving permutation problems. It also implements minor modifications in the genes that facilitate the production of new solutions without significantly modifying the sequence.
8. **Initialization**: The initial population includes the SJF sequence and randomly generated sequences. By incorporating the SJF sequence, an excellent starting point is established, while the inclusion of randomly generated sequences adds variety to the initial population.
9. **Termination Criteria**: Limiting the GA to 100 generations avoids prolonged computing time. Moreover, the algorithm will terminate if there is no enhancement in the optimal solution for ten consecutive generations. This ensures the algorithm stops once it converges to a solution, conserving computational resources.

The Table 1 resume the proposed hybrid GA parameters.

4.4. The objective fitness function

The selection process in our genetic algorithm is governed by a dual-objective fitness function, which ensures that only the most optimal solutions are retained for subsequent generations.

- Fitness Function I: This function calculates the sum of delays across all aircraft. Its goal is to minimize the overall delay.

$$F_I(D_i) = \sum_{i=1}^{n}(D_i)$$

  where, n is the total number of aircraft and D_i represents the delay of the aircraft i.
- Fitness Function II: This function determines the maximum delay that a single aircraft can experience. The aim here is to minimise the worst-case delay.

$$F_{II}(D_i) = Max(D_1, D_2, ..., D_i, ..., D_n)$$

  where, n is the total number of aircraft and D_i represents the delay of the aircraft i.

The selection process follows these steps:

- Step 1: Evaluate Fitness Function I (sum of delays)
  - If the result is positive (indicating an acceptable total delay), the solution is considered viable and is kept in the population.
  - If the result is negative (indicating an unacceptable total delay), the algorithm proceeds to step 2.
  $$\begin{cases} \text{if } F_I(D_i) > 0 & \text{the solution is viable based on } F_I \\ \text{if not, proceed to step 2} & \end{cases}$$
- Step 2: Evaluate Fitness Function II (Maximum Delay)
  - If the result is positive (indicating the maximum delay is within acceptable limits), the solution is considered viable and is kept in the population.
  - If the result is negative (indicating the maximum delay exceeds acceptable limits), the solution is discarded.
  $$\begin{cases} \text{if } F_{II}(D_i) > 0 & \text{the solution is viable based on } F_{II} \\ \text{if not, disregard the generation.} & \end{cases}$$

Using this dual-objective approach, we prioritize solutions that minimize both the overall delay and the worst-case delay. This ensures a more balanced and effective optimisation by disregarding solutions that fail to meet these criteria, thereby preventing their propagation into future generations.

4.4.1. Delay computation: In the context of sequencing departure aircraft, we aim to minimize the total delay. The delay for each aircraft is calculated based on the actual departure time, which is influenced by the occupation time of the preceding aircraft and the complexity of the followed SID.

Key variables:

- Scheduled Departure Time: S_i - The scheduled departure time for the i-th aircraft.
- Occupation Time: O_i - The time the i-th aircraft occupies the runway.
- Actual Departure Time: A_i - The actual departure time for the i-th aircraft.
- Delays: D_i - The delay for the i-th aircraft.

Formulas:

- Occupation Time O_i: Obtained from table **??**.
- Actual Departure Time A_i: $A_1 = S_1, \quad A_i = \max(S_i, A_{i-1} + O_{i-1})$, for i ≥ 2.
- Delay Calculation D_i: $D_1 = 0, \quad D_i = A_i - S_i$, for i ≥ 2.
- Total Delay: $\sum_{i=2}^{n} D_i = \sum_{i=2}^{n} (\mathrm{A}_i - \mathrm{S}_i)$.

5. Dataset and final algorithm illustration

5.1. Dataset

This dataset represents a real-world traffic scenario at Mohammed V International Airport on May 27, 2024, specifically covering the period from 15:25 to 16:25. The arrival traffic data have been removed to streamline the dataset and focus on the key elements of interest, enabling a concentrated analysis of departure operations.

To ensure the dataset is in a more structured and usable format, the time data has been adjusted. All time entries have been normalised to start from zero, with time increments recorded in minutes only. This adjustment simplifies temporal analysis and allows for easier comparison and visualisation of the departure sequence.

In addition to basic traffic information, further data enhancement has been performed to provide a richer dataset. For instance, performance indices have been derived from the aircraft types, offering insights into the speed, climb rate, and other relevant performance metrics. Furthermore, the complexity of each departure aircraft has been evaluated based on the assigned SID route, considering factors such as route length, required turns, and airspace constraints.

These enhancements to the dataset enable a deeper analysis, facilitating more accurate simulations and scenario planning. The enriched dataset serves as a valuable tool for exploring the intricacies of departure management and optimising runway operations at Mohammed V International Airport.

5.1.1. Data preparation: The dataset was prepared by processing various elements related to aircraft departures. The key components of the data preparation process are outlined below:

- Flight Index (FI) According to Predicting Situation: Each flight was assigned a unique index based on the predicted situation, which helped categorise and prioritise departures according to operational needs and anticipated traffic flow.
- Flight IDs (FId) List: A list of identifiers (Flight Ids) was compiled for each aircraft, serving as the primary reference for individual flights within the dataset. These Ids are critical for tracking and analysis.
- Departure Times (DT): The original dataset included expected departure times for each aircraft (ODT). These times were modified to include the taxiing time and standardised to fit a consistent format, starting from a zero baseline. The adjusted times facilitate chronological analysis and scenario simulation.
- Aircraft Type (AT): Information regarding the type of aircraft for each flight was included. Aircraft type is essential for understanding performance characteristics and predicting behaviour during departure.
- Performance Indices (PI): Based on the type of aircraft, performance indices were extracted. These indices represent critical performance metrics such as speed, climb rate, and fuel efficiency, which influence departure sequencing and runway utilisation. (The performance indice in Table 2 is calculated according to altitude 6000ft)
- Destination (Dest): The dataset also includes the destination for each departing aircraft. This information is critical for understanding the broader traffic network and the potential downstream effects of departure scheduling.
- Main SID (M SID): The main SID route assigned to each flight was extracted. The SID indicates the planned flight path for the aircraft immediately after departure, including any altitude, speed, or directional instructions. Each SID was assigned a number (M SID N)

Table 2. SID conflict grade explanation

Conflict Grade	The Altitude to be leaved by the precedent aircraft to release the next one
Same SID	10000 ft
First Grade C1	8000 ft
Second Grade C2	6000 ft
Third Grade C3	4000 ft
Fourth Grade C4	3000 ft

Table 3. Exctracted flight data

FI	ODT	FId	DT	AT	PI 60	Dest	M SID	M SID N	C1	C2	C3	C4
1	15:25	AZT 732	0	E90	300	MARSEILLE	agdl	1	2	3	4	5
2	15:27	3ZO 492	2	A320	250	NAPLES	bism	2	3	4	5	1
3	15:29	AZT 970	4	B738	220	MADRID	lkam	3	4	5	1	2
4	15:33	AZT 798	8	B738	220	BORDEAUX	agdal	1	2	3	4	5
5	15:34	QZR 1395	9	B789	200	MARRAKECH	nkzo	4	5	1	2	3
6	15:36	AZT 984	11	AT7	500	MALAGA	lakm	3	4	5	1	2
7	15:38	AZF 1597	13	A320	250	PARIS-CDG	agdl	1	2	3	4	5
8	15:41	AZT 200	16	B789	200	NEW YORK	odxa	5	1	2	3	4
9	15:42	AZT 960	17	B7M8	210	BARCELONE	lakm	3	4	5	1	2
10	15:46	WZT 8735	21	AT7	500	MADRID	lkam	3	4	5	1	2
11	15:50	AZT 425	25	B738	220	AGADIR	nikzo	4	5	1	2	3
12	15:51	AZT 982	26	B738	220	LISBONNE	lakm	3	4	5	1	2
13	15:53	AZT 218	28	B788	200	WASHINGTON	odaxa	5	1	2	3	4
14	15:53	TZP 1438	28	E95	300	LISBONNE	lakm	3	4	5	1	2
15	15:59	AZT 1414	34	B738	220	LAÂYOUNE	nkzo	4	5	1	2	3
16	16:02	XZY 8166	37	A333	250	JEDDAH	bismi	2	3	4	5	1
17	16:07	3ZO 437	40	A320	280	ISTANBUL	bismi	2	3	4	5	1
18	16:08	AZT 1402	43	AT7	500	OUJDA	bismi	2	3	4	5	1
19	16:12	AZT 968	47	E90	240	VALENCIA	agdal	1	2	3	4	5
20	16:15	TZK 618	50	A359	180	ISTANBUL	bismi	2	3	4	5	1
21	16:25	TZO 3068	60	A32N	250	PARIS-ORLY	agdal	1	2	3	4	5

- Conflicted SID and Conflict Grade (C1 to C4): Conflicts between SIDs were identified and categorized. In the studied scenario we have five SIDs. Each SID conflict was graded based on its severity, with grades ranging from 1 to 4 as shown in Table 2. The conflict grade reflects the complexity and risk level associated with managing multiple aircraft on conflicting SIDs, enabling better decision-making in departure sequencing.

These steps in data preparation ensure a comprehensive and organised dataset, which is ready for in-depth analysis, simulation, and optimisation of departure operations at Mohammed V Airport.

5.1.2. Extracted data: The Table 3 was obtained based on the gathered reel data, the instructions of the previous section and other extracted data.

5.1.3. Delay computation: The delay of each aircraft depends on the followed SID, the conflict grade with the previous aircraft SID and its performance. Delays are given for 3000ft, 4000ft, 6000ft, 8000ft, and 10000ft altitudes as shown in Table 4.

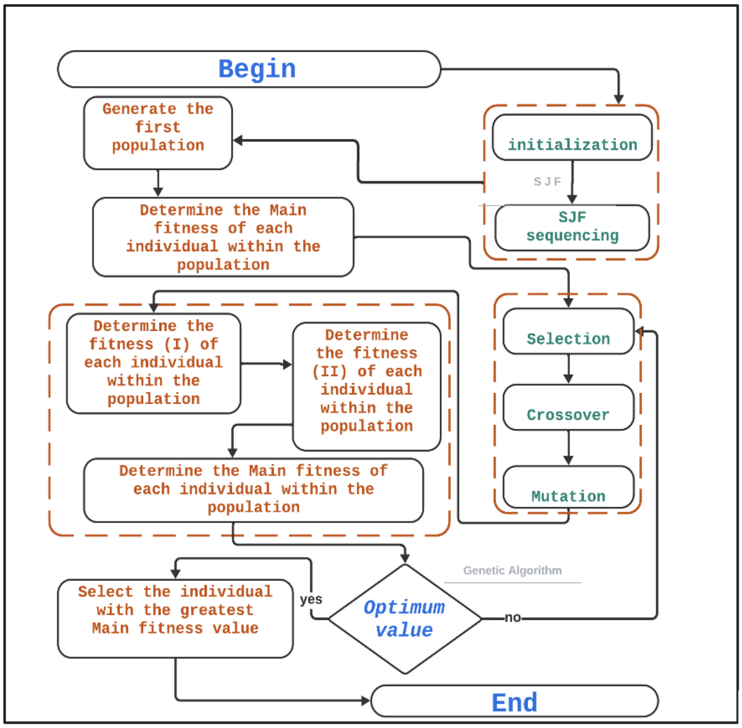

Figure 1. Hybrid GA

5.2. *Final algorithm illustration*

1. Data Representation: the aircraft data contains aircraft details, delays at different altitudes, SIDs, and conflicts with other SIDs.
2. Fitness Calculation: it Computes the total delay for a sequence of aircraft considering conflicts at different altitudes.
3. GA Initialization: initiate the first population using the SJF method.
4. GA Operators: Tournament Selection, PMX Crossover, and Swap Mutation: As described earlier.
5. GA Execution:
   - Initialize Population: Create a mix of SJF and random sequences.
   - Evolve Population: Apply selection, crossover, and mutation.
   - Terminate: Stop after a fixed number of generations or if no improvement is observed for 10 consecutive generations.
6. Output:The best sequence (indices of aircraft) and the total delay for that sequence.

The proposed approach will provide the best sequence of aircraft departures to minimize the total delay, considering the complexities of different SIDs and their associated conflicts at various altitudes. Fig 1 summarise the hybrid genetic process.

6. Simulation Results

The Table 4 represents the first planned sequence with a total accumulated delay of 5845s. After applying the hybrid algorithm for 100 generations, the new departure sequence was obtained, as shown in the Table 5. The new total accumulated delay is 4228s. the total delay value was reduces with approximately 27.67% (1617s).

Table 4. Delay computation of the first planned sequence

FI	ODT	ATD	TC1	TC2	TC3	TC4	TS	M SID	M SID N	C1	C2	C3	C4	D
1	15:25	15:25	90	120	300	390	480	agdl	1	2	3	5	4	0
2	15:27	15:32	75	100	250	325	400	bism	2	1	3	5	4	390
3	15:29	15:34	66	88	220	286	352	lkam	3	5	4	1	2	75
4	15:33	15:38	66	88	220	286	352	agdal	1	2	3	5	4	220
5	15:34	15:40	60	80	200	260	320	nkzo	4	5	3	1	2	88
6	15:36	15:44	150	200	500	650	800	lakm	3	5	4	1	2	200
7	15:38	15:53	75	100	250	325	400	agdl	1	2	3	5	4	500
8	15:41	15:55	60	80	200	260	320	odxa	5	3	4	1	2	100
9	15:42	16:00	63	84	210	273	336	lakm	3	5	4	1	2	260
10	15:46	16:06	150	200	500	650	800	lkam	3	5	4	1	2	336
11	15:50	16:15	66	88	220	286	352	nikzo	4	5	3	1	2	500
12	15:51	16:19	66	88	220	286	352	lakm	3	5	4	1	2	220
13	15:53	16:24	60	80	200	260	320	odaxa	5	3	4	1	2	286
14	15:53	16:29	90	120	300	390	480	lakm	3	5	4	1	2	260
15	15:59	16:34	66	88	220	286	352	nkzo	4	5	3	1	2	300
16	16:02	16:36	75	100	250	325	400	bismi	2	1	3	5	4	66
17	16:07	16:43	84	112	280	364	448	bismi	2	1	3	5	4	400
18	16:08	16:51	150	200	500	650	800	bismi	2	1	3	5	4	448
19	16:12	17:02	72	96	240	312	384	agdal	1	2	3	5	4	650
20	16:15	17:08	54	72	180	234	288	bismi	2	1	3	5	4	312
21	16:25	17:12	75	100	250	325	400	agdal	1	2	3	5	4	234

Table 5. Delay computation of the generated sequence

FI	ODT	TC1	TC2	TC3	TC4	TS	M SID	M SID N	C1	C2	C3	C4	D	NDT
4	15:33	66	88	220	286	352	agdal	1	2	3	5	4	0	15:33
5	15:34	60	80	200	260	320	nkzo	4	5	3	1	2	88	15:35
1	15:25	90	120	300	390	480	agdl	1	2	3	5	4	60	15:36
8	15:41	60	80	200	260	320	odxa	5	3	4	1	2	120+180	15:41
2	15:27	75	100	250	325	400	bism	2	1	3	5	4	80	15:43
12	15:51	66	88	220	286	352	lakm	3	5	4	1	2	75+360	15:51
7	15:38	75	100	250	325	400	agdl	1	2	3	5	4	220	15:55
3	15:29	66	88	220	286	352	lkam	3	5	4	1	2	100	15:57
15	15:59	66	88	220	286	352	nkzo	4	5	3	1	2	220	16:01
16	16:02	75	100	250	325	400	bismi	2	1	3	5	4	66	16:03
6	15:36	150	200	500	650	800	lakm	3	5	4	1	2	75	16:05
18	16:08	150	200	500	650	800	bismi	2	1	3	5	4	500	16:14
13	15:53	60	80	200	260	320	odaxa	5	3	4	1	2	150	16:17
11	15:50	66	88	220	286	352	nikzo	4	5	3	1	2	210	16:21
17	16:07	84	112	280	364	448	bismi	2	1	3	5	4	66	16:23
9	15:42	63	84	210	273	336	lakm	3	5	4	1	2	84	16:25
10	15:46	150	200	500	650	800	lkam	3	5	4	1	2	336	16:31
20	16:15	54	72	180	234	288	bismi	2	1	3	5	4	500	16:40
14	15:53	90	120	300	390	480	lakm	3	5	4	1	2	54	16:41
19	16:12	72	96	240	312	384	agdal	1	2	3	5	4	300	16:46
21	16:25	75	100	250	325	400	agdal	1	2	3	5	4	384	16:53

7. Conclusion

Minimising departure air traffic delays significantly enhances fleet management efficiency, increases the dynamism of air transport operations, reduces greenhouse gas emissions, and optimises airport capacity utilisation.

This research study presents a novel sequential hybridisation approach designed to assist air traffic controllers in optimising the departure air traffic sequence following standard instrument departure routes SIDs after takeoff. The suggested strategy employs the GA meta-heuristic method, enhanced by the PMX technique. Additionally, it employs the SJF conventional sequencing method to initialise the first population. The objective of this research is to approach the ideal configuration of the departure traffic sequence as closely as feasible.

The results demonstrate the effectiveness of the proposed technique, with the total delay reduced by approximately 30%, which is a substantial improvement in terms of time, cost savings, and energy efficiency. Future research could explore novel hybridisations and comparisons to provide a comprehensive overview of meta-heuristics and identify the most effective approaches for further optimizing results.

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