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Geographical information system for air traffic optimization using genetic algorithm

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Abstract

The primary concern of an air traffic controller is to ensure the safety and fluidity of ever-increasing air traffic. This requires effective training through practical work supervised by instructors. Based on certain rules called separation rules, the trainee must find a solution to a traffic configuration defined by flight plans (FPL) initially containing a number of conflicts. This solution will then be compared to the one proposed by the instructor. The purpose of this article is to replace the instructor with a Geographical Information System (GIS) solution combined with a genetic algorithm which, from a set of FPLs, will find the best solution to ensure on the one hand the safety of the aircraft but also minimizing the distance and the changes to be made. The application will use the GAMA platform, very suitable for this and a set of tests composed of actual exercises will be performed to validate the work.

Keywords Air traffic control · GIS · Genetic algorithms · GAMA platform

1 Introduction

With the increase in global air traffic (+ 4.2 % in 2019 [1]), we quickly see problems of traffic congestion rising operating costs [2] and CO2 emissions growth [3]. As a result, in addition to ensuring the safety and fluidity of air traffic, the current challenge for air traffic control and safety organizations is therefore to optimize this traffic in order to best address these problems. During the life of a flight, the aircraft (noted as A/C) goes through several phases. They are managed by different structures because each phase requires specific

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rules and techniques.Thus, phases from the start-up of the aircraft until its take-off usually depend on the control tower.The climb phase depends ontheapproach control. Finally, the en-route phase (where the aircraft is stable) depends on theen-route control managed by the RCC (Regional Control Center).The airspace controlled by the RCC is generally divided into sectors where each sector is under the responsibility of an air traffic controller often assisted by an assistant. Over time, the controller in charge of a given area receives traffic data concerning him from controllers of adjacent areas, towers or approaches. These data are in the form of flight plans (FPL) summarizing the details of the route that each aircraft must travel through its sector. Through this information, the controller has a situation of the coming traffic and therefore must detect any conflicts that may arise. He has also to include solutions by changing certain flight details of the aircraft that the pilots will apply once they have entered his sector. In addition to ensuring the safety of aircraft (respecting separation rules), these solutions have to minimize changes in planned flight plans. To achieve this, the controller must undergo qualifying training in the control sector and in which it is a question, among other things, of practical work consisting of exercises. Each exercise consists of a set of FPLs. At the end of each exercise, a solution is proposed by the trainee controllers and verified by the instructors. It is in this context that the work exposed in this article is situated. It's about replacing the solution proposed by the instructor by that of the machine. The interest of this is widely explained in [4] dealing with, among other things, financial and time savings. In what follows, we propose a GIS tool based on genetic algorithms which aim to find an optimal solution from a traffic configuration previously given in the form of FPLs. The problem addressed is limited to the en-route phase and the solution must not only eliminate conflicts between aircraft but also minimize the overall crossing time and the overall number of modifications made to the initial FPLs. Given the geographical nature of the problem, we opted for the open source GAMA platform allows the manipulation of geographical data and the simulation of the results. Furthermore, since the controller's real working conditions require a real-time response, we will limit ourselves to the working conditions of a trainee controller during practical work. In order to validate our work, we will apply this algorithm on the control area of the TMA (Terminal Medium Area) East of the FIR (Flight Information Region) of Algiers in which a set of exercises will be tested. The results are then compared to the initial FPLs. This article is organized as follows. We start with a state of the art in air traffic optimization. Section 3 provides a detailed description of the problem and its modeling by genetic algorithms. In the fourth section, we present our experimentation environment followed by tests. We will end with a discussion of the results and finally a conclusion.

2 State of the art

Work on air traffic optimization is not new, and dates back to 1980s [4].In order to better understand our present work, and starting from the classification work of [5], we propose a new classification of these different works. We classify the most recent ones according to the following criteria: flight phases, objects/structures optimization, the objectives to be achieved, the criteria followed and the methods/techniques used. The first criterion which is the flight phases, relates to the flight phase concerned by the optimization and its structure. Thus, [6], was interested in the conflicts generated during the aerodrome phase. Authors in [7] have tackeled optimizing the scheduling of takeoffs and landings (ASP: Aircraft Scheduling Problem) while [8] was limited to landings (ALP: Aircraft Landing Problem). Works presented in [9] and [10] focused on the Approach phase and more specifically on diversions and rescheduling of flights near aerodromes. Several works have revolved around the en route phase, let us quote the works of [3] on the simulation of optimized 4D trajectories, those of [11] on fragmented control spaces and also those of [12] for the dynamic configuration of the control space. The second classification criterion is more concerned with the purpose of optimization, that is, what is optimized. This can affect the scheduling of flights such as the work of [13] on departure planning, those of [14] or those of Kolker and Lutjens [15] on airline flight planning. Optimization can also be applied to flight plans, which determine in advance the paths aircraft should follow. We can cite the work of [16] and those of [17]. Optimization on air routes has had its share of works such as [11] who worked on the Air Route Network (ARN) and [18] whose work focused on the design of optimal routes in an airspace. Other work has focused on the positioning of waypoints in an ARN such as those by [19] and [20]. Sectorisation and division of control areas is also an object of optimization, particularly with the SESAR [21] and NextGEN [22] projects. In the same context, Sergeeva et al. [23] sought to automatically adapt the airspace configurations according to the evolution of traffic. Finally, means of communication and localization have also been the subject of several optimization works such as those carried out by [24]. The objectives to be achieved constitute a third criterion. Although they have in common the safety and reliability of air traffic, the proposed solutions all have ancillary objectives to achieve. Thus, [20] worked on optimizing air routes by avoiding special status areas. Others focused on solutions meeting meteorological objectives such as [25] and [26]. Gerdes et al. [17] and Patron et al. [27] focused on fuel consumption while [28] looked at CO_2 emissions. The time factor, an important objective, as well, appears in many studies such as those of [7] and [8]. Another key objective was the elimination of aircraft conflicts, which were the aim ofworks of [6, 29, 30]. Other objectives were treated in the literature such as the optimization of the sectors capacity and the traffic congestion in [31] and [2], the controller's workload (ATC workload stress problem) dealt with in [32] and [33] and the maneuvers / actions to be performed by the pilot in [34]. The fourth and last criterion relates to the optimization methods and techniques used. In [35], Bertsimas et al. used linear programming to solve an Air Traffic Flow Management (ATFM) problem while [26] used the geometric model in their work. Artificial intelligence like graph theory is also present with the A^* algorithm in [3] and weighted graphs in [12]. For their part [36] use dynamic programming. Game theory was used in [37] and the agent approach in [2] to solve the traffic congestion problem. On the metaheuristic side, we find ant colonies in [38] to solve large problems involving up to 30 airplanes, neural networks [39] for simulating traffic and particle swarms for optimizing the layout of waypoints. Genetic algorithms (GAs) have played a prominent role, as they appear in almost all of the classification forms mentioned above. Thus, they are found in [6] for resolving conflicts arising during the aerodrome phase, [7] for planning issues, for route optimization [18] or also to aggregate the passengers and also to reduce route changes and the travel time for travelers [40]. They also appear in [23] for the revitalization of airspace. Their use with GIS (Geographic Information Systems), very suitable in complex problems [41], appears in transport problems optimization like the bus network [42] or the air route network [43]).

3 Problem description

As mentioned above, the route that an aircraft must follow is defined by its FPL. This provides information on the points, called report points or waypoints through which the aircraft must pass, as well as its passage height or flight level (called FL: Flight Level). Each waypoint represents either a ground radio navigation device, an aerodrome (departure or destination), or even a geographical position. These points are known and defined in the various aviation manuals as well as on aeronautical charts (see Fig. 1). In addition, each control sector contains a certain number of these waypoints.

3.1 Aircrafts separation

During their evolution, it happens that two aircraft get too close to each other and thus threaten their safety. That is why a set of rules have been defined by the ICAO (International Civil Aviation Organization). These rules, called separation rules, consider:

- The position of the aircraft, estimated in distance or time in relation to a ground radio navigation aid,
- The flight level (FL) given by the aircraft altimeter
- The attitude: aircraft climbing, descending or stable on its flight level
- The speed of the aircraft

Thus, there are several separation rules that a controller will apply as appropriate to ensure the safety of aircraft.

3.2 Aircraft separation rules

Separation rules differ by the phase of flight. Since our problem is in the en-route phase, we will settle for separations in the cruise phase (en route). Furthermore, we will not cite all the cases mentioned in the ICAO documents [45], and we will limit ourselves to the separations used in our algorithm.

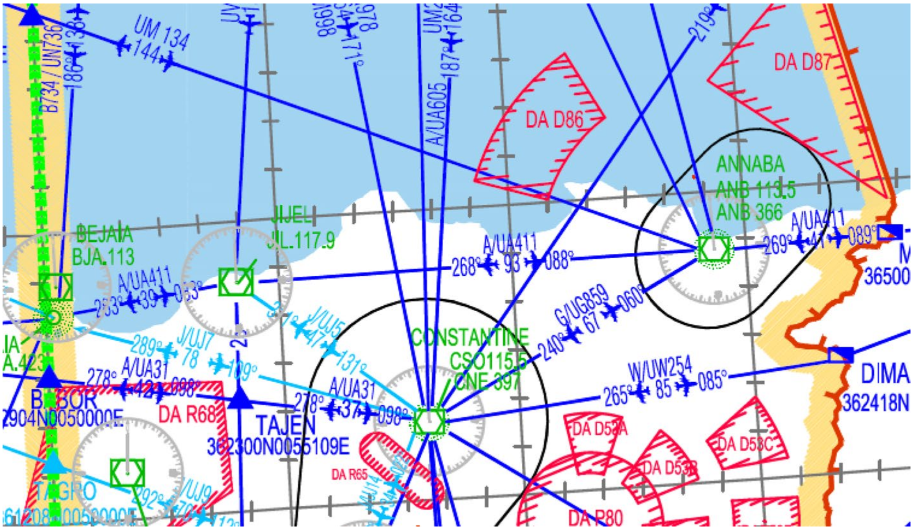


Fig. 1 Portion of an en-route aeronautical chart representing part of the TMA-East of the Algiers FIR [44]

3.2.1 Vertical separation

A minimum vertical distance of 300 m (1000 feet) between two aircraft passing one above the other (1 flight level, also called FL: Flight Level, equals 100 feet).

3.2.2 Horizontal separation

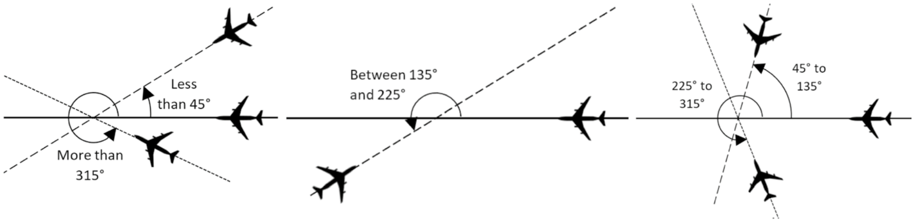
It breaks down into two separations: lateral and longitudinal. The first, the lateral separation of the aircraft is ensured by asking these aircraft to follow separate routes or to fly over different geographical points formally indicating that the aircraft are over different geographical points. In the case of intersecting routes, the separation will be established such that an aircraft following a route converging to that of another aircraft is laterally separated until it reaches a point of lateral separation at a distance of specified distance measured perpendicular to the track of the other aircraft. The same is true for divergent roads except that the distance must be after the crossing point [45]. Longitudinal separation shall be applied in such a way that the interval between the estimated positions of aircraft to which this type of separation applies is never less than a prescribed minimum value. The application of this type of separation differs according to the three traffic configurations: same route (Fig. 2a), routes in the opposite direction (Fig. 2b) and converging routes (Fig. 2c).

There are several types of rules applicable in the case of longitudinal separation: based on time, distance and speed (Mach number) [45]. In this work, we will settle with the first two types of longitudinal separations.

Longitudinal separation based on distance shall be achieved by maintaining at least the specified distances between the position of the aircraft, reported by reference to the DME (Distance Measuring Equipment) in conjunction with other appropriate navigation aids (NDB, VOR or other). When the aircraft have the same FL, whether they are on the same route (Fig. 3a) or converging (Fig. 3b), the difference in distance between the two aircraft must be at least 20 NM (Nautical Miles,$1NM = 1.60934Km$) and using the same DME (in some cases 10 NM [45]). The separation in the case of roads in the opposite direction is not applicable in this case.

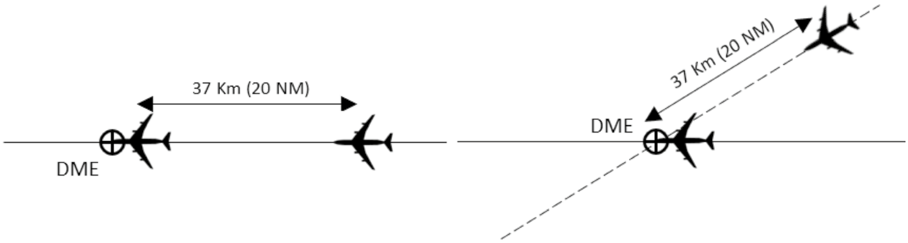
3.2.3 Flight plan

One of the essential information in ATFM is the FPL. This contains the route that the aircraft must follow from its point of departure to its arrival. To manage its traffic, the controller responsible for managing a given sector will not be interested in all the content of



(a) Same route (b) Route in the opposite directions (c) Converging routes

Fig. 2 Aircraft configurations for longitudinal separation



(a) Same route

(b) Converging routes

Fig. 3 Separation based on DME distance between same level aircraft

the FPL, but only in the part that concerns its sector, that is to say: the code the aircraft (ACID), its departure and destination aerodrome, the estimated time to enter its sector, the waypoints (wpts) through which it will pass as well as their FLs (see Fig. 4).

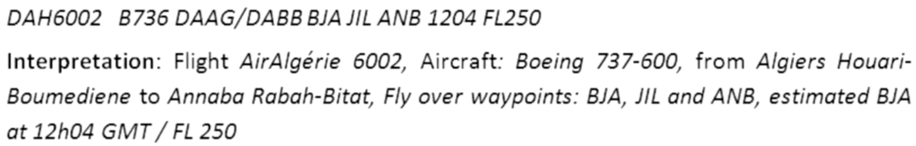
To facilitate his work, this information is recorded on a flight progress sheet called Strip that the controller must fill out manually or print when the control center is equipped with an ATFM system.

3.2.4 How is the operation going?

As mentioned in the introduction, the controller manages its traffic as and when aircraft enter its control sector. It proceeds as follows:

- The controller receives the traffic data (FPL) from his colleagues in the adjacent or underlying sectors (Approach or Tower) or directly from the ATFM system (by broadcasting to all sectors affected by the traffic)
- He records its information in a strip and stores it with the strips of other managed aircraft in its sector
- He detects conflicts that may be generated with other aircraft in flight and classifies the strips by group of aircraft generating conflicts between them
- He decides on the directives to be taken by the aircraft (for example, asking an aircraft to change FL) to ensure the separations between aircraft and contacts the affected aircraft. Notifies the changes on the strips
- Finally, he removes the strip of each aircraft that has left the control sector

In the practical work for the training of controllers, the situation is similar except that the trainee is suddenly assigned a list of flights to manage. He must therefore pass this information on to the strips before the exercise begins. It is precisely this situation that interests us. The reasons for this choice are various: First, unlike real conditions where traffic arrives



DAH6002 B736 DAAG/DABB BJA JIL ANB 1204 FL250

Interpretation: Flight *AirAlgérie 6002,* Aircraft: *Boeing 737-600,* from *Algiers Houari-Boumediene* to *Annaba Rabah-Bitat, Fly over waypoints: BJA, JIL and ANB, estimated BJA at 12h04 GMT / FL 250*

Fig. 4 Portion of a flight's traffic data and its interpretation over time, the traffic information to be managed is given at a time, so it is easier to model. Moreover, the real-world problem requires a real-time resolution, which is not necessarily guaranteed in our case. However, in a training situation, there is more time.

4 Geographic operations for conflict detection

To ensure traffic safety, the controller must provide a conflict-free solution between aircraft and therefore ensure that there is no conflict between each pair of flights. Upon receipt of the forecasted traffic, the controller will calculate the Estimated Time of Overflow (ETO) for each aircraft by each waypoint provided in the FPL based on two main elements: the estimated time of sector entry (for overflight or arrival) / take-off (for departure) and the aircraft speed. From there, he will make sure that one of separation rules mentioned above is applied. If it does not, he will give direction to one or both aircraft to avoid conflict. In our case, the same principle of calculating estimates is applied, but we simply apply the rules of vertical and horizontal separations based on distance and time for the evaluation of conflicts. Vertical separation requires a vertical distance of at least 1000 feet (10 FL) between two aircraft crossing or not in space. Horizontal separations are applied only to aircraft whose routes intersect (otherwise, these aircraft are considered separate). However, this is subject to the condition that each FPL consists solely of waypoints published in the control area navigation chart. We will see later that it is only this kind of FPL that we will handle.

4.1 Types of crossings

When two aircraft intersect, several configurations may occur:

4.1.1 3D crossing

The crossing is represented by a single point or by a segment of FPL defined by 3D coordinates (longitude, latitude and FL). Longitudinal separations should therefore be applied at this point because vertical separation is no longer assured ($\Delta z = 0$).

4.1.2 2D crossing

In this case, the routes of the two aircraft intersect in longitude and latitude but not in FL. In other words, one aircraft passes below the other as summarized in Table 1:

4.2 Longitudinal separation checks steps

To check the longitudinal separation, we proceed as follows:

- Calculate the intersection angle of the two roads at the crossing point to determine if it is traffic on the same route, converging or in the opposite direction. If the traffic is in the opposite direction, there is a separation break between these two aircraft regardless of the distance between them

Table 1 Summary of checks and operations for different aircraft configurations in case of 2D Crossing

AC1	AC2	Checks	Operations
Stable	Stable	The two aircraft are separated vertically	No operation
Stable / Climbing / Descending	Climbing above / Descending below	Verify that A/C 2 did not cross the FL of A/C 1 before the crossing point	If necessary, apply longitudinal separations
	Descending above / Climbing below	Verify that A/C 2 will not cross the FL of A/C 1 after the crossing point	If necessary, apply longitudinal separations

- For distance separations: calculate the remaining distance between the second aircraft and the crossing point when the first aircraft passes over that point. Check the existence of the minimum distance of 20 NM (1NM = 1.60934 Km) or 10 NM if the speed difference between the first and second aircraft is greater than 37 Kts (1Kt = 1.852)
- For time separations: calculate the ETO of the crossing point of each aircraft and ensure that the difference between the two estimates is greater than 15 minutes (general case)

5 Modeling of the problem by GAs

In this section, we present our modeling of the problem by genetic algorithms. Traffic information is given in the form of an exercise consisting of several aircraft having to cross the sector (over flight), take off from an aerodrome or, on the contrary, land at an aerodrome in the sector. In our problem, a traffic solution must not suffer from any conflict between aircraft and must best meet certain objectives. It is therefore quite natural to model the individual (phenotype) as the set of FPLs constituting a given traffic situation.

5.1 Individual

An individual will be composed of F genes representing F flights and described by their FPLs. Since the order of the flights of an exercise is fixed, a gene in an individual will necessarily indicate the same flight. Figure 5 shows the modeling of an individual as well as its geographical representation (phenotype) from data from an exercise consisting of two flights. The gene consists of a label identifying the flight and containing fixed information such as the flight identifier, its origin and destination and the type of the device. It also contains the details of the flight route represented by a series of combinations (wpt, FL). Each gene j has a fixed number of flight details noted n_j. Whatever the individual, the total number of flight details (noted N) remains fixed because it is nothing other than the sum of n_j. For what follows, we give the different expressions used:

- Individual X_i corresponds to the i^{th} configuration of the different flights where X_0 is the given original configuration in the exercise,
- $X_{i,j}$ represents the gene j of individual i with $j = 1, 2, ...F$.
- $X_{i,j,k}$ designates the detail (flight detail) k of gene (flight) j of individual i. with $k = 1, 2, ...n_j$

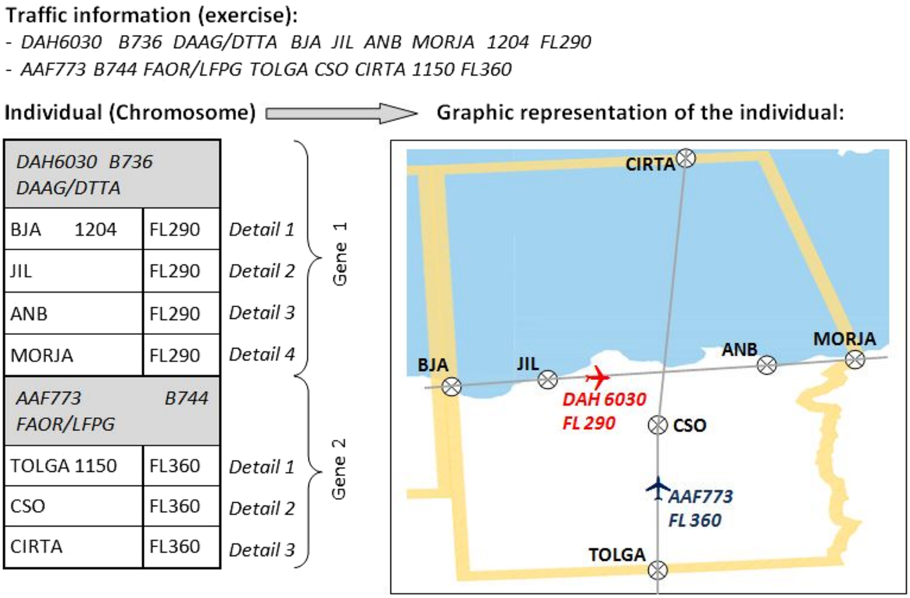


Fig. 5 Modeling of an individual and its geographical representation based on data from an exercise consisting of two flights

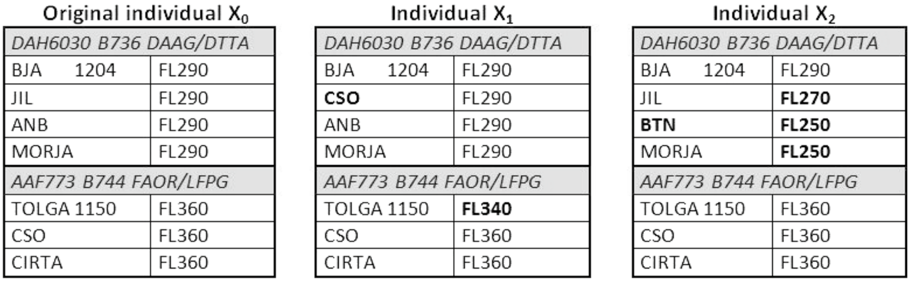
5.2 Population

The generation of the initial population is done from the original individual X_0 created by the exercise data. The other individuals are created by duplicating X_0 and modifying the details of its genes: wpt, FL or both at the same time (Fig. 6).The choice of the data to be changed is made randomly but respecting certain constraints:

- The sector entry / exit waypoints do not undergo any modification except that of the FL because this requires coordination with the adjacent sector
- The waypoints of the departure or take-off aerodromes do not undergo any change. However, it is possible to shift the ETD (Estimated Time of Departure) by a few minutes with a maximum of 5 minutes,
- No waypoint is added or deleted in a chromosome.

5.3 Fitness

The evaluation of X_i is based on two criteria: the verification of separations between aircraft and an aggregation function of two sub-criteria: the overall distance travelled and the overall number of changes of FLs.



Original individual X_0

DAH6030 B736 DAAG/DTTA	
BJA 1204	FL290
JIL	FL290
ANB	FL290
MORJA	FL290
AAF773 B744 FAOR/LFPG	
TOLGA 1150	FL360
CSO	FL360
CIRTA	FL360

Individual X_1

DAH6030 B736 DAAG/DTTA	
BJA 1204	FL290
CSO	FL290
ANB	FL290
MORJA	FL290
AAF773 B744 FAOR/LFPG	
TOLGA 1150	**FL340**
CSO	FL360
CIRTA	FL360

Individual X_2

DAH6030 B736 DAAG/DTTA	
BJA 1204	FL290
JIL	**FL270**
BTN	**FL250**
MORJA	**FL250**
AAF773 B744 FAOR/LFPG	
TOLGA 1150	FL360
CSO	FL360
CIRTA	FL360

Fig. 6 Generation of two individuals X_1 and X_2 from the original individual X_0 by changing some details on the genes of the chromosomes (in bold)

5.3.1 Verification of separations between aircraft

It is based on the two types of separation chosen: vertical and horizontal separation (distance and time). For an individual X_i, we count the number of conflicts $C(X_i)$ generated where $C(X_{i,j}, X_{i,l})$ represents the number of conflicts between the aircraft of flight j and that of flight l for this individual i.

$$C(X_i) = \sum C(X_{i,j}, X_{i,l}) \tag{1}$$

with $j, l = 1, .., F$ and $j \neq l$ When $C(X_i) > 0$, this is enough to disqualify X_i as a feasible solution.

5.3.2 The total distance traveled

The distance traveled by X_i, denoted by $D(X_i)$ represents the sum of the distances traveled by each of the flights j ($X_{i,j}$) denoted by $d(X_{i,j})$. Due to fuel consumption and CO_2 emissions, it is obvious that the smaller $D(X_i)$ is, the more the flight configuration and therefore the individual is favorable.

FPLs as filed by airlines are generally optimized (shortest route, most optimal FLs), the closer $D(X_i)$ gets to the initial $D(X_0)$ configuration, the better the solution. It is even possible that $D(X_i) < D(X_0)$, X_i will therefore be considered better than X_0 in terms of distance.

The distance difference Δ_i is then defined as:

$$\Delta_i = D(X_i) - D(X_0) \tag{2}$$

Moreover, between two solutions i and h such as $D(X_i) = D(X_h)$, we prefer the one that affects the most FPLs, which implies fewer modifications in each of the initial FPLs. We then define δ_i, a modification rate such as:

$$\delta_i = (N - n_i)/N \tag{3}$$

The role of δ is to promote, among the solutions with an equal Δ, that which distributes Δ over the greatest number of FPLs. However, when $D(X_i) < D(X_0)$, Δ_i will be less than 0 but $\delta_i > 0$, which will somewhat distort the assessment of $X_i i$. To remedy this, and to keep the same sign between Δ_i and δ_i, we multiply Δ_i by $\frac{\Delta_i}{|\Delta_i + \varepsilon|}$.

The role of ε is simply to avoid a division by zero in the case of a solution equal to the initial solution in terms of overall distance. Its value is negligible (of the order of a metre). The assessment of individual i according to the overall distance travelled is expressed as follows:

$$G(X_i) = \Delta_i(1 + \delta_i/|\Delta_i + \varepsilon|) \tag{4}$$

5.3.3 The global change in FLs

We try to minimize the number of global changes in terms of FLs for an individual X_i, compared to the initial configuration. For each flight detail $X_{i,j,k}$, we calculate the difference of FL noted $f_{i,j,k}$ compared to the initial configuration $X_{0,j,k}$. Concretely, by how many FLs, the aircraft executing the FPL j will change (up/down) when it flies over waypoint k compared to what was initially planned for that same waypoint. Moreover, for reasons of passenger comfort, fuel consumption or other reasons, the greater the fijk gap, the more it is binding for the pilot. A pilot is more willing to change flight level three times with a deviation of 1 FL than to change once with a deviation of 3 FL. The function Φ_i is then defined as a quadratic sum differences of FL for the individual i:

$$\Phi_i = \sum f_{i,j,k}^2 \tag{5}$$

with $j = 1, 2, ..F$ and $k = 1, 2..n_j$.

On the other hand, between two solutions i and h having the same Φ value, the preference goes to that which affects the largest number of genes (of waypoints). This is expressed by the function φ as:

$$\varphi_i = \begin{cases} (N - nf_i)/N & \text{if } \mathrm{n}f_i > 0, \\ 0 & \text{otherwise (no change in FL)} \end{cases} \tag{6}$$

where nf_i is the number of waypoints that undergone the change in.

The role of φ is the same as that of δ, that is to say to favor, among all the individuals having the same value Φ, the one who best distributes Φ over the different FPLs. The assessment function of the individual i in relation to the FL amendments is calculated as follows :

$$M(X_i) = \Phi_i + \varphi_i \tag{7}$$

5.3.4 The fitness function

The more a solution minimizes G and/or M, the better it is. The objective function $Z(X_i)$ can therefore be calculated as follows:

$$Z(X_i) = \alpha G_i + \beta M_i \tag{8}$$

α and β are weighting factors such as $\alpha, \beta \in N$.

The aggregation of these two sub-criteria is explained by the fact that they are not conflicting objectives(for G, this represents a change in (x, y) while for M, it is a change in z). Both of sub-criteria reflect in their own way the changes that a potential solution proposed in relation to the initial solution.

For our part and for the tests we have carried out, we will take $\alpha = \beta = 1$, which gives equal importance to the two sub-criteria as is the case during the training of the trainee controllers. The individual X_i passes first through a first stage of conflict assessment and then through a stage of calculation of $Z(X_i)$.

5.4 Selection

We use a simple selection operator which is the weighted roulette technique where candidates are selected with a probability proportional to their fitness. The better an individual is, the more likely he is to be selected.

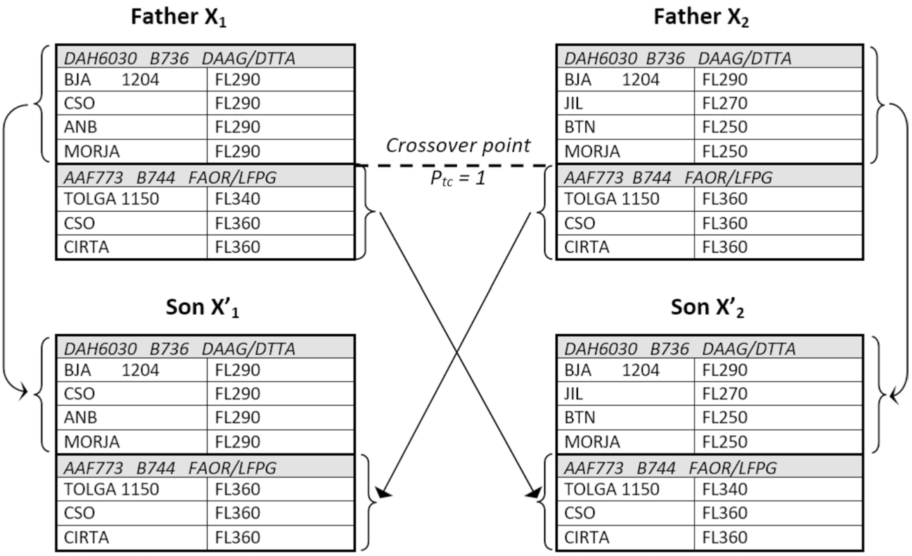
5.5 Genetic operators

5.5.1 Crossing over operator

The crossing used between two individuals X_a and X_b is a unipoint crossover. It is done according to a crossing probability Pc. Considering the Ptc crossing point, the offspring individuals $X'_a$and X'_b are made up, for X'_b of the first Ptc genes of X_a and $F - Ptc$, the remaining genes of X_b, the reverse as for X'_b made up of the Ptc first genes from X_b and F-Ptc remaining genes from X_a. Figure 7 shows the crossover operation.

5.5.2 Mutation operator

The mutation reaches an individual with a probability P_m. It affects one of the individual's genes and more exactly one of the details: the waypoint, the FL or both at the same time.



Father X_1

DAH6030 B736 DAAG/DTTA	
BJA 1204	FL290
CSO	FL290
ANB	FL290
MORJA	FL290
AAF773 B744 FAOR/LFPG	
TOLGA 1150	FL340
CSO	FL360
CIRTA	FL360

Father X_2

DAH6030 B736 DAAG/DTTA	
BJA 1204	FL290
JIL	FL270
BTN	FL250
MORJA	FL250
AAF773 B744 FAOR/LFPG	
TOLGA 1150	FL360
CSO	FL360
CIRTA	FL360

Son X'_1

DAH6030 B736 DAAG/DTTA	
BJA 1204	FL290
CSO	FL290
ANB	FL290
MORJA	FL290
AAF773 B744 FAOR/LFPG	
TOLGA 1150	FL360
CSO	FL360
CIRTA	FL360

Son X'_2

DAH6030 B736 DAAG/DTTA	
BJA 1204	FL290
JIL	FL270
BTN	FL250
MORJA	FL250
AAF773 B744 FAOR/LFPG	
TOLGA 1150	FL340
CSO	FL360
CIRTA	FL360

Fig. 7 Crossing of two individuals X_1 and X_2 at the crossing point Ptc = 1

However, an exception is made for departures where it is possible to modify the ETD by a maximum of 5 minutes as is usually practiced in reality by controllers.

5.5.3 Replacement of individuals

The replacement strategy is random where each offspring randomly chooses one of the individuals among the population of parents to replace him, except for the best individual among the parents who is maintained and cannot be replaced. Moreover, the best individual among the offsprings will automatically replace one of the individuals among the parents. The choice of this strategy is based on a compromise between keeping the best individuals (the best of parents and the best of children) for the next generation according to the very essence of genetic algorithms: “survival of the fittest” and the desire to keep a greater space to seek and avoid falling too early in a local optimum.

6 Experimentation

To validate our work, we experimented with our algorithm on an en route control sector on which we applied tests in the form of exercises.

6.1 Experimentation sector

The sector we have chosen is the TMA North-East of the Algiers FIR for the control of en-route phase aircraft, those landing / taking off from aerodromes in this sector or coming from / going to the CTA (Control Terminal Area, approach sectors of Annaba and Constantine). It is bounded to the north and east by two foreign FIRs (Marseille and Tunis), while we find the TMA Center and the South-center sector to the west and the South-East sector to the south. The TMA is made up of 25 waypoints distributed among geographical points or radio navigation aids, located at the boundary of the FIR / sector or inside (see Fig. 8).

6.2 Benchmarks

The used benchmarks are exercises on which we have performed our tests come from real exercises used by the instructors for the training of air traffic controllers. They are inspired by real life situations that present recurring conflicts between aircraft. The difficulty of the exercise increases with the number of aircraft. They are in the form of a portion of FPL as given in Fig. 6.

6.2.1 Software environment

For the implementation of our GIS tool and the execution of the tests we used the GAMA platform UMMISCO [46] under the Windows environment. There are two reasons for choosing this platform: GAMA is an integrated and comprehensive development environment for modeling and simulation. In addition, it allows manipulation of geographic information and connection to geographic databases. So this is an environment that is very suitable for the intended purpose.

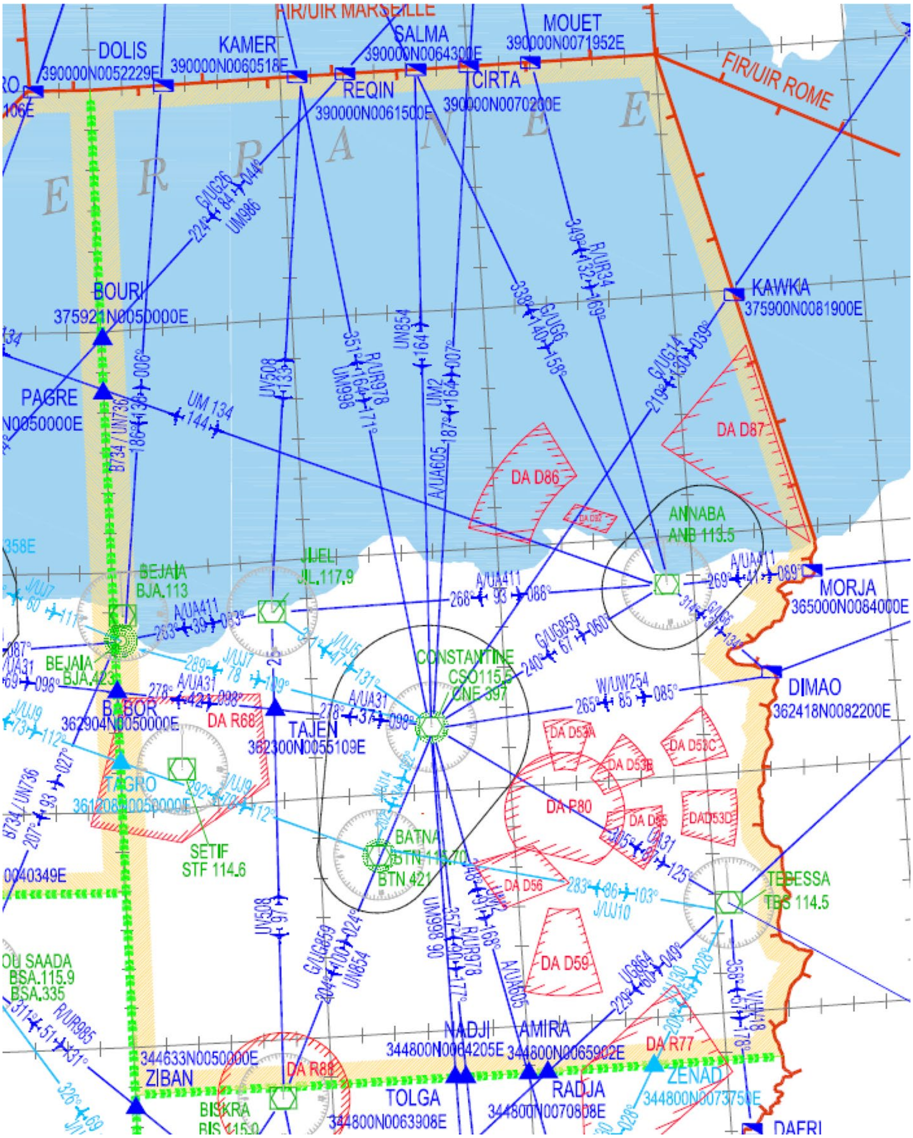


Fig. 8 Experimentation area,TMA North-East of the Algiers FIR [44]

7 Tests and results

7.1 Data set

As mentioned above, the tests are carried out on practical exercises of air traffic controller training. We have selected ten exercises whose composition is available in [47] and summarized in Table 2.

Table 2 Composition of the exercises used for the tests

Exercise	Number of flights F	Departures	Arrivals	Over flights	$D(X_0)(km)$	$C(X_0)$	N
1	12	5	4	3	3092.58	9	32
2	11	3	4	3	3430.25	10	27
3	12	4	5	3	2989.05	18	32
4	11	5	2	4	3454.65	16	31
5	12	6	4	2	3267.07	5	32
6	12	5	3	3	3659.17	10	33
7	16	5	6	5	4699.15	19	46
8	14	4	5	4	4664.86	21	39
9	14	4	6	4	3756.2	22	39
10	13	6	5	2	3508.72	7	34

Table 3 Parameter setting

Parameter	Setting
Population Size	5
Number of Iteration	1000
Crossover rate	0.7
Mutation rate	0.4

7.2 Genetic algorithm parameters

The parameter values for our genetic algorithm were obtained after a dozen tests carried out on each of these parameters and fixing the others. The values used are: (see Table 3)

7.3 Results and discussion

In order to evaluate our work, we carried out 10 tests for each of the exercises according to the parameters used (see Table 4). Bold lines represent the best solution for the corresponding exercise. Table 5 summarize the results obtained. It is divided into two parts: the best solution (Table 5a) and the average solution (Table 5b) for each exercise.

In order to better illustrate the results obtained, we will take an example. For exercise 3, the best solution found (Table 4, test $n^o 1$) increases the distance traveled D by $166.45km$ on the seven (7) flights having undergone a modification of FPL. This implies an average increase of $23.77km$ for each flight, which is very acceptable.

From the point of view of the change of FLs,$\Phi(X^*) = 26$. However, this does not necessarily mean 26 level changes (see Sect. 5.3.3). A detailed comparison of this solution with the original solution shows the results shown in Table 6 and the graphical representation of the two solutions can be summarized in Fig. 9.

We note that FL changes affect 7 FPLs (1, 4, 5, 7, 10, 11 and 12) spread over 12 wpts with a maximum FL change equal to 3 (FL 260 instead of 290 for the 2nd wpt of FPL

Table 4 Test results over the ten exercises

Exercise	N^o	C	$D(km)$	$\Delta(km)$	n	δ	G	θ	nf	φ	M	Z
1	1	0	3336.17	243.59	3	0.75	246.59	26	9	0.72	26.72	273.31
	2	0	3288.33	195.75	5	0.58	200.75	4	4	0.88	4.88	205.63
	3	0	3246.83	154.25	3	0.75	157.25	37	4	0.88	37.88	195.13
	4	0	3186.34	93.76	3	0.75	96.76	8	5	0.84	8.84	105.60
	5	0	3139.59	47.01	2	0.83	49.01	1	1	0.97	1.97	50.98
	6	0	3160.3	67.72	4	0.67	71.72	14	6	0.81	14.81	86.53
	7	0	3746.04	653.46	7	0.42	660.46	10	7	0.78	10.78	671.24
	8	0	3299.32	206.74	5	0.58	211.74	21	16	0.50	21.50	233.24
	9	0	3272.3	179.72	6	0.50	185.72	35	15	0.53	35.53	221.25
	10	0	3485.88	393.3	4	0.67	397.3	16	5	0.84	16.84	414.14
2	1	0	3454.46	24.21	3	0.73	27.21	50	16	0.5	50.5	77.71
	2	0	3455.51	25.26	3	0.73	28.26	8	6	0.81	8.81	37.07
	3	0	3456.23	25.98	4	0.64	29.98	18	16	0.5	18.5	48.48
	4	0	3456.09	25.84	2	0.82	27.84	10	5	0.84	10.84	38.68
	5	0	3489.84	59.59	4	0.64	63.59	40	9	0.72	40.72	104.31
	6	0	3456.23	25.98	4	0.64	29.98	6	4	0.88	6.88	36.86
	7	0	3453.74	23.49	2	0.82	25.49	10	3	0.91	10.91	36.4
	8	0	3516.97	86.72	2	0.82	88.72	1	1	0.97	1.97	90.69
	9	0	3462.96	32.71	2	0.82	34.71	1	1	0.97	1.97	36.68
	10	0	3536.94	106.69	2	0.82	108.69	0	0	1	1	109.69
3	1	0	3155.5	166.45	7	0.42	173.45	26	12	0.63	26.63	200.08
	2	0	3256.23	267.18	7	0.42	274.18	431	14	0.56	431.56	705.74
	3	0	3221.51	232.46	7	0.42	239.46	360	15	0.53	360.53	599.99
	4	0	3100.43	111.38	5	0.58	116.38	611	12	0.63	611.63	728.01
	5	1	3456.98	467.93	6	0.5	473.93	210	14	0.56	210.56	684.49
	6	0	3640.29	651.24	5	0.58	656.24	27	11	0.66	27.66	683.9
	7	1	3478.56	489.51	6	0.5	495.51	79	10	0.69	79.69	575.2
	8	1	3287.72	298.67	5	0.58	303.67	369	12	0.63	369.63	673.3
	9	0	3272.3	179.72	6	0.50	185.72	35	15	0,53	35.53	221.25
	10	0	3131.78	142.73	7	0.42	149.73	87	18	0.44	87.44	237.17
4	1	0	4165.49	710.84	6	0.45	716.84	148	17	0.45	148.45	865.29
	2	1	3778.3	323.65	6	0.45	329.65	119	16	0.48	119.48	449.13
	3	0	3858.49	403.84	6	0.45	409.84	333	19	0.39	333.39	743.22
	4	0	3824.06	369.41	5	0.55	374.41	81	11	0.65	81.65	456.05
	5	0	3696.99	242.34	6	0.45	248.34	63	22	0.29	63.29	311.63
	6	0	3989.73	535.08	6	0.45	541.08	951	19	0.39	951.39	1492.46
	7	0	3698.34	243.69	6	0.45	249.69	46	9	0.71	46.71	296.39
	8	1	3747.17	292.52	7	0.36	299.52	26	16	0.48	26.48	326
	9	2	3573.36	118.71	5	0.55	123.71	98	13	0.58	98.58	222.29
	10	0	3696.36	241.71	6	0.45	247.71	808	20	0.35	808.35	1056.06
5	1	0	3336.17	243.59	3	0.75	246.59	26	9	0.72	26.72	273.31
	2	0	3288.33	195.75	5	0.58	200.75	4	4	0.88	4.88	205.63
	3	0	3246.83	154.25	3	0.75	157.25	37	4	0.88	37.88	195.13
	4	0	3186.34	93.76	3	0.75	96.76	8	5	0.84	8.84	105.60

Table 4 (continued)

Exercise	N^o	C	$D(km)$	$\Delta(km)$	n	δ	G	θ	nf	φ	M	Z
	5	0	3139.59	47.01	2	0.83	49.01	1	1	0.97	1.97	50.98
	6	0	3160.3	67.72	4	0.67	71.72	14	6	0.81	14.81	86.53
	7	0	3746.04	653.46	7	0.42	660.46	10	7	0.78	10.78	671.24
	8	0	3299.32	206.74	5	0.58	211.74	21	16	0.50	21.50	233.24
	9	0	3272.3	179.72	6	0.50	185.72	35	15	0.53	35.53	221.25
	10	0	3485.88	393.3	4	0.67	397.3	16	5	0.84	16.84	414.14
6	1	0	3649.07	-10.1	6	0.5	-16.1	10	10	0.7	10.7	-5.41
	2	0	3674.81	15.64	5	0.58	20.64	199	15	0.55	199.55	220.19
	3	0	3692.47	33.3	5	0.58	38.3	189	21	0.37	189.37	227.67
	4	0	3618.95	-40.22	5	0.58	-45.22	48	13	0.61	48.61	3.39
	5	0	3673.35	14.18	5	0.58	19.18	21	7	0.79	21.79	40.97
	6	0	3601.88	-57.29	3	0.75	-60.29	23	4	0.88	23.88	-36.42
	7	0	3630.8	-28.37	5	0.58	-33.37	185	15	0.55	185.55	152.18
	8	0	3758.32	99.15	4	0.67	103.15	65	14	0.58	65.58	168.73
	9	0	3811.92	152.75	4	0.67	156.75	129	17	0.49	129.49	286.24
	10	1	3929.03	269.86	6	0.5	275.86	62	19	0.43	62.43	338.29
7	1	0	5465.78	766.63	0	1	766.63	139	8	0.83	139.83	906.46
	2	1	4746.12	46.97	1	0.94	47.97	7	4	0.92	7.92	55.89
	3	1	4746.12	46.97	1	0.94	47.97	38	3	0.94	38.94	86.91
	4	1	5130.89	431.74	1	0.94	432.74	4	4	0.92	4.92	437.66
	5	1	5001.82	302.67	1	0.94	303.67	138	6	0.87	138.87	442.54
	6	1	4746.12	46.97	1	0.94	47.97	10	2	0.96	10.96	58.93
	7	1	4943.45	244.3	1	0.94	245.3	398	8	0.83	398.83	644.13
	8	1	4748.48	49.33	1	0.94	50.33	52	4	0.92	52.92	103.25
	9	1	4805.65	106.5	1	0.94	107.5	175	10	0.79	175.79	283.29
	10	1	5233.74	534.59	1	0.94	535.59	317	13	0.72	317.72	853.31
8	1	0	5198.47	533.61	6	0.57	539.61	212	17	0.57	212.57	752.18
	2	3	5183.75	518.89	6	0.57	524.89	312	20	0.49	312.49	837.38
	3	0	4934.9	270.04	6	0.57	276.04	620	19	0.52	620.52	896.56
	4	0	5008.84	343.98	6	0.57	349.98	811	20	0.49	811.49	1161.47
	5	0	5070.58	405.72	5	0.64	410.72	188	13	0.67	188.67	599.39
	6	1	5236.03	571.17	7	0.5	578.17	232	18	0.54	232.54	810.71
	7	1	5394.68	729.82	8	0.43	737.82	467	17	0.57	467.57	1205.39
	8	1	5149.71	484.85	7	0.5	491.85	960	15	0.62	960.62	1452.47
	9	1	5273.73	608.87	5	0.64	613.87	136	8	0.8	136.8	750.67
	10	2	5150.67	485.81	7	0.5	492.81	1132	20	0.49	1132.49	1625.3
9	1	0	4595.16	838.96	6	0.57	844.96	238	17	0.57	238.57	1083.53
	2	0	4662.28	906.08	8	0.43	914.08	492	23	0.42	492.42	1406.5
	3	0	4876.15	1119.95	9	0.36	1128.95	783	20	0.49	783.49	1912.44
	4	4	4498.48	742.28	7	0.5	749.28	750	23	0.42	750.42	1499.7
	5	1	4115.82	359.62	6	0.57	365.62	812	21	0.47	812.47	1178.09
	6	1	4180.01	423.81	8	0.43	431.81	1224	22	0.44	1224.44	1656.25
	7	2	4933.82	1177.62	9	0.36	1186.62	243	21	0.47	243.47	1430.09
	8	1	4496.18	739.98	9	0.36	748.98	581	21	0.47	581.47	1330.45

Table 4 (continued)

Exercise	N^o	C	$D(km)$	$\Delta(km)$	n	δ	G	θ	nf	φ	M	Z
	9	0	3614.76	-141.44	4	0.71	-145.44	47	8	0.8	47.8	-97.65
	10	2	4465.27	709.07	8	0.43	717.07	1457	24	0.39	1457.39	2174.46
10	1	0	3481.28	-27.44	2	0.78	-29.44	0	0	0.88	0.88	-28.57
	2	0	3564.45	55.73	4	0.64	59.73	25	7	0.7	25.7	85.43
	3	0	3490.67	-18.05	2	0.78	-20.05	22	4	0.77	22.77	2.72
	4	0	3511.77	3.05	2	0.78	5.05	63	14	0.52	63.52	68.57
	5	0	3563.66	54.94	3	0.71	57.94	81	8	0.67	81.67	139.61
	6	0	3614.76	106.04	4	0.64	110.04	47	8	0.67	47.67	157.71
	7	0	3535.09	26.37	2	0.78	28.37	31	8	0.67	31.67	60.04
	8	0	3556.22	47.5	4	0.64	51.5	16	5	0.75	16.75	68.25
	9	0	3647.23	138.51	5	0.57	143.51	15	12	0.57	15.57	159.08
	10	0	4014.56	505.84	5	0.57	510.84	65	14	0.52	65.52	576.36

Table 5 Summary of the results of the executions

(a) Best Solution X^*

Exercise	$C(X^*)$	$\Delta(X^*)$	n^*	$\theta(X^*)$	$G(X^*)$	nf^*	$M(X^*)$	$Z(X^*)$
1	0	47.01	2	49.01	1	1	1.97	50.98
2	0	32.71	2	34.71	1	1	1.97	36.68
3	0	166.45	7	173.45	26	12	26.59	200.04
4	0	243.69	6	249.69	46	9	46.71	296.39
5	0	-0.31	1	-1.31	0	0	0	-1.31
6	0	-57.29	3	23	-60.29	4	23.88	-36.41
7	0	766.63	0	139	766.63	8	139.83	906.45
8	0	405.72	5	188	410.72	13	188.67	599,387
9	0	-141.44	4	47	-145.44	8	47.79	-97.645
10	0	-27.44	2	0	-29.44	0	0.87	-28.59

(b) Average Solution X_m

Exercise	$C(X_m)$	$\Delta(X_m)$	n_m	$\theta(X_m)$	$G(X_m)$	nf_m	$M(X_m)$	$Z(X_m)$
1	0	223.53	4.2	227.73	17.2	7.2	17.98	245.71
2	0	43.65	2.8	46.45	14.4	6.1	15.21	61.66
3	0.4	366.94	6.2	373.14	287.8	13.1	288.39	661.54
4	0.4	348.17	5.9	354.07	267.3	16.2	267.78	621.85
5	0	39.38	2.2	40.98	73.8	4.5	74.66	115.44
6	0.10	44.89	4.8	93.1	45.89	13,5	93.69	139.58
7	0.90	257.67	0.9	127.8	258.57	6.2	128.66	387.23
8	0.90	495.276	6.3	507	501.57	16.7	507.57	1009.148
9	1.10	687.59	7.4	662.7	694.19	20	663.19	1357.38
10	0	89.25	3.3	36.5	91.75	8	37.17	128.916

4). This remains acceptable especially since the flight corresponding to FPL 4 must land at the next wpt (3rd wpt).

In Table 4, it is noted that in most of the tests performed, the "zero conflicts" result is achieved, particularly for Exercise 1, 2, 5 and 10 where all results indicate $C = 0$. For Exercise 6, 9 tests out of 10 resolved conflicts. We even observe an improvement in the solution for the other objectives (tests 1 and 6). For exercises 3 and 4, we achieved some results with $C = 1$ (1 conflict) and $C = 2$ (only one case for exercise 4). Exercises 8 and 9 give mixed results where we observe 4 tests having eliminated the conflicts, but much worse results as for test n° 4 of exercise 9 (4 conflicts). However, we note the obtaining of

Table 6 Detailed comparison between the initial solution and the best solution found from exercise 3

		Initial solution X_0			**Best solution X^***				
N°FPL	**Flight ID**	**wpt**	**ETO**	**FL**	**wpt**	**ETO**	**FL**	f	f^2
1	DAH6003	DABB	06:55:00	0	DABB	06:55:00	0	0	0
		JIL	07:07:53	260	CSO	07:04:03	250	1	1
		BJA	07:13:46	260	BJA	07:15:42	260	0	0
2	DAH1126	DABC	06:57:00	0	DABC	06:58:00	0	0	0
		KAMER	07:19:48	300	KAMER	07:20:48	300	0	0
3	DAH6017	DABC	07:00:00	0	DABC	07:03:00	0	0	0
		BJA	07:11:38	260	BJA	07:14:38	260	0	0
4	DAH6711	BJA	07:04:00	290	BJA	07:04:00	290	0	0
		JIL	07:09:52	290	CSO	07:15:38	260	3	9
		DABB	07:22:46	0	DABB	07:24:42	0	0	0
5	7TWRE	BABOR	07:02:00	170	BABOR	07:02:00	180	1	1
		TAJEN	07:12:09	130	TAJEN	07:12:09	140	1	1
		DABC	07:21:03	0	DABC	07:21:03	0	0	0
6	DAH6000	BJA	07:07:00	250	BJA	07:07:00	250	0	0
		JIL	07:12:52	250	CSO	07:18:38	250	0	0
		DABB	07:25:46	0	DABB	07:27:42	0	0	0
7	7TWIC	NADJI	06:52:00	300	NADJI	06:52:00	310	1	1
		DABC	07:05:06	0	DABC	07:05:06	0	0	0
8	DTH2106	NADJI	06:55:00	280	NADJI	06:55:00	280	0	0
		DABC	07:07:27	0	DABC	07:07:27	0	0	0
9	7TVPR	DABC	06:55:00	0	DABC	07:00:00	0	0	0
		BJA	07:05:57	320	BJA	07:10:57	320	0	0
10	DTH2105	BJA	07:02:00	250	BJA	07:02:00	250	0	0
		JIL	07:07:52	310	CSO	07:13:38	310	0	0
		ANB	07:20:46	350	ANB	07:22:42	340	1	1
		MORJA	06:55:00	370	MORJA	07:28:31	380	1	1
11	DLH573	TOLGA	07:07:53	360	TOLGA	06:58:00	350	1	1
		CSO	07:13:46	360	ANB	07:14:07	380	2	4
		CIRTA	06:57:00	360	CIRTA	07:30:47	370	1	1
12	THY5YN	MORJA	07:19:48	360	MORJA	07:02:00	380	2	4
		ANB	07:00:00	360	JIL	07:20:42	360	0	0
		PAGRE	07:11:38	360	PAGRE	07:30:25	370	1	1

a result with 0 conflicts and a shortening of the overall distance covered D (test n°9, exercise 9). We can explain this by the fact that these two exercises have the highest number of initial conflicts with a number higher than the norm applied in the control sector. The worst results concern exercise 7, the tests of which give a single result with 0 conflicts. This can be justified in view of the number of flights (the highest) combined with a significant number of initial conflicts. As regards to the assessment of the overall distance travelled D, the solution is acceptable and accepted by pilots when the delay due to the course change does not exceed five minutes of flight (around $40km$ for medium-sized aircraft). From this, the results indicate acceptable average values (Table 5-a). However, we note that for some results (tests: $n^0$7/exercise 1, n^0 5, 6, 7 and 9/exercise 3, $n^0$1, 3 and 6/exercise 4), G is above the acceptable threshold. For example, in the case of test $n^0$7 of exercise 1, $G = 660.46$, which is really $\Delta = 653.46$ spread over 12 flights. A simple division operation results in an average of 54.45 km more for each flight. We also note that these results are related to and increase with the number of initial conflicts. This can be explained by the fact that the more conflicts there are, the more it is necessary to move the planes between them and therefore, to move them away from their initial routes and thus lengthen the distance travelled (see Fig. 9).

On the other hand, a FPL with many FL changes is certainly feasible but inadvisable for the above-mentioned reasons (see Sect. 5.3.3). Based on this, and based on air traffic controllers' field experience, a FPL is suitable if it is limited to a few FL changes. There is no precise value because it also depends on the size of the change difference made each time. In order to evaluate our results, we consider that the solution is suitable if the value of M does not exceed 50, which corresponds to an average of 4 changes of FL/FPL. Of course, this value remains subjective and subject to discussion because it does not obey specific criteria.

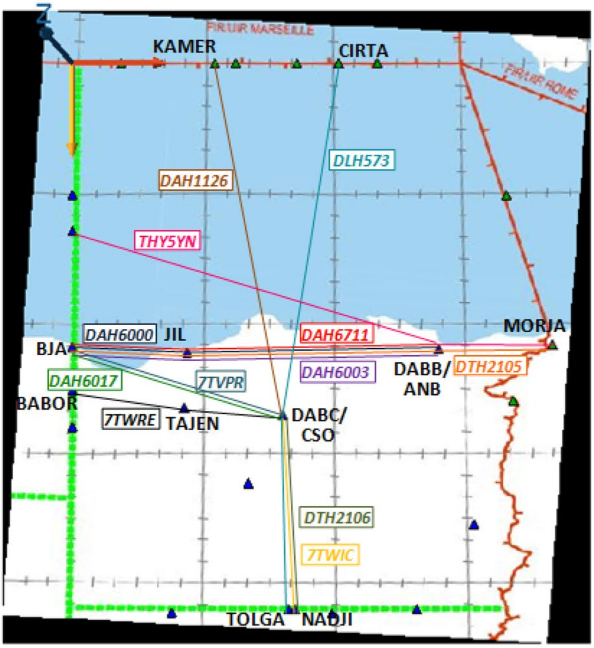
Consequently, we can deduce that the results obtained for exercises 1, 2, 5 and 10 are satisfactory for this criterion: 100% of the results are below the threshold set for exercise 1 and 70% for exercises 5 and 10 but only 20% for exercises 3 and 4. The results are even better than the initial configuration for the results of tests 1 and 7 of exercise 5 where G is negative ($G = -1.31$) so the distance traveled D is shorter and $M = 0$ (no change in FL).

In the end, we can say that the results of F are satisfactory for exercises 1, 2, 5 and 10 but remain limited for exercises 3, 4 and 6. On the other hand, they are less good for exercises 7, 8 and 9 . The number of flights certainly has something to do with the results since it broadens the search space. The number of initial conflicts also influences because it requires more changes at the level of wpts, FL or both at once. In the mutation section, we also talked about an ETD-altering mutation, the time an aircraft must depart from an aerodrome. Even if it is limited to departures, it makes it possible to eliminate certain conflicts without having to change the routes of the flights concerned by these conflicts.

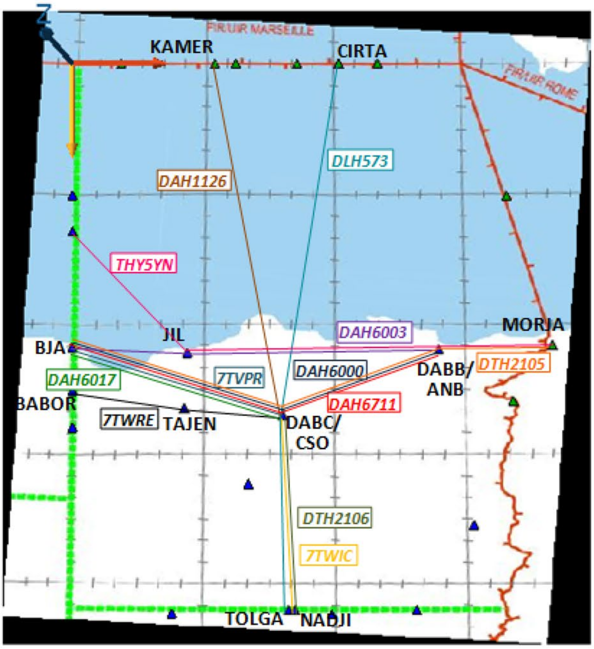
8 Conclusion and perspectives

The current challenge for air traffic control and safety agencies is to optimize ever-increasing air traffic while ensuring its safety and traffic flow. To achieve this, the controller must undergo qualifying training on a control area, which includes traffic management exercises. It must use certain rules, called separation rules on a set of FPLs representing aircraft routes, to propose a conflict-free solution. At the end of each exercise, this solution is checked and compared with that of the instructors. This is the context of the work

Fig. 9 Graphic representation solutions from exercise 3



(a) Initial solution



(b) Best solution

described in this article, where it is a matter of proposing a machine-generated solution to the instructor.

After a description of the problem and the associated geographic operations to solve it, we got down to modeling the problem using genetic algorithms, very suitable for GIS. As separation rules, we have limited ourselves to vertical and longitudinal separations and the objectives taken into account are first of all the elimination of conflicts between aircraft but also the reduction of the total distance traveled and the number of FL changes of the different aircraft.

In order to test our algorithm, we took a set of operational exercises dedicated to the actual training of air traffic controllers on the control sector of the North-East TMA of the Algiers FIR. The results obtained are globally satisfactory because in the majority of the cases, the conflicts are eliminated and the route changes (in distance or FL) remain acceptable. We even got better solutions than those initially announced. However, when the number of conflicts increases, the algorithm becomes less efficient. This is all the more remarkable when the number of flights exceeds the operational capacity of the control sector. In the future, it would be useful to continue the work with a simulation of the results, which we are currently working on. It would also be interesting to integrate the other separation rules (lateral, number of mach, etc.) and to take into account certain specificities of the control area such as status areas.

Declarations

Conflicts of interest The authors declare that they have no conflict of interest.

References

1. ICAO (2019) The world of air transport. https://www.icao.int/annual-report-2019/Pages/the-world-of-air-transport-in-2019.aspx. Accessed 27 May 2021
2. Adacher L, Flamini M, Romano E (2017) Rerouting algorithms solving the air traffic congestion. In: AIP Conference Proceedings, AIP Publishing LLC, vol 1836. p 020053
3. Rosenow J, Fricke H, Schultz M (2017) Air traffic simulation with 4d multi-criteria optimized trajectories. In: 2017 Winter Simulation Conference (WSC). IEEE, pp 2589–2600
4. Demetriou D, See L, Stillwell J (2014) Integrating GIS and genetic algorithms for automating land partitioning. In: Second International Conference on Remote Sensing and Geoinformation of the Environment (RSCy2014), International Society for Optics and Photonics, vol 9229. p 922908
5. Zhong ZW (2018) Overview of recent developments in modelling and simulations for analyses of airspace structures and traffic flows. Adv Mech Eng 10(2):1687814017753911
6. Guo H (2012) Application of genetic algorithms in the new air ttraffic management simulation system. Phys Procedia 33:604–611
7. Sun F, Han S, Yang Y, Qian G (2016) A multi-objective genetic algorithm based optimum schedule under variety capacity restriction. In: First International Conference on Micro and Nano Technologies, Modelling and Simulation. IEEE
8. Ikli S, Mancel C, Mongeau M, Olive X, Rachelson E (2019) An optimistic planning approach for the aircraft landing problem. In: Air Traffic Management and Systems IV: Selected Papers of the 6th ENRI International Workshop on ATM/CNS (EIWAC2019). Springer Nature, p 173
9. D'Ariano A, Pistelli M, Pacciarelli D (2012) Aircraft retiming and rerouting in vicinity of airports. IET Intel Transport Syst 6(4):433–443
10. Sama M, DÁriano A, Pacciarelli D, (2013) Rolling horizon approach for aircraft scheduling in the terminal control area of busy airports. Procedia Soc Behav Sci 80:531–552
11. Shijin W, Xi C, Haiyun L, Qingyun L, Xu H, Yanjun W (2017) Air route network optimization in fragmented airspace based on cellular automata. Chin J Aeronaut 30(3):1184–1195

12. Li J, Wang T, Savai M, Hwang I (2010) Graph-based algorithm for dynamic airspace configuration. J Guid Control Dyn 33(4):1082–1094
13. Lee LH, Lee CU, Tan YP (2007) A multi-objective genetic algorithm for robust flight scheduling using simulation. Eur J Oper Res 177(3):1948–1968
14. Tsai MW, Hong TP, Lin WT (2015) A two-dimensional genetic algorithm and its application to aircraft scheduling problem. Math Probl Eng 2015
15. Kölker K, Lütjens K (2015) Using genetic algorithms to solve large-scale airline network planning problems. Transp Res Proc 10:900–909
16. Dancila BD, Botez RM (2018) Vertical flight path segments sets for aircraft flight plan prediction and optimisation. Aeronaut J 122(1255):1371–1424
17. Gerdes I, Temme A, Schultz M (2020) From free-route air traffic to an adapted dynamic main-flow system. Transp Res Part C: Emerg Technol 115:102633
18. Choi S, Robinson JE, Mulfinger DG, Capozzi BJ (2010) Design of an optimal route structure using heuristics-based stochastic schedulers. In: 29th Digital Avionics Systems Conference. IEEE, pp 2–A
19. Jin C, Zhu Yb, Fang J, Li Yt (2012) An improved methodology for ARN crossing waypoints location problem. In: 2012 IEEE/AIAA 31st Digital Avionics Systems Conference (DASC). IEEE, pp 4A5–1
20. Wang SJ, Gong YH (2014) Research on air route network nodes optimization with avoiding the three areas. Saf Sci 66:9–18
21. Undertaking SJ (2018) Sesar investigates benefits of dynamic airspace configuration. https://www.sesarju.eu/news/sesar-investigates-benefits-dynamic-airspace-configuration. Accessed 27 May 2021
22. FAA (2003) Nextgen: The next generation air transportation system. https://www.faa.gov/nextgen. Accessed 10 March 2021
23. Sergeeva M, Delahaye D, Mancel C, Vidosavljevic A (2017) Dynamic airspace configuration by genetic algorithm. J Traffic Transp Eng (English Edition) 4(3):300–314
24. Morgenstern R (2008) Spectrum demand for air/ground air traffic management communications. In: 2008 Integrated Communications, Navigation and Surveillance Conference. IEEE, pp 1–6
25. Schilke C, Hecker P (2014) Dynamic route optimization based on adverse weather data. Fourth SESAR Innovation Days
26. Yoon Y, Hansen M, Ball MO (2012) Optimal route decision with a geometric ground-airborne hybrid model under weather uncertainty. Transp Res Part E: Logist Transp Rev 48(1):34–49
27. Patron RF, Kessaci A, Botez RM (2013) Flight trajectories optimization under the influence of winds using genetic algorithms. In: AIAA Guidance, Navigation, and Control (GNC) Conference. p 4620
28. Fanti MP, Mininel S, Nolich M, Stecco G, Ukovich W, Bernabo M, Serafino G (2014) Flight path optimization for minimizing emissions and avoiding weather hazard. In: 2014 American Control Conference. IEEE, pp 4567–4572
29. Chen XW, Landry SJ, Nof SY (2011) A framework of enroute air traffic conflict detection and resolution through complex network analysis. Comput Ind 62(8–9):787–794
30. Ruiz S, Piera MA, Del Pozo I (2013) A medium term conflict detection and resolution system for terminal maneuvering area based on spatial data structures and 4D trajectories. Transp Res Part C: Emerg Technol 26:396–417
31. Taylor C, Masek T, Bateman H (2013) Framework for high-density-area departure and arrival traffic management. J Guid Control Dyn 36(4):1134–1149
32. Lovato AV, Fontes CH, Embiruçu M, Kalid R (2018) A fuzzy modeling approach to optimize control and decision making in conflict management in air traffic control. Comput Ind Eng 115:167–189
33. Bongo MF, Alimpangog KMS, Loar JF, Montefalcon JA, Ocampo LA (2018) An application of DEMATEL-ANP and PROMETHEE II approach for air traffic controllers' workload stress problem: A case of Mactan civil aviation authority of the Philippines. J Air Transp Manag 68:198–213
34. Hu J, Prandini M, Sastry S (2002) Optimal coordinated maneuvers for three-dimensional aircraft conflict resolution. J Guid Control Dyn 25(5):888–900
35. Bertsimas D, Lulli G, Odoni A (2011) An integer optimization approach to large-scale air traffic flow management. Oper Res 59(1):211–227
36. Lieder A, Briskorn D, Stolletz R (2015) A dynamic programming approach for the aircraft landing problem with aircraft classes. Eur J Oper Res 243(1):61–69
37. Xu K, Yin H, Zhang L, Xu Y (2015) Game theory with probabilistic prediction for conflict resolution in air traffic management. In: 2015 10th International Conference on Intelligent Systems and Knowledge Engineering (ISKE). IEEE, pp 94–98
38. Durand N, Alliot JM (2009) Ant colony optimization for air traffic conflict resolution. In: ATM seminar

39. Shmelova T, Sikirda Y, Zemlyanskiy A, Danilenko O, Lazorenko V (2016) Artificial neural network for air traffic controller's pre-simulator training. Proceedings of the National Aviation University 3:13–23
40. Borhani M (2021) Evolutionary multi-objective network optimization algorithm in trajectory planning. Ain Shams Eng J 12(1):677–686
41. Borhani M, Akbari K, Matkan A, Tanasan M (2020) A multicriteria optimization for flight route networks in large-scale airlines using intelligent spatial information
42. Huang Z, Liu X, Huang C, Shen J (2010) A GIS-based framework for bus network optimization using genetic algorithm. Ann GIS 16(3):185–194
43. Updegrove JA, Jafer S (2017) Optimization of air traffic control training at the federal aviation administration academy. Aerospace 4(4):50
44. SIA-ENNA (2020) Navigation chart DAAA. https://sia-enna.dz/PDF/AIP/AD/AD2/Croisiere.pdf. Accessed 05 May 2021
45. ICAO (2016) Doc 4444 : PANS-ATM (Procedures for Air Navigation Services-Air Traffic Management), 16th edn. The International Civil Aviation Organization
46. UMMISCO (2021) Gama platform. https://gama-platform.github.io. Accessed 10 May 2021
47. Amara R (2022) Optiawy, Mendeley data, v3. https://doi.org/10.17632/vsdfjy84zs.3. https://data.mendeley.com/datasets/vsdfjy84zs.3. Accessed 10 May 2021

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