# A COMPARATIVE STUDY FOR MERGING AND SEQUENCING FLOWS IN TMA

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## RESUMEN

***Se ha previsto diversos escenarios para explorar el futuro Sistema de Transporte Aéreo. De acuerdo con EUROCONTROL, el escenario más probable de los movimientos de vuelo IFR en Europa hasta 2035, prevé 14,4 millones de vuelos, lo cual es 50% más que en 2012. [10] El aumento en el tráfico aéreo se está traduciendo en diversos problemas tanto en el lado aire como en tierra. En el lado aire, se hace más evidente en el espacio aéreo circundante a los aeropuertos, donde las llegadas y salidas sirven a un gran número de aviones que están sometidos a diversos problemas logísticos que continuamente hay que resolver para asegurarse de que cada vuelo y pasajero viaje con seguridad y eficiencia hasta su destino final. La presente investigación propone una metodología basada en algoritmos evolutivos para resolver el problema de fusión y secuenciación de un conjunto de aeronaves. Para dicho fin, se realiza un análisis del diseño de la topología de las rutas de aterrizaje. Este enfoque propone para cada aeronave una nueva ruta y perfil de velocidad con el fin de evitar posibles conflictos en los puntos de fusión, mientras que se mantienen las normas de separación de la OACI. La función objetivo se basa en adquirir la desviación mínima de cada aeronave con respecto a su plan de vuelo original. El algoritmo se ha aplicado con éxito en el aeropuerto de Gran Canaria en España con muestras de la demanda de tráfico reales para lo que se ha encontrado una configuración óptima para la alimentación óptima pista.***

***The imminent growing in the Air transport System has forecast diverse scenarios to explore the future of the aviation. According to EUROCONTROL forecast of IFR flight movements in Europe up to 2035, the most likely scenario predicts 14.4 million flights, which is 50% more than in 2012. [10] This increase in the air traffic is translating into diverse problems in the airside and landside. In the airside, it becomes more evident in the airspace surrounding airports, where the arrivals and departures serve a large number of aircraft which are subjected to many logistical problems that must continuously be solved to make sure each flight and passenger travels safely and efficiently. The present research proposes a methodology based on evolutionary algorithms to tackle the merging and sequencing problem of a set of aircraft by analyzing the topology design of the landing routes. It is proposed to merge the arrivals from different routes by changing the topology design of the STARs (Standard Terminal Arrival Route). The approach proposes to each aircraft a new route and speed profile in order to avoid potential conflicts at merging points while maintaining ICAO separation standards. The objective function is based on achieving the minimum deviation of each aircraft from it original flight plan. This algorithm has been successfully applied to Gran Canaria airport in Spain with real traffic demand samples for which conflict free flow merging is produced smoothly with optimal runway feeding.***

**Palabras clave:** TMA, Optimization, Algoritmos Evolutivos, Merging and sequencing.

## INTRODUCTION

The imminent growing in the Air transport System has forecast diverse scenarios to explore the future of the Air Transportation System. According to EUROCONTROL forecast of IFR flight movements in Europe up to 2035, the most likely scenario predicts 14.4 million flights, which is 50% more than in 2012. [10] This increase in the air traffic is translating into diverse problems in the airside and landside. In the airside, it becomes more evident in the airspace surrounding airports, where the arrivals and departures serve a large number of aircraft which are subjected to many logistical problems that must continuously be solved to make sure each flight and passenger travels safely and efficiently.

For the sustainability of the Air Transportation System not only in Europe but all over the world, it has been proposed diverse ideas to alleviate airspace congestion such as the minimum spacing requirements, revisit separation requirements, improved sequencing of landings and takeoffs, and the construction of additional runways, among others. Even though, more fundamental changes are needed to improve the use of available air capacity in terminal area. However, more fundamental & innovative changes are required to improve the use of available air capacity. To deal with this future situation, different ATM modernization projects have been started. The Single European Sky ATM Research (SESAR) launched by the European Community and the Next Generation Air Transportation System (NextGen) launched by US government are future projects aim to ensure the safety and fluidity of air transport over the next thirty years.

In this work, the Terminal Maneuvering Area (TMA) is considered as the block of airspace above the airport designed to handle aircraft arriving and departing and perhaps one of the most complex types of airspace, as shown in Figure 1. Its complexity is enforced by different factors such as very dense traffic, frequent large turns, incompletely specified flight plan, complex set of separation standards, incomplete or undefined Arrival and Departure routes, or lack of navigation systems for guidance, among others. Hence, major benefits can be expected if areas with a high traffic density like the TMA are analyzed to assess the performance of new ATM concepts, like 4D-trajectory planning and strategic de-confliction allowing ATC efficient procedures to merge and sequence aircraft. Therefore, innovative concepts of an advance Terminal Airspace Area and Operations has been introduced as part of the previously modernization projects. The main idea is to transformed arrivals with a random pattern into an ordered optimized sequence.

An aircraft approaching typically follows a Standard Terminal Arrival (STAR) providing the transition from the En-Route structure to Terminal Airspace. Aircraft are differentiated by their categories, velocities, incoming points and separations need. To optimized arrivals in a given runway, the individual paths of each aircraft have to be gradually merged until the active landing runway. Aircraft are required to maintain pre-specified separation distance.

One of the prevalent initiatives all over the world is to introduce more Area Navigation (RNAV), RNP Standard Terminal Arrival (STAR) and Standard Instrument Departure (SID) procedures in the Terminal Airspace, and to introduce RNAV and/or RNP routes into the en-Route airspace.. SIDs and STARs are both very similar in many aspects e.g. offering the pilot pre-planned Instrumental Flight Rule (IFR) procedures. STARs are designed to expedite ATC arrival procedure and facilitate the transition between en-route and instrument approach segment as well as to streamline approach flows and to give a more regular approach to an airport. RNAV procedures refer to the ability to execute point to point navigation. These procedures allow flying an optimized path without the need to fly directly toward or away from a ground-based navigation aid (NAVAID) because the utilization of a mix of instruments such as the global positioning satellite system (GPS). Other benefits of this approach is the ability to facilitate closely-spaced parallel arrivals and departures in the terminal, and allow a redesign of en-Route airspace with an increased number of closer routes, essentially establishing additional routes to optimize these procedures. [11]

It has been said, that some of the key factors to obtaining these advantages (particularly in TMA) is the need for arrival and departure routes (STARs/IFPs and SIDs) to be designed as a function of the interaction between them as well as servicing the traffic's desired track and ensuring obstacle clearance; but also an efficient design of route topologies in the Terminal Airspace could affects some performance metrics such as runway delays, throughput, fuel efficiency, and robustness to uncertainties in operations. [10] ,[11]

Diverse potential benefits can be pointed out with the introduction of RNAV arrival and departure procedures, such as: reduce the need to vector aircraft; fewer radio transmissions due to less need for Controller instructions; reduce flying time and distance, i.e. more direct routing; increased airspace/runway capacity through the use of defined paths.

This work addresses the sequencing and merging problems for arrivals in TMA using an Evolutionary approach. An stochastic optimization algorithm has been developed in order to remove conflicts at merging points and to maintain the minimum separation between aircraft following the same route link according to their wake turbulence constraint. The optimization criteria are based on the minimum deviation from the initial path planning while solving all conflicts. As a result, it is proposed to each aircraft a new route and speed profile. Different topologies have been compared to analyze the potential benefits of these configurations to merge multiple arrivals. The algorithm has been successfully applied to Gran Canaria airport (Spain) with real traffic demand samples for which conflict free flow merging is produced smoothly with optimal runway feeding. The model has being prepared to be applied to Queretaro airport (Mexico). Therefore, a search of the literature was conducted to identify the main aspects related to both, the airspace design and the merging and sequencing problem.

Numerous modeling approaches (both exact and heuristic algorithms) have been proposed to deal with the merging and sequencing problem but recently the approximate algorithms gained importance in the literature due to the fact that for large instances it may take a long time to obtain optimal solutions. The Aircraft Sequencing Problem (ASP) aims to optimize the assignment of aircraft to runways while optimizing the sequence of aircraft departures and arrivals on each runway. It has been of interest for the research community since the late 70s as in [3] where it was first observed that FIFO policy was inefficient for a medium and long term strategies. It was introduced a decision methodology called Constrained Position Shifting (CPS).

Following these ideas, Dear et al. [3] and [8] presented a CPS heuristic for the static and dynamic case of the Aircraft Landing Problem (ALP). The ALP is aim to decide a landing time for each aircraft such that each one lands within predetermined time window and that separation standards are respected. Different approaches for the ALP have been studied, some implement the CPS method and some others develop their own heuristics. For example, a Dynamic-Programming-based approach which used a method called Constrained Position Shifting (CPS) as in [1] and [4] and [2] is a class of algorithms that is able to handle commonly-encountered operational constraints for the sequence problem. In [3] based on Linear Programming which solves the static case presenting a mixed-integer zero-one formulation of the problem together with a population heuristic algorithm.

Other approaches such as the method called "Point Merge technique" [5] and [11] aims to merge arrival flows of aircraft without using heading instructions. Its principle is to achieve the aircraft sequence on a point with conventional direct-to instructions, using predefined legs at iso-distance to this point for path shortening or stretching.

The authors have previously addressed these two most common approaches; in [16] the CPS has been used to merge and sequence aircraft with a causal modeling approach; in [17] a topology structure similar to the Point merge has been proposed to deal with the CD&CR in en-Route and TMA using also a causal approach; and in [18] an optimization algorithm has been developed to merge and sequence aircraft in TMA.

The reminder of this works presents in next Section introduces the modeling approach to formulate the problem; the topologies to be analyzed and the mathematical model and a summary of the Evolutionary Algorithms (EAs) techniques. The results obtained from a sample simulation study are presented in Section V. Finally, conclusions and future works are discussed at the end of the paper.

## METODOLOGY

As state in [6] and [7], scheduling landing aircraft aims to determine the landing times & sequence of arrivals associated with a particular runway with the final general objective of increasing the throughput of the runway system while satisfying diverse operational and safety constraints of the system. Furthermore, different objectives can be pointed out such as flight efficiency, environmental mitigation, safety & operational aspects which at the begging tend to be in conflict but are not mutually exclusive. It is actually possible to design terminal routes and achieve most of the (apparently conflicting) objectives.

The common approach for sequencing aircraft has been to maintain the First-Come-First-Served (FCFS) order. Even though the determination of assignment times for a given set of aircraft is a static problem. The arrival of a new aircraft into the system requires to revise the cut-tent schedule which by its nature it is a dynamic problem. However, as the objective of this work is to compare the topology efficiency, the determination of landing times for a given set of aircraft is considered as a static problem.

The main objective of this approach is to find conflict free trajectories for a given set of aircraft landing at the same runway by changing either their routes, their speeds or both. This approach is primarily use to schedule arrivals at a runway, but the modeling approach described can also be utilized for departure runway scheduling.

The mathematical formulation has been previously presented in [18] and requires the following parameters:

$f_i$ : the flight planned to land in a given time horizon $[0, T_{max}]$, $f_i = \{1, \dots, n\}$ ,
$e_i$ : the entry point of flight $f_i$ in the TMA $i \in f_i$ ,
$t_i$ : the time of flight $f_i$ at entry point $i \in f_i$ ,
$v_i$ : the speed of aircraft $(f_i)$ $i \in f_i$ ,
$r_j$ : the original route of aircraft $(f_i)$ $i \in f_i$ ,
$wt_i$ : the wake turbulence category (heavy, medium, light)
$mss_{ik}$: the required minimum safe separation between aircraft $i$ and $k$ if $i$ lands before $k$, $mss_{ij} \geq 0 \forall\ i, k \in f_i$ due to their wake vortex constraint.
$d(f_i, f_j)$ : the distance separating aircraft $i$ and $k$ if $i$ lands before $k$ .

The TMA has been modeled by a graph:

$$G = \{N, A\}$$

Where:
$N$ ; represent the set of nodes and,

$A$ : represent the set of links.

A *route* is conformed from diverse numbers of links which join an entry point to runway. Meanwhile a *link* is defined as a portion of a route which connects two waypoints (or *nodes*). For each route $r_j$ , it is defined a set of *alternative routes*, noted as *alt(li)*. These alternative routes are noted as:

$$Alt(r_j) = \prod_{k=1}^{k=L(r_j)}$$

Where:
$L(r_j)$ : is the number of links of route $r_j$ having alternatives choices.

The modeling approach considers two kinds of conflicts: Node conflict and Link conflict. A *Link conflict* is predicted if aircraft flying on the same link have lost the minimum safe separation ($mss_{ik}$) between aircraft $i$ and $k$ depending on the aircraft's wake turbulence category, i.e. $mss_{ij} \geq d(f_i , f_j) \ \forall \ t \in [0,T] \ \ d(f_i , f_j)$ , if $i$ lands before $k$, $mss_{ij} \geq d(f_i , f_j) \ \forall \ i , k \in f_i$ ). A *Node conflict* is predicted when an aircraft $f_i$ is flying over a node $n_k$, other aircraft have to be 5NM away from the node. The optimization process is subject to speed constraint $mss_{ij} \ \forall \ f_i \in F \ v_i \in [v_{imin} , v_{imax}]$

Regarding the safety constraints, all aircraft should be scheduled in such a way that a minimum safe separation (*mss*) is always maintained. In this work, the International Civil Aviation Organization (ICAO) separation standards are adopted in a distance-based function, ICAO Doc 4444 (Procedures for Air Traffic Management).

## USING EVOLUTIONARY ALGORITHMS TO MODEL THE PROBLEM

Evolutionary algorithms (EAs) inspired by both natural selection and natural genetics. It.is an abstraction of evolutionary biology which focuses in problem solving systems based on principles of evolution and hereditary to find approximate solutions to optimization problems. [12], [13], [14]

The EAs maintain a population of individuals called $POP(k) = \{x_1,...x_n\}$ for each iteration $k$. An individual represents a potential solution to the problem to be solved and is represented by a list of parameters, called chromosome or genome. EAs are initialized with a population of guesses, these are usually random and will be spread throughout the search space. The choice of the population size must be always of a trade-off between efficiency and effectiveness. A typical algorithm then uses three operators, selection, crossover and mutation to direct the population (over a series of time steps or generations $k$ towards convergence at the global optimum. This initial population is then processed by the three main operators.

Selection attempts to apply a *fitness function* where poorer performing individuals are weeded out and better fitter, individuals have a greater than average chance of promoting the information they contain within the next generation. In addition, some individual of the new population undergo transformations by means of three main "genetic operators" to form new solutions: nothing, crossover, and mutation. The recombination of individual is carried out using simple analogies of genetic "crossover" and "mutation".

Crossover results in two new child chromosomes, which are added to the next generation population. The chromosomes of the parents are mixed during crossover. These processes ultimately result in the next generation population of chromosomes $POP(k+1)$ that is different from the initial generation. This generational process is repeated until a termination condition has been reached. Mutation is used to modify (flip) an individual to form another. The value of chromosomes within individual strings are then 'randomly' change.

As for each aircraft, it has to be found an optimal route and speed regulations, the coding is gather together the decisions variables: route and speed, for all the aircraft involved in the same time window. The chromosome consists in two parts: the first part is link to the speed changes and the second one describes the alternatives route for a given aircraft. Depending of the entry point, aircraft may have different number of alternative. In order to memorize the performances of a given decision, it is gather the number of conflicts a given aircraft has encountered on his route. This information will be used by the recombination operators in order to focus on aircraft involved in conflict.

For each gene $i$ (representing the aircraft), the summation of conflict number in both parents ($P1, P2$) is computed as:

$$S = ni(P1)+ni(P2)$$

The probability $P_C$ to transfer the decision variable of gene $i$ in both children is computed by the following expression:

$$P_c = 1-ni(P1)/S$$

The total number of conflict is computed as follows:

$$N_{conf} = \sum_{i=1}^{i=N} n_i$$

The cumulative following summation is computed by:

$$S(k) = \sum_{i=1}^{i=k} \frac{n_i}{N_{conf}}$$

The mutation may change the speed of an aircraft, its route or both depending of the configuration of the GA.

The fitness function is composed by two objectives: first to minimize conflicts and secondly, to minimize the speed changes and extra distance introduce:

$$fitness = \frac{1}{0.01+y_1} + \frac{1}{0.01+y_2}$$

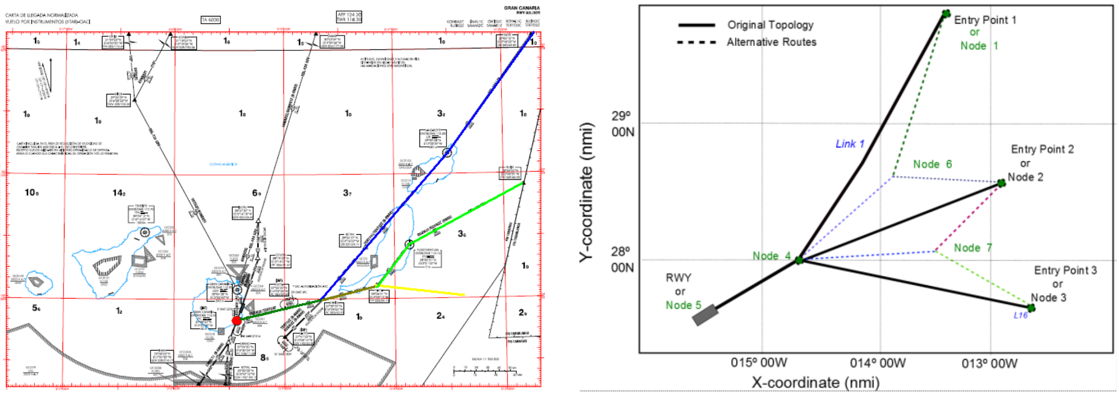
Where:

$y1$ : corresponds to the minimization of both types of conflict; node and link conflict, and,

$y2$ : corresponds to the minimization of the speed changes and extra distance introduce.

## RESULTS

In a previous work of the authors [18], the model has been validated using Gran Canaria TMA, see Figure 1. Two scenarios have been investigated with 35 and 50 aircraft respectively on the same time period (1 hour). The results have proved to find optimal solutions to both scenarios. In this work, a new synthetic STAR has been proposed. Figure 1c depicts this STAR.

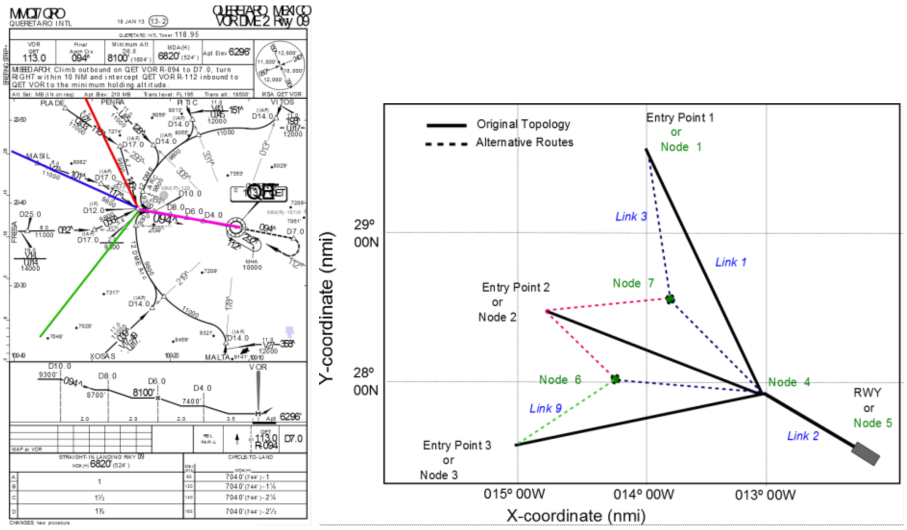


a) b)

**Figura 1.** a) Gran Canaria STAR. b) Synthetic Gran Canaria STAR

For comparative purposes, the model has been adapted to Queretaro TMA. Figure 2 presents the both, the STAR of Queretaro TMA (Mexico) and a synthetic STAR to test the benefits of the proposed topology. In current operations of the arrival phase, six routes fuse into one single route towards the final approach (runway 09L/27R) by merging in only one waypoint. Figure 2 a) depicts this topology design by the Mexican Aeronautical authorities. Meanwhile, in the synthetic STAR (Figure 2 b), three routes were defined which correspond to current entry points (as defined by the Mexican Aeronautical authorities) but routes have been change. The waypoints sequence for each of the three STARs is as follows:

- SLP - D12 (Before entering by PITIC)
- BJX - D12 (Before entering by MASIL)
- MLM - D12 (Before entering by XOSAS)



a) b)

**Figura 2.** a) Queretaro STAR. b) Synthetic Queretaro STAR

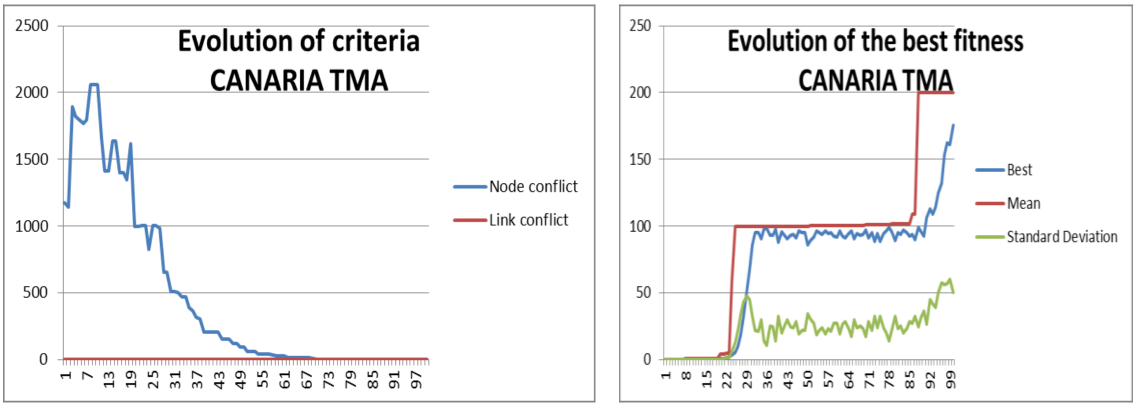
As previously said, these approach has been designed to solve potential conflicts which have been detected between TMA entry point till the initial approach fix point (MASIL waypoint) by amending the speed, the trajectory or both in such a way that the conflict is resolved and no new or secondary conflicts are produced, and the aircraft accomplish its original required arrival time.

Diverse scenarios have been tested with different parameters. This paper presents the most representative ones as preliminary results for the research. More tests should be done, using different topologies to exploit the benefits of the algorithm.

The GA parameters used for the first scenario are the following:

**Tabla 1.** GA parameters for testing scenarios**.**

| | 37 aircraft scenario |
|---|---|
| Number of generation | 100 |
| Pop size | 100 |
| Probability of Crossover | 0,3 |
| Probability of Mutation | 0,3 |



**a)** **b)**

**Figura 3.** a) Evolution of the fitness for Gran Canaria, Spain TMA. b) Evolution of the best fitness (Gran Canaria TMA); average fitness and standard deviation of the best individual with generations

Figures 3a) & 4a) represent the evolution of the fitness features with generation for a 37 aircraft scenario for Gran Canaria, Spain TMA & Queretaro, Mexico TMA, respectively. The evolution of the fitness features is summarized for which the fitness of the best individual, the average fitness on population and the standard deviation are plot with generations.

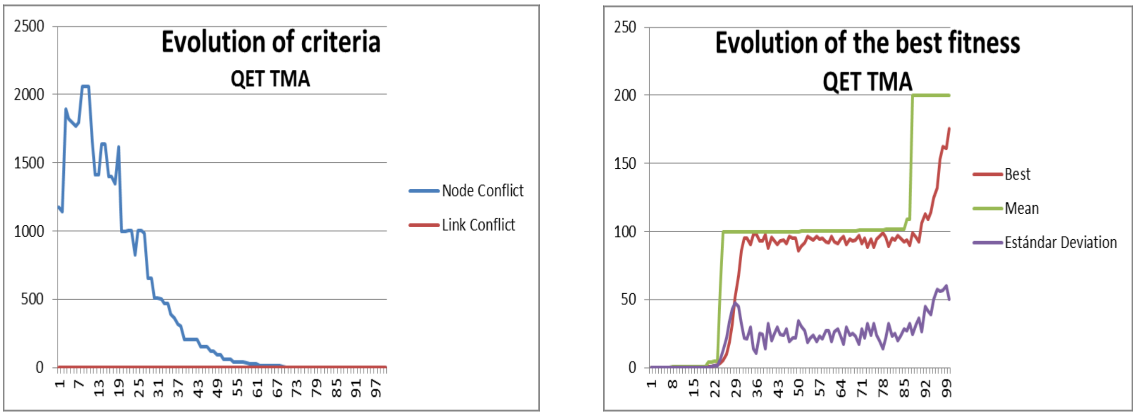


**Figura 3.** a) Evolution of the fitness for Queretaro, Mexico TMA. b) Evolution of the best fitness (for Queretaro, Mexico TMA); average fitness and standard deviation of the best individual with generations

**Tabla 2.** Summary of converging values**.**

| | Link conflict | Node conflict |
|---|---|---|
| Gran Canaria, Spain TMA | 11 | 81 |
| Queretaro, Mexico TMA | 25 | 88 |

Table 2 summarizes the information of the Evolution Algorithm, it can be notice that after 81 generations the algorithm finds an optimal solution (y1 =y2 =0, objective function=200) for Gran Canaria, Spain TMA meanwhile it took 85 generations to find an optimal solution for Queretaro, Mexico TMA. But in both scenarios, it is much harder to remove node conflict than link conflict. This could be due to the size of extended TMA that has been used. In the case of Gran Canaria, the distance from entry point to IAF is almos almost 1/2 of the size of Queretaro TMA (approximately 75 km for the second one).

These preliminary results should be validated in a more extensive manner; first of all, a more similar but complex synthetic TMA have to be design in both scenarios. Secondly, more loaded scenario should be tested, and finally a more extensive comparative analysis should be done using not only one but several topologies.

## CONCLUSIONES

The present research proposes a comparative methodology for merging and sequencing aircraft in TMA. Two different TMAs have been proposed to be compared Gran Canaria, Spain & Queretaro, Mexico. For both scenarios, two synthetic STARs have been design and validation test were conducting using the same load (37 aircraft in 1 hour time window). For each aircraft a new route and speed may be selected to avoid potential conflicts. The mathematical model presented by the authors in [18] has been adapted for such. Stochastic optimization is the most adapted approach to address such problem due to the complexity analysis previously conducted. An Evolutionary Algorithm has been applied with real traffic demand samples. In both situations, all conflicts have been successfully removed on links and at merging points.

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