MECHANICAL ENGINEERING | RESEARCH ARTICLE

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Abstract: Flight route planning in civil aviation seeks to minimize the total cost of the operation while maintaining high safety standards. Therefore, the increase in the number of air routes as well as air traffic in commercial aviation poses new challenges for planning optimal routes. This work proposes a method to plan routes using a bio-inspired technique called Particle Swarm Optimization (PSO). Such method aims to obtain the shortest distance between two points, thus reducing NO_X, CO_2 and H_2O emissions. The analysis of fuel consumption and emissions was carried out using a multidisciplinary simulation tool, the Preliminary Multidisciplinary Design Framework (PMDF). The latter was applied to an aircraft

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PUBLIC INTEREST STATEMENT

Aircraft are thought to contribute about 3.5% to the climate change. Despite regular improvements in fuel efficiency, emissions will carry on increasing and several solutions need to be identified. This work proposes a method to plan routes using a bio-inspired technique called Particle Swarm Optimization (PSO). Such method aims to obtain the shortest distance between two flight points, thus reducing NO_X, CO_2 and H_2O emissions. The planner provides a new route with the shortest possible flight distance and, at the same time, it considers unexpected obstacles on the route, thus minimizing fuel consumption and possible polluting emissions into the atmosphere. The use of this type of route optimizer leads to significant benefits with respect to aircraft environmental impact.

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with a conventional configuration powered by an innovative turbofan engine. The planner provides a new route with the shortest possible flight distance and, at the same time, considers unexpected obstacles on the route, thus minimizing fuel consumption and possible polluting emissions into the atmosphere. This is one of a series of works that will use the proposed design tool. Different economic and environmental scenarios will be evaluated once such studies are concluded.

Subjects: Aerospace Engineering; Mechanical Engineering; Power & Energy; Technology; Transport & Vehicle Engineering

Keywords: aircraft emissions; Sustainable Development Goals; trajectory planning; multi-objective optimization; optimal trajectory

1. Introduction

The International Civil Aviation Organization (ICAO) is in charge of promoting civil aviation standards and regulations (International Civil Aviation Organization, 2006). Said standards and regulations are adopted by government agencies responsible for setting out the local regulations and establish the airways that have protected areas that allow aircraft to safely fly in the trajectory and at cruising speed.

The Civil Aviation Authority of Colombia is the governmental body responsible for adopting the recommendations of the ICAO. Besides, it establishes the air routes and the necessary standards for instrument-assisted air navigation and Visual Flight Rules (VFR) (Aeronáutica Civil Colombiana, 2015). The route is the set of geographic coordinates an aircraft must follow to go from a start point to a destination. Route planning is completed prior to the flight to optimize fuel consumption and reduce the aircraft's operating cost (Aeronautica Civil Colombiana, 2014a, 2014b).

Efforts to improve the performance of commercial aircraft and reduce pollution levels have been made in aircraft design (Carlos, Quintero, & Carlo, 2009) (Berton & Guynn, 2012) and flight route planning systems. In that sense, most commercial airplanes have advanced navigation systems to plan their route. They are called Flight Management Systems (FMS) and are based on performance to enable the aircraft to fly between two geographic coordinates that depend on a flight plan. FMS are bound to a fixed flight plan. As a result, unexpected events in the flight route—such as conflicts with other aircraft or weather changes—cause altitude or direction variations that had not been previously considered and, consequently, are not shown in the trajectories. Recently, experiments have been conducted with FMS platforms in simulated environments and different flight conditions have been presented to the route planner; this enabled to analyze the results of different configurations (Paglione, Musialek, Pankok, & Young, 2011).

Besides, other works aimed to generate new techniques and simulation algorithms that allow to evaluate the behavior of the aircraft by creating a flight profile at cruising altitude. The efforts revolve around planning the flight route in order to minimize operating costs and reduce the pollution resulting from the operation of the aircraft. Other authors (Colmenares Quintero et al., 2010) used the tool named Preliminary Multidisciplinary Design Framework (PMDF) to obtain the 2D optimized flight profile of an aircraft that moves between two points (Jardin, 2003).

The techniques of optimization in the route planning allow obtaining the best route. For example, the particle swarm optimization (PSO) explore space of solutions using stochastic evolutionary in function of social behavior. There are several works that deal with the subject route planning using PSO algorithm. Goez (2018) using a method for route planning based in PSO algorithm with the final purpose that a UAV evasion of obstacles in real time.

In this work, we propose a method to plan the route in real time in case of unexpected obstacles in the trajectory (such as a storm) based on Particle Swarm Optimization and the method proposed by (Colmenares-Quintero & Góez-Sánchez, 2018). The algorithm uses a conventional flight profile previously obtained with the PMDF tool as a reference. The route planning algorithm compares such profile with the results of the optimized route.

This document is divided into sections. Section 2 presents the proposed method for route planning and the optimization algorithm that was used. Section 3 describes the methodology and the simulations that were conducted. Finally, Section 4 lists the results and Section 5 presents the final conclusions and guidelines for future work.

2. Route planning

2.1. Route planning algorithm
The method to plan the route is based on the evaluation of every possible trajectory generated by the individuals. The optimization algorithm PSO, evaluated possible solutions, such evaluations enable to obtain the coordinate of the best point found by the population, where the new obtained coordinate $x*$ serves as a direction vector and it is used as a base to determine the new coordinate forward as a function of cruising speed, taken from (Colmenares-Quintero & Góez-Sánchez, 2018; Góez, Velásquez, & Botero, 2016). The set of all the coordinates that are found is stored in a matrix **P**, where the i-th row corresponds to the i-th execution of the algorithm (1).

$$\rho^{(i)} = \rho^{(i-1)} + v_{cr} * t^{(i)} * \frac{(x* - \rho^{(i-1)})}{\|x* - \rho^{(i-1)}\|} \tag{1}$$

where $\rho^{(i)}$ is the coordinate calculated at iteration I, $t^{(i)}$ the time in seconds the optimization algorithm takes to provide a new coordinate of iteration I and v_{cr} the aircraft cruising speed (of the aircraft).

The following is a list of the parameters that constitute the input of the system:

- Database that corresponds to the matrix of altitudes of each coordinated point, H.
- Target coordinates in latitude and longitude ρ_s.
- Start coordinate in latitude and longitude ρ_s, updatable at each new coordinate provided by the route optimization algorithm.
- Turn speed = rate of turn θ_t given in degrees/second.

The search space is given by the simulated radar range (δ), where the particles are initially dispersed in the search space with a normal distribution as a function of the sight range. The search space is therefore expressed in (2):

$$x_j = \alpha_1 \delta + \rho_s \tag{2}$$

Where x_j is the j-th particle of the initial population, $\alpha_1 \approx (0,1)$ a random variable retrieved from a Gaussian distribution with a zero median and variance of one and $\rho_s = \rho^{(i)}$, the initial position that serves as a reference to center the search space.

2.2. Cost function
In this case, the cost function is a minimization function expressed as follows:

2.2.1. Distance cost
Distance cost C_{dist} in (3) indicates how close the particle is to the target coordinate, thus enabling to evaluate and select the particles closer to the destination. Their degree of importance w_1 in the cost function equals 1.

$$C_{dist} = \frac{(\vec{u}_1 - \vec{u}_2) - \vec{u}_2}{\vec{u}_3} \tag{3}$$

Where

$$\vec{u}_1 = \left\| \rho^{(i)} - x_j \right\| \tag{4}$$

$$\vec{u}_2 = \left\| x_j - \rho_s \right\| \tag{5}$$

$$\vec{u}_3 = \left\| \rho^{(i)} - \rho_s \right\| \tag{6}$$

And ρ_s indicates reference coordinate.

2.2.2. Distance cost

This component enables to select the particle that provides smooth direction changes that do not exceed the airplane's rate of turn per second. The turning radius cost is expressed as follows:

$$c_\theta = \theta_t \tag{7}$$

The angle θ_t in (8) corresponds to the aircraft's turning radius, where the turning radius used for the reference points in the flight is based on the *roll* (θ) at the actual TAS speed given in km/h (ICAO, 2009).

$$\theta_t = \frac{6355 * \tan(\theta)}{\pi * v_{cr}} \tag{8}$$

The weight w_2 of C_Θ in the cost function depends on θ_μ, where $w_2 = \begin{cases} 0.1 * \theta_t \, si \theta_\mu \geq \theta_t \\ 0.00001 * \theta_t \, si \theta_\mu < \theta_t \end{cases}$, where

θ_μ in (9) is the angle resulting from the magnitude of the vector defined by the start coordinate $\rho^{(i)}$, the coordinate the airplane is following at moment i indicated by the direction vector $\mu^{(i-1)}$, and coordinate x_j, proposed by the particle at the i-th execution of the optimization algorithm (Góez et al., 2016; Colmenares-Quintero & Góez-Sánchez, 2018).

$$\theta_\mu = ar\cos . \frac{(x_j - \rho^{(i-1)})(x^* - \rho^{(i-1)})}{\left\| x_j - \rho^{(i-1)} \right\| \left\| x^* - \rho^{(i-1)} \right\|} \tag{9}$$

Where $\mu^{(i)} = \frac{(x^* - \rho^{(i-1)})}{\left\| x^* - \rho^{(i-1)} \right\|}$

2.2.3. Cost of obstacles on the route

Cost $\bar{\omega}$ is the evaluation of the unexpected obstacles on the flight route associated with atmospheric phenomena or other aircraft moving on the same route or presenting danger of collision. This component evaluates the particles above the minimum flight altitude over the mountains that present some type of obstacle in their vision horizon and a significance degree w_2 of 1. The cost resulting from unexpected obstacles is then expressed as follows (10) (Colmenares-Quintero & Góez-Sánchez, 2018):

$$c_\varpi = \begin{cases} 0 \rightarrow si \rightarrow R_g > R_{min} \\ \infty \rightarrow si \rightarrow R_g \leq R_{min} \end{cases} \tag{10}$$

where R_g is the distance between the aircraft and the possible obstacle and R_{min}, the safety distance that must be respected between the aircraft and the possible obstacle so that the flight is safe.

The total course cost c_{course} in (11) is expressed as follows:

$$c_{course} = \begin{cases} w_1 c_{dist} + w_2 \varpi + w_3 c_\theta \rightarrow si \rightarrow h_{min} \leq h \leq h_{max} \\ \infty \rightarrow si \rightarrow h_{min} \leq h \rightarrow o \rightarrow h > h_{max} \end{cases} \tag{11}$$

where h is the element in the altitude matrix $\boldsymbol{H}$ that corresponds to the position of the analyzed particle.

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2.3. Particle swarm optimization (PSO)

Particle Swarm Optimization is a series of methods and heuristic optimization algorithms that simulate the behavior of bee swarms in the nature, the movements of big groups of insects or schools of fish (Lamont, Slear, & Melendez, 2007; Peng & Li, 2012). Therefore, each one of their movements is driven by three variables: the experience of the best places where it has been so far; the best place discovered by some other member of the swarm; and a component of inertia resulting from the previous movement that controls the speeds of particles (Lee & Kim, 2013). The parameters and actualizations of the personal experience and global experience are taken from (Clerc, 2012a, 2012b; Leonard & Engelbrecht, 2013; Clerc, 2005).

$$v_j^{(n)} = \varphi_1 . v_j^{(n-1)} + \alpha_1 . \varphi_2 . (\lambda_g - x_j^{(n-1)}) + \alpha_2 . \varphi_2 . (\lambda_j - x_j^{(n-1)}) \tag{12}$$

where $v_j^{(n)}$ Adjusted speed, $\varphi_1 . v_j^{(n-1)}$ particle inertia, φ_1 inertia coefficient, φ_2 Self-confidence coefficient, λ_j better previous position of the particle, λ_g better previous position found by the group, $x_j^{(n)}$ current position of the particle and $\alpha_1, \alpha_2 \sim$ N (0,1) are random variables extracted from a Gaussian distribution with zero median and variance one.

3. Methodology

The methodology is based on obtaining a flight profile using the Preliminary Multidisciplinary Design Framework (PMDF) tool on a direct flight without obstacles and compared with a flight optimized with obstacles. The PMDF was chosen as it has models developed by National Aeronautics and Space Administration (NASA) available for research and combined with some in-house models. A further description of this framework is given below.

The simulations used a database ranging from latitudes between 4.4029 degrees N and 5.8860 degrees N and the longitudes −76.3969 to −74.9069 degrees; they correspond to an altitude matrix of 217*314 dimensions. Table 1 lists the flight parameters.

The initial parameters of the optimization algorithm are shown in Table 2.

The reference flight profile at cruising speed was obtained with the PMDF tool and it follows a straight line between two geographic coordinates. Figure 1 provides a general overview of the PMDF tool.

Table 1. Simulation parameters	
Description	**Parameter**
Cruising speed	800 km/h (0.78 Mach)
Roll	45
Rate of turn	2.33 degrees/second
Altitude	Variable for each experiment
Search space per iteration	20 km

Table 2. Initial parameters of the optimization algorithm	
Description	**Parameter**
Members of the population	40
Inertia coefficient	$\frac{1}{2\ln(2)}$
Self-confidence coefficient	$\frac{1}{2} + \ln(2)$
Social confidence coefficient	$\frac{1}{2} + \ln(2)$

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Figure 1. General description of the PMDF tool (Colmenares Quintero et al., 2010**).**
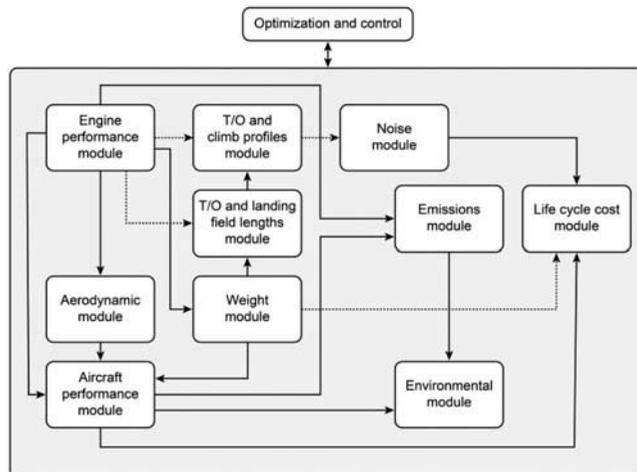
PMDF is composed of several interconnected modules linked to an optimization and control unit. The following is a short description of such modules:

- **Engine performance module.** It enables modeling the performance of a conventional and innovative turbine engine. The cycle analysis is based on a one-dimensional steady-state model that combines several configurations of Mach number and altitude.

- **Aerodynamic module.** It is based on an empirical estimation technique that uses the "Delta Method" developed by "Lockheed" in cooperation with NASA.

- **Aircraft performance module.** The weight and performance data of the engine are entered in this module. A user can program a cruise flight from 10 options, including optimum altitude and/or Mach number.

- **Weight module.** It estimates the weight of an aircraft using empirical correlations. In addition, the weight module can calculate the center of gravity of an airplane and the moment of inertia.

- **Take-off and landing field lengths module.** It calculates takeoff and landing distances. The results comply with FAR Part 25 and/or MIL-STD-1793 regulations depending on the application.

- **Take-off and climb profiles module.** It can calculate the takeoff and climb profile. Different profiles can be created since different power settings can be implemented.

- **Noise module.** It calculates the aircraft noise at an airport and the noise radiated to the community in compliance with FAR Part 36 regulations. The noise module generates noise footprints for airports.

- **Emissions module.** The polluting emissions that are calculated in this module are carbon monoxide (CO), carbon dioxide (CO_2), unburned hydrocarbons (UHC), water vapor (H_2O) and nitrogen oxides (NO_x). These emissions are determined through the Emissions Index (EI).

- **Validation and engine data.** PMDF is validated with the data of an Airbus A320 mounted with CFM56-5 turbofan engines. The data for the validation are obtained from the public domain (PD) as shown in Table 3.

The main performance parameters for the GTF CVC are given in Colmenares Quintero et al. (2010) (refer to Table 4).

4. Results and analysis

The studies involved selecting three start coordinates and three different destination coordinates, which resulted in three test routes. Besides, an alternative route was established for each simulation.

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Table 3. Validation results			
Parameter	**Units**	**PMDF**	**PD**
SFC_{sls}	lb/lb/hr	0.317	-
SFC_{cr}	lb/lb/hr	0.586	0.600[1]
FN_{sls}	lb	27000	27000*
FN_{cr}	lb	4288	-
Engine weight	lb	5248	5250*
Engine length	in	108.7	102.4*
Fan diameter	in	69.4	68.3*
Design range	nm	2617	2600[2]
Block fuel	lb	34774	-
Block time	hrs	6.08	-
MTOW	lb	172483	162920[3]
ZFW	lb	135878	134500‡
Climb time to FL350	min.	19.5	-
Climb distance	nm	127.9	-
Climb fuel	lb	3413	-
Descent time	min.	22.4	-
Descent distance	nm	109.2	-
Descent fuel	lb	570	-
Flyover noise	EPNdB	82	88*
Sideline noise	EPNdB	93.6	94.4*
Combined noise	EPNdB	175.6	182.4*
LTO EI_{NOx}	g/kN	30.8	29.57[4]
Total RF	W/m^2	1.27E-05	-
Price CFM56	USD	6.98	6.95[5]
Price Airbus A320	USD	77.17	76.9†
Total maintenance	$ct/ASM	2.02	2.01[6]
Engine maintenance	$ct/ASM	0.68	0.67

1. Source: Jane's Aero Engines 21st ed.

2. Source: Airbus.

3. Source: Jane's All the World's Aircraft ed. 2006–2007.

4. Source: ICAO Annex 16 Volume 2.

5. Source: CFM International.

6. Source: Aircraft Commerce February/March 2007.

Table 4. Main performance parameters for GTF CVC		
Parameter	**Units**	**GTF-CVC**
TET	K	1650
BPR	-	8.2
FPR	-	1.45
OPR	-	38.6
Mass flow	lb/s	926.9

The planning algorithm was executed five times for each route. The data were then compared to the flight profile provided by the PMDF and the new data when an obstacle was introduced in the flight route. Figure 2 shows the three routes analyzed and executed in Matlab on x 86–64 architecture.

Figure 2. Analyzed routes in contour map. Source: Authors' own work.
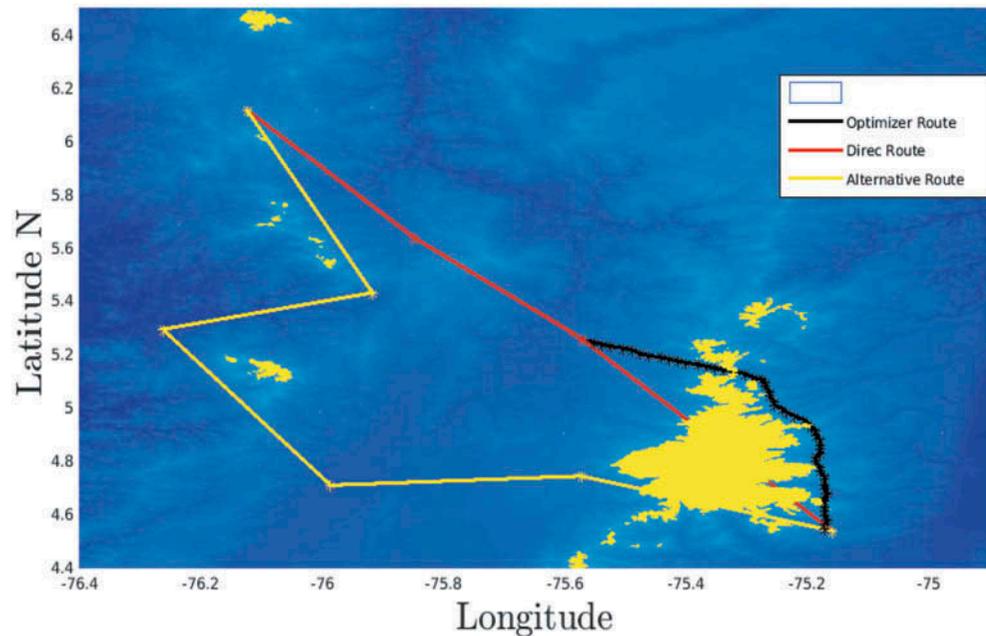
The route marked in red does not contain any obstacles and it is proposed for the flight plan. The yellow route is the proposed alternative that includes obstacles in the flight plan (no optimization), and the black line marks the route proposed by the optimizer developed in this work.

4.1. Simulation results
The simulation results of different flight profiles are presented below.

Table 5 shows the traveled distance under three flight profiles: direct route, alternative route and route proposed by the optimizer. The results reveal that the route provided by the optimizer is 21% shorter than the alternative route designed in the original flight plan in case obstacles arise, and nearly 11% longer than the direct route without obstacles.

Covering longer or shorter distances depending on the flight route the aircraft follows involves an increase or decrease in fuel consumption. Table 6 shows the fuel consumption results for each route and the flight time of the aircraft.

Regarding time, it can be observed that the differences are not substantial, which would not greatly affect the punctuality of the aircraft. The worst case was the alternative route: 19 min longer than the direct route. In turn, the route proposed by the optimizer in this work is 5 min longer than the direct one. Although longer flight times seem insignificant, they do create the need for greater fuel consumption. The results show that the alternative route required 18% more fuel than the direct route, whereas the route proposed by the optimizer would consume almost 6% more than the direct option.

| Table 5. Total distance per route		
Total distance of the route	**Distance (ft)**	**Altitude (ft)**
Direct route of the flight plan	676148.3	33000
Alternative route of the flight plan	952066.9	33000
Route proposed by the optimizer	749540.7	33000

Table 6. Total distance per route			
	Direct route	**Alternative route**	**Optimized route**
Time [hrs]	1.04	1.23	1.09
Fuel [lb]	4080.4	4992.7	4322.5

Table 7. Polluting emissions by route			
Cruise segment	**NO_X[lb]**	**CO_2[lb]**	**H_2O[lb]**
Direct route	5.3	1108.1	432.7
Alternative route	12.2	2194.7	857.0
Optimized route	7.1	1290.6	504.0

Figure 3. Analyzed routes in bar graph. Source: Authors' own work.
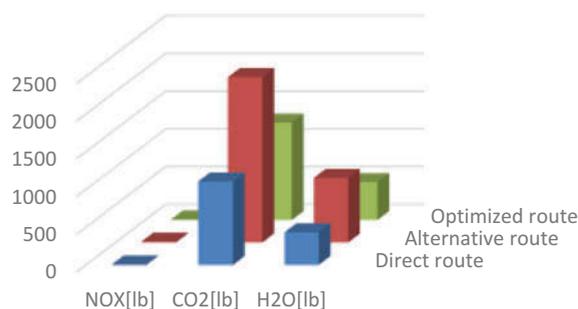
The difference in fuel consumption and longer traveled distance directly affect the emission of greenhouse gases. Table 7 and Figure 3 list the emissions of NO_x, CO_2 and H_2O into the atmosphere by the three flight profiles in the simulation.

The results indicate that the alternative route proposed in the flight plan generates 57% more nitrogen oxide than the direct route. The route proposed by the optimization algorithm generates 25% more emissions than the direct one. In the case of carbon dioxide, the result reveals that the proposed route produces 41.1% less emissions than the alternative route and 14.1% more CO_2 than the direct route. Regarding water vapor emissions, the results show that the alternative route generates almost 50% more water vapor, whereas the route proposed by the optimization algorithm generates 14% more water vapor than the direct route.

4.2. Analysis of the results

In order to evaluate the route optimization algorithm proposed in (Góez, 2016) to reduce fuel consumption and greenhouse gases, three route profiles were implemented. Two profiles were proposed in the offline route plan; they were defined as direct route (free flight) and alternative route, which is taken in case there are obstacles on the direct route. The third flight profile was provided by the route optimization algorithm, which avoids obstructions on the direct route.

The results show that the proposed algorithm enabled to approximate a route that was not considered in the original flight plan in order to reduce the traveled distance. It should be clarified that the planner has the capacity to provide a direct route; however, considering the penalties caused by obstructions on the route, the planner provides an alternative, an option to the original flight plan. In this sense, the route provided by the planner presented less fuel consumption and, consequently, a reduction in the emissions of greenhouse gases. In terms of traveled distance, the

results established that the optimization algorithm provides a 21% shorter trajectory than the alternative route. As a consequence, the algorithm enabled to reduce fuel consumption in 13% compared to the alternative route. As a result, NO_x, CO_2 and H_2O emissions decreased considerably with respect to the latter.

5. Conclusion

This work evaluated the behavior of a real-time route planning system. It enables pilots and air traffic controllers on the ground to have possible routes that had not been considered in the route pre-planning when the flight plan is going to be submitted. It is worth noting that the recommendations and suggestions by the ICAO to maintain air safety include procedures for circumstances that make drastic changes in the primary flight route and alternative route necessary.

In this sense, this work proposes a technique that aims to support real-time route planning and offers options in the design of a new route that maintains the shortest traveled distance compared to the direct route. It also seeks to reduce fuel consumption and the emission of greenhouse gases.

The results have demonstrated that it is possible to propose routes that had not been considered before. This is, the traveled distance was reduced in the first segment of the route (Figure 2) when an electrical storm occurred. Consequently, total fuel consumption and the emission of greenhouse gases into the atmosphere were reduced.

Nomenclature

BPR	ByPass Ratio
CO	Carbon Monoxide
CO_2	Carbon Dioxide
EI	Emission Index
ICAO	International Civil Aviation Organization
FAR	Federal Aviation Regulations
FN	Net thrust
FMS	Flight Management Systems
FPR	Fan Pressure Ratio
GTF CVC	Constant Volume Combustor Geared Turbofan
H_2O	Water Vapor
LTO	Landing and Take-Off
MTOW	Maximum Take-Off Weight
NASA	National Aeronautics and Space Administration
NO_x	Nitrogen Oxides
OPR	Overall Pressure Ratio
PD	Public Domain
PMDF	Preliminary Multidisciplinary Design Framework
PSO	Particle Swarm Optimization
RF	Radiative Forcing
SFC	Specific Fuel Consumption
TAS	True Air Speed
TET	Turbine Entry Temperature
UHC	Unburned HydroCarbons
VFR	Visual Flight Rules
ZFW	Zero Fuel Weight

Subscripts

c	Combustor
cr	Cruise condition
sls	Sea Level Static

their assistance in the creation of the environmental impact models and their contribution to the discussion of the results.

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