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Flying Like Geese: Green, Sustainable, and Efficient

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Formation flights hold significant potential for reducing the environmental impact of aviation and offer a means to streamline airspace complexity. The selection of candidates for formation pairing among the intense traffic of continental routes (Europe to Asia) plays an important role in savings. This article enables a better understanding of how deviations from the initially planned route may impact the performance of aircraft. The fuel consumption assessment is made by trajectory simulations, allowing a comparison considering different air traffic scenarios.

Nowadays, an important concern in aviation is the environmental impact generated by all the daily air traffic. Some studies estimate that aviation is responsible for 12% of global CO_2 emissions.[1] The development of new flying procedures that could reduce emissions, costs, and air traffic congestion is a hot research topic in the context where an increase in the number of flights is expected.[2] Inspired by migratory birds that use the "V" formation to enhance aerodynamic efficiency and increase flight distance, according to certain articles,[3] its application in commercial aviation, known as *formation flight* (*FF*), could result in significant fuel savings. This could potentially lead to significant reductions in CO_2 emissions and costs.

An industrial research project led by Airbus, GEESE[4] analyzes the implementation of FF procedures in Atlantic and Continental Airspace from a holistic perspective to identify those aircraft pairing policies that would reduce the trail aircraft fuel consumption by using the air upwash generated by the leading aircraft vortex. Furthermore, the airspace capacity could be increased as air traffic controllers (ATCs) workload could be decreased, because in FF, instructions from controllers will be given only to the lead aircraft and the trailing aircraft will follow the movements of the leader.

The FF is structured into three main phases: merging, rendezvous, and splitting. The merge point is where both aircraft meet and start the positioning for the FF segment. The rendezvous starts once both aircraft are on the same track, separated vertically, and finalizes with the joint-up of both aircraft with an horizontal separation reduced to 1.5–2 nmi. The split point marks the end of the FF segment, where the aircraft separate to proceed to their destination. These points will vary depending on both traffic needs and the initial separation between aircraft.

In Figure 1, the three crucial parts of an FF are outlined: the merge point between the aircraft, the shared segment where fuel savings are achieved, and the split point, where the aircraft finish the formation.

At the merge point, it will be necessary to set a request time of arrival (RTA) as the aircraft must arrive at the right moment to ensure the necessary separation for the FF and maintain the same and constant speed during the formation segment.

FFs can be planned in advance by establishing merge and separation points as well as the optimal route and time planning before departure. However, planned FF have low tolerance for unforeseen events in departure. Any delay or lack of adherence to the

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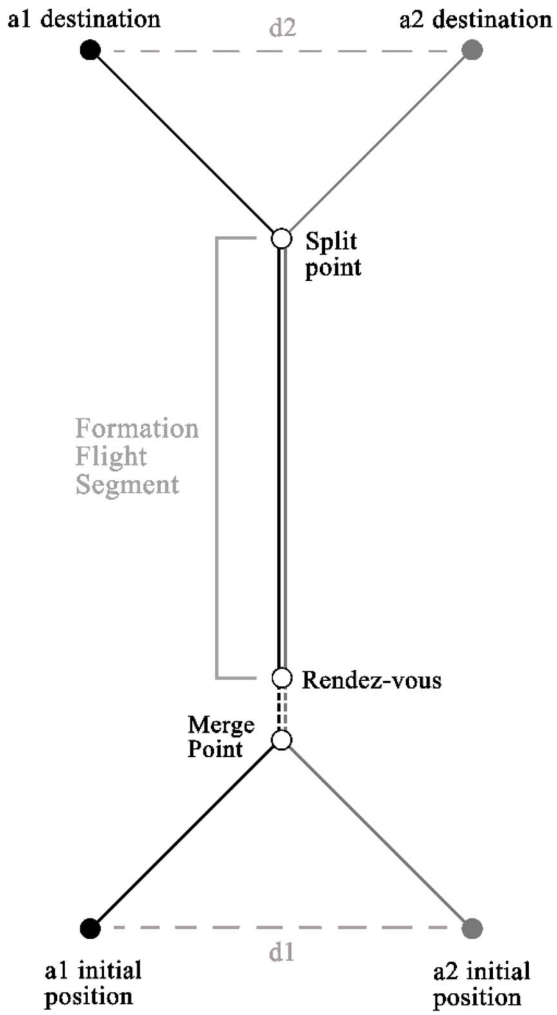

FIGURE 1. FF segments, a merge point, rendezvous, and formation segment.

flight plan in one of the aircraft forming the pair can result in a lost opportunity to conduct an efficient and cost-effective FF.

On the contrary, in opportunistic formation, there is no prior planning, and the pairing, establishment of merge points, and the new route for the aircraft are determined in real time once the aircraft are already en route. This reduces the risk of the unpredictability associated with planned FFs but requires computationally efficient air traffic simulation models to identify the most advantageous flight pair among the different pairing candidates.

Causal simulation models become essential to tackle opportunistic FFs. Note that deviations from preferred trajectories for a rendezvous entails an increment of fuel that may not be compensated for during the formation keeping, especially if this last phase is too short. Considering that, a single aircraft in domestic traffic may have several FF potential candidates; the use of simulation models provides the appropriate technological support to compare possible aircraft pairings by performing a tradeoff among deviations from original trajectory, route traffic complexity, and fuel consumption factors to identify those that can better benefit of an FF.

An important factor in the implementation of FF within the European airspace might be the use of airstreams.[5] In this approach, the structuring of air traffic routes would shift to main corridors called *airstreams*, which would be segmented by flight levels (FLs), and horizontally. This would allow flying in parallel and grant priority over traffic outside these airstreams through these principal corridors over Europe.

On the other hand, by having priority over traffic outside the airstreams and the airstream structure itself, maneuvers such as rendezvous and splits as well as formation flying per se, would be significantly facilitated. This article illustrates the framework of simulation that combines air traffic, aircraft performance, and heuristics as a key approach to identify the best flight pairs for opportunistic FFs. It also establishes a procedure for finding the optimal partner for an aircraft, considering the complexity of airspace and performance considerations.

The article is organized as follows. In the next section, a review of the related literature is conducted, followed by the methodology employed for analyzing the FF scenarios and the performance results obtained. The article concludes with a discussion and a summary of the obtained results.

STATE OF THE ART

Various studies conclude that the use of FFs can result in significant fuel savings,[6] directly impacting the operational and environmental costs of a flight operation.

Airbus, with the Fello'fly project, conducted an FF test over the Atlantic, where two A350s performed an oceanic FF on 9 November 2021, from Toulouse, France, to Montréal, Canada. The route for both aircraft was established prior to departure, achieving significant fuel savings. This project was focused on Atlantic flights, which represents a simplification in terms of air traffic complexity and route restrictions in comparison of continental airspace. The advantage of FF in domestic traffic is the high probability to identify potential pairings in which the trail aircraft could benefit from a fuel reduction.[4]

However, all the data and hypotheses correspond to planned FF, presenting a significant challenge for deployment in realistic continental operational conditions. In case of a minor time or space deviation from the initial plan, it might be necessary to increase speed to meet the RTA at the planned merge point waypoint for the participating aircraft. An aircraft speeding above its cost index usually leads to an increase in fuel consumption prior to the merge point, which could even exceed the fuel savings of the formation-keeping phase. The application of opportunistic FFs at real time in domestic traffic opens a new research area in which simulation models can contribute to the design of new procedures for a more efficient air traffic management system.

One of the challenges that arises is the choice of the route for the FF as an aircraft can have multiple potential pairing candidates. Many variables come into play when deciding which of the candidates is the "ideal" match. The choice of the route is a crucial factor, and also deciding whether deviations from the initial route will be necessary. In the case of deviation, the decision must be made on whether to deviate from only one aircraft or apply modifications to the routes of both planes.

Some studies explore an approach to optimize the routes of FFs,[7] establishing positions, structures, and heuristics that can enhance the potential of an FF route, paving the way for an estimation of the potential savings of a pair.

Nevertheless, there is a lack of research literature with tradeoff mechanisms to tackle the extra fuel of deviations from airline preferred trajectories with the fuel savings during the formation keeping, under realistic operational conditions.

On the other hand, airspace density is a key factor in choosing the optimal route for an FF. In this regard, some studies present various tools for conflict detection (CD) and conflict resolution,[8] which are essential for considering the various scenarios when selecting the optimal FF route. A route passing through a high traffic density sector has more probability of a conflict with surrounding traffic, which could rise an FF split and posterior resume maneuvers with an impact on fuel consumption. The research on CD exclusively for FFs has not been addressed so far but is crucial for the practical application of this technique and calculating the tradeoff.

The integration of these theoretical foundations in a simulation model is key for a successful deployment at operational level of the opportunistic FF in realistic continental airspace scenarios. Some studies leverage simulation for efficiency and fuel savings[6] or aircraft route calculations,[7] however, the real-time application of simulation in the search for opportunistic flight pairs represents a new FF research area.

This study aims to fill some gaps in the existing literature on FFs through a simulation framework that integrates an airplane flight simulator (XPlane), air traffic simulators (BlueSky), a set of heuristics, and a search engine to identify efficient FFs, in which synchronization mechanisms among simulation models play a crucial role in studying and implementing the necessary tools for opportunistic FF in continental airspace.

METHODOLOGY

As mentioned in the previous section, an aircraft will have several candidates, and it will be necessary to choose the one with the greatest potential to perform the FF. Once we know those aircraft that have a similar trajectory and significant potential for FF, simulation comes into play. BlueSky[9] is used to simulate different trajectories and choose the one that results in better performance. The first step is to select an en-route aircraft to search for its potential candidates.

The simulation scenario sets the airborne traffic with the planned trajectories and feeds new trajectories according to planned departures considering different time uncertainties. Once the aircraft is en route, trajectory deviations will be applied along the planned route. Formation flying, consisting of two aircraft, leader (referred as *a1*) and trail (referred as *a2*), presents the following three possible deviation scenarios to execute the trajectory:

1) *Scn1*: Only a1 deviates, while a2 maintains its planned trajectory.
2) *Scn2*: Only a2 deviates, while a1 maintains its planned trajectory.

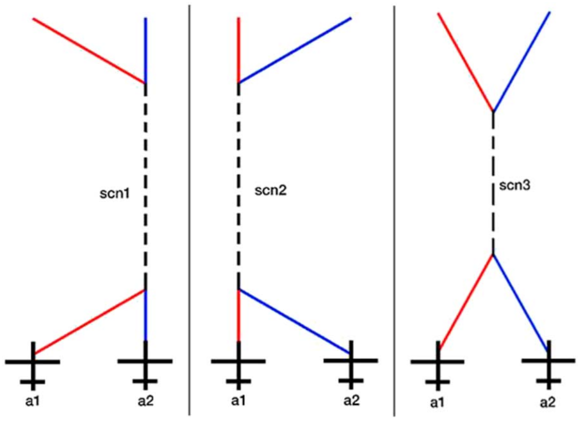

FIGURE 2. Scn1 aircraft a1 changes its trajectory (red color) and Scn2 aircraft a2 changes its trajectory (blue color), while in Scn3, both aircraft change their planned route.

FIGURE 3. Wake vortex modeled simulation in XPlane 12.

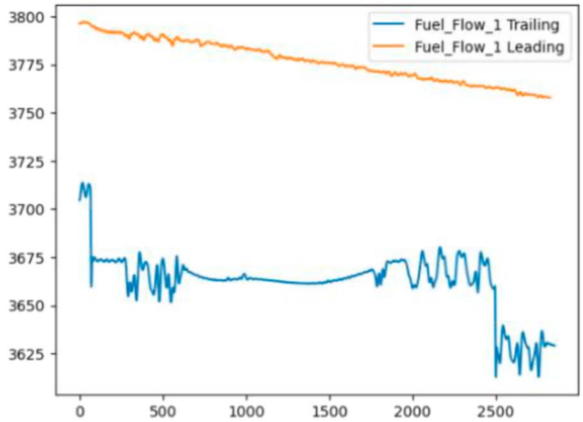

FIGURE 4. Fuel flow comparison graph.

3) *Scn3*: Both a1 and a2 deviate. In this case, both aircraft change their planned trajectory for a route midway between them. The merge point and the separation point are calculated. These two points will form the segment of the route where formation flying will take place. This segment is calculated by averaging the coordinates of both aircraft to find the midpoint of each.

As illustrated in Figure 2, the different possible scenarios are analyzed considering the deviation maneuvers for each pair candidate to determine the pairing and the scenario that exhibits better performance. These simulations can be sent to a cluster for parallel execution, optimizing the computational times complying with the temporal constraints of the Airline Operation Centre (AOC) to start the information flow to ATCs for the FF.

Fuel flow, flight distance, flight time, and speed data will be recorded during the simulation at a pace of 1 s to analyze performance dynamics of the aircraft during flight. A baseline scenario is generated to quantify fuel savings in which a1 and a2 will maintain their trajectories.

Once the simulation results are available, the fuel consumption needs to be calculated for each scenario and airplane. BlueSky does not account for wake turbulence in its simulations, meaning that fuel savings cannot be considered. To address this, the fuel savings must be applied to the results considering the distance of the segment where the FF will occur.

To validate the fuel savings from an FF, XPlane12 is used to simulate a flight taking advantage of wake vortex for drag reduction. Both aircraft have the same weight at the start of the flight and maintain formation at an FL of 350 and a Mach speed of 0.8.

In Figure 3, the positioning of the aircraft is shown to establish the sweet point that provides the greatest reduction in fuel flow. XPlane allows for the collection of data from the aircraft, and as a result of the simulation, a 3.03% savings in the fuel flow of the trailing aircraft was achieved.

Figure 4 describes a comparison of the fuel flow (pounds per hour) of the aircraft in formation, demonstrating lower fuel consumption throughout the entire flight.

To estimate the resulting fuel consumption for the FF in BlueSky, the following formula uses the fuel savings obtained in the XPlane for a trail aircraft in similar operating conditions (FL 350, A320):

$$\mathrm{FC} = \mathrm{tFF} * aff * (1 - 0.0303) + \mathrm{tFF} * \mathrm{aff}. \quad (1)$$

FC=Fuel consumed.
tFF=Formation-keeping time.
tNFF=No formation-keeping time.

TABLE 1. Initial conditions of each flight.

Flight Id	Departure ICAO	Arrival ICAO	Initial point (latitude, longitude)
EZY34QN	LGKR	EGGW	(40.47111111666666, 18.76833333333333)
RYR913K	LGSA	EGNX	(40.789999995833334, 19.808125000000004)
EZY74EY	LTFE	EGGW	(41.247222216666664, 22.758333333333333)
EZY85PT	LICC	EGGW	(38.17583333333334, 15.2325)

ICAO: International Civil Aviation Organization.

TABLE 2. Fuel consumed estimation in BlueSky for the planned trajectory without FF nor deviations.

Flight	Initial fuel consumption (kg)	Initial flight distance (km)	Initial flight time
EZY34QN	2473.53	1981.58	2 h 19 min
EZY74EY	2696.18	2124.01	2 h 33 min
RYR913K	2566.89	2084.74	2 h 30 min
EZY85PT	2482.28	1978.58	2 h 19 min

aff=Average fuel flow.

$$\mathrm{IFC} = \mathrm{tflight} * \mathrm{aff}. \quad (2)$$

IFC=Initial fuel consumed.

aff=Average fuel flow.

tflight=Overall time flight.

In (1), a 3.03% fuel savings during the FF period is considered, thus obtaining the predicted fuel consumption for the aircraft in that scenario. In (2), the consumed fuel is calculated without any savings applied; this formula is used for the scenario with the initial flights without performing FF.

With the results obtained from applying those formulas for each scenario, the consumptions of both aircraft are added to consider the collective savings. This sum is then subtracted from the fuel consumed if the FF had not occurred. Equation (3), which provides an estimator whether deviating from the trajectory for the savings of FF, is worthwhile. The estimated fuel savings is expressed in the following formula:

$$\mathrm{FS} = (\mathrm{a1FC} + \mathrm{a2FC}) - (\mathrm{a1IFC} + \mathrm{a2IFC}). \quad (3)$$

FS=Fuel saved.

a1 and a2=Aircraft 1 and 2.

If the result of (3) is negative, it means that this scenario represents fuel savings compared to the initially planned trajectory. Conversely, if the result is greater than or equal to zero, there is no savings, and the scenario is discarded. Among the scenarios with fuel savings, they will be ranked from highest to lowest, and these can be sent to the AOC, which will implement the necessary modifications to the flight pair's route.

In the event of any unforeseen circumstance or if the pilot aircraft refuses to perform the FF, the AOC can choose the next pair that represents fuel savings. However, even if it is negative, a minimum savings threshold must be established. If the savings are too small, it may not be worthwhile to deviate from both aircraft.

RESULTS

The operational conditions for these simulations assumes no conflicts with surrounding traffic, no weather impact on the flown routes, and trajectory amendments due to ATC instructions.

TABLE 3. Estimated fuel savings (FS) for each flight pair and scenario, the result of (3).

Flight pair	FS scenario 1 (kg)	FS scenario 2 (kg)	FS scenario 3 (kg)
(EZY34QN and RYR913K)	−44.98	+144.04	−111.62
(EZY34QN and EZY74EY)	+ 41.17	+ 47.49	−94.33
(EZY34QN and EZY85PT)	+ 52.2	+ 207.64	−120.18

The flights described in Table 1 are the ones to be analyzed. The EZY34QN flight will serve as the reference, and the objective is to determine which of the following trajectories exhibits the highest estimated fuel savings and what type of deviation results in more savings. The initial position is the position when time is zero.

In Table 2, the initial route values are computed using BlueSky, initiating the simulation once the aircraft are already en route. Therefore, the fuel consumption during climb and takeoff is not included in the calculations.

As observed in Table 3, the flight pair that exhibits the highest fuel savings is (EZY34QN and EZY85PT) in scenario 3, where both aircraft deviate. Scenario 3 presents the highest fuel savings compared to the other scenarios. The new trajectory is modified as follows.

Table 4 describes the fuel consumption, flown distance, and time for the opportunistic FF. This trajectory accounts for deviation of both aircraft. The total shared distance of this flight represents 68% of the total distance of EZY85PT and 69% of EZY34QN. This fuel saving represents a reduction of 2.17% for the trail aircraft considering the estimated fuel consumed in the planned trajectory, and the speed modifications due to RTA.

In Figure 5(a), the planned trajectories are represented, while in Figure 5(b), the FF trajectories with the amended deviations can be observed.

Finally, Figure 6 displays the modeled route in the BlueSky simulator, highlighting the intersection point and the trajectory of the new flight.

TABLE 4. New trajectory performance, with deviations applied.

Flight	Modeled fuel consumption	Flight distance	Flight time
EZY34QN	2407.37 kg	1948.29 km	2 h 32 min
EZY85PT	2428.26 kg	1987.5 km	2 h 33 min

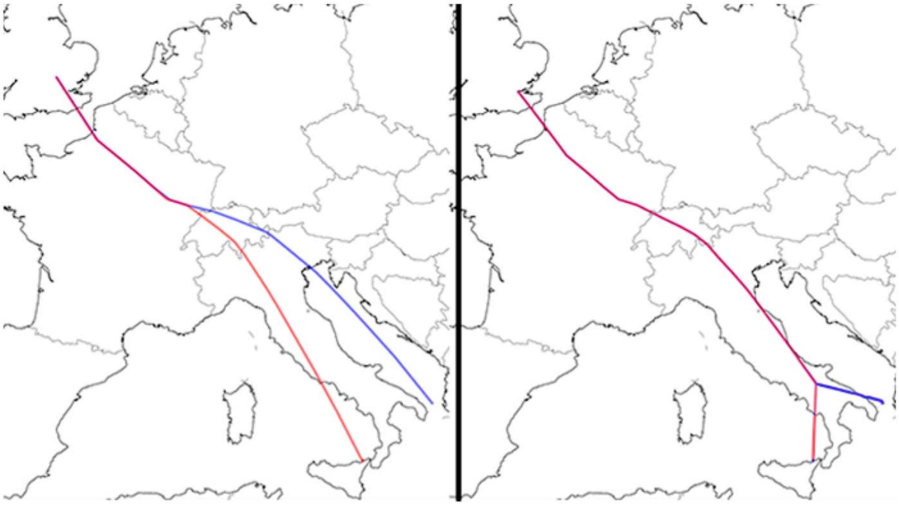

FIGURE 5. (a) Initial trajectory and (b) modeled trajectory.

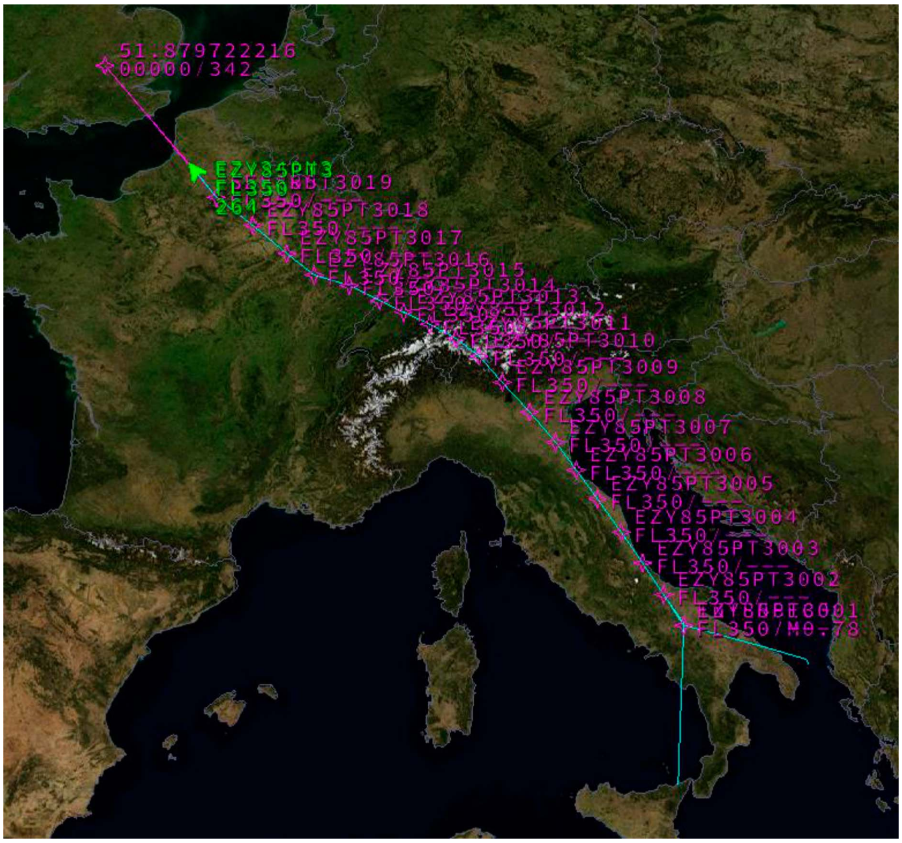

FIGURE 6. BlueSky simulation trajectory.

CONCLUSION

FFs present a new way to improve current air traffic and a novel methodology to reduce environmental impact by saving fuel. Pairing candidates selection is a crucial research topic that is partially investigated in the literature. The study presented in this article offers a new perspective on candidate selection and route planning for FFs.

The presented results highlight the potential of the simulation approach to manage FF in European airspace to obtain the highest fuel savings considering the different opportunistic parings. Simulations have also shown that accommodation of a new FF route can even lead to an increase in fuel consumption. Accordingly, the scenario where both aircraft deviate shows greater fuel savings. Nevertheless, it must be considered that these results are sensitive to multiple factors, such as weather conditions and airspace density.

FUTURE WORK

FFs are quite sensitive to several factors, the most important of which are weather conditions, airspace complexity, and deviations to perform the pairing. These factors have a direct impact on fuel consumption as well as an effect on the safety of the maneuvers to face these situations. In this article, an approximation is made in the estimation of fuel consumption in different scenarios, but in its continuation, it will be important to evaluate the external factors that have a great impact on the viability of formation flying. Additionally, an analysis of wake vortex savings must be established to generate an estimation table considering factors such as aircraft weight, FL, speed, and cost index compatibility between aircraft. The XPlane flight simulator incorporates wake vortex dynamics, which is an important enabler of FF traffic scenarios, and quantifies the fuel savings estimation coefficient.

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