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A Model to Analyze the Potential Environmental Benefits of Continental Formation Flights

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Abstract

Currently, one of the main issues within the aviation industry is the reduction of CO2 emissions. The motivation for this paper is to further emphasize the importance of technological advancements in achieving sustainable development within the aviation industry, particularly with regard to reducing fuel consumption and CO2 emissions.

The primary aim of this document is to analyze the feasibility and potential benefits associated with the implementation of formation flights within European airspace. To accomplish this objective, a model has been implemented that employs filters and policies to meticulously identify feasible flight pairs suitable for integration into an effective Formation Flight strategy. Through a careful analysis of the results derived from this study, this paper presents a continental air traffic strategy (Formation Fly), which could be implemented within the European airspace, as an innovative means to reduce CO_2 emissions on every flight.

Keywords: Formation Flight, Environmental impact, Causal Modeling, Opportunistic Cooperative Mechanisms.

1. Introduction

The aeronautical industry is under huge pressure to improve the quality of the services and the financial gains while minimizing at the same time the environmental impact.

The fragility of airlines during COVID-19 lockdown scenarios is well described in (Kalic et al., 2022) together with the economic and operational changes experienced in the aeronautical industry. The successful transformation of the aviation industry towards a resilient, sustainable, and competitive transport system demands a comprehensive approach that entails strategic planning, meticulous execution at both operational and tactical levels, and concerted efforts among the different stakeholders. Furthermore, according to Silas Nzuva (Nzuva, 2020) environmental impact and sustainability in airlines have become a common key performance area (KPA's) within the aeronautical industry.

Achieving this objective requires an in-depth understanding of market dynamics, regulatory frameworks, technological advancements, customer needs as well as effective collaboration within the industry.

Besides the fierce competition among airlines, new cooperative-competitive mechanisms among the Air Traffic Management (ATM) stakeholders seems to provide an efficient and effective field of opportunities to implement structural and operational modifications within the aeronautical industry. In this context, SESAR (Single European Sky ATM Research) and NextGen programs (Bolić & Ravenhill,2021; Next Generation Air Transportation System, nd.) paves the way for new ATM solutions relying on cooperative mechanisms among ATM stakeholders.

As a result of these facts, all airlines and operators are trying to find new and innovative ways to improve their operations, increase profitability, enhance customer experience, and reduce environmental impact. This approach to operations management will promote the pursuit of collaboration among rival airlines, seeking to identify mutually beneficial trade-offs that enhance the Key Performance Indicators (KPIs) of their respective operations.

This paper introduce the results of an analytic study to estimate the opportunities for an aircraft flying in the European airspace to benefit from a nearby aircraft flying in formation by retrieving the energy lost by the wake of the leader aircraft, flying in the smooth updraft of air it creates, which provides lift to the follower aircraft, allowing it to decrease engine thrust and therefore reduce fuel consumption in the range of 5-10 per cent per trip.

Research is to explore the feasibility to match couples of aircrafts while they are flying that could joint in a Formation Fly by modifying their original optimal trajectory to a new trajectory that would a substantial reduction in fuel consumption, a significant decrease in CO_2 (Carbon Dioxide) emissions and it could reduce operating workload for air traffic controllers.

Through the spatio-temporal analysis tools implemented in a traffic simulation, this study aims to discover more opportunities at operational level to Formation Flight (FF) in European Airspace.

Worthwhile to note that FF has been utilized by in military operations employs it during operations to save fuel burn (Flanzer & Bieniawski, 2014; Pahle et al.,2012). FF has its roots on birds (Billingsley et al.,2022) flying together in formation while migrating to reduce exhaustion and cover long distances efficiently. Such examples illustrate the significance of utilizing collective strategies that can contribute towards achieving common goals.

This paper aims to estimate the feasible opportunities of pairing aircraft for formation flying within European airspace. This will be done by using a model that analyze historical data of one-day flight paths within European airspace and detect trajectory affinities. The primary aim of this task is to ascertain the maximum number of viable pairs that can be formed to conduct Formation Flights within European airspace. The proposed method implements different causal filters that considers various factors such as coexistence of trajectories in a nearby airspace, the horizontal and vertical distances between aircrafts as well as directional angles.

Ultimately, this study's results will contribute to the understanding of the feasibility and probable consequences associated with introducing Formation Flights in commercial aviation. Furthermore, this research will emphasize the economic advantages of forming flights for airlines in terms of fuel savings and reduced carbon emissions.

This paper has been organized into 5 sections. Section 2 summarizes main insights that can support the implementation of continental Formation Flights. Building upon this foundation, Section 3 describes the methodology implemented, while in Section 4 the outcomes achieved are presented. Finally, Section 5 summarizes main conclusions achieved and potential opportunities for future implementations.

2. State of Art

2.1. SESAR

To revolutionize the air traffic industry and improve ATM key performance indicators, a European program known as SESAR (Bolić & Ravenhill,2021) was created. This innovative program stands as the technological foundation of the European Commission's Single European Sky Initiative, which aims to modernize ATM practices to improve efficiency, capacity, safety protocols, and environmental sustainability measures.

Remarkable progress was achieved in the development of new Air Traffic Management techniques (Ntakolia et al., 2019; Tomlin et al.,1996); however, progress could be limited without a joint approach to implementing ATM stakeholders' cooperative solutions. Despite the remarkable progress made in technology and communication within the aviation industry, effectively replicating best practices to generate significant trade-offs for both airlines and air traffic controllers continues to be a formidable challenge. A solution to this problem requires numerous alterations that have not yet been implemented, including but not limited to enhancing collaboration among all stakeholders involved, leveraging cutting-edge technological tools, and investing in new development programs for effective decision-making under dynamic circumstances (Bianco & Bielli, 1992).

The successful implementation of the Single European Sky ATM Research (SESAR) (Bolić & Ravenhill,2021) program will succeed in consolidating a new era of aviation, replete with challenges that can be considered innovative opportunities for improvement. Among these opportunities is the integration of Formation Flight into European airspace.

2.2. CO_2 emissions

The aviation industry, like other industries, prioritizes profit generation and greater operational efficiency. However, there has been a change in recent times where greater importance has been given to minimizing CO_2 emissions. This is due to the current problem of climate change.

Over the years, a multitude of research has been conducted to identify and assess the most efficient techniques for reducing CO_2 emissions (Morrell, 2009). In addition, in-depth analyses have explored CO_2 emission patterns across various air routes with detail and accuracy (Pagoni & Psaraki-Kalouptsidi, 2007) . These studies aim to address the important issue of CO_2 emissions by the aviation industry.

To achieve this goal, various measures must be considered such as researching hydrogen engines and other alternative fuels (Detsios et al.,2023; Adami et al.,2021) which have lower CO_2 emissions than traditional jet fuel. In addition, identifying more environmentally flight trajectories (Otero et al.,2022) or developing innovative methods of operating within airspace domains are all necessary steps forward toward greener practices.

Though implementing these solutions may require significant investment at both operational and technical levels, it will mean an improvement in the environmental impact of air operations. Nonetheless, there exist immediate strategies that could be put in place presently to significantly enhance CO_2 emissions, such as the implementation of formation flying.

Airbus has developed the innovative "Fello'fly" project (Airbus, nd.), which offers a technical solution aimed at significantly reducing CO_2 emissions for Atlantic flights. The project, based on implementing an efficient Formation Flight strategy, is capable of delivering emission reductions of up to 5%-10% per trip. The carefully designed approach involves close collaboration and coordination between aircrafts, resulting in optimal positioning that significantly decreases carbon dioxide output while simultaneously increasing fuel efficiency. Such innovative solutions are essential in tackling climate change issues and ensuring sustainable aviation practices for future generations to come.

As a result, the implementation of Formation Fly represents a significant step forward in the aviation industry's efforts to address and achieve climate change mitigation objectives (Tait et al.,2022; Wagner et al., 2002). This approach has the potential to reduce CO_2 and fuel emissions per operation by 5%-10% (Airbus, nd.).

2.3. Competitive and Cooperative Management

The aviation industry is a complex sector that always strives to maintain perfect operational safety. Furthermore, the rivalry that exists in the aviation industry between companies and airline operators makes them strive to optimize their financial benefits. This situation creates a highly competitive market in which agents continuously seek new strategies and solutions to make their operations profitable (Alderighi et al., 2012; Barrett, 2000).

To achieve leadership in the aviation industry, airlines must use management strategies that not only seek to compete but also resort to mutual collaboration among all interested parties. In this sense, both competitive and cooperative management approaches are essential to achieving the desired results.

For air traffic controllers and pilots, their main objective is to maintain proper separation between aircraft (Williamson & Spencer, 1989) , which obliges them to apply appropriate procedures and strategies in these scenarios where a minimum separation infringement between aircraft can arise. This field has experienced significant development that has led to faster and safer air transport protocols.

But to maximize the benefits of the European airspace and ensure the efficiency of daily operations, airlines must focus on a collaborative strategy approach (Milovanovic, 2015; Hurter et al.,2016). Thus, the European aviation sector can achieve new efficiency and profitability objectives.

With careful analysis and innovative strategies in airline management, it is possible to explore alternative approaches that can transform a difficult situation into a way to improve Key Performance Indicators. Airlines in collaboration with industry manufacturers, airline operators, and aeronautical organizations can develop new strategies that would facilitate the resolution of current problems at operational levels, and it will be a first step toward future events within the aviation industry in terms of operation, operational efficiency, and even new business models. These measures require a change in the usual strategy followed in the airline industry currently and thus implement new business management where cooperation among different agents predominates.

Airlines try to fly the optimal trajectory between the origin and destination airport considering different factors, such as the available airspace capacity, the weight of the aircraft, and the meteorology among others. Pairing aircraft for a Formation Flight will require that one or both aircraft must change the optimal trajectory to allow a follower aircraft to join a leading aircraft with a minimum cost. Thus, a horizontal deviation of 50 Nm (Nautical Miles) or a flight level change of 3000 feet from the original trajectory could be easily accepted if the FF last for 2000 Nm. As it can be observed, there is a tradeoff

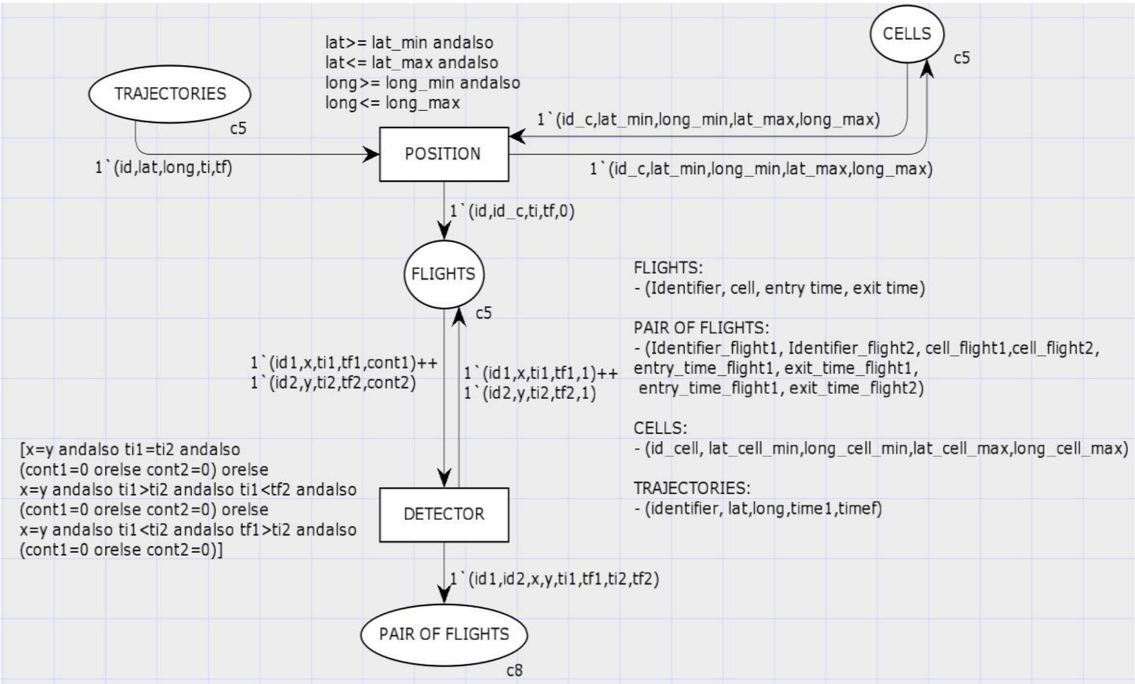

Figure 1. Colored Petri net model of aircraft spatio.temporal relationships

between the changes to apply to the optimal trajectory concerning the length of the trail aircraft that can benefit from the leading aircraft. Therefore, it will be necessary to search for a business model that seeks the best possible maneuvering and matching to compensate for changes to be applied in the initial trajectories. This is because the fuel spent in a horizontal deviation maneuver of 50 Nm will not be compensated for an FF length of 30 Nm.

By analyzing spatio-temporal interdependencies among trajectories, it is possible to gather pairs of flights and the required trajectory ammendments to a common trajectory suitable for FF. The proposed approach simulates the merging of two different flight trajectories to perform a Formation Flight.

The adoption of Formation Flight in continental airspace not only can improve safety measures but also offers the possibility of improving airlines' efficiency and reducing the workload of air traffic controllers while mitigating the latent capacity in European airspace. Achieving these objectives requires the implementation of a strategy that is both collaborative and competitive in airspace management.

3. Materials and Methods

To accomplish the goals outlined in this research study, the spatio-temporal interdependencies among aircraft arising within European airspace during an entire day of operational activity (October 5, 2022) have been analysed. Original traffic has been filtered to consider as FF candidates only enroute trajectories. This pursuit aimed to identify and analyze the number of potential pair of flights that could operate into a Formation Flight in European Airspace.

To achieve this, a comprehensive data set comprising diverse flight routes is used. The analysis incorporates crucial factors such as the departure and arrival locations, precise latitudinal and longitudinal coordinates, alongside specific time-stamp for every waypoint on the trajectory and the total distance of the trajectory. Consequently, we analyze a comprehensive record of every flight delineated by its unique identifier alongside the corresponding register of latitude, longitude, and time data of the complete trajectory that requires thorough examination.

To identify potential pairs of flights within the European airspace, a space-time relationship analysis among enroute aircraft is used.

Figure 1 illustrates a Colored Petri Net (CPN) model (Jensen, 1996) that formalizes the causal spatio-temporal interdependencies among aircraft trajectories. The CPN model serves as a mathematical specification of system dynamics. The proposed model formalizes the aircraft status for a formation fly procedure. For this system, the different transitions and attributes of each object have been designed to represent in a simple and detailed way the process of simulating the causal spatio-temporal interdependences. Transition "Position" assigns each flight to its respective cell according to the latitudes and longitudes of each waypoint in its trajectory. Each cell is determined by the latitudes and longitudes of the cell boundaries, so only the cells that include the trajectory waypoints are assigned to it. Transition "Detector" analyze the flight pairs that can be formed. Place node "Flights" record the space in which the trajectory waypoints are located," Detector" transition analyzes whether these waypoints meet the simultaneity constraints which is computed mathematically by the entry and exit times to the cell, of the two waypoints involved, leading to a temporal relationship. The resulting node would store the flight pairs formed according to this space-time analysis, along with the respective necessary data of each flight for the following processes.

To further refine the model detection capabilities for potential pairs of flights, a new algorithm has been implemented that evaluates horizontal separation distance and vertical separation distance across all cells in the matrix. Through the utilization of this technique, an initial measure has been taken towards identifying feasible combinations of flights that can be adapted to a strategy involving Formation Flight.

In this stage of the process, the azimuths of the pairing candidates are analyzed to determine if the flights are parallel or semi-parallel to each other. The primary objective behind this step is to eliminate any conflicting scenarios where the trajectories intersect or travel in opposite directions.

After analyzing the minimum horizontal and vertical distances, as well as the trajectory directions of each flight pair candidates, it is imperative to identify those that possess a substantial amount of shared navigation points. This will enable to select flight pairs that exhibit significant potential for studying Formation Flights. The filter was implemented through an analysis of commonly utilized navigation point segments during air operations within the European airspace.

Using this method, it is possible to obtain as a result, the number of flight pairs that meet the filtering requirements obtained, according to the study and analysis of flight data from the various operations carried out in European airspace on October 5th, 2022.

4. Results and Discussion

After successfully implementing the methodology described in the preceding section, an estimated count of potential flight combinations that satisfy the criteria vertical and horizontal distance between aircraft, trajectory orientation, as well as identification of navigation points has been evaluated.

To analyze the outcomes, it is imperative to consider the number of flight pairs that are established through the utilization of this approach.

An illustrative example of parallel trajectory would be the following:

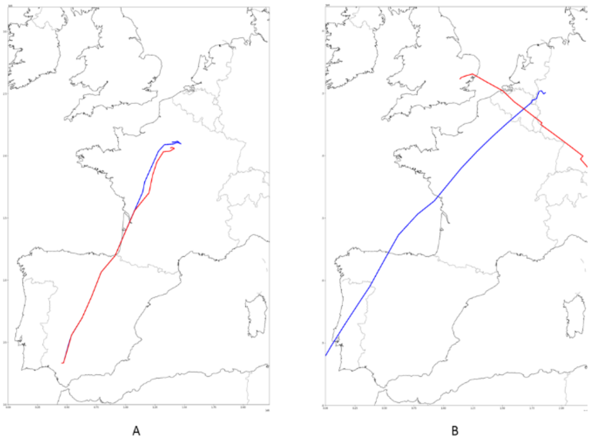

Figure 2. Two Trajectories representations of the case A: flight VLG22TN represented in blue and the flight TVF37TS represented in red. Both flights belonging to October 5, 2022. And of the case B: flight EWG9558 represented in blue and the flight RYR2MJ represented in red. Both flights belonging to October 5, 2022.

Figure 2 is an illustrative example of two cases of the trajectories made by four flights on October 5th. It can be observed that in the case A, this potential pair of flights satisfies the necessary conditions to execute the Formation Flight strategy. On the other hand, case B is a trajectory where the directions of each trajectories are almost perpendicular. The Formation Fly strategy cannot be implemented in this case because the intersection angle between the trajectories does not meet the necessary conditions.

The analysis of this example can also be complemented and completed with the representation of the different altitudes (Figure 3), latitudes, and longitudes (Figure 4) along the trajectory of each flight. With these three graphs and Figure 3, better conclusions can be drawn about the result obtained.

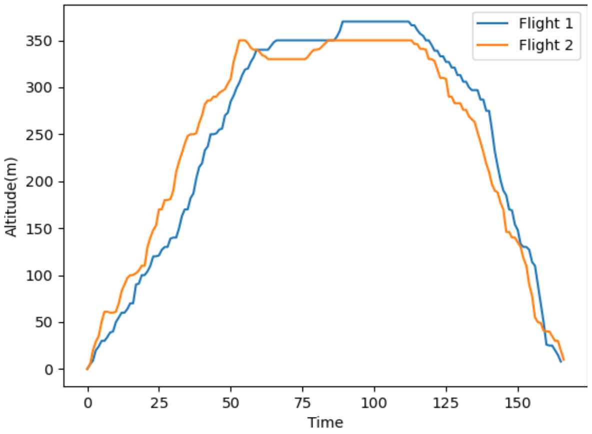

Figure 3. Altitudes representation of the flight MSR758 represented in blue and the flight MSR778 represented in orange. Both flights belonging to October 5, 2022.

As we meticulously analyze Figure 3, it becomes evident that the two trajectories showcase a strikingly pronounced resemblance in terms of their altitude. This correlation between the altitudes leads us to believe that there exists a complex interdependence between them that spans across both space and time.

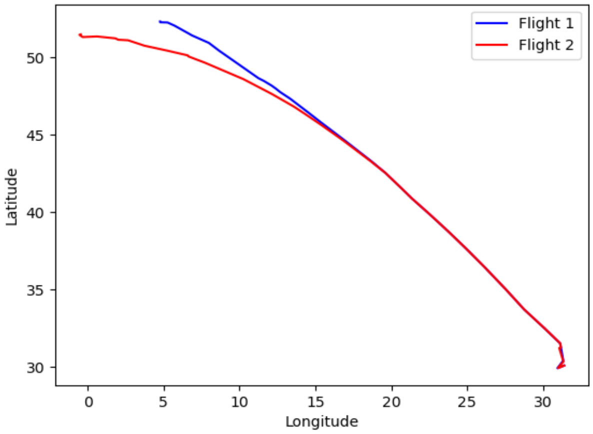

Figure 4. Latitudes and Longitudes representation of the flight MSR758 represented in blue and the flight MSR778 represented in red. Both flights belonging to October 5, 2022.

Upon analysis of Figure 4, it is evident that there exists a correlation between the space trajectories of VLG22TN and TVF37TS.

Therefore, it is crucial to analyze the results of the total number of flights obtained, specifically the azimuth difference between their trajectories, to determine the number of flight pairs that have parallel or semi-parallel paths. A histogram is generated that reflects the number of flight pairs according to the azimuth difference of their trajectories.

To achieve more precise result of the amount of potential FF candidates, a histogram with the flight pairs formed as a function of the difference in azimuth without applying any heuristics for the filter is shown in Figure 6. This histogram provides a nuanced depiction of the distribution of flight pairs formed based on their differences in azimuth, which shall serve as a valuable tool in the analysis of the results.

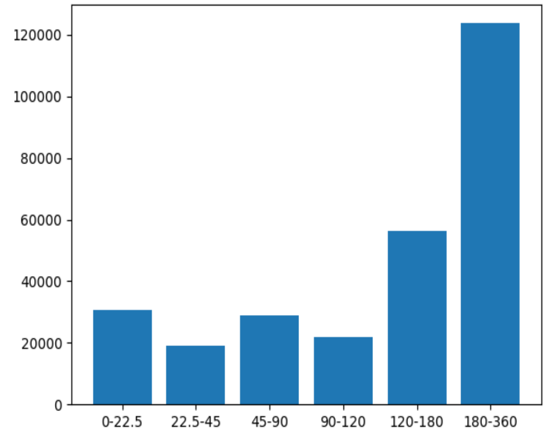

Figure 5. Histogram of the number of flight pairs according to the difference between the azimut of the respective trajectories.

Based on the histogram at the Figure 5 and considering that the total amount of flights on October 5 was 29109 flights, it is evident that a significant amount of flight pairs tends to follow parallel and semiparallel trajectories (azimuth between 0^{o} and 45^{o}) as the example of the Figure 2 case A.

Results achieved shows several candidates for a given aircraft, however, in order to reduce the set of candidates that can provide longest shared trajectories, it is necessary to examine at which flight stage each candidate aircraft is in when they become pairs, whether in the initial (T1), intermediate (T2), or final (T3) stage. By doing so, flights that approach their final trajectory segment can be eliminated to find the most optimal flight pairs and use a Formation Flight strategy aimed at achieving greater benefits in terms of costs and CO$_2$ emissions. Flight pairs where either flight is in its final or intermediate trajectory segment would not be suitable for the final analysis. Therefore, by carefully analyzing the stage at which each flight becomes a pair, the most viable flight pairs can be selected for further analysis and evaluation.

To perform this analysis, we will use the 5578 flight pairs that are formed after filtering the total pairs by the difference in azimuth.

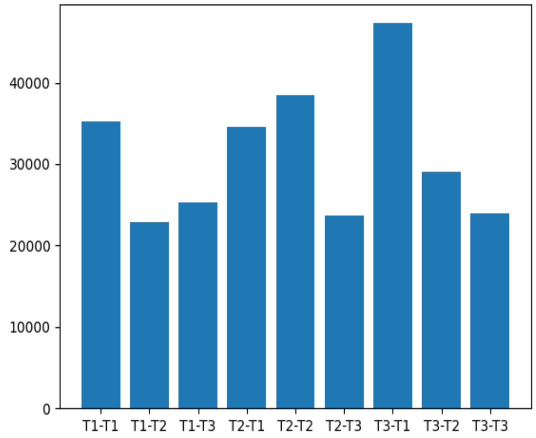

Figure 6. Histogram of the number of flights according to the location of the trajectory section they were on.

In order to gain a deeper comprehension of the analysis presented in Figure 6, it is imperative to have knowledge about the application of the trajectory section filter. The division of each flight's trajectory into three distinct sections was carried out according to specific criteria and can be outlined as follows:

- T1: represents the ascent phase. This section goes from when the aircraft is on the ground until it reaches a height of 180 FL (Flight Level), which is the height considered by the top of climb, the point at which the climb phase is completed and the aircraft moves on to the cruise phase.
- T2: represents the cruise phase of the aircraft.
- T3: descent phase. This section goes from when the aircraft descends to less than 180 FL and arrives at the destination.

Figure 6 represents the results achieved by the pairing algorithm, segmented by the flight stage. This graph uses the potential pair of flights without any prior filtering. This information is quite relevant in the design of a Formation Flight strategy.

Upon analyzing Figure 6, it becomes evident that the majority of aircraft encounters happen during the middle segment of their respective trajectories (T3-T1). This crucial information sheds light on potential areas where action can be taken to execute the Formation Flight strategy. Furthermore, after careful consideration, we can confidently eliminate any flight pairs involving an aircraft in its final trajectory segment (T3), as that flight is not likely to be of benefit in applying the Formation Fly strategy if it is in its final leg of the route. Therefore, for the analysis conducted in this study, only those pairs that are both in the initial segment of their trajectory (T1-T1) should be considered, as these are the ones that will benefit the most from the Formation Fly strategies.

However, some pairs of trajectories that are not in their initial segment during the encounter are currently excluded from consideration. To incorporate these trajectories as potential pairs for implementing formation flights, diverse business strategies can be employed to bring them together sooner. Among these strategies is the approach discussed in section 2.3 of this article titled "Competitive and Cooperative Management." By applying this specific strategy along, it would be possible to expand the pool of feasible pairs and facilitate more efficient implementation of formation flights.

To effectively analyze the benefits of a Formation Flight strategy, must be explored further and a complete example of trajectories that would comply with such a strategy must be provided. By doing so, an in-depth understanding can be gained of how this approach can result in substantial savings not only in terms of CO2 emissions but also in fuel consumption. Thus, by exploring various trajectory options and analyzing their potential impact on the environment and economy, the true value of implementing Formation Flight strategies within aviation industries is better appreciated.

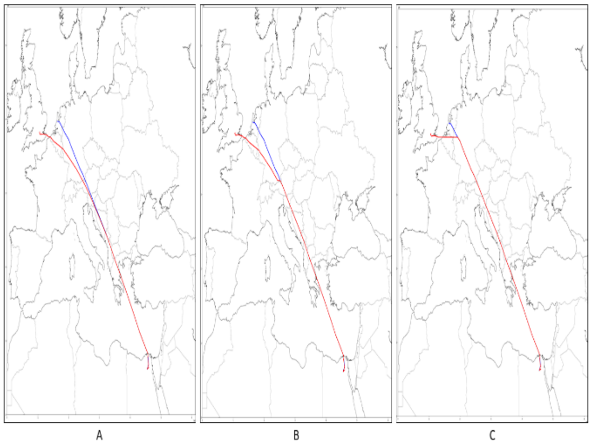

Figure 8. Three Trajectories representations of the case A: the actual trajectory of flight MSR758 represented in blue and the actual trajectory of flight MSR778 represented in red. Both flights belonging to October 5, 2022. The case B: a simulation trajectory of flight MSR758 represented in blue and a simulation of flight MSR778 represented in red. Both flights belonging to October 5, 2022. And the case C: another simulation trajectory of flight MSR758 represented in blue and another simulation of flight MSR778 represented in red. Both flights belonging to October 5, 2022.

Figure 8 on the case A, shows a particular pairing candidate obtained as a result of the causal model and described filtering processes. It becomes clear that the space-time trajectories of MSR758 and MSR778 are indeed interrelated. There exists a distinct correlation between these two aircraft's movements in the sky which hints at their ability to adopt coordinated flight strategies. This is particularly noticeable when observing the point (41.669999999999995, 20.529999999999998) where both trajectories intersect with one another while maintaining a vertical difference of precisely 20FL. In this case, these two flight pairs share a trajectory of 871.49 nautical miles.

Figure 8 on the case B, is a simulation of the modified trajectories of these two flights. The trajectory of flight MSR778 has been modified to intersect with flight MSR758 at point [47.733333333333334, 12.7], thus increasing the number of nautical miles they can operate together in the Formation Flight strategy. By establishing spatial-temporal contact at that point, the two flights would remain together for 1365.12Nm.

Finally, a third simulation has been run, reflected in Figure 8 in case C. In this simulation, the trajectory of the flight MSR778 has also been changed to establish a space-time contact at the point [51.21305555, 7.322222216666666]. This would imply that both flights could remain together for 1660.78 Nm in a Formation Flight strategy.

It can be argued that this intersection represents an optimal position for both planes to employ formation flying techniques and capitalize on each other's presence to achieve greater efficiencies and improve overall performance during flights. Given all these factors taken together, it is confidently to conclude that this particular pairing serves as an ideal case study for exploring the successful implementation of formation flying strategies within aviation contexts today.

After meticulously filtering and analyzing the flight trajectories, 2564 optimal pairs of flights that are capable of executing a Formation Flight strategy have been identified within European airspace. The sheer magnitude of this figure is noteworthy as it represents 8,8% of a total of 29109 potential pairings on October 5th, 2022.

It is important to note that there is an additional set of potential flight pairs that do not meet the applied filters of the criteria for maximum segment sharing between paired flights. To expand further into such possibilities would necessitate significant changes being made in various aspects related to aviation sector practices - specifically concerning creating new trajectories or altering existing ones - or the implementation of new business strategies would be required if there is a real desire to make further progress towards achieving greater efficiency through the implementation of future iterations using formation fly methodologies.

These results demonstrate a realistic and optimistic possibility of implementing Formation Flights within European airspace. Therefore, the technologies and procedural changes implemented in the Atlantic flights to support planned FF can be extended to European airspace under an opportunistic framework.

5. Conclusions

The objective of this paper is to delve into the feasibility study of implementing a strategy that involves Formation Flights within European airspace.

A causal model and a set of constraints (i.e., spatio-temporal Filters and different Heuristics) were implemented to support an in-depth analysis by studying flight trajectories on a particular day. Based on the analysis, it was concluded that the implementation of Formation Fly could be considered a positive strategy for improving efficiency and effectiveness in European airspace.

After the execution of the implemented model, the analysis of the obtained results, and the identified potential regarding the conducted study, it is important to highlight various issues and limitations encountered for future consideration or related research. Although formation fly may become a reality in the future, and their scalability can offer significant advantages, there are still several gaps that need to be addressed. Formation fly has several planning and execution challenges. Adequately equipped aircraft, technologies, procedures, and trained pilots must be available. At the ATM level, it will be necessary to establish new procedures and new forms of communication, both between ATM-Pilot and Pilot-Pilot, to carry out formation flights globally and ensure safety at all times.

To further enhance this study, it is suggested to conduct a new analysis aimed at optimizing business strategies among agents, cost studies that need to be carried out to determine the potential of the identified pairs, as well as the ability to adapt this system to real-time with the application of Artificial Intelligence models. These improvements would allow optimizing the selection process when choosing suitable flight pairs to execute this strategy.

Given the obtained results, we could be facing the possibility of incorporating a change in the European airspace that would bring significant advantages, reducing the CO_2 emissions emitted daily and increasing the operational benefits for the airlines by the implementation of Formation Flight strategies.

Acknowledgements

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