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A Decentralized Approach to Formation Flight Routing

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ABSTRACT

This paper describes the development of an optimization-based cooperative planning system for the efficient routing and scheduling of flight formations. This study considers the use of formation flight as a means to reduce the overall fuel consumption of civil aviation in long-haul operations. It elaborates on the operational implementation of formation flight, particularly focusing on formation flight routing. A completely decentralized approach is presented, meaning that formation flight is not anticipated pre-flight and is not subjected to any predefined routing restrictions. A greedy communication scheme is defined through which all participating aircraft are allowed to communicate with neighboring aircraft in order to establish flight formations. The communication range of aircraft is used as a system parameter to control the allowed communications. A constraint on formation flight induced additional flight time is introduced in order to suppress the occurrence of large detours in the assembly of flight formations. A transatlantic case study is presented that contains 347 eastbound flights. Assuming a 10% fuel flow reduction for any trailing aircraft in formation, overall obtainable fuel savings were estimated at 4.3% at the expense of an additional flight time of 10.3 minutes per flight on average. In this transatlantic long-haul scenario, a formation flight usage rate of 73% was realized.

KEY WORDS: flight formations, flight routing, decentralised planning, fuel-efficiency

1 INTRODUCTION

Over the past decades, formation flight has become a recognized method when considering possibilities to increase the fuel efficiency of civil aviation. Compared to other efficiency measures, such as innovative aircraft designs, formation flight requires a limited amount of new technology, as implementation largely boils down to operational changes. Therefore, formation flight is an attractive potential efficiency measure, as it could be implemented by airlines without requiring extensive new equipage and related investments.

By examining the flight behaviour of birds, as done by Lissaman in 1970, a general understanding of the (aero)dynamics of formation flight was developed [Lissaman and Shollenberger, 1970] . As the potential for fuel savings became more apparent, flight tests were conducted to confirm this finding [Ray et al, 2002] , and more recently in [Flanzer and Bieniawski, 2014]. The latter study considered formation flight of two military C-17 aircraft and reported achieved fuel savings of 5-10% for the trailing aircraft, increasing with mission length.

To make use of the acquired knowledge, the practical implementation of formation flight was explored. In [Ribichini and Frazzoli, 2003] an approach to formation flight routing for UAVs was presented. In this study a greedy algorithm was applied that considered formation flight as an in-flight option. This locally coordinated use of formation flight characterizes what will be called a *decentralized approach*. In later years, the focus in the research area shifted to the routing and scheduling of formation flights for an entire fleet. Such an approach will be called a *centralized approach*, since formations are pre-determined at a network level. An example of such a centralized approach was presented in [Kent and Richards, 2012]. In this study, a geometric formation flight routing method is developed that also has been adopted and extended in the present work. In a transatlantic case study, Kent et al. estimate the overall achievable fuel savings to be slightly over 10%, using formations that comprise up to 4 aircraft.

According to [Xu et al., 2014] a centralized approach has several weaknesses, such as its vulnerability to delayed flights and computational inefficiency in larger scenarios. Theoretically, however, a centralized approach could provide estimations regarding the highest possible fuel savings that can be obtained from introducing formation flight on a certain set of routes. Recent works were limited in applying the required global optimizations, due to exponentially increasing computation times with increasing formation and network sizes. In an effort to further decentralize the organization of civil formation flight [Xue et al., 2012] considered the use of corridors in the sky over North America along which each flight would be routed. While residing in a corridor, flights were allowed to adjust their speed in order to form a formation. The authors showed that this approach made it possible to manage delayed flights as these were able to find alternative formation flight partners within the corridors. However, redirecting all flights through the corridors required a significant fuel investment for all aircraft, without having a guarantee that they would all be included in a formation.

The research presented in this study aims to evaluate the fuel saving potential for civil aviation of a completely decentralized approach to formation flight routing, inspired by [Ribichini and Frazzoli, 2003]. When a decentralized approach is considered, the issues related to delayed flights and computational limitations are potentially circumvented. This research aims to elaborate on this, as well as on the costs of postponing the decision to fly in formation. The sections that follow will provide a problem formulation and the proposed operational concept. Next, this paper discusses the routing method and the calculation of fuel consumption. A transatlantic case study is presented, from which the conclusions of this paper originate.

2 PROBLEM STATEMENT

Due to its nature, a centralized approach provides results that are heavily dependent on the ability to stick to the original flight schedules [Xue et al., 2012], [Kent and Richards, 2013]. The estimation of obtainable fuel savings decreases near-proportionally with the percentage of delayed flights [Xue et al., 2012]. Since flights are often delayed in every day operations, the preferred formation flight implementation method is able to permit delayed flights to become part of a formation as well. In general, a disruption in one of many flight plans, which is a local event, should be solved locally as well, seeing that re-optimizing unaffected parts of a set of flight plans is likely to be inefficient. In other words, when a disruption in the implementation of formation flight occurs, a decentralized view is suitable for resolving the disruption.

A second challenge is identified in providing the required computational resources that are required by centralized approaches. These approaches already push calculation times to workable limits [Xue et al., 2012], [Kent and Richards, 2012], [Kent and Richards, 2013]. Because of the computational load, proposed centralized approaches are not able to consider formations comprising more than four aircraft and they do not permit an aircraft to become part of consecutive formation flight missions. It is expected that larger formations will be relatively more beneficial [Herinckx et al, 2011]. Also, when a single aircraft can be part of more than one formation during its flight, the use of formation flight will become more flexible. This flexibility may facilitate the implementation of formation flight in disrupted or more diverse flight scenarios.

In order to benefit from formation flight, an initial investment is inevitable. Flights must invest time and fuel to join a formation. When their cumulative investment is more than compensated for by the obtainable fuel savings during the formation flight, the overall formation flight mission might be preferable over a set of solo missions. If the elapsed time between the decision to fly in formation and the actual initiation of the formation increases, so does the risk that is associated with the fuel and time investments. This risk needs to be managed carefully for formation flight to become a reliable method for fuel consumption reduction. These identified challenges motivated the development of a decentralized approach to formation flight routing.

3 OPERATIONAL CONCEPT

3.1 Optimal control formulation

Inspired by [Ribichini and Frazzoli, 2003, a decentralized approach to formation flight routing is considered, in which formation flight is not anticipated pre-flight. Formation flight is treated as an in-flight option. This means that any decision related to formation flight is made based on available in-flight information. By postponing the decision to fly in formation as long as possible, the risk of an unsuccessful formation flight attempt is reduced.

While flying, all involved aircraft may communicate with other aircraft within a certain communication range. The communication range is defined as the radius of a circle around each aircraft. When two circles of neighboring aircraft touch or overlap, the corresponding aircraft can communicate. Communications are herein defined as the formulation and evaluation of a possible formation flight decision. If an opportunity to fly in a formation presents itself, the potential benefits are compared with the required investments in terms of fuel consumption and the formation flight option is either accepted or rejected. Once a formation is formed, the formation leader may again communicate in order to add consecutive formation flight segments to the flight plan of the formation that he represents. Any aircraft can communicate with at most one other aircraft at a time. These aircraft may be solo flight or formation leaders.

Figure 1 presents a flow diagram of the developed operational concept. Each aircraft that is considered in this work behaves in accordance with Fig.1. There are several loops in the decision scheme in Fig. 1. These illustrate the continuous effort of flights to find potential formation flight partners with whom they may team up to achieve additional cumulative fuel savings.

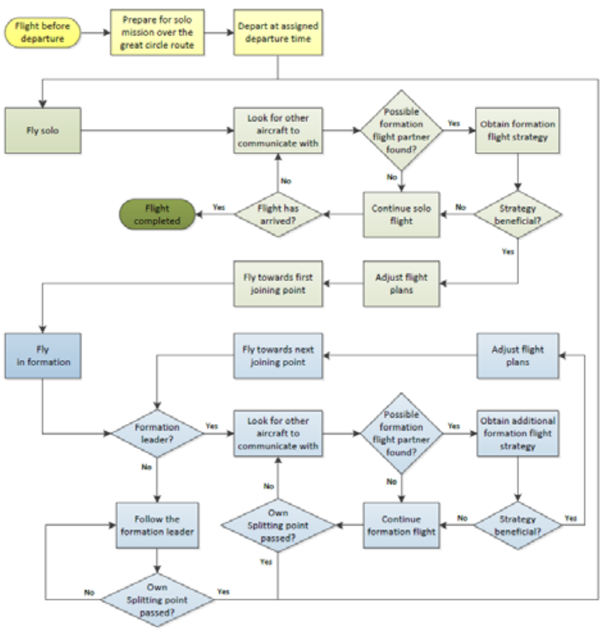

Figure 1: Flowchart of the operational concept

As soon as flights are ready, meaning that their starting weight and their initial heading have been determined, they depart at their assigned departure time. Note how each flight starts out on a solo flight segment that might extend all the way to the intended destination. This is a key feature of the developed decentralized approach; individual flights do not anticipate the use of formation flight. At some point in time, two flights may commit to a formation flight decision and adjust their flight plans accordingly. They alter their heading and speed in order to meet each other at the agreed time and location, the latter of which is called the “joining point”. The process during which aircraft invest time and fuel to join a formation is hereafter referred to as ‘synchronization’. When two, or more, flights have successfully joined in a formation, one of the aircraft has to be assigned as the formation leader. Within the scope of this work, the formation leader does not experience any benefits from formation flight. To track the fuel requirements of each flight, a leader must therefore be selected in each newly formed formation.

The formation leader may, similarly to a solo flight, attempt to communicate with other aircraft as a means to find additional formation flight partners. Note how the formation leader follows the same decision scheme as a solo flight, be it on behalf of the entire formation. The formation continues to exist up until the ‘splitting point’, defined as a point where a flight leaves a formation. After flying over a splitting point, the two flights that committed to that splitting point, head off to their respective individual destinations. Note that these destinations may correspond to the splitting points of smaller formations that together, until recently, formed a larger string. A flight that does not lead a formation, is referred to as a ‘follower’. Followers may not change their own flight plan any further, until they have reached their splitting point. The formation leaders ensure that they only commit to consecutive formation flight decisions that result in cumulative benefits.

Figure 1 suggests that each last segment of a mission is a solo flight segment. In both reality and within this work, this is most likely to occur, hence the process is represented as such. However, it is noted that the developed model allows communicating flights with common destinations to place their splitting point on this common destination.

4 FUEL CONSUMPTION ASSESSMENT

The transatlantic routes are modeled in this study as great circle paths from origins to destinations. Moreover, it is assumed that the entire route is flown in cruise at a constant altitude and at constant speed. The fuel consumption along the routes is estimated using the well-known Breguet-range equations [Vinh, 1993], assuming the absence of wind. The constant speed along the route is taken as the best specific-range speed at maximum take-off weight. This typically results in a speed close to the maximum cruise speed. Since we consider all aircraft to be of the same type, it also implies that all aircraft essentially fly at the same speed (except during synchronization flight legs) in this study. The aircraft model parameters, based on data of the B777, have been extracted from [Kent and Richards, 2012].

The actual take-off weight for a specific flight is calculated using the Breguet-range equation assuming that at destination the weight of the aircraft is equal to the zero-fuel weight plus the weight of the reserve fuel. Given the aircraft weight at destination, and the distance covered along the route, the aircraft weight at the origin can be assessed using the Breguet-range equation, for the assumed speed and altitude. To allow for the fact that aircraft may have to fly detours and thus longer routes in order to engage in flight formation, the initial fuel load is increased by 10%, increasing the take-off weight accordingly.

As indicated, in the present scenario aircraft essentially fly at one and the same speed throughout their flight. The only exception is when aircraft execute a synchronization flight leg in order to rendezvous with their formation partners, in which case one of the two aircraft has to slow down. Note that the minimum speed in a synchronization flight leg is the maximum endurance speed. In case that flying at the maximum endurance speed is not sufficient to absorb the required delay time, the joining point will need to be adapted. Flying a synchronization flight leg at a lower speed typically results in a fuel penalty.

In this study it is assumed that flying in a formation will generate a 10% reduction in fuel flow for any trailing aircraft in a flight formation (regardless of the size of the formation). This is a rather conservative estimate which will to some extent compromise the overall benefits of flight formation.

5 FORMATION FLIGHT ROUTING

To generate routes for the assembly of formation flights, a routing method was used based on [Kent and Richards, 2012]. In this approach a formation flight route is obtained through the minimization of weighted distance. The routing method from Kent & Richards is extended herein for application within the developed decentralized approach.

5.1 Geometric routing method by Kent & Richards

In [Kent and Richards, 2013], a simple geometric method to construct a formation flight routing is proposed, based on a classical mathematical problem posed by Fermat in the 17th century. The problem is illustrated in Fig.2. Given a triangle ABC (Fig.2.a), find a point P such the that the sum of the distances $\|AP\|$, $\|BP\|$ and $\|CP\|$ is minimized. The geometric approach to construct the solution to this problem is illustrated in Fig.2.b. The method is based on constructing outwardly three equilateral triangles along the sides AB, BC and CA. Then the lines from the outer vertex of each new triangle to its opposite vertex of the original will intersect at a single point, which is the desired point P. Equivalently, the point P can be found as the intersection point of the circumscribed circles of each of the three new equilateral triangles.

Fermat's problem provides a good analogy to the formation flight assembly problem, if it is assumed that fuel consumption is proportional to the distances covered. However, it is readily that the fuel consumption per unit distance along the solo arcs $\| AP \|$ and $\| BP \|$ differs from that on the formation flight arc $\| PC \|$. To resolve this issue Kent & Clarke formulated a weighted-arc version of the problem, where the weights reflect the different fuel consumption per unit distance. More specifically, to represent the cost of flying a unit of distance, the routing weights w_A, w_B, and w_C are introduced for the segments AP, BP, and PC, respectively. Note that the value of w_C is typically set equal to the combined values of w_A and w_B, while applying some discount factor to represent the fuel savings due to induced reduction of the trailing aircraft.

Thus, in the modified problem the location of the joining point P has to be selected such that the total cost of distance, expressed by Eq.1 is minimized:

$$\underset{P}{Minimize}: \quad f(P) = w_A \cdot \| AP \| + w_B \cdot \| BP \| + w_C \cdot \| PC \| \tag{1}$$

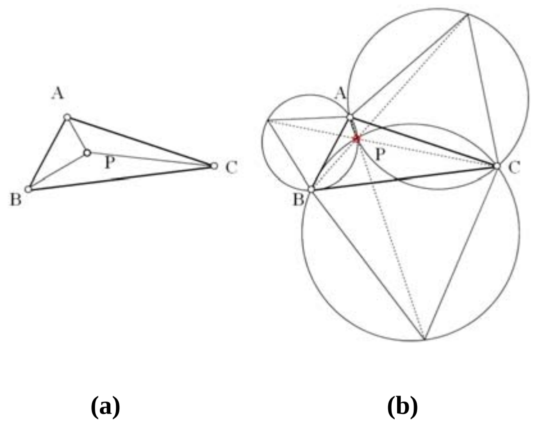

Figure 2: Geometric construction to locate the optimal joining point P [Kent and Richards, 2013]

Following Kent & Richards, the location of point P that minimizes Eq. 1 must satisfy the vectorial equilibrium condition expressed by Eq. 2:

$$w_A \cdot \frac{AP}{\| AP \|} + w_B \cdot \frac{BP}{\| BP \|} + w_C \cdot \frac{PC}{\| PC \|} = 0 \tag{2}$$

Application of the law of cosines to Eq.(2) yields expressions for the intersection angles ∠APB, ∠APC, and ∠BPC. Since the angle ∠APB represents the intersection angle between the two solo legs AP and BP, it is referred to as the "formation angle". Equation 3 gives the expression for the resulting formation angle θ_f:

$$\theta_f = \cos^{-1}\left(\frac{-w_A^2 - w_B^2 + w_C^2}{2 w_A w_B} \right) \tag{3}$$

Note that the formation angle θ_f only depends on the routing weights w_A, w_B, and w_C. The formation angle is illustrated in Fig. 3. It is noted that as long as the weights w_A, w_B, and w_C are not changed, also the formation angle θ_f remains unaffected. As a result, the point C can be shifted freely along the line PC, without altering the solution.

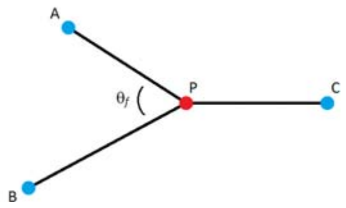

Figure 3: Illustration of formation angle

The method for locating point P can be extended to a scenario in which the two flights do not have a common destination C. Figure 4 illustrates two solo routes connecting origins A and B to destinations C and D, respectively. The joining point J and the splitting point S are to be determined. Since the formation angle condition must be satisfied at both J and S in order to minimize the weighted distance, one can draw two circular arcs from A to B and from C to D along which the formation angle is constant and equal to the value obtained from Eq. 3. These arcs are can be found in Fig. 5.

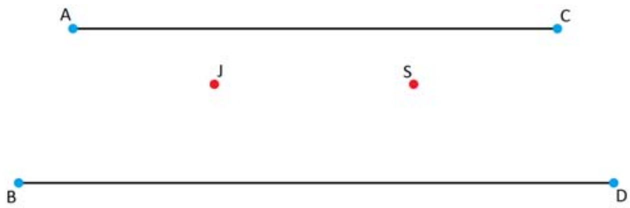

Figure 4: By locating J and S, a formation flight route is obtained for the solo routes AC and BD

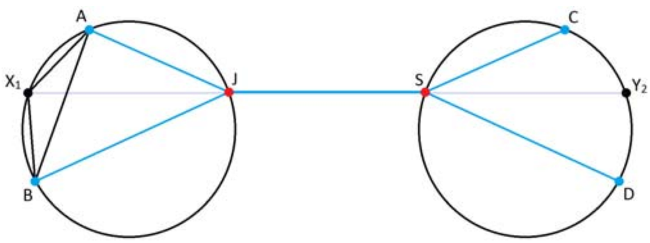

Figure 5: Geometric construction of the formation flight route

The point X_1 in Fig. 5 is obtained by making use of the fact that Eq.(4) holds in triangle ABX_1:

$$|AB|:|BX_1|:|X_1A| = w_C : w_A : w_B \tag{4}$$

Mirroring the described steps at the destinations C and D provides the point Y_2. The locations of J and S that minimize the weighted distance from A to C and from B to D are obtained from the intersections of the line from X1 to Y2 and the arcs of constant formation angle.

Figure 6 illustrates how the formation flight route would change if $w_A > w_B$. The green route shows the effect on the formation flight route of using $w_A > w_B$ with respect to the blue route where $w_A = w_B$. Since the flight from A to C is now considered more expensive per unit of distance, the detour for the corresponding aircraft is reduced in length.

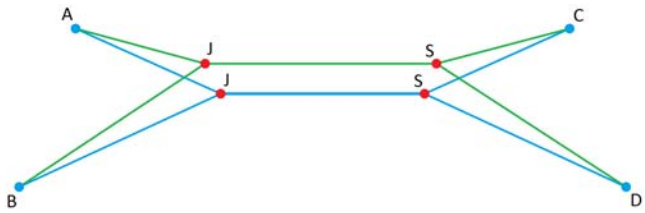

Figure 6: Flight formation route assembly; for the blue route $w_A = w_B$, for the green route $w_A > w_B$.

5.2 Accommodating synchronization in the basic routing method

In contrast to the work of Kent et al., or to any centralized approach, the decentralized approach that is developed herein considers formation flight to be an in-flight option. Therefore, any set of flights that will use the routing method, will do so while flying towards their respective destinations. For formation flight to be realized, the route must be constructed such that the two (strings of) aircraft are able to arrive at the joining point simultaneously. Ensuring the latter is referred to as "enabling synchronization". For relatively symmetric routes, synchronization may often be accomplished by slightly slowing down one of the aircraft. If the obtained formation flight route does not enable synchronization, the joining point must be relocated. Accordingly, one aircraft is slowed down to V_{min} (i.e, the maximum endurance speed which is the speed with lowest consumption per unit of time) while the other maintains its cruise speed V_{cruise} (which is close to the maximum cruise speed). It was chosen to restrict the possible relocations of the joining point J_{new} to be on the original formation flight segment $J_{old}S$. Moving J closer towards S will postpone the initiation of formation flight, but will reduce the detours that both aircraft have to fly.

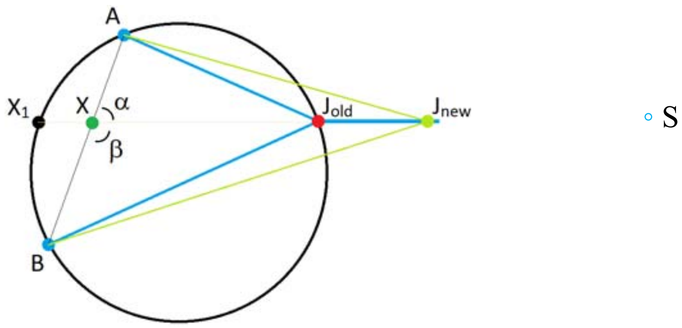

Figure 7: Relocation of joining point J to enable synchronization

In Fig. 7, the current locations A and B with the originally determined joining point, indicated as J_{old}, are Shown. The point X shown in Fig. 7 is defined as the intersection of the lines AB and X_1J_{old}. Application of the law of cosines to the triangles AXJ_{new} and BXJ_{new} , yields the following quadratic relation, for any given speed ratio $\gamma = V_B/V_A$:

$$\left(\gamma^2-1\right)^2\left(XJ_{new}\right)^2+\left(2XB\cdot\cos\beta-\gamma^2\cdot 2XA\cdot\cos\alpha\right)XJ_{new}+\gamma^2\left(XA\right)^2-\left(XB\right)^2=0 \text{ ,} \quad (5)$$

where it is assumed that V_A is equal to V_{min} and V_B equal to V_{cruise} in the sketched geometry ($AJ_{new} < BJ_{new}$). Equation 5 can be solved for the side length XJ_{new}, that can subsequently be used to construct the location of the new joining point J_{new} that enables synchronization.

6 TRANSATLANTIC CASE STUDY

6.1 Baseline scenario

The proposed operational concept as presented in Fig. 1 is applied to 347 eastbound transatlantic flights. The routes included in the case study, given in Fig. 8, are obtained from an available data set [Van Lith, 2012] by means of selecting longitude/latitude of the origins and destinations. No distinction was made between operating airlines or any other route specifics.

In the simulation set-up, the location of each aircraft along a great circle route is integrated numerically with a time step size of 5 minutes. This time step size was found to be sufficiently small to demonstrate the potential of the developed method. All other aircraft parameters, such as speed, heading, current weight, fuel flow settings, and formation flight status are only revisited when required. There are three types of events that may trigger such an update: (i) two flights commit to a formation flight decision, (ii) a joining point is passed, or (iii) a splitting point is passed.

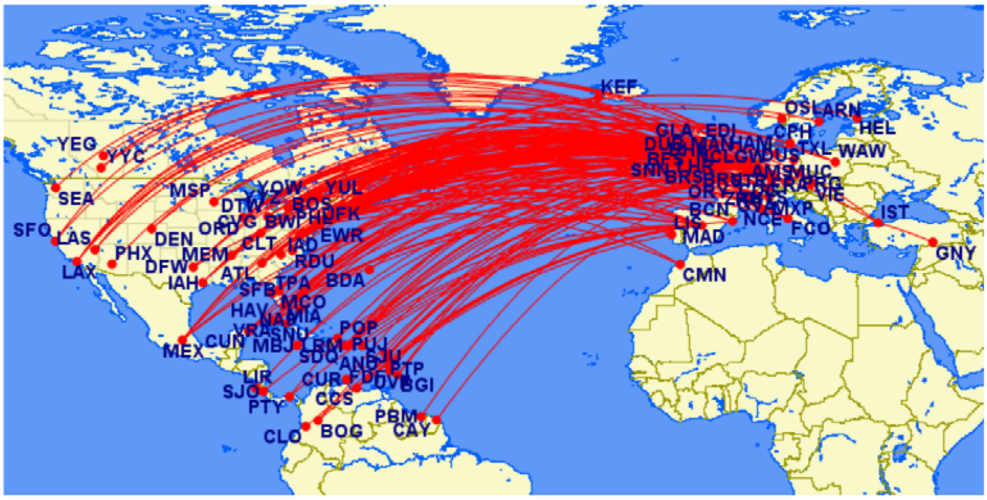

Figure 8: Route set used in the case study (created using Great Circle Mapper;www.gcmap.com)

Table 1 provides the configuration of the model in the baseline scenario. The communication range is set to 250 km and all aircraft successfully depart according to the original schedule. Any formation flight option that saves any amount of fuel is immediately accepted, regardless of the increase in flight time that flights will experience. In this model configuration, a typical simulation of the baseline scenario requires about 6 minutes of calculation time on a standard PC, including result visualization in graphs and the creation of an animation.

Table 1: Model configuration parameters

Parameter	Value
dt	5 min
Communication Range	250 km
Allowed additional flight time/decision/aircraft	∞ min, no limit
Departure times	According to schedule
Accept formation flight route if	It saves any amount of fuel

Figure 9 shows a snapshot of the simulation 200 minutes into the flight. Referring to the legend in Table 2, several observations can be made with respect to the results shown in Fig. 9. It is noted that an engaged formation of flights will still be shown in purple. A flight is referred to as engaged, when it is committed to a particular flight formation but is still flying towards a joining point.

From the origins shown in the left half of Fig. 9 (indicated by blue dots) flights are departing. As they fly towards their destination, they start out as a green dot, as they are still flying solo. After some time, most flights engage to another flight to join in formation, causing them to change their flight plan and to turn cyan in the figure. Some flights are still flying solo, even though they have been in the air for a while. Note that most of these flights are not in the vicinity of other aircraft that are allowed to communicate. Later on, the majority of these flights will be part of a formation, illustrating the sub-optimality of the greedy communication algorithm. The purple dots show the formed formations and their size. In the middle, already two formations of size 5 have been established. In the top region, many cyan flights are seen, which are flying along synchronization segments towards their joining point.

Table 2: Legend to Figs. 9-11

Dot property	This represents:
Blue	Origin/Destination location
Green	Solo flight
Cyan	Engaged flight
Purple	Formation
Dot size	Proportional to formation size

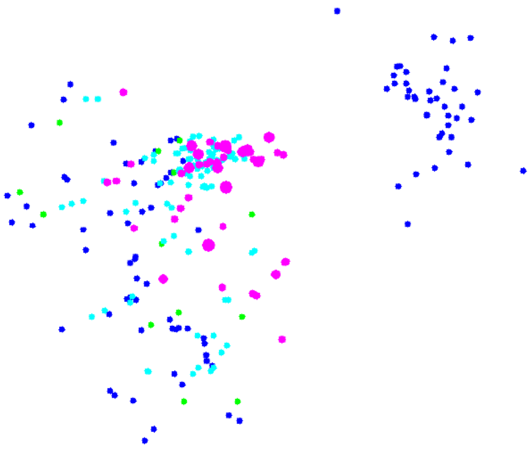

Figure 9: Snapshot at time step 41

Figure 10: Snapshot at time step 81

Moving on to Figure 10, showing the same flights 200 minutes later, it can be seen that the supply to the eastbound stream of aircraft has reduced. As a matter of fact, all flights have departed at this stage of the simulation. Many formations of different sizes have emerged in the top half of the figure. The largest formation in use at this point, and at any point, comprises 15 aircraft. A closer inspection showed that a formation of size 8 and a formation of size 7 had earlier accepted a formation flight decision. The green dots at the front indicate flights that have split off from their formations; they are heading towards their destination by means of a solo flight segment.

Figure 11 provides the situation another 200 minutes later, at which point quite some flights have reached their destination. Many solo flights are completing their final segment towards their destination. While only three cyan dots are distinguishable at this specific time step, it was found that many flights and formations re-engage to a next formation flight decision in the second half of their respective missions. It is not surprising that a few of the flights that were last in line to depart, do not manage to become a formation member. The combination of the location of their origin and their departure time prevents them from encountering any formation flight options.

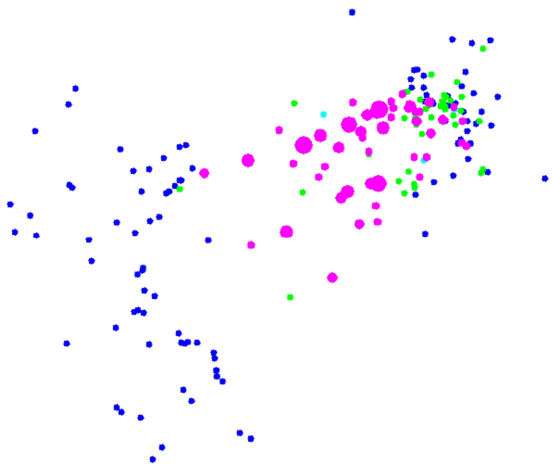

Figure 11: Snapshot at time step 121

Figure 12 presents the additional flight times that aircraft have to incur due to the implementation of formation flight. The average additional flight time is about 17.6 minutes. Figure 13 shows the distribution of the total flight time over the used formation sizes. It is noted that 72% of the total flight time is spent in a formation. Significant use is made of formations that comprise up to 7 aircraft. Occasionally, larger formations occur.

Table 3 summarizes the main performance results obtained in the conducted simulation. The overall obtained fuel savings amount to 3.6% relative to using only solo flights. For operations with the standard aircraft that was defined (B777), this would be equivalent to saving $5.6 \cdot 10^5$ kg of fuel. From analysis of the used flight trajectories, it was found that significant fuel investments are required to realize synchronization. This obviously compromises the overall obtainable fuel savings to quite an extent.

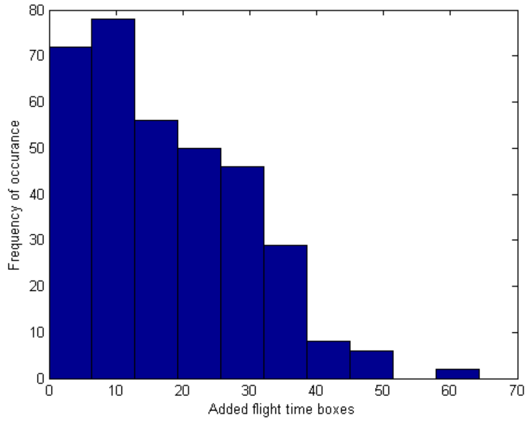

Figure 12: Additional flight time distribution in baseline scenario

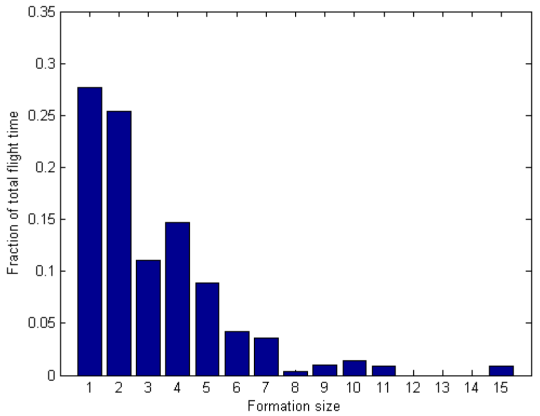

Figure 13: Flight time distribution over formation sizes in baseline scenario

A similar simulation effort was performed for the case that flights were randomly delayed. The obtained overall fuel savings and the use of formation flight were found to be very similar. The decentralized implementation of formation flight allows delayed flights to participate in formation flight with any aircraft that it may still encounter.

6.2 Adding an incremental flight time constraint to the baseline scenario

The significant additional flight times that were found in the baseline scenario, as displayed in Fig 12, motivated a model set up in which the additional flight time was limited. A limit was introduced on the additional flight time that an aircraft was allowed to incur from a single flight formation decision. In this study a 10 minute limit is applied to each formation decision in the simulation. It still remains possible for an aircraft to take part in multiple formations throughout its flight in this scenario.

Figure 14 presents the new distribution of additional flight times over all the involved aircraft. The average additional flight time has decreased to about 9.9 minutes. Figure 15 displays the new distribution of the total flight time over the used formation sizes. While the usage rate of formations of size 4 has increased, the general use of formations is quite similar. Remarkable is the fact that the overall obtained fuel savings have actually increased to 4.2%. This can be explained from the fact that a greedy algorithm has been employed, as will be outlined in more detail in the next section.

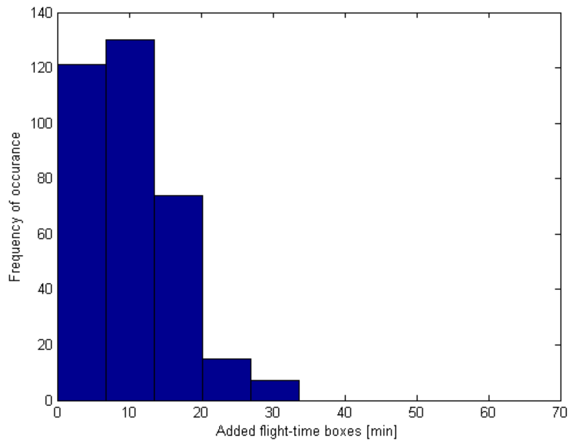

Figure 14: Additional flight time distribution in modified scenario

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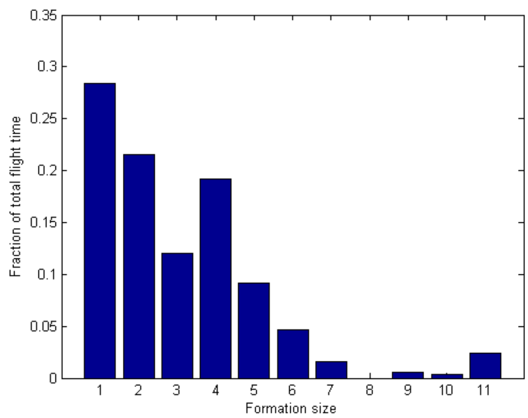

Figure 15: Flight time distribution over formation sizes in modified scenario

6.3 Influence of communication range

Since the communication range directly determines the nature of the formation flight options that flights can encounter, a study is performed that assess how the overall obtainable fuel savings vary with the communication range. Given the positive relation that was observed between the overall obtained fuel savings and the limit on additional flight time, the communication range is varied with and without the use of this limit.

Figure 16 shows the results of 120 (60 per scenario) Monte Carlo simulations of the 347 transatlantic flights in this case study, featuring stochastic variations in schedule delay. The blue line represents the results for the scenario without the limit on additional flight time. As the communication range is increased, flights are allowed to communicate with other flights that are further away. Up to a communication range of 50 km, a steep increase in obtained overall fuel savings is recorded. This can be explained by the fact that the amount of encounters between aircraft has increased significantly. This leads to more formation flight options being evaluated and, evidentially, accepted. For communication ranges of 50 to 120 km, the increase in obtained fuel savings persists albeit with a smaller average gradient. Indeed, the system model still finds additional/more beneficial formation flight options. At a communication range of about 120 km, the maximum obtainable fuel savings are recorded. These savings amount to 4.2% relative to solo flights over all simulated routes. Increasing the communication range from 120 to 600 km reveals a gradual decrease in obtained fuel savings that appear to level off at around 3.0%. The gradual decrease in obtained savings can be readily explained. When the communication range is increased beyond 120 km, formation flight options that require relatively larger detours are encountered. Some of these will be accepted by the greedy communication algorithm, if they will result in cumulative fuel savings. Apparently, these decisions can be sub-optimal, as the overall obtained fuel savings decrease when the communication range is increased beyond 120 km.

The green curve in Fig. 16 relates to the simulation results for the scenario where the limit on additional flight time is included. Note how, after arriving in the 4.2% region, overall fuel savings are maintained as the communication range increases further. It is concluded that the limit on additional flight time counteracts the negative effect that encountering sub-optimal formation flight decisions has on the overall obtainable fuel savings, by restricting the acceptable detours to establish formation flight. The highest estimation of overall obtainable fuel savings, which amounts to 4.3%, is obtained for a communication range of 440km, while using the limit on additional flight time of 10 minutes per aircraft per formation flight decision.

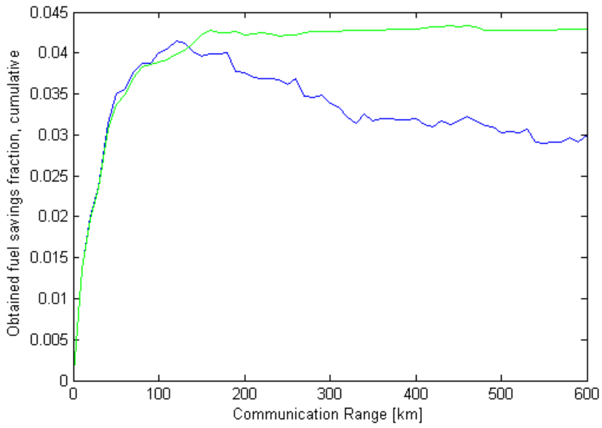

Figure 16: Obtainable fuel savings vs. communication range.
Blue: no limit on additional flight time;
Green: limited additional flight time

7 CONCLUSIONS

This paper proposes a decentralized cooperative planning system for the efficient routing and scheduling of flight formations. In the case study that was presented, the planning system proved to be flexible, reliable and efficient. The formation flight routes that were generated exhibited many similarities to those found in the literature. However, the developed decentralized approach is able to efficiently evaluate scenarios where there is no limit on formation size. Additionally, this work includes the use of consecutive formation flight options, which delivers a significant increase in the overall formation flight usage rate. Introducing formation flight as an in-flight option enables delayed flights to contribute to the fuel saving objective.

For future research it is recommended to enable aircraft to communicate with multiple neighbors at the same time. Accordingly, the forming of formations may be realized more efficiently. Delayed flights do not pose challenges to the decentralized approach to formation flight implementation. However, the developed decentralized approach may bring about significant fuel penalties to realize synchronization. Possibly, these penalties can be attenuated by applying some form of pre-flight planning. These notions suggest a combined approach to formation flight planning that incorporates both centralized and decentralized elements.

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