A decentralized approach to formation flight routing

First A. Author[1] and Second B. Author, Jr.[2]
Business or Academic Affiliation 1, City, State, Zip Code

Third Author[3]
Business or Academic Affiliation 2, City, Province, Zip Code, Country

This paper considers the use of formation flight with passenger aircraft as a means to reduce the overall fuel consumption of civil aviation. It elaborates on the operational implementation of formation flight, focussing on formation flight routing. A completely decentralized approach is presented, meaning that formation flight is not anticipated pre-flight and that there are no predefined routing restrictions. A greedy communication scheme is defined through which all aircraft are allowed to communicate with other aircraft in order to form formations. The communication range of aircraft was used to control the allowed communications. A constraint on formation flight induced additional flight time aided in suppressing the willingness of aircraft to fly large detours. A transatlantic case study is presented that contains 347 eastbound flights. Assuming a 10% fuel flow reduction for any trailing aircraft, overall obtainable fuel savings were estimated at 4.3%. With respect to total flight time, a formation flight usage rate of 73% was realised.

Nomenclature

C_D	Drag coefficient	[-]	A,β	Angles	[deg]
C_L	Lift coefficient	[-]	ρ_∞	Free-stream density	[kg·m^{-3}]
C_t	Thrust specific fuel consumption	[-]	θ_f	Formation angle	[deg]
dt	Time step	[min]	A/B	Origins A and B	[-]
R	Range/segment length	[km]	C/D	Destinations C and D	[-]
S	Wing surface area	[m^2]	J	Joining point	[-]
T_A	Available thrust	[kN]	S	Splitting point	[-]
$V_{max}/_{min}$	Maximum/minimum speed	[ms^{-1}]			

I. 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 limited amounts of new technology, since implementing it could mainly be an operational change. Therefore, formation flight is an attractive potential efficiency measure, as it could be implemented by airlines without the requirement for new equipment and related investments.

By examining the flight behaviour of birds, as done by Lissaman in 1969, a general understanding of the (aero)dynamics of formation flight was developed[7]. As the potential for fuel savings became more apparent, flight tests were conducted to confirm this, i.e. by Ray et al in 2002 and more recently by Flanzer et al. in 2014 [9,3] The latter used 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 considered. In 2003, Ribichini et al. presented their approach to formation flight routing for UAVs[10]. They used a greedy algorithm 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 turned 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 on a network level. An example of such a centralized approach was published by Kent et al. in 2012[5]. They developed a geometric formation flight routing method

[1] Insert Job Title, Department Name, Address/Mail Stop for first author.
[2] Insert Job Title, Department Name, Address/Mail Stop for second author.
[3] Insert Job Title, Department Name, Address/Mail Stop for third author.

that has been adopted and extended in this work. In a transatlantic case study, Kent et al. estimate overall achievable fuel savings to be slightly over 10%, using formations that comprise up to 4 aircraft.

According to Xu et al., a centralized approach has several weaknesses, such as its vulnerability to delayed flights and computational inefficiency in larger scenarios[12]. 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. considered the use of corridors in the sky over North America along which each flight would be routed[13]. While in a corridor, flights were allowed to adjust their speed in order to form a formation. They showed that their approach was able to manage delayed flights as these were able to find alternative formation flight partners in 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 part of a formation.

The research presented in this article aims to evaluate the fuel saving potential for civil aviation of a completely decentralized approach to formation flight routing, inspired by Ribichini et al.[10] When a decentralized approach is considered, the threats of delayed flights and computational limitations are potentially circumvented. This research aims to elaborate on this as well as on the costs of postponing de decision to fly in formation. The sections that follow will provide a problem formulation and the designed operational concept. Afterwards, 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.

II. Problem formulation

Through the nature of a centralized approach, the results that it provides are heavily dependent on flight schedules[6,13]. The estimation of obtainable fuel savings decreases close to proportionally with the percentage of delayed flights[13]. Since flights are often delayed in every day operations, the preferred formation flight implementation method is able to let delayed flights 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[5,6,13]. Because of this, they are not able to consider formations comprising more than four aircraft and they cannot let an aircraft be part of consecutive formation flight missions. It is expected that larger formations will be relatively more beneficial[4]. Also, when a single flight can be part of more than one formation, 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 become a formation member. When their cumulative investment is more than compensated for by the obtainable fuel savings, the formation flight mission may be elected 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.

The challenges that were identified in the current literature, inspired the development of a decentralized approach to formation flight routing.

III. Operational Concept

Inspired by Ribichini et al.[10], 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 with in-flight available 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 touch or overlap, the corresponding aircraft can communicate. Communications are herein defined as the formulation and evaluation of a possible formation flight strategy. If an opportunity to fly in a formation presents itself, the potential benefits are compared with the required investments 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 in 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 achieve additional cumulative fuel savings.

As soon as flights are prepared, meaning that they have determined their starting weight and their initial heading, they depart at their assigned departure time. Note how each flight starts out on a solo flight segment that may extend itself all the way to the respective 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 strategy 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 herein referred to as ‘synchronization’.

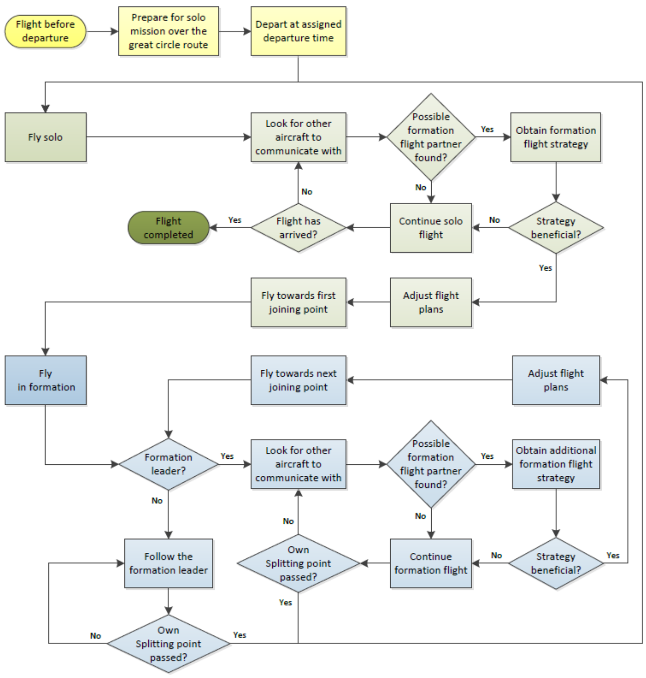

Figure 1: Flowchart of the operational concept

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 individual destinations. Note that these destinations may correspond to the splitting points of smaller formations that together, until recently, formed a larger formation. 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 strategies 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.

IV. Fuel consumption calculations

Within the scope of this work, any route consists of segments of steady, level cruise flight at 11km altitude in standard atmosphere. Accordingly, any route segment is a straight line segment with a certain length. Since the Breguet Range equation is well suited for the evaluation of weight changes over these segments, a modified version of the Breguet range equation is used to determine the fuel consumption of aircraft. Kent et al. have derived the relation given in Eq. 4 [6]. Starting from Eq.1, which relates a change in weight over a certain amount of time to the available thrust, specific fuel consumption and duration, they derive the relation given in Eq.2. Here, W_0 represents the starting weight, W_1 the end weight, and R the length of a segment. All other parameters are combined in one constant parameter M, specified by Eq.3. Substituting Eq.3 into Eq.2 allows for re-writing Eq.2 into the expression given by Eq.4, that is herein used to evaluate weight changes of aircraft.

$$dW = -C_t T_A dt \qquad (1)$$

$$R = \sqrt{\frac{2}{\rho_\infty S}\frac{C_L^{\frac{1}{2}}}{C_t C_D}}\left(2W_0^{\frac{1}{2}} - 2W_1^{\frac{1}{2}}\right) \qquad (2)$$

Kent et al. assume that the coefficient of lift, C_L, and drag, C_D, the thrust specific fuel consumption, C_t, the free stream density ρ_∞, and the wing surface area S are constant for a specific aircraft on a specific segment. The constant terms in Eq.2 are collected into the parameter M, herein referred to as the 'M-value'. This M-value is used as a controller for an aircraft's fuel flow. When calculating the fuel consumption of each aircraft individually, any benefits from formation flight can be accounted for by adjusting the M-value for each segment of an aircraft's mission.

$$M = \sqrt{\frac{2}{\rho_\infty S}}\frac{C_L^{\frac{1}{2}}}{C_t C_D} \quad (3)$$

$$W_1 = \left(\frac{M\sqrt{W_0} - R}{M}\right)^2 = \left(\sqrt{W_0} - \frac{R}{M}\right)^2 \quad (4)$$

In the performed simulations, the assumptions of Kent et al., used to obtain Eq.4, are slightly adjusted, without affecting Eq.4. For all simulated flights, this paper assumes the free stream velocity to be constant over a segment. This is in violation with the combination of the definition $W = L = {}^1/_2 \rho V^2 S$ and the other assumptions of this work; the free stream velocity must change if the weight is to change. Since the optimum flight conditions for formation flight are still a current research topic, and since this method for fuel consumption calculations already presents a severely simplified reality, this work assumes that slight variations in the coefficients C_t, C_L, C_D along a segment allow for the velocity to be simulated as being constant on a segment.

It is assumed that any trailing aircraft experiences a fuel flow reduction of 10%. This value is set to equal the fuel flow reduction that Flanzer et al. reported as sustainable for the trailing aircraft in a flight test with two military C-17 aircraft[3].

All flight are performed with the same standard aircraft, that has been defined based on the Boeing 777 [2]. Table 1 gives the properties of the standard aircraft. These figures provide a calibration point for the determination of the M-values in different flight states.

Table 1: Properties of the standard aircraft

Aircraft Property	Value
Zero fuel weight	171 $tons$
Maximum speed/cruise speed	251 m/s (M0.85 @ 11 km altitude in ISA)
Maximum endurance speed = V_{min}	207 m/s (M0.70 @ 11 km altitude in ISA)
Design range	7500 km
Fuel consumption on design mission	47.3 $tons$
Starting weight on design mission	171 + 47.3 = 218.3 $tons$

In Table 1, one finds the zero fuel weight, which is assumed to be equal to the end weight W_1, and the fuel consumption for a design mission of the standard aircraft. Accordingly, assuming that there is no contingency fuel included, Eq. 4 can be used to derive the M-value that must be used to retrieve the starting weight W_0. An M-value of 140 was found. Next, the fuel consumption on the design mission was lowered by 10%, in order to obtain the M-value that would account for an entire design mission performed as a trailing aircraft in formation flight. A value for M of 158 was determined. For segment lengths from 100 to 10.000 km, it was experimentally verified that changing the M-value from 140 to 158 resulted in a fuel consumption reduction of approximately 10% over the entire segment.

In the performed research, it is assumed that flying at the maximum endurance speed, used as the minimum speed V_{min}, increases the fuel flow of the aircraft by 10% with respect to flying at the cruise speed, which is set as the maximum speed V_{max}. This increase in fuel flow of 10% has been deduced from a study on the fuel consumption of a C-141 Starlifter aircraft done in a paper by Visser in 1991 [11]. To account for the increased fuel flow, simulations were performed to find M-values that would represent this increase. It is assumed that the M-value that corresponds to flying at some speed between the minimum and the maximum speed, may be obtained through linear interpolation of the two determined extremes.

Note how the M-value of 143.8, corresponding to a trailing aircraft flying at V_{min}, does not intuitively reflect the fact that the aircraft consecutively increases and decreases its fuel flow by 10%. This is due to the fact that the current M-value is corrected for speed. Accordingly, a trailing aircraft that flies at V_{min} experiences a 2% fuel flow reduction with respect to flying solo at V_{max}. The fact that a slight advantage remains for flying in formation was inspired by the notion of Ning et al., stating that formation flight at marginally lower Mach numbers would be slightly more efficient[8].

Table 2: Possible M-values of the standard aircraft

Aircraft Property	Value
M-value solo/leader, V_{max}	140
M-value trailing, V_{max}	158
M-value, solo/leader, V_{min} to V_{max}	linear interpolation between 127.4 and 140
M-value, trailing, V_{min} to V_{max}	linear interpolation between 143.8 and 158

Table 2 presents an overview of the M-values that this work uses to model the effect of formation flight on the fuel consumption of aircraft. In the developed model, the M-value of an aircraft is revisited after each adjustment to its speed or formation flight status. In this way, the model specifies a new fuel flow setting for an aircraft, for each consecutive segment that is flown by the corresponding aircraft.

It is assumed that the standard aircraft is able to carry the required fuel for any mission it is assigned to in this work. It is noted that this work aims for a relative study with and without formation flight. In general, slight deviations in the properties given in Table 1 are not expected to lead to significant changes in the final result.

This work assigns the flight with the lowest flight number to be the formation leader. This decision was made with the idea of a standard aircraft in mind. Later, during the development of this work, it was experimentally verified that the overall obtainable fuel savings could safely be assumed to be independent of which aircraft was assigned to be the formation leader. This finding can be explained by the fact that all aircraft in the performed simulations are very similar, both in gross-weight and in fuel requirements.

V. Formation flight routing

Like the method for calculating the fuel consumption of aircraft, the used routing method was based on the work of Kent et al.[5] Through the minimization of weighted distance, a formation flight route is obtained. The routing method from the literature is extended for the developed decentralized approach.

A. Geometric routing method by Kent et al.

Consider the left part of Fig. 2. Two flights are departing from origins A and B respectively. They will join in formation at point P and continue towards the common destination C. The objective is to find that location of P that will provide the highest amount of overall fuel savings. Given the strong correlation between fuel consumption and the distance that needs to be flown, the distance that needs to be flown will be minimized. 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 depends on the values of w_A and w_B.

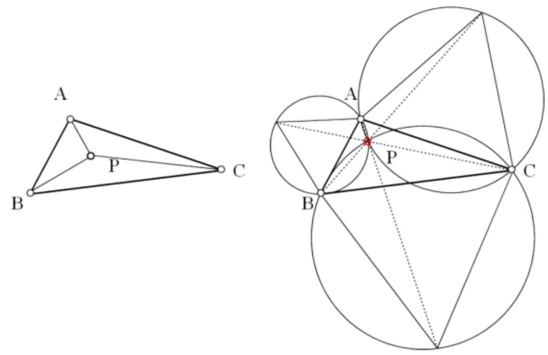

Figure 2: The location of point P is to minimize the distance AP+BP+PC [6]

Thus, it is desired to minimized the total cost of distance as given in Eq.5. The location of point P is the design variable in this minimization. Following the derivation of Kent et al., the location of point P that minimizes Eq. 5 will follow from the mechanical equilibrium that will be reached, if three strings are tied together on one end and consecutively exposed to outward forces proportional to the weights w_A, w_B, and w_C along the segments AP, BP, and PC respectively. Accordingly, the equilibrium given in Eq. 6 needs to be satisfied.

$$Minimize: w_A \cdot \| AP \| + w_B \cdot \| BP \| + w_C \cdot \| PC \| \quad (5)$$

$$w_A \cdot \frac{AP}{\| AP \|} + w_B \cdot \frac{BP}{\| BP \|} + w_C \cdot \frac{PC}{\| PC \|} = 0 \quad (6)$$

Through applying the law of cosines in the triangle that is obtained from placing the three vectors in Eq.6 root to end, the angles ∠APB, ∠APC, and ∠BPC are obtained. Since the angle ∠APB represents the angle at which the trajectories AP and BP meet at P, it is referred to as the "formation angle". Equation 7 gives the expression for the formation angle θ_f. Note how the formation angle only depends on the routing weights w_A, w_B, and w_C.

$$\theta_f = \cos^{-1}\left(\frac{-w_A{}^2 - w_B{}^2 + w_C{}^2}{2 w_A w_B} \right) \quad (7)$$

Returning to Fig. 2, it is found that the location of P that minimizes the expression in Eq. 5 is obtained from the intersection of three circles drawn through the corner points of three triangles on sides AB, AB, and BC. The side lengths of these triangles are proportional to the weights w_A, w_B, and w_C. It is noted that when the weights w_A, w_B, and w_C are kept constant, destination C can be moved freely without affecting the formation angle. Accordingly, it is known that the location of point P that minimizes Eq.5 satisfies ∠APB=θ_f.

The method for locating point P can be extended to a scenario in which the two flights do not have a common destination. Figure 3 contains the 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 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. 7. These arcs are can be found in Fig. 4. The point X_1 is obtained from knowing that Eq. 8 holds in triangle ABX_1.

$$|AB| : |BX_1| : |X_1A| = w_C : w_A : w_B \qquad (8)$$

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 X_1 to Y_2 and the arcs of constant formation angle. The resulting formation flight route is given in Fig. 5. 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.

B. Extensions to the routing method

The geometric routing method that was developed by Kent et al. does not return the minimum weighted distance route for any set of solo routes AC and BD. When the origins or destinations are located such that their separation is much greater than their distance to the line that specifies the average intended flight direction, the obtained found formation flight route may not be longer than necessary. Figure 7 presents such a scenario. The grey route that contains J and S may be returned by the geometric routing method as reported by Kent et al.[5] Not how the flight on route BD is instructed to initially fly away from its destination. From geometric observation of Fig 7, it is found that the overall distance that has to be flown can be reduced by moving J over the arc of constant formation angle towards origin B. Both the length of the formation flight segment JS and the sum of the lengths of solo segments AJ and BJ will be reduced in the process. This will reduce the overall weighted distance, regardless of the used routing weights. Accordingly, the black route that contains J' is obtained. The splitting point S has been moved to S', as a

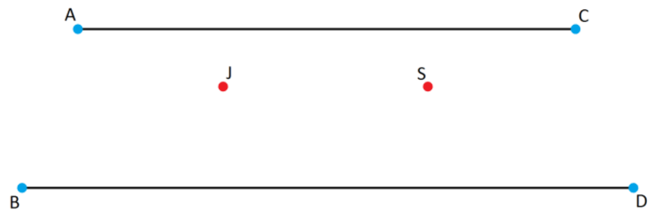

Figure 3: By locating J and S, a formation flight route is obtained for the solo routes A and BD

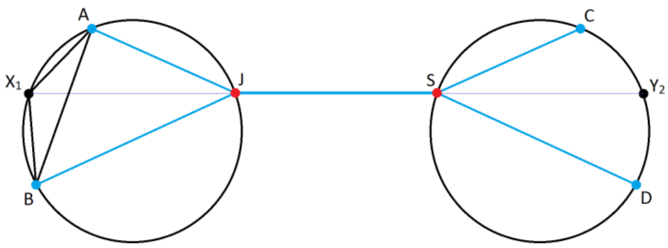

Figure 4: Construction of the formation flight route

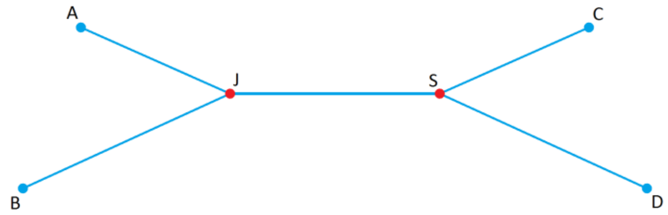

Figure 5: Geometrically obtained formation flight route connecting A to C and B to D

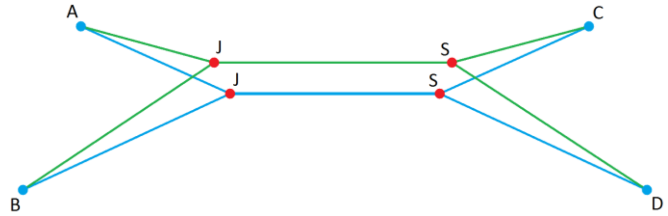

Figure 6: Obtained formation flight routes. For the blue route $w_A = w_B$, for the green route $w_A > w_B$.

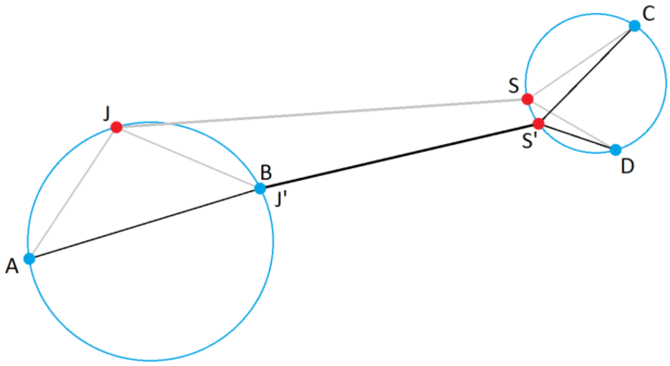

Figure 7: Grey: suboptimal route. Black: optimal route

consequence of relocating J to J'. The black route in Fig. 7 was found to be the minimum weighted distance route that connects A to C and B to D, while including a formation flight segment.

Contrarily to the work of Kent et al., or to any centralized approach, the decentralized approach that is herein developed 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 (groups 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}, while the other maintains its cruise speed, which is equal to V_{max}, referring to Table 1. It was chosen to restrict the possible locations of J_{new} to the determined formation flight segment $J_{old}S$. Moving J closer to the aircraft locations A and B, as opposed to further away from locations A and B, is likely to result in a larger increase in the overall weighted distance that has to be flown. Also, it will require more severe heading changes which may be operationally unattractive. Moving J towards S will postpone the initiation of formation flight, but will reduce the detours that both aircraft have to fly.

In Fig. 8, the current locations A and B with a determined joining point, indicated as J_{old}, are repeated. The point X is defined on the intersection of the lines AB and X_1J_{old}. Through applying the law of cosines to both the triangles AXJ_{new} and BXJ_{new} , and by using that V_{max}/V_{min}= 1.21, the quadratic relation in Eq. 8 can be obtained. Equation 8 can be solved for the side length XJ_{new}, that can consecutively be used to construct the location of the new joining point J_{new} that enables synchronization.

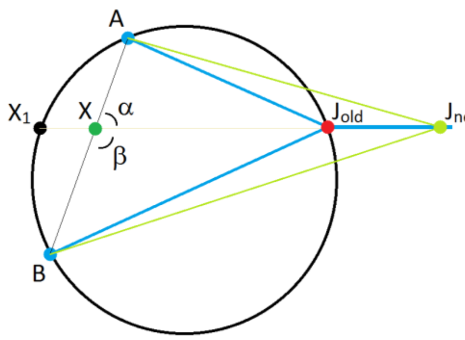

Figure 8: Relocation of J to enable synchronization

$$\left(1.21^2-1\right)^2\left(XJ_{new}\right)^2+\left(2XB\cdot\cos\beta-1.21^2\cdot 2XA\cdot\cos\alpha\right)XJ_{new}+1.21^2\left(XA\right)^2-\left(XB\right)^2=0 \qquad (8)$$

Since this work aims to formulate a routing method that can be used to re-route formations as well as solo flights, the routing weights w_A, w_B, and w_C have to be quantified further. This work defines w_A, and w_B as the number of aircraft that is part of the formation at location A or B respectively. In doing so, it ensures that larger formations receive relatively shorter detours, since the overall cost for a formation to fly a unit of distance increases with formation size. The routing weight for the formation flight segment, w_C, is determined from w_A and w_B. As formation sizes grow, it is assumed that they become more reluctant to be rerouted once more.

C. Verification of routing method

To proof that the obtained geometric routing method is able to return the minimum weighted distance route for any combination of solo routes AC and BD, an example route is generated and the weighted distance evaluated for alternative locations of J and S respectively. Figure 9 contains the example route. The color scale in Fig. 10 presents the resulting overall weighted distance savings for every location of J and S in a 200x200 km square around their originally determined locations. It is concluded that the locations for J and S that where returned by the routing method are indeed part of the minimum weighted distance route. This verification step was automated and repeated for 10.000 random sets of solo flights. The average solo range was increased to 7000 km to create similarity with transatlantic flights. The x- and y-coordinates of the origins and destinations where randomly generated from

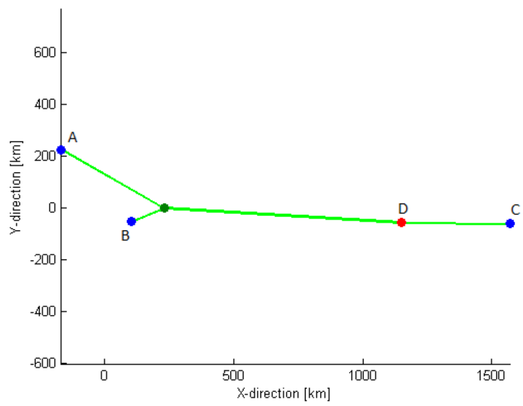

Figure 9: Example route for verification of the routing method

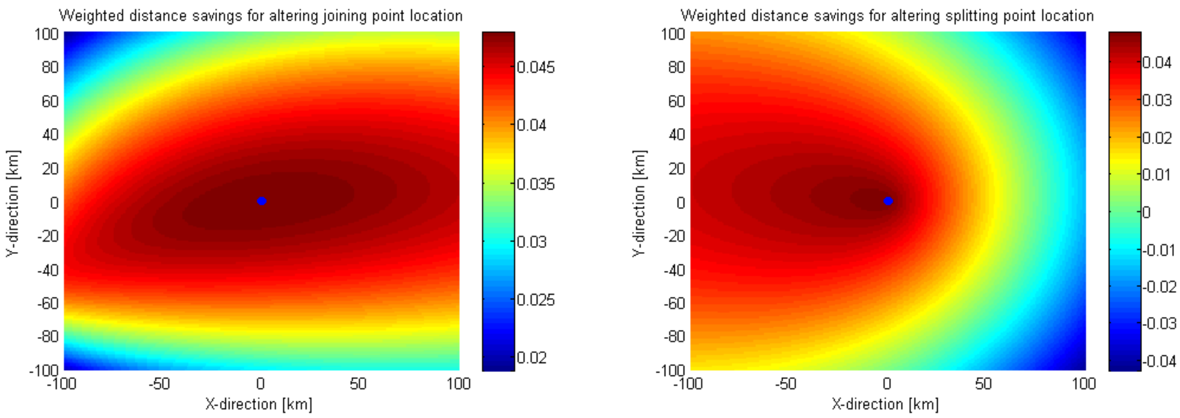

Figure 10: The overall weighted distance savings for varying locations of J and S

a normal distribution with a standard deviation of 500 km. The mean origin and destination were located at the points [0,0] and [7000 km,0], respectively. Figure 11 show the results of the verification simulation. It can be observed that it is safe to assume that the routing method is able to generate the minimum weighted distance route for any set of flights that can within reason be expected to be able to benefit from formation flight.

The synchronization method is not included in this verification, since it purposely instructs aircraft to deviate from the minimum weighted distance route.

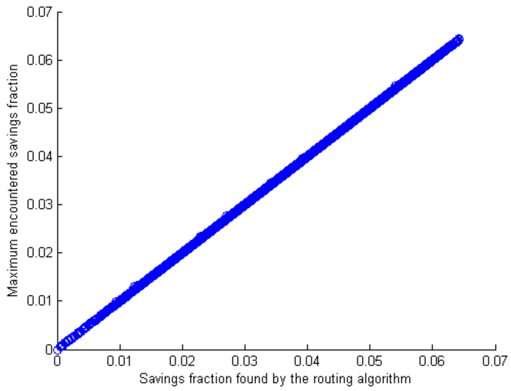

Figure 11: Maximum encountered vs. determined savings

VI. Transatlantic case study

The formulated operation concept from Fig. 1 is applied to 347 eastbound transatlantic flights. The included routes, given in Fig. 12, are obtained from an available data set by means of selection on maximum and minimum longitude and latitude of the origins and destinations. No distinction was made between operating airlines or any other route specifics. Since this work considers two dimensional routes described in Cartesian coordinates, the data was projected by means of an azimuthal equidistant projection method.

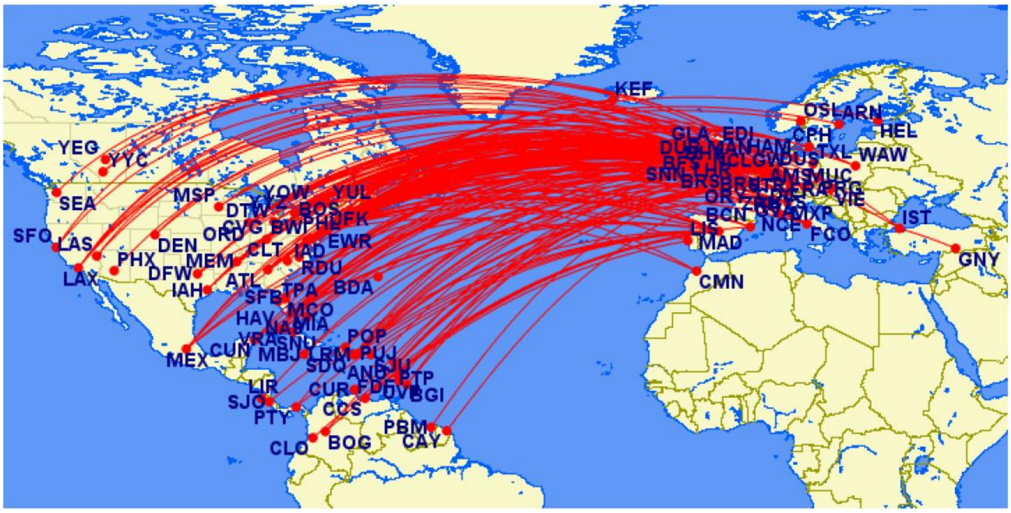

Figure 12: Route set used in the case study.[1]

The location of each aircraft is simulated continuously through time with a time step size of 5 minutes. This time step size was found 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.

Table 3: 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

There are three events that may trigger such an update: two flights commit to a formation flight strategy, a joining point is passed, or a splitting point is passed. These events can be diverse in nature.

Table 3 provides the configuration of the model. 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 accepted, regardless of the increase in flight time that flights will experience. In this model configuration, a typical simulation of the case would require about 6 minutes of calculation time on a standard university PC, including result visualization in graphs and the creation of a .gif animation.

Figure 13 shows a snapshot of the simulation at the 41st time step. Referring to the legend in Table 7, several observations can be made from Fig. 13. 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 flying towards a joining point.

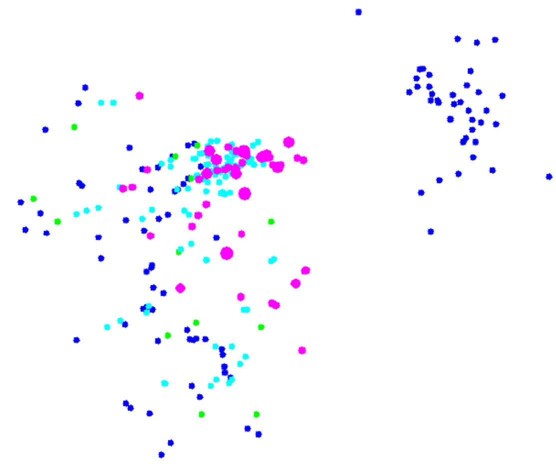

Figure 13: Snapshot at time step 41

Table 7: Legend to Fig. 13-15

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

From the origins in the left half of Fig. 13, 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, 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, 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, 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.

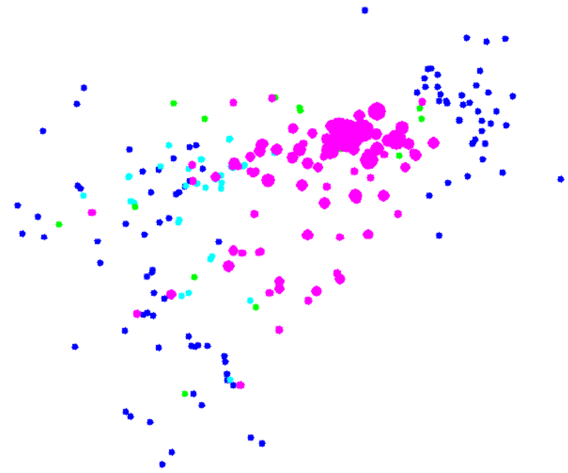

Figure 14: Snapshot at time step 81

Moving on to Figure 14, showing the same flights 200 real minutes later, it can be seen that the supply to the eastbound stream of aircraft has reduced. In fact,

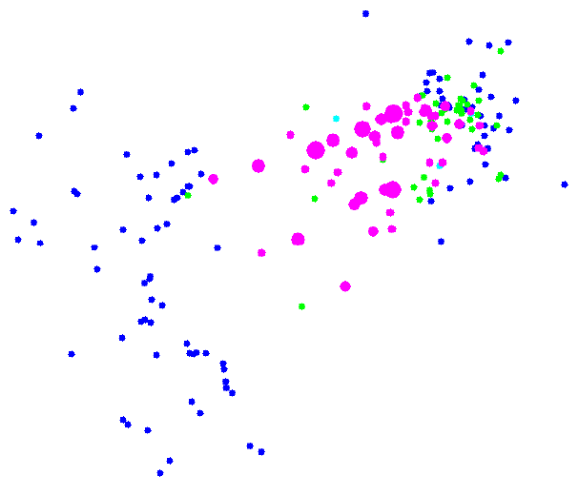

Figure 15: Snapshot at time step 121

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. Analysis showed that a formation of size 8 and a formation of size 7 had earlier accepted a formation flight strategy. The green dots at the front indicate flights that have separated from their formations; they are heading towards their destination by means of a solo flight segment.

Figure 15 provides the situation another 200 real 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 strategy 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.

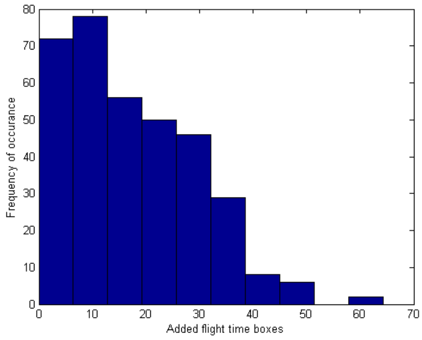

Figure 16: Additional flight time distribution

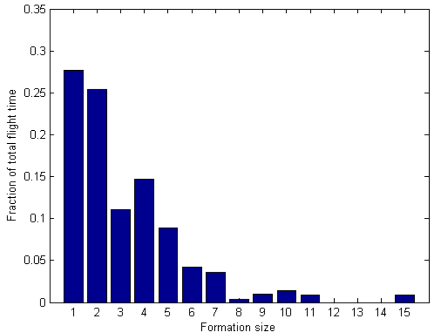

Figure 17: Flight time distribution over formation sizes

Figures 16 presents the additional flight times that aircraft have to incur due to the implementation of formation flight. The average additional flight time is 17.6 minutes. Figure 17 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 8 contains results from the performed simulation. The overall obtained fuel savings amount to 3.6% with respect to using only solo flights. For operations with the standard aircraft that was defined in Table 1, 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 weighs down the overall obtainable fuel savings.

Table 8: Results for 347 flights

Parameter	Value
Overall fuel saved	$5.6 \cdot 10^5\ kg$
Overall fuel savings	3.6%
Average added flight time	17.6 min
Maximum added flight time	64.2 min
Formation flight usage rate	72%

An identical simulation was performed where flights where 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.

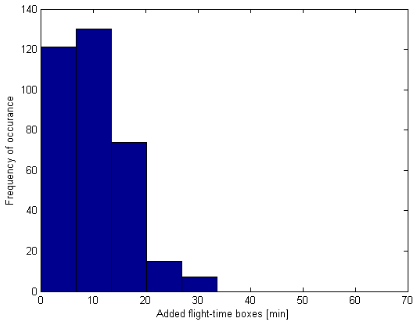

Figure 18: Added flight time distribution

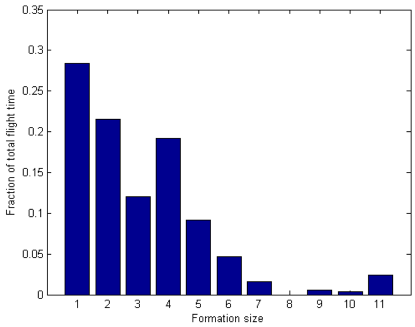

Figure 19: Flight time distribution over formation sizes

A. Limited additional flight time

The significant additional flight times that are found in Fig 16. inspired a simulation 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 formation flight strategy. This limit was set to 10 minutes. Figure 18 presents the new distribution of additional flight times over all the involved aircraft. The average additional flight time has decreased to 9.9 minutes. Figure 19 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 similar. Notable is the fact that the overall obtained fuel savings increased to 4.2%. This can be explained by the fact that a greedy algorithm is used, as covered by the next section.

B. Vary the communication range

Since the communication range directly determines the nature of the formation flight options that flights can encounter, a study is performed that considers the overall obtainable fuel savings at different values of 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 20 shows the results of 120 (60 per model configuration) independent simulations of the 347 transatlantic flights in this case study.

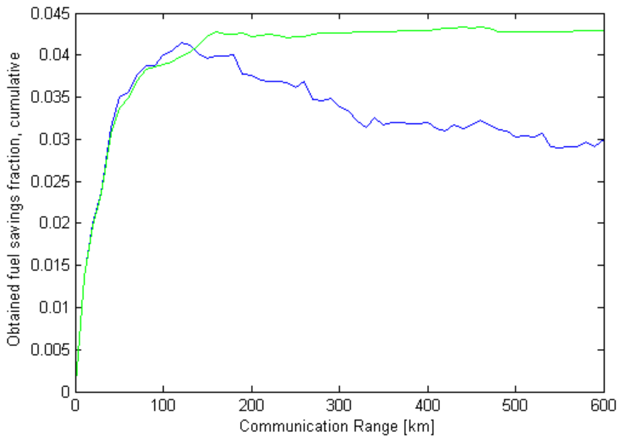

Figure 20: Obtainable fuel savings vs. communication range. Blue: no limit on additional flight time. Green: limited additional flight time

The blue line represents the results 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 increases 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 continues with a smaller average gradient. The model still finds additional/more beneficial formation flight options. At a communication range of 120 km, the maximum obtainable fuel savings are recorded. These savings round up to 4.2% with respect 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 appears to level of around 3.0%. The gradual decrease in obtained savings can be explained. As the communication range is increased above 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 above 120 km.

Consider the green line in Fig. 20, for increasing values of the communication range. In these results, 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 strategies 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.

C. Increased benefits from formation flight

To approach the assumption of Kent et al. with respect to formation flight benefits[5,6], a simulation is performed in which any trailing aircraft experiences a 20% reduction in fuel flow. With the communication range set to 440 km, the overall obtained fuel savings amount to 9.7%. Noteworthy, is the fact that the use of formation flight was very similar to the results that were previously shown. The used formations became twice as beneficial by assumption. As the overall obtained fuel savings were more than doubled, it is concluded that the increase in assumed benefits of formation flight lead to the use of new formation flight strategies.

VII. Conclusion

The developed model was able to simulate the decentralized implementation of formation flight in civil aviation. In the performed case study, the model showed to be flexible and reliable. The formation flight routes that were obtained show many similarities to those that are 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.

It is recommended to enable aircraft to communicate with multiple others at the same time. Accordingly, the forming of formations may be realized more efficiently. The significant investments that the developed decentralized approach requires to realize synchronization, may be compensated for by a form of pre-flight planning. Delayed flight do not pose challenges to a decentralized approach to formation flight implementation. These notions suggest a combined approach to formation flight implementation that incorporates both centralized and decentralized elements.

References

[1] Great Circle Mapper, on www.gcmap.com, 2015

[2] Boeing Company. *B777-200 performance summary*, published in 2009, http://88.198.249.35/d/Boeing 777 Takeoff.pdf. Source verified on the 26th of June, 2015.

[3] Tristan C Flanzer and Stefan R Bieniawski. *Operational Analysis for the Formation Flight for Aerodynamic Benefit Program*. In 52nd Aerospace Sciences Meeting, number January, pages 1-19, National Harbor, Maryland, 2014.

[4] L.E. Herinckx, T.L.M. Gutleb, R. van Nunen, E. Van Rompuy, D.A. Bos, H.P.A. Dijkers, J. de Wit, H. Radfar, S.E. Sahin, and W.W.A. Beelearts van Blokland. *Formation flying as an innovative air transportation system for long-haul commercial flight: A focus on operational feasibility and potential gain*. In 11th AIAA Aviation Technology, Integration, and Operations (ATIO) Conference, including the AIA, number September, Virginia Beach, 2011. American Institute of Aeronautics and Astronautics.

[5] Thomas E Kent and Arthur G Richards. *A Geometric Approach to Optimal Routing for Commercial Formation Flight*. In AIAA Guidance, Navigation, and Control Conference, number August, pages 1-17, 2012.

[6] Thomas E. Kent and Arthur G. Richards. *On Optimal Routing For Commercial Formation Flight*. AIAA Guidance, Navigation, and Control (GNC) Conference, pages 1{11, August 2013.

[7] PB Lissaman and CA Shollenberger. *Formation Flight of Birds*. Science, 168(May1970):1003-1005, 1969.

[8] S. Andrew Ning, Ilan Kroo, Michael J. Aftosmis, Marian Nemec, and James E. Kless. Extended Formation Flight at Transonic Speeds. Journal of Aircraft, 51(5):1501-1510, September 2014.

[9] Ronald J Ray, Brent R Cobleigh, M Jake Vachon, and Clinton St.John. *Flight Test Techniques Used to Evaluate Performance Benefits During Formation*. NASA Center for AeroSpace Information (CASI), (August), 2002.

[10] Gabriele Ribichini and Emilio Frazzoli. *Energy-Efficient Coordination of Multiple-UAV systems*. In AIAA Guidance, Navigation, and Control Conference and Exhibit, number August, Austin Texas, 2003.

[11] H. G. Visser. *Terminal area traffic management*. Prog. Aerospace Sci., 28:323-368,1991.

[12] Jia Xu, S. Andrew Ning, Geoffrey Bower, and Ilan Kroo. *Aircraft Route Optimization for Formation Flight*. Journal of Aircraft, 51(2):490-501, March 2014.

[13] Min Xue and Gregory S. Hornby. *An Analysis of the Potential Savings from Using Formation Flight in the NAS.* In AIAA Guidance, Navigation, and Control Conference, number August, pages 1{12, Minneapolis, Minnesota, 2012.