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INFLUENCE OF AIRCRAFT TYPE AND ORDER ON FUEL SAVINGS GAINED BY TWO-AIRCRAFT FORMATIONS

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Abstract

The work presented in this paper investigates the influence of aircraft pairing and order on the fuel savings gained by two-aircraft formations. It will be analyzed if in terms of formation efficiency as well as with respect to the maximum fuel savings favorable aircraft pairings exist. To achieve this goal, a detailed trajectory analysis including an aerodynamic model to calculate the aerodynamic benefits of the formation is performed for a predefined set of formation geometries and formation pairings thus creating a formation flight database that can be used for the evaluation. It will be shown by statistical analysis, that differences in formation flight performance exist depending on pairing and order. In addition to the full initial set of samples a subset of the formation geometries representing missions over the North Atlantic will be evaluated. It will be shown, that differences compared to the full set of samples exist. As the weight of the leader is a strong driver for the formation efficiency it will be analyzed, if the take-off weights of the formation members allow an estimation of the achievable benefits. Furthermore it will be shown, how the database can be used to create surrogate models for a specific formation pairing and how these models can be utilized to evaluate specific formation geometries.

1 Introduction

The concept of formation flight that can be observed in nature at migrating birds is long since known and was first described by Wieselsberger [1] in the year of 1914. Since that time, scientists strive to transfer this principle to aircraft and until today a number of theoretical analyses and flight experiments were performed that promise that substantial fuel savings and in a consequence reduced emissions can be expected by the introduction of this new concept. Despite these promises, no application of aerodynamic formation flight exists in today's civil aviation and the reasons for this can not only be found in the technological challenges inherent to the forming and maintaining a formation, as another important aspect is given by the integration of the new concept into the air transportation system. Hence the system induced inefficiencies that arise from detours, speed and altitude adaption, aircraft types, pairing and order as well as timing and delays complicate the prediction of the remaining benefits. The many influences still remain unclear and therefore need to be further investigated. Beside the technical aspects of formation flight several works therefore deal with the operational aspects of the new concept that arise with the integration into the air transportation system. One major aspect concerning this integration is the route optimization and partner allocation problem that arises with formation flight. Kent et al. [2, 3] show, that a fast definition of optimal formation routes is possible using a geometric approach and that up to 8,6% fuel savings can be achieved for a transatlantic scenario by two-aircraft formations. Another work from Xu e al. [4] shows for a North Atlantic scenario that for an airline network fuel savings of up to 6,8% can be achieved by formation flight. In addition to these operational analyses investigations concerning the aerodynamic interactions between a limited quantity of different aircraft types exist (see Nangia et al. [5], Bower et al. [6]).

A essential question however that arises with the evaluation of formation flight is the selection of the aircraft types building a formation. To answer this question, basically two options exist. The first option is the development of new formation-optimized aircraft as it is proposed in [7]. The second option is the modification of existing aircraft with the necessary formation flight systems. This approach is followed within this study as it can be expected that a modification on an aircraft is less complex and therefore less expensive than the complete new. This approach however raises the question of which aircraft to select for the modification in order to achieve the highest formation flight benefits for a given use case. One way to answer this question is to select the most frequently used aircraft types serving the desired routes. Although this is a reasonable approach, it might lead to suboptimal formation flight performance, as for the desired routes another aircraft type might be suited better. Another way to select the aircraft is by physical consideration. It can be expected, that a heavy leader generates stronger wake vortices and thus produces a high benefit at the follower. Also it is shown in [5], that the relative size of the leader strongly influences the aerodynamic benefits of the follower. However, depending on the flight performances of the considered aircraft and the missions they are serving, it can occur, that a specific aircraft type turns out to be inappropriate as a leader even if it is heavier than the follower. This can be especially true if leader and follower are the same aircraft types.

In contrast to the works mentioned above, this work tries to answer the question by statistical analysis of formation flight. It will be analyzed if favorable formation pairings for a predefined set of formation geometries exist that achieve higher benefits than others. Previous works by the author deal with the parametrization of formations [8, 9], the route-optimization and partner allocation [10] as well as with the evaluation of formation flight on dedicated *Formation Corridors* on the North Atlantic [11] and are the basis for the work presented in this paper.

Eventually this work might help to answer the question which operational aircraft should be primarily certified for formation flight, as only if the concept of formation flight is proven to achieve the promised significant benefits in an operational scenario, aircraft manufacturers will be interested in developing the necessary technologies and systems and in elaborating the necessary procedures in order to integrate the new concept into the air transportation system.

2 Methods

2.1 General Approach

For the basic modeling of the formation flight in this work some general assumptions are made that are listed below.

- Two-aircraft formations
- No positional changes
- Planned formation flight
- Constant *Formation Cruise Speed* (FCS)
- Constant *Formation Cruise Altitude* (FCA)

These assumptions are based on the prospect that the simplest possible aerodynamic formation flight will be the first to be implemented, why aspects requiring elaborated coordination of multiple aircraft can be abandoned in a first step. Based on these assumptions within this work for a set of formation geometries and for a number of aircraft types and the resulting pairing combinations the formation benefit will be calculated using a detailed trajectory simulation. The formation geometries are thereby chosen to evenly cover all possible geometries in a predefined design space so that general statements about the suitability of an aircraft for formation flight can be made. On the basis of these calculations different kinds of analyses can be performed that will be presented thereafter. The different aspects of the approach as well as basic assumptions are described in more detail in the following.

2.2 Formation Geometry

As a consequence of the assumptions made in chapter 2.1 a *formation geometry* for a two-aircraft formation can be defined that is essential to describe a specific formation. This geometry can be modeled laterally as shown in figure 1. After take-off a formation member reaches the *Top of Climb* (TOC) and begins with the cruise flight. The member then reaches the *Deviation Starting Point* (DSP) where necessary altitude and speed adaptions begin that are necessary to reach the *Formation Cruise Altitude* (FCA) and *Formation Cruise Speed* (FCS). At the *Rendezvous Starting Point* (RSP) the formation member is in close vicinity of the formation partner and the rendezvous maneuver begins that is finished at the *Formation Starting Point* (P+).

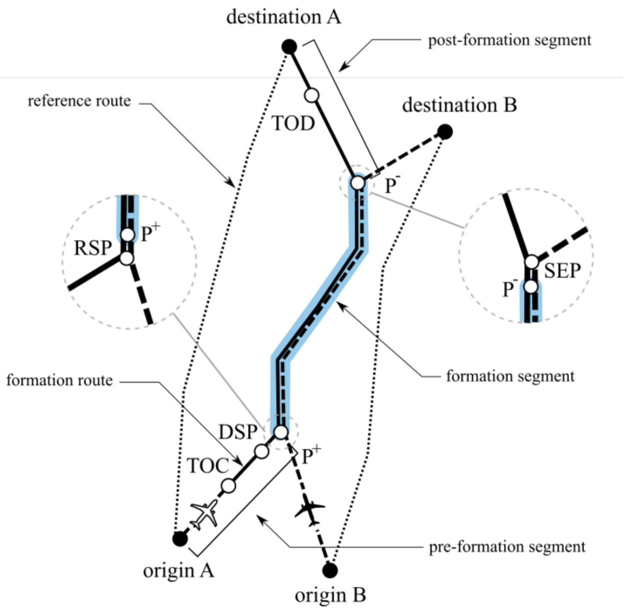

Fig. 1 Schematic lateral formation geometry of a two-aircraft formation

After P+ the *formation phase* (index *ben*) begins wherein the aerodynamic formation is maintained. In this phase no altitude or speed adaptions occur and the positions of the aircraft within the formation remain unchanged. At the *Formation Ending Point* (P-) the separation maneuver begins that ends at the *Separation Ending Point* (SEP). The formation members continue their flights toward their destinations. As *reference route* (index *ref*) the route the formation member would preferably fly in solo flight is selected.

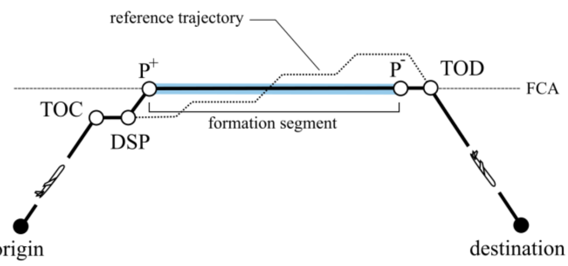

Fig. 2. Typical vertical flight profile of a formation member

The vertical flight profile of a formation member can be modeled as shown in figure 2. It is assumed, that the formation only takes place within the cruise segment and that the FCS remains constant during the formation. The vertical profile of the reference mission can be different form the formation mission, e.g. including step climbs. The inefficiencies resulting from flying at a constant altitude are therefore covered by the *formation efficiency metric* (see chapter 2.5).

2.3 Formation Nomenclature

In order to uniquely label a formation the two aircraft names of a formation-pairing (e.g. AC_1 and AC_2) are connected by a symbol. This symbol denotes which of the aircraft is the leader and which is the follower and it can be either "<", ">" where the edge points into the direction of the leader (e.g. AC_1>AC_2, where AC_2 is the leader). If the leader is not determined, the "-"-symbol is used (e.g. AC_1-AC_2). The sequence of the aircraft names can be used to determine which aircraft flies on which mission. In such a case the first position equals the mission A, the second mission B. If the missions are switched, meaning AC_1 flies on the mission of AC_2 the order is changed (e.g. AC_1>AC_2 becomes AC_2<AC_1 where AC_2 remains the leader).

2.4 Formation Parameters

In order to evaluate a two-aircraft formation it can be represented by a set of unique parameters that describe the formation geometry and the general properties of the formation (see [9]). This set comprises parameters of the single formation members (detours, length of the formation and pre-formation segments, loadfactors, length of the ground tracks) as well as parameters inherent to the whole formation (*Formation Cruise Speed* (FCS) and *Formation Cruise Altitude* (FCA)). Table 1 gives an overview of all relevant formation parameters used in this approach.

symbol	description
$\boldsymbol{\sigma}$	relative detour
$\boldsymbol{\xi}$	relative segment length
S	absolute route length
lf	loadfactor
FCA	formation cruise altitude
FCS	formation cruise speed

Tab. 1. Overview of formation parameters used to describe a formation geometry

The *relative detour* $\boldsymbol{\sigma}$ describes the elongation of the groundtrack of the formation mission relative to a reference mission for a formation participant (indices leader *ld*, follower *fw*). The *relative segment length* $\boldsymbol{\xi}$ describes the length of a lateral route segment as a percentage of the overall lateral route length. It can be derived for the pre-formation segment (index *a*), the post-formation segment (index *b*) and the formation segment (index *ben*). To scale the formation geometry the *absolute route length S* of the ground track of a formation participant can be used. The *loadfactor lf* describes the actual payload of an aircraft in relation to its maximum payload.

2.5 Formation Efficiency Metrics

The benefit achieved by the formation can be described by the relative fuel savings of the formation mission in relation to the reference mission. This metric is called *formation efficiency metric* λ.

$$\lambda = \frac{\Delta F}{F_{ref}} = \frac{F_{ref} - F_{form}}{F_{ref}} \qquad (1)$$

The formation efficiency metric can be defined for both leader (λ_{ld}) and follower (λ_{fw}) or can be combined for the whole formation (λ_F). The latter assumes a cost sharing model between the formation participants and is of major importance for the comparison of two formations. For this reason it will be the metric mainly used within this study. Next to the formation efficiency metric the *absolute fuel savings* ΔF_F gained by the formation are of major interest for the evaluation.

2.6 Trajectory Calculation

In order to calculate the benefits of a formation a trajectory calculation is performed that includes the aerodynamic interactions within the formation based on an aerodynamic model. This calculation is conducted using the *Trajectory Calculation Module* (TCM) [12] that is developed at the *German Aerospace Center*. The TCM calculates the fuel consumption of a predefined mission based on the *Base of Aircraft Data* (BADA) total energy approach provided by Eurocontrol. For the simulation of formation flight the TCM has been expanded by taking into account the reduced drag of the follower resulting from the aerodynamic interactions with the wake vortex of the leader. For this the aerodynamics within the formation are modeled using two parallel Hallock-Burnham [13] vortices using a core radius $r_c = 0.35 \cdot b$ [14] where b is the wingspan of the aircraft (for more details refer to [9]).

2.7 Surrogate Models

It has been shown by the author in [9] that surrogate models to describe the formation efficiency metric λ_F as a function of the formation parameters of the form

$$\lambda_F = f(\sigma_{ld}, \sigma_{fw}, \xi_{ald}, \xi_{afw}, \xi_{benld}, \xi_{benfw}, lf_{ld}, lf_{fw}, S_{ld}, FCA, FCS) \qquad (2)$$

can be derived. These surrogate models can be determined by performing a multiple linear regression on a dataset obtained from a number of trajectory calculations for different formation geometries. These formation geometries are defined by *Design of Experiments* (DoE) methods as will be described in the following.

2.8 Design of Experiments

In order to analyze the influence of aircraft type and order on the formation benefits, numerous calculations of different formation geometries have been performed within this study. The parameters of these formation geometries were thereby varied by a latin hypercube sample plan to achieve an even distribution of the parameters within the design space. This approach was chosen to allow a general comparison of the aircraft pairings and to enable the surrogate models to cover the whole range of potential formation geometries including the ones not suitable formation flight. The design space underlying the studies was assumed as described in table 2.

symbol	description	min	max
σ_{ld}	relative detour (leader)	0	0.15
σ_{fw}	relative detour (follower)	0	0.15
ξ_{benld}	rel. formation length (leader)	0.1	0.9
ξ_{benfw}	rel. formation length (follower)	0.1	0.9
ξ_{ald}	rel. pre-formation segment length (leader)	0.1	0.9
ξ_{afw}	rel. pre-formation segment length (follower)	0.1	0.9
S_{ld}	absolute formation length [km] (leader)	1000	14000
lf_{ld}	loadfactor (leader)	0	1
lf_{fw}	loadfactor (follower)	0	1
FCA	formation cruise altitude [ft]	30000	44000
FCS	formation cruise speed [mach]	0.76	0.86

Tab. 2. Parameter limits for the formation parameters to calculate a sample plan

The sample amount was initially set to 3000 samples that represent a theoretical assumption as interdependencies between the parameters exist and hence not all samples can be translated to adequate formation geometries. For this reason for all samples valid formation geometries were generated. This was accomplished by an optimization algorithm that searches a geometrical solution that ideally fits the demanded parameters. After this translation process, some missions no longer fit into the desired design space so that a reduced set of 896 valid samples remained. This set is referred to as the *complete set*. In addition to the *complete set* a *reduced set* was defined by selecting all formation geometries that basically represent geometries suitable for transatlantic formations. The set comprises all missions that are longer than 5000 km and feature formation segment lengths $\xi_{benld} > 0.25$ and $\xi_{benfw} > 0.25$. These limits resulted from a study performed by the author using the *Organized Track System* (OTS) on the North Atlantic to define *Formation Corridors* (FOCOs) that are dedicated for formation flight (see [11]).

2.9 Aircraft Types

The aircraft types subject to evaluation in this paper have been identified in [11] as the most frequently used aircraft on the North Atlantic. As a two-aircraft formation can get critical from an aerodynamic point of view (e.g. if the occurring rolling moments cannot be compensated by the follower) only *long-haul* aircraft of the wake turbulence category *Heavy* and *Super Heavy* are being considered reducing the aircraft types to the ones listed in table 3.

ICAO-code	detailed ac-type
A333	Airbus A330-300
A343	Airbus A340-300
A388	Airbus A380-800
B744	Boeing B747-400
B763	Boeing B767-300
B772	Boeing B777-200
B788	Boeing B787-8

Tab. 3. Overview of aircraft types evaluated in this study based on [11]

For all resulting 49 two-aircraft formation-pairing combinations types the formation geometries defined in the sample sets were calculated using the trajectory calculation described in chapter 2.5.

2.10 Formation Database

These numerous calculations provide a database for a general statistical analysis as well as for more detailed analyses of subsets of the data as well as for single formation pairings. The database is part of the *MultiFly* toolkit currently developed at the *German Aerospace Center* (DLR) and is planned to be extended to more aircraft types and more formation geometries.

3 Results

The results presented in the following are divided in three sections. In the first section a general statistical analysis concerning the *complete set* and the *reduced set* of formation geometries as defined in chapter 2.8 is presented. The second section deals with the influence of the take-off weights of the formation members on the formation benefits. Finally in the last section the exemplary evaluation of a specific formation geometry using the surrogate models will be shown.

3.1 General statistical analysis

Although all formation geometries of the sample sets are valid with respect to the design space not all samples can be successfully be performed by a considered formation-pairing. This is due to flight performance reasons, as for example the demanded FCA or FCS cannot be achieved by one of the formation members or the flight distance of one member exceeds the range of the aircraft. For this reason the initial set of formation geometry samples is being reduced during the calculation process. In order to assess the suitability of a formation-pairing for formation flight the amount of samples that yield a result can be a first measure.

Figure 3 shows the percentage of samples of the *complete* and the *reduced set* that were successfully calculated in relation to the overall samples of the particular set. It can be found, that the values for leader and follower are similar and the general distribution remains comparable for the two sample sets although the magnitude is decreased for the *reduced set*.

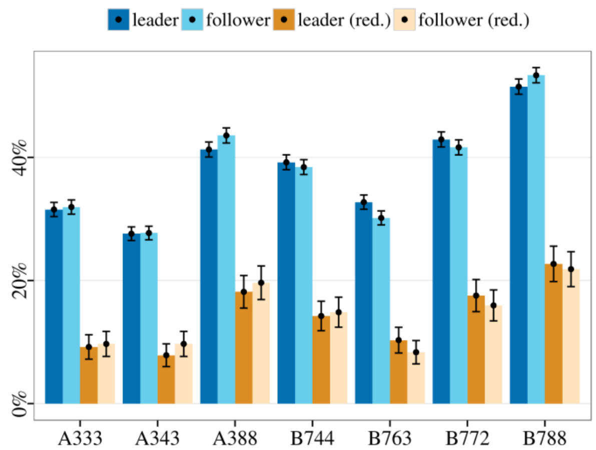

Fig. 3. Percentage of formation geometry samples that have been successfully calculated (cumulated for all leaders and followers)

The amount of samples with a positive formation benefit can be used to further evaluate the suitability of an aircraft type. Figure 4 shows the percentage of beneficial missions for the considered aircraft types cumulated for leaders and followers in relation to the overall samples of the particular set.

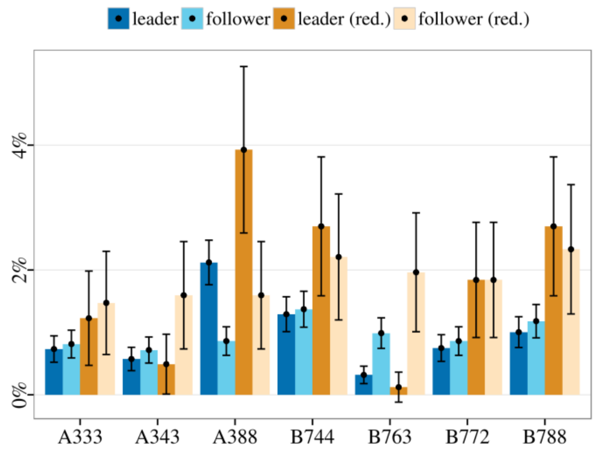

Fig. 4. Percentage of formation geometry samples with positive formation metric λ_F (cumulated for all leaders and followers)

The generally low values shown in figure 4 are due to the fact that the even distribution of the samples within the design space leads to many formation geometries that are not ideal for formation flight, e.g. featuring long detours or short formation segments. However, figure 4 implies, that the percentage of successful missions strongly varies with the aircraft types. Some aircraft types such as the A388, B744 and B788 created more successful missions than the other types. According to the data, the order of the aircraft shows also a significant influence on the formation performance as it can be found for the A388 and B763 where the A388 performs better as a leader in contrast to the B763 that can be expected to perform better as a follower. The values for the *reduced set* show a slightly higher percentage of beneficial missions compared to the *complete set* but generally follow the same pattern. This can be attributed to the fact, that the reduced design space focusing on long routes over the North Atlantic with long formation segments by definition creates more beneficial missions.

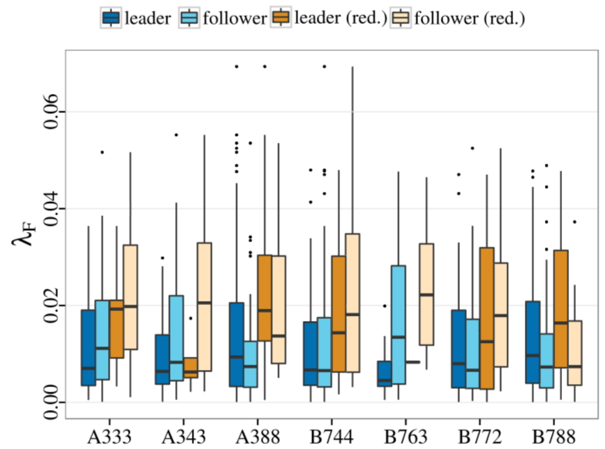

Fig. 5. Boxplots of formation efficiency metric λ_F of formation geometry samples with positive λ_F (cumulated for all leaders and followers)

For the comparison of the different aircraft-pairings also the efficiencies of the beneficial formations is an important criterion. If con-sidering $\boldsymbol{\lambda_F}$ a slightly different picture can be observed as is shown in figure 5. This figure shows boxplots of $\boldsymbol{\lambda_F}$ for all beneficial samples cumulated for all leaders and followers for the *complete* and the *reduced set*. It can be found, that the values are more equally distributed and that the B744, B763, A333 and A343 produce higher values for $\boldsymbol{\lambda_F}$ as a follower, whereas all other aircraft perform slightly better as leader. Especially the advantage of the A388 (see figure 4) is put into perspective. For the *reduced set* the values and relations basically remain comparable slightly shifted towards higher values. The maximum benefits above 6% were only reached by A388 as leader and B744 as follower.

Another criterion to evaluate the suitability of a formation pairing is the average fuel saving $\boldsymbol{\Delta F_F}$. Figure 6 shows the boxplots of $\boldsymbol{\Delta F_F}$ for the considered aircraft types cumulated for leaders and followers and separated for both sample sets.

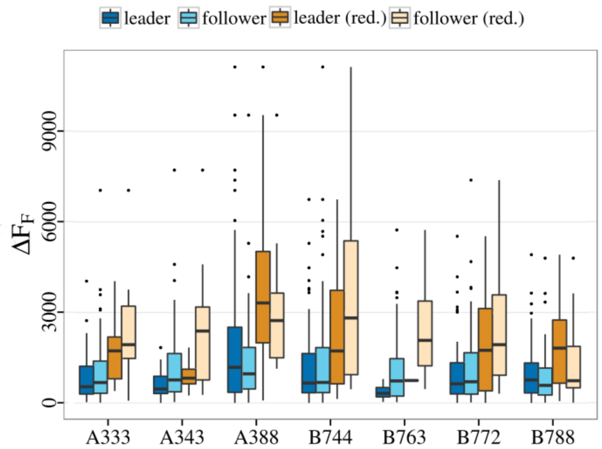

Fig. 6. Boxplots of fuel savings ΔF_F of formation geometry samples with positive λ_F (cumulated for all leaders and followers)

It can be found, that compared to $\boldsymbol{\lambda_F}$ the fuel savings $\boldsymbol{\Delta F_F}$ considerably change with the aircraft type and the position of the aircraft in the formation. Still the A388 as leader and the B744 as follower perform best and produce the maximum savings >9000kg, what can be attributed to the higher weights and sizes of the aircraft as mentioned above.

3.2 Influence of take-off weights

As mentioned earlier, the weight of the participating aircraft of a two-aircraft formation is a strong driver for the fuel saving benefits that can be achieved. As the prediction of the weight during the actual formation flight might be difficult beforehand it is interesting if the weights at take-off might qualify to estimate the potential fuel saving benefits of a formation.

This question will be analyzed in the following using the formation database.

Figure 7 shows the *take-off weights* (TOW) of leader and follower as well as the values for $\boldsymbol{\lambda_F}$ and $\boldsymbol{\Delta F_F}$ for the *complete* set and all aircraft pairings. All samples with positive $\boldsymbol{\lambda_F}$ are colored and the sizes of the bubbles indicate the magnitude of $\boldsymbol{\Delta F_F}$. All other successfully calculated samples with no or negative benefits are shown in gray color. From this diagram it can be found, that a formation is more likely to produce a fuel saving benefit if the TOW of the leader is higher than that of the follower. Also a high absolute fuel saving seems to be more likely if the leader is heavier at take-off than the follower. However the graphic also shows that some missions exist where a lighter follower can produce beneficial missions.

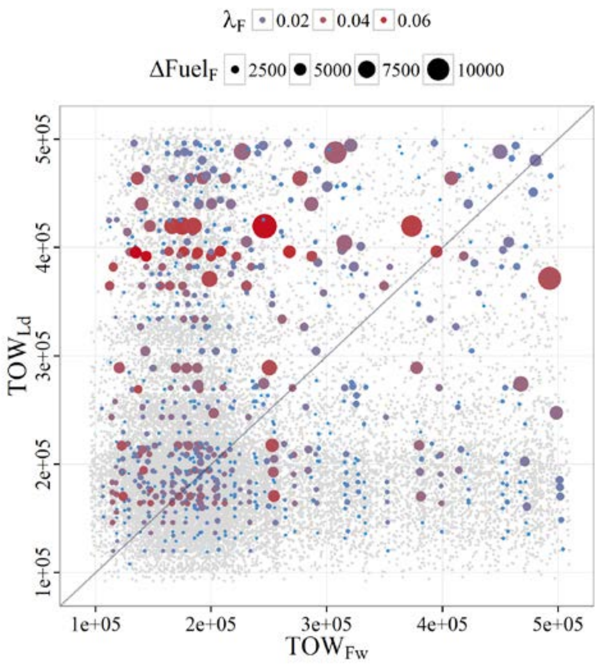

Fig. 7. Samples with positive formation metric λ_F over take-off weights of leader and follower (color indicating the magnitude of λ_F, bubble size indicating the magnitude of ΔF_F)

For better comparison of the TOWs a weight quotient Q_{TOW} can be defined as

$$Q_{TOW} = \frac{2(TOW_{ld} - TOW_{fw})}{TOW_{ld} + TOW_{fw}} \qquad (3)$$

Figure 8 shows Q_{TOW} against $\boldsymbol{\lambda_{Fw}}$, $\boldsymbol{\lambda_F}$ and $\boldsymbol{\Delta F_F}$ for the *complete set* and all formation pairings. It can be found, that according to the available data high values for $\boldsymbol{\lambda_{Fw}}$ can only be reached for high values of Q_{TOW} respectively. This effect can also be observed for $\boldsymbol{\lambda_F}$ however in less distinct form. Considering the even distribution of the samples and the different aircraft types used in this approach, it can be assumed that if the take-off weights are known, the maximum achievable efficiency of a formation might be estimated using Q_{TOW}. The effect cannot be found so clearly for $\boldsymbol{\Delta F_F}$ as seen in figure 8.

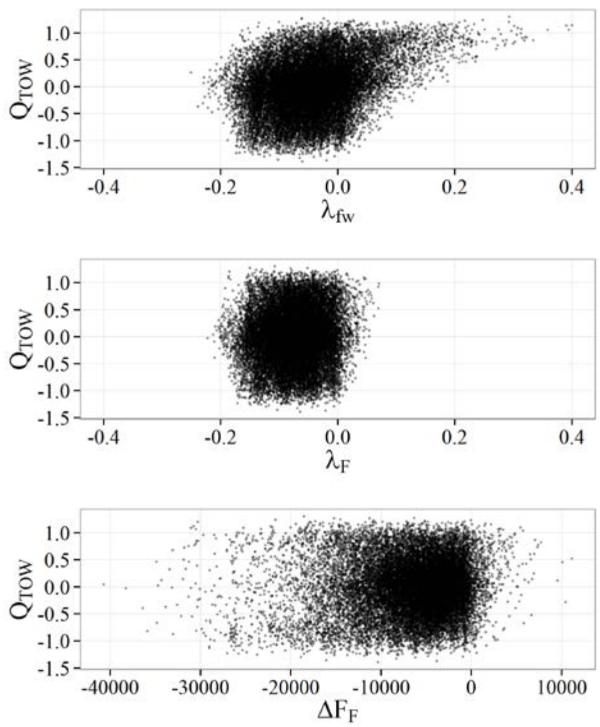

Fig. 8. Weight quotient Q_{TOW} over λ_{fw}, λ_F and ΔF_F for the *complete set* and all formation pairings

3.3 Evaluation using surrogate models

As the results presented above are of statistical nature and strongly depend on the considered use-case, for a specific formation geometry the benefits need to be assessed separately. As the FCA and FCS remain constant during the formation segment, choosing the best leader and the optimal operating point of the formation is important to maximize the benefit. In this chapter it will be shown, how this question can be solved using surrogate models for the formation pairings. The formation database provides the foundation to derive these models for all considered formation-pairings. Figure 9 shows a typical North Atlantic formation mission that will be examined in more detail. The formation geometry can be described by the formation parameters shown in table 4. It is assumed that the FCS is not defined and that the FCA is set to be 39000ft.

Fig. 9. Exemplary typical North Atlantic two-aircraft formation using a formation corridor

The reference routes are considered as great circles between origin and destination and in the above case with negligible detours coincide with the formation routes. It will be analyzed which formation pairing of same aircraft types is suited best for the given formation geometry. The surrogate models for these formation pairings can be determined from the database as described in chapter 2.6. As the differences for a changed leader are small only the formations AC_1<AC_1 (not AC_1>AC_1) are evaluated.

	route A	route B
origin	LHR	GVA
destination	YUL	JFK
σ	0.0	0.0
ξ_{ben}	0.0.4997	0.4142
ξ_a	0.1994	0.0.2808
lf	0.9	0.9
S	5217 km	6295 km

Tab. 4. Exemplary parameter values for routes A and B describing the formation geometry over the North Atlantic as shown in figure 9

In order to find the best FCS for the given formation geometry and to compare formation pairings a formation diagram can be constructed. This diagram is based on the surrogate models of different formation arrangements, a specific formation geometry and either on a fixed FCA or a fixed FCS.

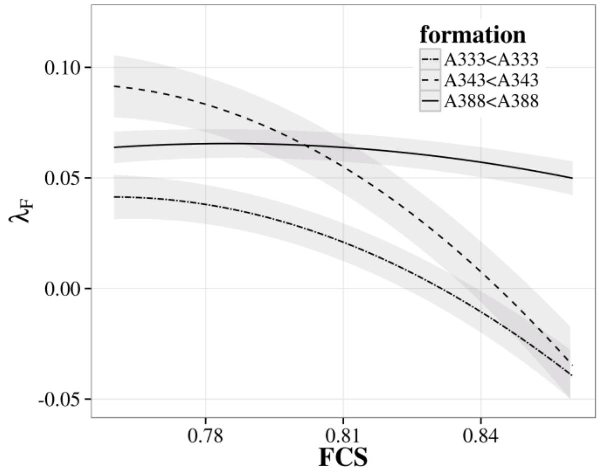

Fig. 10. Formation diagram for the formation geometry defined in table 4 (Airbus)

Figure 10 shows the resulting diagram with fixed FCA for the formation geometry defined in table 4 for all Airbus aircraft. It can be found, that for higher FCS the benefits of the formations decrease. For lower speeds the A344<A344 formation and for speeds above mach 0.8 the A388<A388 can be expected to produce higher formation benefits.

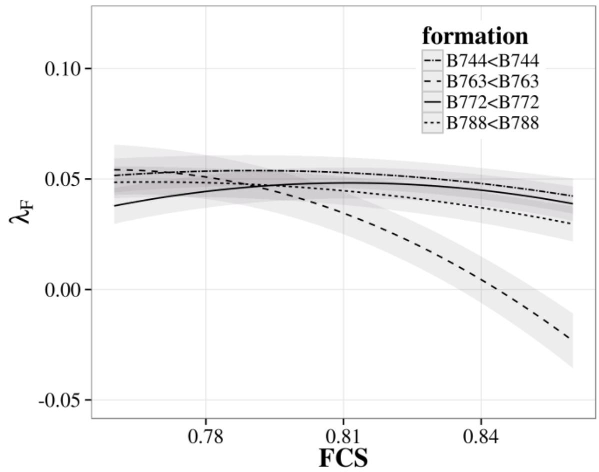

Fig. 11. Formation diagram for the formation geometry defined in table 4 (Boeing)

Figure 10 shows the resulting diagram with fixed FCA for all Boeing aircraft. It can be found, that except for the B763 all aircraft produce almost constant benefits for all speeds around 5%.

4 Conclusion and Outlook

In this work statistical analyses of numerous formation geometries were performed and it was shown, that depending on the underlying use-case some formation pairings with respect to aircraft types and the order of the aircraft within the formation seem to be more suitable for formation flight than others. Furthermore it was shown, that the take-off weights of the formation members qualify to estimate the maximum formation flight efficiency that can be reached by a formation. As the benefits strongly depend on the considered formation geometry, it was presented how the formation flight database that was elaborated within this work can be used to determine the most suitable aircraft pairing and order for a formation based on surrogate modeling.

Following this work it is planned to expand the database to more formation geometries and aircraft types and to further investigate the influences of the remaining formation parameters on the achievable benefits finally leading to a quick and accurate prediction model.

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