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QUANTIFICATION OF FORMATION FLIGHT BENEFITS UNDER CONSIDERATION OF UNCERTAINTIES ON FUEL PLANNING

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Abstract

Within this study, a method is proposed that allows an effective fuel planning for a follower aircraft in aerodynamic formation flight missions. The special characteristic of such formation missions in the context of fuel planning is the uncertainty of the successful formation execution. The required trip fuel of the follower, therefore, strongly depends on the unknown factor of the formation success. The proposed method aims at minimizing costs due to carrying excess fuel and balancing the expected benefits with potential costs that might result from a refueling stop.

For a set of 14 atmospheric days of the year 2012, the fuel planning by the proposed method is applied. It is shown, that an accurate fuel planning can help saving major amounts of fuel and money additionally to the formation benefits itself.

1 General introduction

The more trip fuel is taken on a mission, the more fuel is burned just due to transporting the fuel itself, an effect called the fuel carriage penalty. The examination of the additional cost caused by carrying unnecessary amounts of fuel in aviation was subject to various works. It was shown in [1], that on U.S. domestic flights about 4.48% of fuel consumption (1.38 billion kilograms per year) is caused by carrying unused fuel, whereas the fuel consumption could be reduced by at least 1.04% (0.32 billion kilograms per year) if the airline operators would not load amounts of contingency fuel above a reasonable level. One method to reduce these fuel carriage penalties is the concept of Intermediate Stop Operations (ISO). This concept presumes an intermediate landing along a route, which results in a reduced take-off mass due to a lower fuel demand at the origin airport. In ISO, the reduced take-off mass and, therefore, reduced fuel carriage penalty exceeds the additional fuel, which is needed for the second climb to the cruise altitude after the intermediate stop [2].

A similar concept for reducing the fuel consumption due to less excess fuel is the decision point procedure. It allows fuel planning at a reduced percentage of contingency fuel. However, a big difference to ISO is given by the fact that the contingency fuel will be sufficient under normal conditions. Therefore, the refueling stop is optional. When passing a beforehand specified decision point, it is the pilot's responsibility to decide according to certain rules during the mission, whether a diversion to an En-Route-Alternate airport (ERA) is necessary or not.

Another option to reduce excess fuel is provided by using approved fuel monitoring systems. Analyzing statistical fuel records of past missions helps airline operators to provide evidence, when there is only reduced need for contingency fuel on specific routes [3].

Furthermore, there have been various studies aiming at the determination of optimal amounts of holding fuel, which enable low fuel carriage penalties on the one hand and yet do not put a possibly necessary diversion mission from the destination airport to the alternate airport at risk [4].

The studies presented in this paper deal with the problem of minimizing the fuel carriage penalties for formation flight, a possible future technology in civil aviation with opulent expected fuel savings. These savings for a follower aircraft during a formation flight mission fully depend on successfully meeting with a leader aircraft at the rendezvous start point (RSP) and can lead to savings of up to several tons of fuel until the separation end point (SEP) is reached [5].

As a formation mission yields a higher level of uncertainty in terms of fuel planning than conventional missions, the investigations are aiming at quantifying the benefits of formation flight missions under consideration of different fuel planning strategies and the resulting cost due to fuel carriage penalties.

1.1 Approach

In order to investigate to which extent an early formation break-up or even a total failure of a formation should be considered in the process of fuel planning, a workflow was elaborated which is summarized in Figure 1.

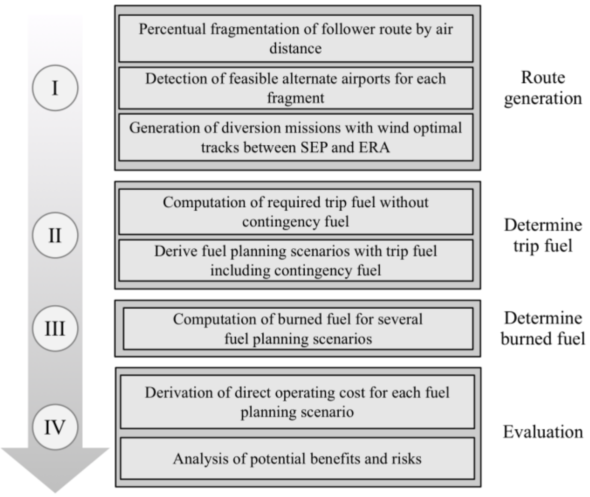

Figure 1: Investigation workflow

In the step of route generation (I), wind optimized formation routes between a set of two origin destination pairs are analyzed in order to generate possible diversion missions.
Subsequently, for all generated missions to the potential diversion- and commercial targets, the trip fuel is determined (II). Adequate amounts of contingency fuel are derived to yield fuel planning scenarios according to the prevailing regulations of the European Aviation Safety Agency (EASA).
Afterwards, in step III the resulting burned fuel, flight time and distance are computed for all considered fuel planning scenarios.
Finally, the results are evaluated in step IV, using a method for calculating the direct operating costs (DOC) for each mission and compared to each other. Financial benefits due to lean fuel planning and the increased risk of diverting to an ERA have to be traded off against each other.

1.2 Scope and model parameters

Within this study several assumptions are taken and boundary conditions are set, which are summarized in Table 1. As it can be assumed, that formations with more than two members are unlikely to be realized in the near future, only two-aircraft formations consisting of a leader (index Ld) and a follower (index Fw) are considered in the scope of this study. To further reduce the complexity of the optimization problems, only one aircraft type namely the Boeing B777-200 was chosen for both formation members with a formation cruise Mach number (FCM) of 0.84 according to the standard cruise Mach number of the B777-200. The load factors of both aircraft were set to 0.8 representing an average value for flights over the North Atlantic. The formation cruise altitude (FCA) was set to 39000 ft as a standard flight level for transatlantic flights.

AC-Type	Boeing 777-200
Formation Cruise Altitude	39000 ft
Formation Cruise Mach	0.84
Load Factor	0.8
Origin Airport Leader	LHR
Destination Airport Leader	JFK
Origin Airport Follower	CDG
Destination Airport Follower	YUL
Meteorological Year	2012
Analyzed meteorological days	14

Table 1: General model parameters and scope

For the origin and destination airports major European and North American airports were chosen with the leader departing from LHR to JFK and the follower from CDG to YUL.

For the studies, 14 different days of the year 2012 were considered. These days are distributed all over the year, such that there is at least one route per month. Since the weather patterns can strongly vary over the year, the resulting formation geometries strongly differ from each other, resulting in different sets of suitable alternate airports.

2 Models and data

In the following, the models and datasets which were used in the course of the examinations are described.

2.1 Meteorological data

Atmospheric data used in this study are provided by the European Center for Medium-Range Weather Forecast (ECMWF) and are taken from the European Reanalysis Interim data set. The reanalysis data are arranged in a coordinate grid with a resolution of 0.75° in latitude and longitude and a vertical resolution of 60 layers between the surface and an altitude level with a pressure of 0.1 hPa. For each grid point several meteorological parameters are available, e.g. temperature, pressure, relative humidity as well as wind speed and direction. In order to evaluate the atmospheric data, a linear interpolation is carried out between the nearest existing atmosphere data points [6].

2.2 Wind optimal routing

An optimal control approach is used to estimate minimum time tracks during cruise in the horizontal plane. In this approach, the aircraft is assumed to be a massless point, that is moving along a spherical earth with the radius R_E with a constant true airspeed v_{TAS} at a constant pressure altitude H_P. The flight direction can be affected by changing the heading angle χ_H which serves as control variable.
Additionally, the surrounding wind and pressure distributions are expected to be stationary. Presuming the flight path angle to be very small (H_P constant) and $H_P \ll R_E$, the aircraft's equations of motion can be formulated according to Equation 1 and 2 with λ representing the longitude, φ the latitude, u_w and v_w the wind speeds in eastward and northward direction.

$$\dot{\lambda} = \frac{v_{TAS} \sin \chi_H + u_w(\lambda, \varphi)}{R_E \cos \varphi} \qquad (1)$$

$$\dot{\varphi} = \frac{v_{TAS} \cos \chi_H + v_w(\lambda, \varphi)}{R_E} \qquad (2)$$

$$J = \int_{t_0}^{t_f} 1 \, dt \qquad (3)$$

Equation 3 shows the cost functional J of the optimal control problem as the flight time between the initial position 0 and the final position f. The optimal control problem can then be defined as the identification of the temporal evolution of the heading angle χ_H minimizing the flight time and satisfying the dynamic constraints defined by Equations 1 and 2 at the same time. This formulation represents Zermelo's problem on a spherical earth [7]. The optimal control law for the heading angle χ_H (Equation 4) can be derived by applying Pontryagin's minimum principle [8] to the resulting optimal control problem. A detailed derivation of Equation 4 can be found in [9].

$$\dot{\chi} = \frac{\partial u_w}{\partial \varphi} \cdot \frac{sin^2 \chi_H}{R_E} - \frac{\partial u_w}{\partial \lambda} \cdot \frac{cos^2 \chi_H}{R_E \cos \varphi} + \left(\frac{\partial v_w}{\partial \varphi} - \frac{\partial u_w}{\partial \lambda} \cdot \frac{1}{\cos \varphi}\right) \cdot \frac{\sin \chi_H \cos \chi_H}{R_E} + \frac{\tan \varphi \sin \chi_H}{R_E} \cdot (v_{TAS} + u_w \sin \chi_H + v_w \cos \chi_H) \qquad (4)$$

The system of differential Equations (1, 2 and 4) is integrated by using a shooting method solving a two-point boundary value problem with given initial and final latitudes and longitudes and various initial headings.

2.3 Trajectory calculation

All fuel calculations were computed with the trajectory calculation module (TCM), that is based on flight performance data provided by the Base of Aircraft Data (BADA) models version 4 by Eurocontrol [10]. These models are based on a total energy model. The formation benefits are estimated by calculating the average upwash at the follower aircraft resulting from the wake of the leader. Details concerning the calculation method can be found in [11].

2.4 Optimized formation geometries

For the 14 selected days of the study wind optimal formation geometries were calculated. The optimization method uses a pattern search algorithm optimizing the RSP and SEP locations of the formation geometry based on surrogate models allowing the estimation of the benefits. A detailed description of the method can be found in [12].

2.5 Airport data

The criteria for airports to be suitable as ERA for a distinct mission with decision point procedure are described in Section 3.2. All airports have to meet specific conditions regarding availability for commercial aviation and infrastructure, such as providing at least one runway with a minimum length of 10000 ft, enabling a B777-200 baseline airplane to take-off on a standard day [13]. The whole set of considered airports is summarized in Table 2. The airport data was provided by [14].

BGR	Bangor International Airport
YBG	Canadian Forces Base Bagotville
YHZ	Halifax Stanfield International Airport
YJT	Stephenville International Airport
YQM	Greater Moncton International Airport
YQX	Gander International Airport
YYR	Goose Bay Airport

Table 2: Considered En-Route-Alternate airports

2.6 Cost model

For a proper financial evaluation of fuel planning scenarios which might result in a diversion, a method for obtaining the direct operating cost (DOC) is employed according to [15]. This approach considers the fuel consumption and the mission time as well as crew-, maintenance-, landing-, navigation- and ground handling-fees. Furthermore, the aircraft size is taken into consideration in terms of maximum take-off mass and payload, which is a relevant factor on depreciation and insurance. The fuel price is assumed based on average values of the year 2016. The remaining costs, based on initial values from 2012, are scaled to the year 2016 considering the U.S. inflation rate of average consumer prices [16].

3 Methods

The prevailing rules for fuel planning with reduced contingency fuel, as they are regulated in [3], are briefly described in the following.

3.1 Regulations on fuel planning

The rules for reduced contingency fuel planning prescribe the airline operators how to calculate the usable fuel for commercial aircraft operations. Different kinds of fuel policies can be selected by the operator in accordance with some further regulations. The regulations for the use of reduced contingency fuel operations are described in the section on fuel policy in [3].
In a default scenario, the usable fuel for a mission is determined by computing the required trip fuel for a given track and flight profile, and subsequently adding an additional amount of 5%, called contingency fuel. This fuel planning scenario represents the reference baseline of this study.

Due to the additional cost of carrying excess fuel, it is in the interest of airline operators to minimize the amount of carried fuel.
A well-established method to reduce the amount of contingency fuel is the decision point procedure (DPP). The idea behind DPP is to take a reduced amount of fuel on a mission and to consider an optional refueling stop beforehand. When passing by the preassigned position in the flight plan, the pilot has to decide, based on the previous fuel consumption, whether the remaining fuel reserves are sufficient and the flight may continue as scheduled, or whether a refueling stop is necessary. Hence, in the case of unfavorable and unexpected wind situations for example, the fuel consumption may increase, causing the need for a refueling stop. However, if remaining fuel reserves are sufficient, the carriage penalty is reduced compared to conventional planning. Within this study, the idea of DPP is adopted in order to develop adequate fuel planning strategies for formation missions. Therefore, the details of a fuel planning according to DPP are described in the following section.

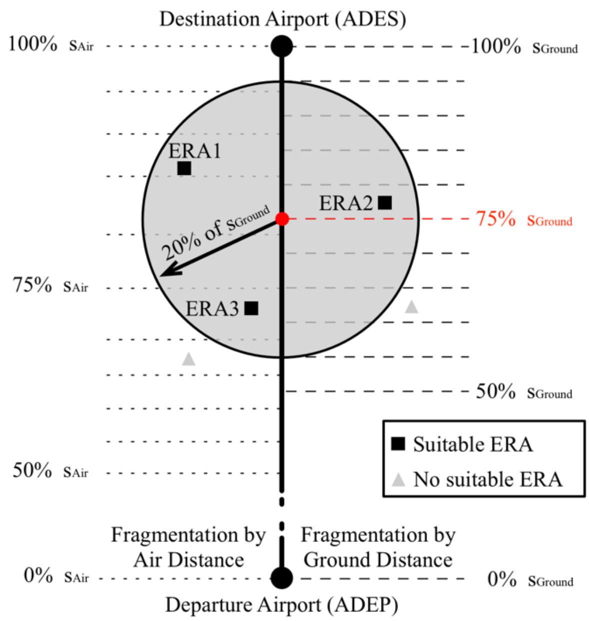

Figure 2: Area of suitable ERA airports and applied route fragmentation by air distance

3.2 Decision point procedure (DPP)

3.2.1 Trip fuel calculation with DPP

An important aspect in flight planning according to the DPP is the availability of suitable ERAs along the planned track. The regulations for selecting the ERAs are summarized in Figure 2. The track from departure to destination airport is fragmented into parts of 1% regarding the ground distance as depicted on the right scale. A circle (shaded) with a radius of 20% of the ground distance around the center of the 75% ground distance mark depicts the area, in which every airport can be considered as suitable ERA, as long as all other criteria (see Section 2.5) are fulfilled.

The rules for calculating the minimum required trip and contingency fuel for the follower are summarized in Equations 5-7 and illustrated in Figure 3. For a proper DPP planning, it is mandatory to first compute the required trip fuel without contingency fuel (index NoCont) from the departure airport (ADEP) via the examined decision point (DEC) to the ERA. The resulting amount of fuel (index Div) is charged with 3% of contingency fuel and is designated $m_{TF,Div}$. This can be considered the required amount of fuel to ensure a safe diversion to the ERA.

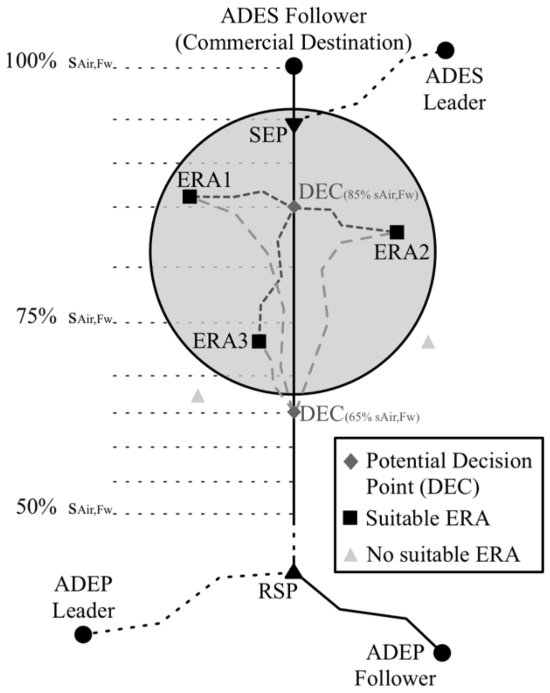

Figure 3: Formation route from the perspective of DPP flight planning

In a second step, the amount of fuel required to fly from ADEP via DEC to the destination airport (ADES) is calculated. This amount of trip fuel is, in compliance with Equation 6, charged with a contingency fuel, which should be at least 5% of the required trip fuel between the examined DEC and the destination airport. This amount of fuel for a mission on schedule (index Sdl) will be designated $m_{TF,Sdl}$.

Finally, Equation 7 dictates that for an examined combination of DEC and ERA, the respective higher value has to be chosen as the minimum required amount of m_{TF}. Repeating these steps for all suitable DECs and ERAs along the route, a combination which optimally fulfills the given boundary conditions can be obtained.

$$m_{TF,Div} = 1.03 \cdot m_{TF,NoCont}(ADEP \rightarrow DEC \rightarrow ERA) \tag{5}$$

$$\begin{aligned} m_{TF,Sdl} &= m_{TF,NoCont}(ADEP \rightarrow DEC \rightarrow ADES) \\ &+0.05 \cdot m_{TF,NoCont}(DEC \rightarrow ADES) \end{aligned} \tag{6}$$

$$m_{TF} = \max(m_{TF,Div}, m_{TF,Sdl}) \tag{7}$$

For the sake of brevity throughout this study, the term trip fuel m_{TF} is always considered to contain contingency fuel according to Equation 7, if not declared otherwise.

3.2.2 Formation flight routes with DPP

As depicted in Figure 3, the DPP planning is carried out for the follower along a formation route. This causes the necessity of an inclusion of the boundary conditions caused by the formation in order to determine the optimal combination of DEC and ERA.

The part between the departure airport and the RSP is called approach phase, where the aircraft climbs on cruise altitude and performs a standard mission. At the RSP, the rendezvous maneuver begins with both aircraft establishing a stable formation.

Between the RSP and the SEP, the two aircraft can be considered to fly in formation and benefits are generated for the follower aircraft. Finally, the continuation segment is the part between the SEP and the commercial destination airport ADES.

For the purpose of finding the optimal DEC, first the examined formation route is divided into percentaged fragments with respect to the follower air distance $s_{Air,Fw}$ which allows an easy definition of DEC positions. Since the search interval covers the follower's air distance from 50% to 100%, the first possible DEC is designated $DEC_{50\%\ Air,Fw}$.

In contrast to the ground distance fragmentation which is applied for the search of suitable ERA airports, meteorological influence like wind and temperature effects are considered.

For each possible DEC, the three closest suitable ERA airports are determined, applying the optimal control method presented in Section 2.2. They are added to the local group of suitable ERAs. For the case of a high airport density, all further airports are added to the group that are in a maximum range of 130% air distance compared to the closest airport, which reflects an estimated wind influence factor. Accordingly, at least 150 different combinations of DEC and ERA are examined for each route.

3.2.3 Determination of required trip fuel and resulting burned fuel

With the formation geometries defined, TCM is used to compute the required amounts of trip fuel according to the listed settings in Table 1. In the first iteration loop, the simulation is executed under consideration of the not usable reserve fuel (see Section 3.2.5) for the purpose of computing $m_{TF,NoCont}$ and deriving $m_{TF,Sdl}$.

The expected formation benefits are fully applied to the determination of $m_{TF,Sdl}$. Hence, the fuel planning is made under the condition, that the follower is only able to reach the commercial destination, as long as the leader shows up at the RSP.

However, a consistent fuel planning needs to hold up against any possible safety issues. To cover the case, that the follower aircraft needs to divert due to a total formation failure or an early formation break-up, the amount $m_{TF,Div}$ is derived without any consideration of formation benefits. Combined with the reserve fuel, the determined ERA is supposed to be reachable by the follower in a self-sustaining way in all obtained fuel planning scenarios.

3.2.4 Consideration of post-diversion missions

In the case of a diversion for refueling, the mission has to be continued to the commercial destination. A post diversion mission is carried out with a conventional fuel planning of 5% contingency fuel.
Secondary effects of that detour, like the inability of passengers to reach possible onward flights in time, are not considered in the course of these investigations.

3.2.5 Alternate fuel and final reserve fuel

This study is focused on the planning optimization of the usable fuel. Nevertheless, the process of flight planning includes additional fuel reserves in order to maintain the ability to fly holding loops at the destination airport for at least 30 minutes at a minimum drag speed. Furthermore, the regulations on reduced contingency fuel in [3] mention the possibility of a required diversion from the commercial destination to an alternate airport, which has to be considered at least in some cases. The required fuel for the holding loops was roughly determined to 3500 kg for a Boeing 777-200 with a load factor of 0.8. Adding a small buffer for the consideration of a possible diversion from the ADES, an amount 6000 kg fuel is added to every fuel planning, that is designated to be still available at the end of the mission. In future investigations, the consideration of the alternate fuel might be part of the optimization process.

4 Analysis of the fuel planning strategies

The introduced method is applied to analyze possible combinations of DECs and ERAs. The reduction of trip fuel m_{TF} and the resulting savings in burned fuel (index BF) are quantified on the base of two exemplary formation routes. Finally, a fuel planning strategy is assessed in terms of DOC savings and compared to potential extra cost.

4.1 Planning by minimum burned fuel

An overview on the two examined follower routes is depicted in Figure 4 and Figure 7. Each of the shown circles represents a possible DEC and was evaluated regarding the local minimum required trip fuel, which is influenced by the airport positions. All ERAs are depicted in specific colors, which are used as their identifiers.

Relative change in m_{TF}

The applied logic behind the assignment of the route points to the colors can be learned from Figure 5 and Figure 8. They show the relative change of m_{TF} for each of the examined DECs, according to Equations 5-7. A fuel planning including 5% contingency fuel without consideration of formation benefits is used as the baseline, representing about 50000 kg of fuel. The light shaded area between the circles and the baseline represents all tolerable combinations of DEC and m_{TF}. The colored lines are the local resulting trip fuels for the corresponding airports. For each DEC, the local minimum of all lines is derived and marked with a circle. The dark shaded area is below these local minima and is, therefore, not permitted.
The dashed vertical lines mark the transition of the quasi-linear gradient on the left side and the curved trend on the right side. This is caused by the change from $m_{TF,Sdl}$ to $m_{TF,Div}$ as the applicable value according to Equation 7.
The consistency between Figure 4 and Figure 5 is distinct. In the first part of the route, the closest ERA is YQX and the minimum required m_{TF} decreases almost linearly. At $DEC_{75\%\,sAir,Fw}$, the required trip fuel reaches a minimum value of about -20% of the baseline. This difference equates to about 10000 kg. With proceeding DEC positions, the optimal ERAs change to YJT, YHZ and finally BGR, while the required m_{TF} grows.

Relative change in m_{BF}

In Figure 6, the resulting savings in burned fuel are shown. It is evident, that the optimal combination in terms of minimal burned fuel is equally reached at $DEC_{75\%\,sAir,Fw}$ with YQX as ERA. The maximum savings in m_{BF} due to the reduced fuel carriage penalty, assuming a successful formation mission, can be identified to almost 5% (~2000 kg) with respect to a successful formation mission with a conventional fuel planning. The second example (Figure 8 and Figure 9) also shows a potential reduction of trip fuel by 20% (~9000 kg) with resulting savings in burned fuel of 3% (~1200 kg).

However, these potential savings presume a successful formation. The grey dashed lines in Figure 6 and Figure 9 refer to the right-hand scale and show the increase of burned fuel for the case of

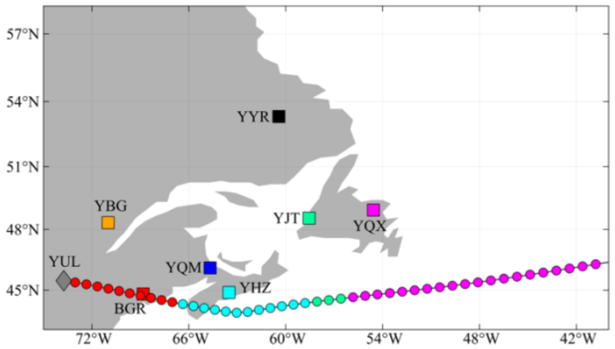

Figure 4: Follower track, potential DECs assigned to ERA with minimum $\mathbf{m_{TF}}$, 22.04.2012

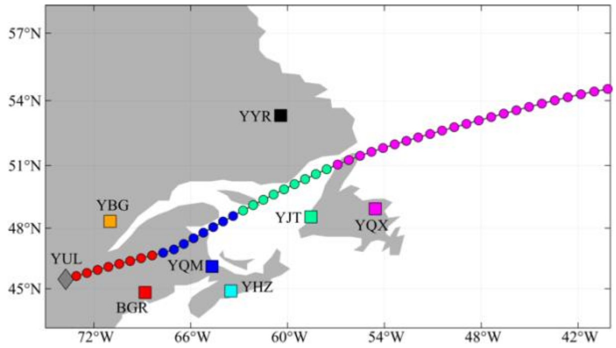

Figure 7: Follower track, potential DECs assigned to ERA with minimum $\mathbf{m_{TF}}$, 04.08.2012

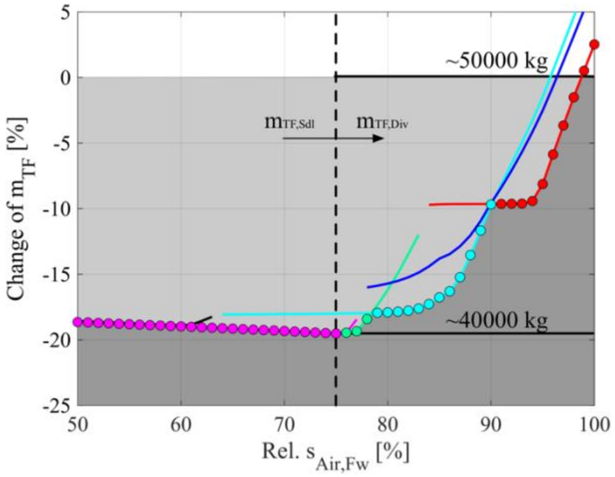

Figure 5: Required trip fuel according to DPP compared to a conventional fuel planning, 22.04.2012

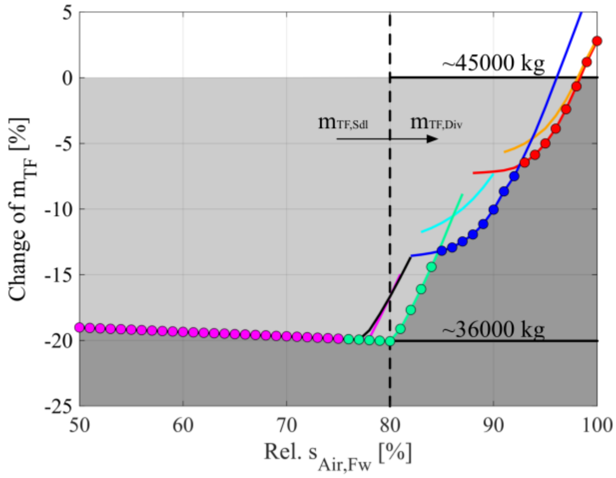

Figure 8: Required trip fuel according to DPP compared to a conventional fuel planning, 04.08.2012

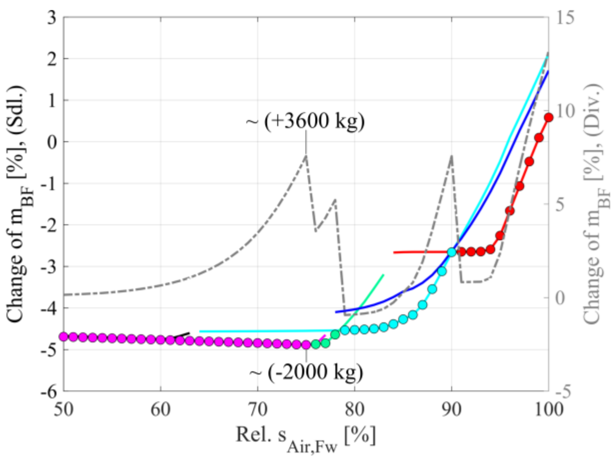

Figure 6: Reduction of burned fuel for DPP planning with formation benefits, 22.04.2012

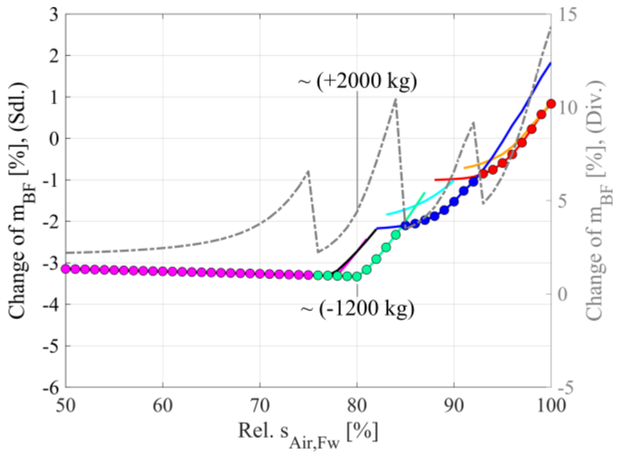

Figure 9: Reduction of burned fuel for DPP planning with formation benefits, 04.08.2012

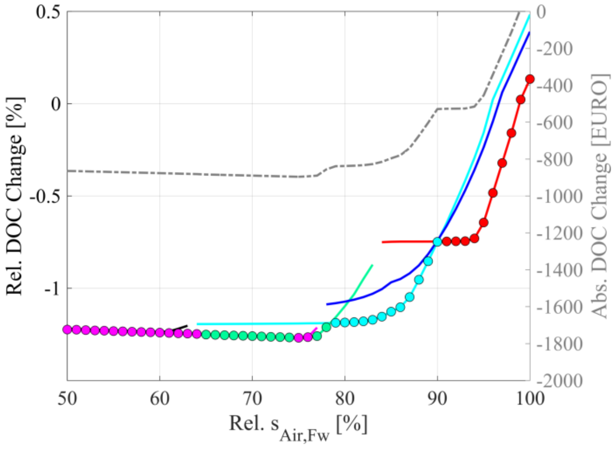

Figure 10: DOC reduction for max. benefit optimization, 22.04.2012

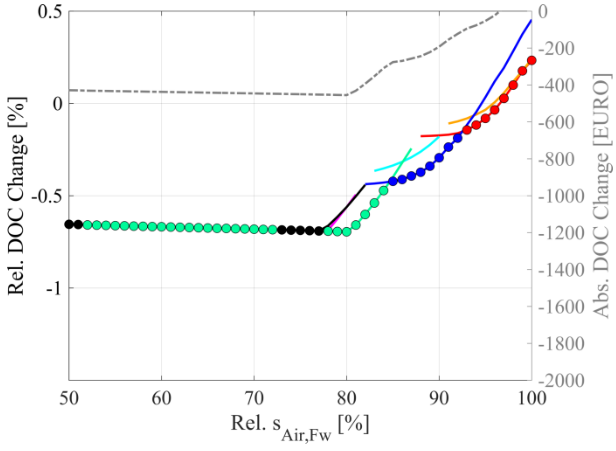

Figure 12: DOC reduction for max. benefit optimization, 04.08.2012

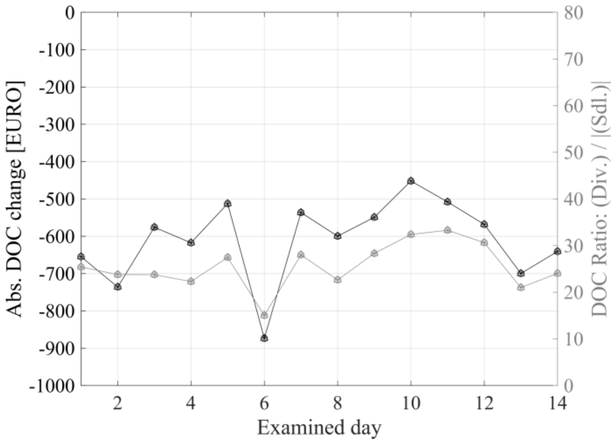

Figure 11:Possible DOC savings for all examined days

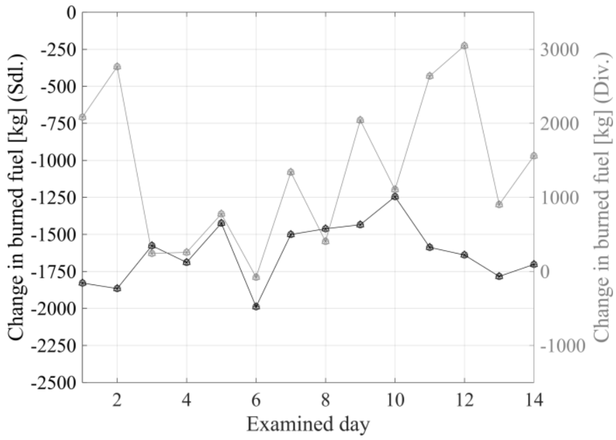

Figure 13: Possible savings in burned fuel for all examined days

the same fuel planning with a total formation failure. In both cases, it can be observed that the increased burned fuel due to the detour to an ERA and the post diversion mission would reach values of +7,5% (~3600 kg) in Figure 6 and +4% in Figure 9 (~2000 kg). For the two examples, the rich potential benefits in terms of reduced burned fuel seem to justify taking the risk of a diversion, since the savings in m_{BF} are high enough, that the balance would still be positive if every third formation would fail. If the DEC is shifted to $DEC_{80\%\, sAir,Fw}$ in Figure 6 or respectively to $DEC_{75\%\, sAir,Fw}$ in Figure 9, the proportions between $m_{BF,Sdl.}$ and $m_{BF,Div.}$ are even more favorable.

However, there are many factors like e.g. time loss (see Section 2.6), demanding a more detailed analysis in terms of DOC.

4.2 Planning by DOC

In order to evaluate the tradeoff between financial benefits due to a lean fuel planning and the resulting savings of burned fuel on the one hand, and a diversion to an ERA leading to a delay and thus to increased fuel- and time-depending costs on the other hand, the DOC method described in Section 2.6 is applied.

The first fuel planning example (Figure 10) optimizes potential benefits in terms of DOC. The comparison between Figure 10 and the planning in Figure 6, which minimizes the amount of burned fuel, show distinct similarities. Both cases share the optimal combination $DEC_{75\%\, sAir,Fw}$ and YQX and show a similar progression of the curve. The resulting savings in terms of DOC were identified to 1.3%, which equates to a saving of about 850€.

The second example (Figure 12) shows high resemblance to its counterpart in Figure 9 as well. The curve progressions look alike and the optimal combination of $DEC_{80\%\, sAir,Fw}$ and YJT are identical. The most evident difference is the appearance of airport YYR, that substitutes the airport YQX. Regarding the savings in DOC, the second example shows leaner benefits with a

maximum saving of 0.6% in DOC, which equates to roughly 450€ in total.
Comparing the results of a fuel planning by DOC and by minimum burned fuel, the latter surprisingly seems to represent the time dependent effects of a diversion on an adequate level in order to find similar results on the optimal DEC and ERA combination.

Statistical overview

Within these studies, formation routes for 14 different days, distributed all over the year were evaluated. The results for the potential savings in DOC and burned fuel in the case of successful formation execution are summarized in Figure 11 and Figure 13.
The possible DOC savings in absolute numbers reach from 450 € up to almost 900 € per mission (left-hand scale). The benefits strongly depend on the route and the corresponding weather situation. On the right-hand scale, the financial loss due to a diversion is normalized by the benefit of the fuel planning for a successful formation. A value of 20 for instance means, that for 20 successful formations one may fail and the net benefit is still positive.
This ratio varies between 15 and 30 and might be used as a baseline in order to decide, whether a formation should be planned lean or rather conservative. The resulting savings in burned fuel, depicted in Figure 13, vary between 1250 kg and 2000 kg. The amounts of additionally burned fuel in the case of a formation failure are depicted on the right-hand scale. A case in which the diversion itself leads to a saving of burned fuel (value smaller than 0) can be identified, which demonstrates the basic idea of intermediate stop operations. In the worst case an additional burned fuel of roughly 3000 kg was estimated.

5 Conclusions and outlook

This study proposed a method for an effective fuel planning of a follower aircraft in an aerodynamic formation, that minimizes the cost induced by carrying excess fuel on a mission. The proposed method is based on the well-established decision point procedure and modifies it, in order to properly consider the special characteristics and additional benefits of a formation flight mission.
A set of 14 wind optimized routes was modified to enable an analysis of the optimal combination of decision point and ERA. The required amounts of trip fuel for the follower were calculated and could be reduced by 20% compared to a fuel planning with a conventional amount of contingency fuel and without consideration of formation effects. It was shown, that the resulting reduction of the take-off mass leads to additional savings of burned fuel up to 2000 kg (5%) compared to the reference value. Furthermore, an analysis was carried out to quantify the possible savings in terms of direct operating costs. It could be shown, that the savings sum up to about 450 € to 900 € (1.3%) per mission, depending on the daily routing and weather situation.
These benefits come with the disadvantage that the follower aircraft has to take a refueling stop if the formation is not successful. The financial consequences of such a diversion mission were quantified using a DOC method, that considers the longer flight time, detour, increased fuel consumption and other aspects. It was shown, that the cost of a diversion can exceed the potential benefits by a factor of 15 to 30.

The results suggest to consider this specific factor as a guide value for developing a procedure, that helps deciding under which conditions a follower should plan the fuel amounts lean or conservative.
The results of this work are based on models with many assumptions which can cause imprecisions in calculating amounts of burned fuel or DOC for instance. The scope of this study with only 14 days of consideration is rather limited for general conclusions. In future investigations, the fuel planning procedures will be implemented on a more elaborated level and on a larger atmospheric scope. In addition to the already considered diversion costs in the case of formation failure, future studies will focus on the costs due to the detour compared to a non-formation routing and include them in the analysis.

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