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POTENTIAL OF INTEGRATED AIRCRAFT ROTATION AND FLIGHT SCHEDULING BY USING INDIVIDUAL TAIL SIGN PERFORMANCE

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Summary

Aircrafts are subject to steady deterioration effects in flight operations. This concerns notably engines and airframes efficiency, but also aircrafts operating empty mass increases over time. As a consequence, the average fuel consumption is higher for the same performed flight with a deteriorated aircraft. Although these effects are already considered in operational flight plans (e.g. fuel calculations), such efficiency parameters are only rarely respected in aircraft rotation planning. In most cases, aircrafts of one fleet series were only treated as identical and are scheduled on the basis of maintenance events and other restrictions. If performance degradation and the resulting cost deviations are considered in the tail assignment process, each aircraft can be allocated to flights such that a cost minimum solution is found. This work investigates the upcoming fuel and cost saving potential by considering different aircraft efficiencies in flight planning. For this purpose, we calculate additional fuel consumption caused by several deterioration effects. By using an integrated flight scheduling and aircraft assignment model we demonstrate cost and fuel minimum rotation solutions. Our research reveals that cost savings of 22,400 kg fuel in a week for a air cargo airline are possible (on average 150 kg per reassigned flight). This assignment problem depends on different cost factors and flown distance in major and lesser in number of cycles and aircraft mass. In addition to the demonstrated saving potential, we give recommendations to consider the tail sign performance in a short term planning phase, where flight plan is almost fixed.

1. INTRODUCTION

1.1. Motivation

Although airlines profitability has increased in the last years and the today's fuel price is low, a furthermore efficient operational planning is essential. In particular, this concerns also the fleet and aircraft rotation planning in respect to flight scheduling. Especially the fleet ties up high capital and has significant influences in direct operating costs (DOC). Whereas aircrafts of several fleet types differ obviously in DOC per flight, same aircrafts of a type series can also lead to various total costs for a flight. This is a result of many factors, for example ageing processes of engine and airframe, increasing in aircraft mass and equipment differences in consequence of continuous fleet acquisition progress. Since these differences are often marginal for one flight, the conventional flight planning takes this only rarely into account. If already done, then only a performance factor is used in flight planning, representing the additional fuel consumption of a unique aircraft (identified by registration or tail sign). However, the other influences in DOC are neglected. One reason can be found in simplifying the flight planning process, which is divided in several steps. Whereas the problem is then less complex, the solution represents often only local optima. In this work, we first determine the operating cost variations for typical performance degradations of Airbus A320 aircrafts exemplary. By this investigation we show the effects of aircrafts deterioration in additional fuel consumption. Second, we take the efficiency differences and show a cost saving potential in flight planning. This is later applied for a fleet of long distance cargo aircrafts and their actual performance factor deviations. Therefore, an integrated flight scheduling and aircraft rotation planning model is used. Direct operating costs and especially fuel costs are estimated by an aircraft performance model. As the integrated fleet planning, scheduling and assigning process is complex and NP-hard, we give further recommendations for a greater applicability in later flight planning steps. By given such guidance rules for the tail assignment, two single flights or strings of flights up to complete rotations can be compared between aircrafts and the cost minimum solution found. The resulting savings potential by reassignment depends on two factors: The first is the heterogeneity of fleets and aircrafts and the second are deviations between number of flight cycles and flight hours of candidate rotations.

1.2. State of the art

1.2.1. Fleet Planning and Flight Scheduling

Given the fact of the relevance of fleet planning related to implied airline costs, comprehensive research work is done in this context [1]. The typical fleet planning process consists of strategic, tactical and operative phases as a gradually detailing of planning tasks. The beginning of the long-term flight planning phase is normally three years before departure, whereas strategic decisions in fleet acquisitions could be made even earlier. At first step in operational fleet planning, a fleet assignment is executed until four weeks before date of departure [2]. In this phase, maintenance and aircraft availability schedules will be used to assign the best suitable fleet (in terms of aircraft performance and capacity) to the predefined flight connections. However, this step does not represent the allocation of individual flights to unique tail signs. This aircraft rotation planning begins about six months before the start of winter or summer flight plan. In this phase of flight planning, the flights are connected to fleets and flight routes as strings are scheduled. These routes are then assigned to unique tail signs, depending of the availability and maintenance plans. Two weeks before departure, fleet planning ends and the timetable is nearly fixed, but small changes are still possible. We give strategies for each planning phase to involve aircraft deterioration effects.

The fleet assignment problem (FAP) is normally solved using a linear programming approach. Sherali et al. [3] carried out key criteria of the FAP and presented a generalized assignment model. Lohatepanont and Barnhart [4], provide an integrated model for schedule design and fleet assignment maximizing airlines profit. In Salhi and Sari [5] a composite heuristic for the vehicle fleet mix using multiple depots is given and Koç et al. [6] solved location-routing problem including time windows. In most FAP, the assigned aircrafts are handled anonymously and only the number of available aircrafts is considered.

The tail assignment problem (TAP) is a similar form of FAP and uses the results achieved in previous fleet assignment. Within one of these fleets' series, individual tail signs are assigned to single flights or complete aircraft rotations [7]. Typically, the planning of rotations is done separately from the allocation of aircraft and solved stepwise, since this is a complex combinatorial problem. It can already be found extensive research work considering this integrated planning and assignment problem. However, aircrafts are often handled as equal and only maintenance events or delay probability in rotations is regarded [8] [9] [10] [11].

Lapp and Wikenhauser [12] show a high cost saving potential if individual tail sign fuel consumption is considered in flight planning and assignment process. So they demonstrated savings of three million dollar per year in fuel costs. However, they only used performance factors as different multipliers for aircraft fuel burn and did not modeled aerodynamic and engine related fuel burn. By using an aircraft performance model, simulated increased drag and also mass variances (e.g. different aircraft loading factors or empty mass) we show a more detailed cost saving potential and influencing parameters. We will also give recommendations for flight planners if detailed individual calculations are not possible.

1.2.2. Aircraft Performance Factor

It is well known, that aircraft fleet series (A320, A321, and B737) often vary substantial in their operating cost structure and performance (e.g. capacity). For this reasons, flights are assigned to the most suitable fleet to maximize the overall profit of the airline. In the next steps we introduce cost and fuel variations of aircrafts which are member of one fleet series.

Even at same operational flight conditions (air traffic control handling, weather and wind conditions, payload and fuel mass) aircrafts show different fuel consumption and DOC for this flight [13]. The DOC can be influenced by differences in leasing costs (for aircraft or engine) and by the maximum take-off mass (MTOM). Since the MTOM is often used in ATC charge and airport fee calculation, such cost differences influence the cost minimum assignment. However, the main reason in cost differences can be found in loss of aircraft efficiency by the effect of deterioration and aerodynamic configurations (e.g. fuel saving of winglets, [14]).

Aircraft efficiency is influenced by:

- operational conditions of engines
- aerodynamic efficiency and resulting drag coefficients of the aircraft
- operating mass empty of aircraft

Airlines express aircraft efficiency loss as performance factor (PF) and adjust with this factor fuel calculations and their flight management system. Airbus assumes that the total aircraft performance factor is composed of 20 % aerodynamic and 80 % engine fuel consumption increase [15].

Engine Performance Factor

Aircraft engines are subject to natural wear and tear depending on the type of use. Especially compressor and turbine deteriorate due to high load and high speed striking projectiles (e.g. dust at desert near airports). The major reasons for engine deterioration are the following [15], [16] :

- adhesion, abrasion and erosion (dirt and dust)
- fretting corrosion (foreign and own object damage)
- blended blades repairing procedure
- by dirt contaminated engine

Primary effect due to engine deterioration is a lower compression ratio at requested thrust setting. For that reason, the rotation speed of fan and compressor has to be increased which results in loss of specific range and increased thrust specific fuel consumption (TSFC). Finally, the process of deterioration is responsible for higher aircraft fuel consumption for identical member of a fleet series. This engine effect can be described by an engine performance factor (EPF).

Aerodynamic Performance Factor

Besides engines efficiency, the aircrafts frame and hull is also subject to wear. Small dust particles hit the aircrafts surface and cause to minor dents. Flaking paint and unclean closed aircrafts parts (doors, flaps) or repairing patches can also result in an increased drag coefficient. This also applies to parts from configuration deviation lists (e.g. seals) which lead to more wind resistance. The air flowing around the aircraft swirls at these irregularities and parasitic drag is increased. A higher fuel flow is the needed, especially in lower altitudes and high velocity. Airbus investigated such growth of drag and performance degradation and provides approximate values for additional fuel consumption. For example, paint peeling at a leading edge slat over a 1 m² area results in a fuel penalty of 1000-1,500 $ at a A320 per year [17]. A survey of Boeing to the impact of increased drag has shown that additional 1% drag results in increased fuel consumption of 56.000 liters for a Boeing 737 [18].

During regular flight operation, the PF cannot be measured. The EPF impact can be estimated in post flight analyses by identifying changes in engine status parameters (exhaust gas temperature, speed of rotation). Therefore, data from flight data recorder is used and a statistical average for the performance factor determined. This is the today common method for calculating additional fuel consumption as an effect of deterioration [19].

As one of the first airlines, Air Berlin has developed a tool to measure irregularities on aircraft surfaces. During maintenance operations, small damages and bumps are measured and recorded. Software estimates for each irregularity the additional fuel consumption by using an aircraft performance model. In a cost-benefit analysis the fuel costs and maintenance man hours can be compared to make a decision if the aircraft is repaired or not. Further systematically measurements and analysis to aerodynamic degradation are not in practice [20].

Contaminated surfaces by dirt are excluded in this study due to their short-term effect. Such fluctuations in efficiency shall not be considered in a long-term flight planning. But attention should be paid to other short-term changes of the PF. Through maintenance or cleaning events the PF can be improved significant. However, this could only be measured within the next months if normal measurements are applied. On this account, greater maintenance activities should be considered in the PF manually to avoid incorrect values. We assume for the next steps, that the PF remains constant for the investigated planning horizons and represents the additional fuel consumption by hull and engine deterioration exactly. Statistical variances, measurement errors of true air speed and deviations from the optimal center of gravity are assumed as already excluded from given PF.

A Eurocontrol study found that the reported engine performance degradation of airlines is between 2% and 6% fuel increase [21]. Airbus reported an increasing in fuel flow of 5%-7% would be the upper extreme case based on their experience [22]. Also according to airbus, there is a loss of 1.3 % specific ranges when there is no engine replacement and only an up to 0.3 % with engine replacement [23].

2. MODEL DESCRIPTION

Our objective is to find the cost or fuel minimum assignment of flights to unique aircrafts within a fleet series. It is assumed, that the fleet assignment is already done before, but different fleet series can also be modeled. As an extension to conventional resource scheduling, we introduce the deterioration of the aircraft as additional cost factor. If other aircraft individual characteristics influence the unique cost performance they can further be included in the model. The resource planning is done using a simultaneous flight scheduling and aircraft assignment model. If needed, time windows can be defined, at which a flight or maintenance event should be happen. If widener time windows are implemented, the models flexibility is increased and a higher potential can be expected. As output the complete aircraft rotation for all aircrafts within the time horizon is given. Total fuel burn will be calculated by a simulation environment and aircraft performance model. If given, other DOC can be included in the cost minimum assignment decision.

2.1. Aircraft Rotation Planning Model

The aircraft rotation and flight scheduling model assigns simultaneously fleets and aircrafts to scheduled flights. Figure 1 shows rotations (a various number of flights) for two aircrafts, colored in red and blue. The model establishes the connections between flights (boxes) and assigns each mandatory flight to an aircraft. Therefore, time and other flight related constraints are taken into consideration. Maintenance events as restrictions were formulated as mandatory for a special aircraft and have to be scheduled sometimes within a given time slot. Operative reserve slots addressed to absorbing uncertainties in flight plan can be served by any aircraft, if payload and range are sufficient.

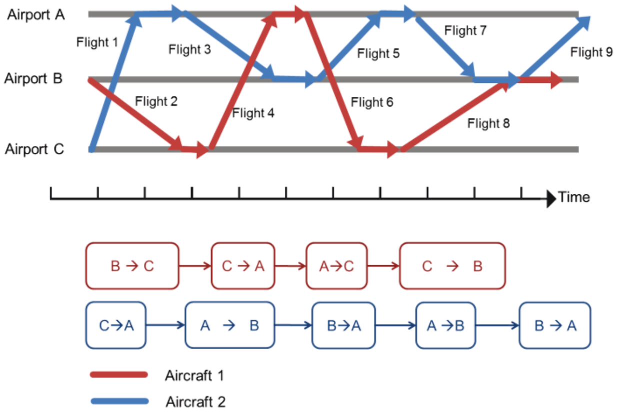

Figure 1: Time-Space-Network and associated flight plan as aircraft rotations

We use a linear optimization model to find a cost minimum solution with binary decision variables for flight assignment. Whereas airlines are interested in optimizing their viability, the target function can also be represented by a maximum profit calculation. Therefore, profits and costs for each flight and aircraft have to be formulated.

The model is based on the methodology of a vehicle routing problem (VRP) where aircrafts are 'routed' to and from flight events. The extension of this model by time windows (VRPTW) gives the possibility to insert mandatory maintenance events in the schedule. Our used model is first formulated by Gheysons et al. [24] and is applied for the scheduling phase. By applying adjacency matrices as additional restrictions (flight series, flight to aircraft assignments) we have the possibility to test different flight planning scenarios or predefine/forbid mandatory assignments. This allows different flight planning strategies, which represents more or less degrees of freedom at certain optimization times. We expect that in normal planning process rough assignments are done early (up to six months before departure) to gain a reliable flight schedule. This plan already includes fleet capacity and maintenance restrictions. In later planning steps, these decisions can be modified due to short-term changes. By using the adjacency matrix we can define mandatory assignments and model following planning horizons from long-term to short-term:

- change complete aircraft rotations up to any single flight with only a few assignment constraints
- the assignment constraints increases and the assignment change of single flights or strings of flights must maintain planned first and last flight of considered rotation (ensures, that the aircraft is before and after reassignment at the right location)

- additional constraints and a tight schedule allows only the change of complete rotations (suitable in short term flight planning and use of latest PF, otherwise high planning effort is necessary)

The size and complexity of the rotation planning model is dependent by the amount of decisions variables respectively by limitations in adjacency matrices. For example, 13 rotations and assignable aircrafts lead to a combination possibility of 6.23E9 assignments. To solve only the rotation planning problem, the exact and fast (complexity (n^3)) algorithm *hungarian method* is recommended [25]. This algorithm solves the assignment problem for weighted graphs and also unequal number of aircraft and/or rotations in a very short term.

The assignment of single and series of flights is much more complex than rotation assignment. The degree of freedom increases as an effect of more possibilities in scheduling and assigning. Figure 2 shows a schematic procedure of the integrated aircraft and flight scheduling model. To reduce computational effort, solvers as IBM CPLEX[1] or SCIP[2] are recommended to retrieve global optimal solutions by applying branch and bound methods.

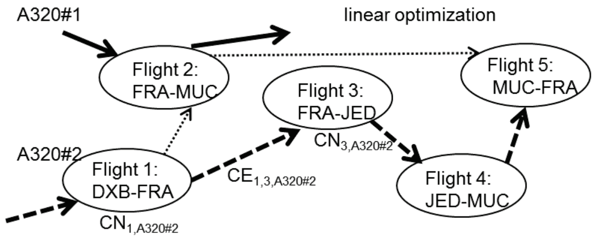

Figure 2: integrated flight scheduling and aircraft assignment model with cost factors CN (node) for cost per flight and aircraft and CE (edge) for ground event costs, bold: assigned aircrafts to flights as final solution

2.2. Trajectory simulation environment

To calculate flight trajectories, operational costs and emissions, a toolchain for multi criteria aircraft trajectory optimization (TOMATO) has been developed. By using an integrated aircraft performance model, weather data (Grib2) and an A star path finding algorithm trajectories can be calculated [26]. The trajectory design criteria can be weighted with different optimization targets such that an emission or cost minimum or something between is found. Radiative Forcing emissions are expressed as CO_2 equivalent emissions by using their global warming potential. By applying an emission trading scheme and a given price for each ton CO_2 equivalent, the emissions are summed up to the cost target function. This function is minimized for the total flight. Figure 3 illustrates the TOMATO optimization process.

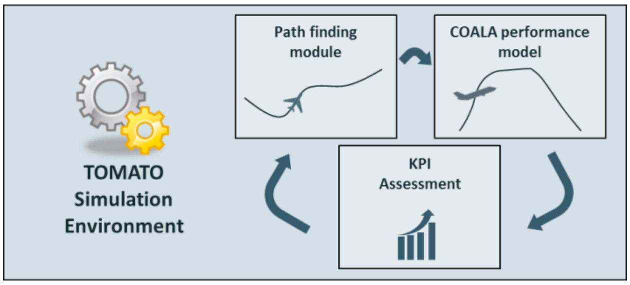

Figure 3: Trajectory calculation and assessment process in TOMATO

At first, for a given flight and target altitude, a cost optimum path is searched in a discretized space grid. The performance model now calculates climb, descent and en-route profiles for each requested altitude. Therefore, the estimated fuel consumption and emitted emissions are based on atmospheric data. At third step, an assessment of each calculated trajectory is done and the optimum depending on the chosen criteria is selected.

Within the TOMATO environment, direct operating costs as crew costs, air traffic control (ATC), airport charges, flight dependent maintenance costs, insurances, and leasing rates can be taken into account. Although not all cost factors are dependent of flight time or aircraft deterioration they will be modeled and considered.

Maximum Take-off mass

In long-term fleet planning and acquisition process, aircrafts are procured and sold depending by the airlines strategy and forecasted passengers demand. Maximum take-off mass (MTOM) differences within a fleet series can occur as a consequence of this acquisition process. Reasons for that are various aircraft equipment configurations (e.g. different capacity). For example, 73.5 t is the minimum A320 commercially available MTOM. The maximum MTOM for A320 is 78 t and for A350 for example a range of 7 t in MTOM is listed [27]. Some operating cost factors can be affected by the registered MTOM, as ATC charges of Eurocontrol are. For such ATC charge calculation is no global regulation available so many countries use their own approach. In order to simplify our further calculation process', we use within TOMATO the approach given by Eurocontrol. The ATC en-route (C_{ENR}) and terminal area charges (C_{TMA}) are calculated on the basis of distance, unit rates and the registered MTOM. We use equations (1) and (2):

$$C_{TMA} = \left(\frac{MTOM[t]}{50}\right)^{0.7} * unit\ rate \tag{1}$$

En-route charges depend on the last filed ATC flight plan and are calculated with:

$$C_{Enr} = \sqrt{\frac{MTOM[t]}{50}} * \frac{Distance[km]}{100} * unit\ rate \qquad (\ 2)$$

The indicated unit rate is estimated for each participating member state and monthly published by Eurocontrol. For every region where no unit rate is available, the statistical average of 67 € of all other countries will be applied. A flight with a distance of 1000 km and a difference in MTOM of 3.5 t (A320) show a cost difference of 21 €

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[1] www-01.ibm.com/software/commerce/optimization/cplex-optimizer/

[2] http://scip.zib.de/

($C_{TMA} + C_{Enr}$). Later detected fuels saving potentials are in range for this flight at a PF deviation of 1-2%. Hence, ATC charges with other tail sign unique cost factors in combination can result to differences between the cost and the fuel minimum solution.

Other operating cost factors

Other unique tail sign cost factors can be leasing rates for airframe or applied engines. In some cases, these leasing rates are flight time dependent and each single flight hour is billed. Depending on contract conditions, some aircraft in airlines fleet are buyed, but induced other depreciation costs. All of these financing models can result in significant differences of total costs per flight and aircraft.

The financing costs depend by airline and cannot be formulated generally valid. Hence, we search in the next steps the fuel minimum solution in contrary to the cost factors. So the cost factors mentioned above remain constant. However, fuel costs are aircraft performance and degradation related and will be investigated in next chapters in more detail.

2.2.1. Performance Model COALA

The COmpromized Aircraft performance model with Limited Accuracy (COALA) is embedded in TOMATO and calculates the trajectory related performance data. We use this performance model to determine detailed aircraft operating conditions and fuel flow. COALA minimizes acceleration forces and energy expenditure in transient flight conditions and is based on equations of motion as described by Rosenow in [26], [28], [29]. For calculations aircraft specific performance characteristics are required, which are read as input from BADA 4.0 data tables. These parameters are maximum thrust in climb phase, fuel flow and drag/lift coefficients. Attention should be paid, that measurements and calculations in fuel flow are afflicted with errors which results in a ‘limited accuracy’. Additional errors occur also by discretization in time (1s) of the motions equalities. The investigated error in fuel flow of BADA is mostly below 5% for an entire flight, considering climb and descent operations with the full range of operating speeds [30]. Table 1 shows A320 fuel flow errors, which can be found in the BADA error results summaries:

Table 1: BADA 4.0 error summary for A320-214

Flight Phase	Error in Fuel Consumption [kg/min]	Error in Fuel Consumption [%]
Climb	1.13	1.48
Cruise	0.82	2.18
Descent	1.21	14.37

We estimate that revealed fuel saving potentials by aircraft reassignment will be equal lower than the total error of fuel flow for an entire flight. However, we compare only fuel burn of flights which are calculated using the same model. Given that fact, we assume that errors in absolute fuel burn values are probable, but the relative potential is a good tendency.

The results of COALA can be both achieved for the international standard atmosphere (ISA) and different weather scenarios. As it is not possible to forecast the weather conditions in flight planning phase, we use only ISA conditions for our analysis.

There is also the possibility to integrate deterioration effects in this performance model. So we are able to model engine and hull degradation by a fuel flow factor and manipulated drag. Operating mass empty as a further degradation effect is represented by modified basic aircraft mass.

2.2.2. Engine Performance Factor

A young fleet with an average age less than ca. 7 years has obviously high fuel efficiency in contrast to significant older aircrafts. The smaller the age differences of the aircrafts are, the lower their spread in deterioration effects and fuel consumption is. But if the aircrafts performance is more heterogeneous, the bigger the potential in fuel saving will be if tail sign optimized flight allocation is applied. We assume that the engine degradation affects are mainly independent from flight phases and other conditions. This means that the fuel burn increases or decreases linearly as function of PF. However, this assumption may lead to small errors in fuel burn calculation, but in phase of resource planning no detailed atmospheric information are available. Moreover, special combustion chamber models will be necessary to formulate different types of deterioration but are not implemented in COALA.

The engine performance degradation will be implemented by multiplying an engine performance factor (EPF) with the actual fuel flow in any time step. Therefore, the basic fuel flow is estimated for a representative specimen aircraft with PF 100 (*FF_t*). Following Airbus, the engine performance degradation represents 80% of the total PF (cf. 1.2.2, eq. (3)). The additional fuel flow for the deteriorated aircraft is calculated using (4) and will be added to FF_t.

$$EPF = \left(\frac{PF\ [\%]}{100} - 1\right) * 0.8 + 1 \tag{3}$$

$$AddFF_{EPF,t} = FF_t * EPF \tag{4}$$

With:

$AddFF_{EPF,t}$ = fuel flow at time t for aircraft with PF

FF_t =fuel flow at time t

2.2.3. Aerodynamic Performance Factor

The remaining 20% efficiency loss due to total PF is attributed to aerodynamic degradation. Minor surface damages result primary in parasitic drag. These damage types remain their position for the entire flight and do not change their form or effectiveness. So we assume the drag remains also constant in several aircraft configurations and flight phases for the investigated flights. It thus follows that the impact of increased drag in fuel burn depends only on aircrafts velocity and atmospheric conditions. For this reason, we estimate a for all configurations constant drag factor which affects the standard drag curves. Within COALA, we multiply the actual drag coefficient with an aerodynamic performance factor (APF_{cw}). This factor shifts the drag curve but does not represent the difference of PF and EPF values. To estimate the APF_{cw} on the basis of the total PF we first determine the additional total and engine related fuel burn $AddFF_{EPF}$. By the help of this, the fuel burn related to total

PF without *AddFF_{EPF}* results in the by the aerodynamic component induced fuel burn $AddFF_{APF}$. This fuel burn can now be estimated iteratively by trying to find the best fitting through several shifting's of the drag curve. For our parametrization we discovered, that *APF+1/3*APF* as *APFcw* fits the nominal and actual total fuel burn very good. For A320 there is an error of 0.1-0.35 % in total fuel burn and 6 % in target-actual-difference (caused by delta PF, actual deviation divided by nominal deviation). The error increases slightly by increasing PFs but considerably by increasing distance.

$$APF = \left(\frac{PF\ [\%]}{100} - 1\right) * 0.2 + 1 \tag{5}$$

$$APF_{cw} = APF + 0.3 * (APF - 1) \tag{6}$$

$$AddFF_{APF,t} = FF_{(cw_t * APF_{cw})} \tag{7}$$

With:

$AddFF_{APF,t}$ = additional fuel consumption by hull at time t

cw_t =wind resistance drag at time t

$FF_{(cw_t * APF_{cw})}$=fuel flow based on drag cw function at time t

The impact of APF and EPF in total fuel consumption is shown in Figure 4 for A320 (left). The 20:80 ratio of APF and EPF in total PF can be seen. On the right-hand part of this illustration the additional fuel burn by the APF related to total fuel burn for various flight distances is plotted. With increasing distance, the flight time in lower altitude and air resistance decreases with lesser fuel consumption.

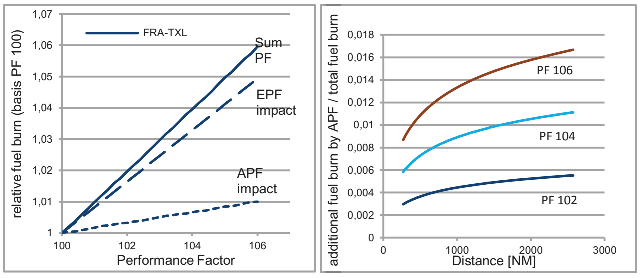

Figure 4: Left: Increasing of relative fuel burn as a function of PF one flight, Right: additional fuel burn by APF in proportion to total fuel burn

2.2.4. Operating Mass Empty/ Loading factor

The aircraft mass and force of gravity have a significant impact on fuel consumption. To achieve a balance of power, the lift force must be generated by adapting the angle of attack or change of the engines rotational speed. This results both in the need of additional thrust which is gained by increased fuel flow. A heavier aircraft requires so more fuel than a lighter to produce the needed lift. Also the operating empty mass (OME, mass without passenger, fuel, crew and catering) of similar aircrafts in a fleet shows differences by several reasons. One reason for this can be found in different equipment (additional fuel tanks, travel class system, light weight seats and trolleys). Another reason is also an aging effect of the airframe. Within the lifespan of an aircraft, the empty mass increases by the accumulation of dirt and moisture. Dirt deposits in places difficult to clean and remains there until major maintenance events. Furthermore, painting without removing old paint leads to increase in mass. However, main increase in mass can be measured by the condensation of water especially at insulation packages near the aircraft windows. Thus, a Boeing 744 gains additional mass up to 150 kg in one year. With increasing age, this effect reduces but within a life span of the aircraft the additional weight can sum up to 500 kg [2]. These several hundred kilograms not only limit the available payload, but also increase significantly the fuel consumption of a specific aircraft.

Figure 5 shows the increase in fuel consumption with increasing OME (+200 kg and +400 kg of A320) for different PF (blue 100, green 103, red 106). The presented fuel consumption increase between the PF is only attributed to the OME. The fuel consumption which is regular affected by PF is excluded in this analysis.

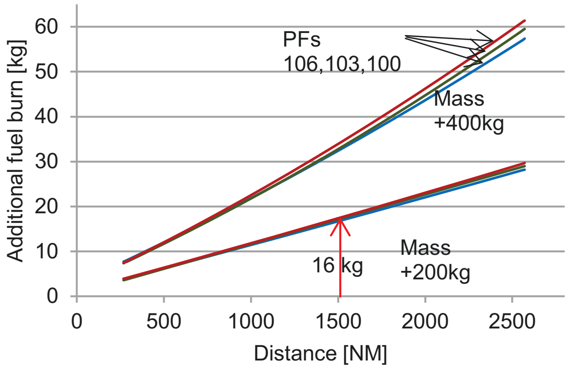

Figure 5: Additional fuel burn by increased OME (fuel consumption excluded, which is attributed to PF), A320

A medium-haul flight with distance of 1500 NM results to fuel burn of ca. 2655 kg for A320 with PF=100. If the OME will be increased by 200 kg, the additional fuel burn is more than 16 kg. If the PF increases now by 6 points (PF=106) the fuel burn is then 18 kg. It can be seen that the effect of aircraft deterioration is very low in small OME increasing. If OME remains constant, a delta PF of 6 points in contrast will lead to fuel consumption deviation of 160 kg at this distance. Assume an aircraft with PF=100, OME=+400kg and one with PF=106, OME=+0kg, it will be much cheaper (saving of 146 kg) to use the aircraft with better PF for this connection. Only within a maximum delta of 0.5 in PF it is better to choose the lighter aircraft for this connection.

We now assume that the aircraft seat load factor (SLF) depends on distance and is within a range from 0.65 to 0.92. Now, the change in mass is not only several hundred kilograms: for medium and long haul aircrafts the mass varies between tens of metric tons. Figure 6 (left) shows for several distances and loading factors the additional fuel consumption as supplement to Figure 5 (base SLF=0.65).

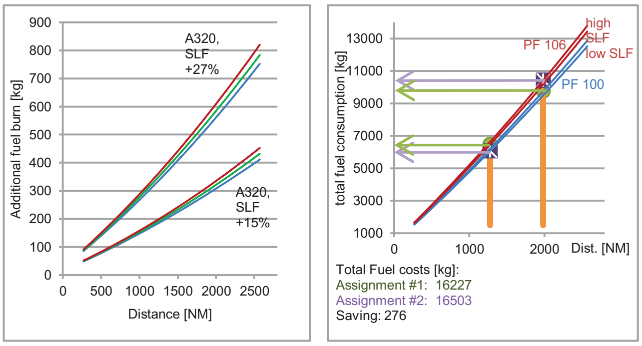

Figure 6: left: additional fuel burn by increased SLF (fuel consumption which is attributed to PF is excluded), right: effect of aircraft assignment by different SLF in total fuel consumption of two flights (1276 NM and 1984 NM)

A additional loading factor of +27% at a 1500 NM distance results in 400 kg fuel burn increase and a loading factor of +15% in ca. 220 kg. As can be seen, the effect of PF is significantly higher using a heavier aircraft. But also it can be seen, that performance degradation related to fuel consumption in aircraft assignment has only a minor effect. Referred only to an assignment decision, the impact of aircraft mass differences in fuel consumption is only ca. 1% (at delta PF of 1 point) on average. This impact decreases with increasing delta PF drastically. Figure 6 (right) shows the impact of SLF in the minimum fuel burn assignment of two aircraft and distances (green and purple). The loading factor increases with distances, but it can be seen that the differences in PF related to fuel burn are much higher than related only to SLF. We can state that the assignment recommendation, to prioritize better PF in longer flights, is still valid and does not change by different seat load factors. To conclude, we can say that different loading factors (usually increasing with distance) just enforce the impact of delta PF. The situation is not much different if we reverse the SLF distribution (long-haul with low SLF): The total saving reduces only by 12%.

As fuel consumption increases with PF and aircraft mass, it will be become even more important to assign aircrafts with better PF to longer flight distances (loading factor depends by distance and not assignment). However, this rule does not always apply if two rotations are significant heterogeneous. One good example is shown in Figure 7.

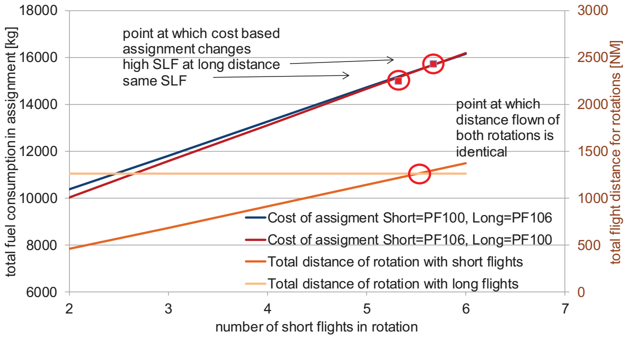

Figure 7: cost and distance intersection points considering different loading factors in flight planning (not shown: cost functions for identical SLF)

Assume two rotations and one aircraft with PF=100, one with PF=106. In the first rotation ('long') there are one or two flights with a relative long flight time/distance and high loading factor (90%, 2300km, 6760 kg fuel burn at PF100). The other rotation ('short') consists at the beginning only of one flight with a short flight time and low loading factor (65%, 422 km, 1500 kg fuel burn at PF100). We add successive similar 'short' flights and remain the 'long' rotation constant. The total flight distance increases now and exceeds at 5 'short' flights the distance of the 'long' rotation. But the optimum cost decision changes a bit later, if different flights are considered almost in more than one additional flight. If the flight planner now has only decided the more efficient aircraft serves the rotation with more total flight time, financial loss would be occurred. The reason for this gap between flight time and minimum cost change are the loading factors and aerodynamic performance as function of low altitudes. If equal loading factors are used, both intersection points do not only approach each other. The assignment changes before the distance flown is equal. Hence, the planner should have assigned the best PF to the higher amount of flights in rotation. This intersection point depends on both rotations and the fuel efficiency of short and long-hauls of the airline and cannot be generalized. However, we expect this heterogeneity in number of flights can be found only rarely in normal flight planning processes. Additionally, we cannot validate this result since the calculated fuel differences are below the estimated error of our performance model (see 0 and 2.3). In airlines daily business the typical cost of weight is between 3 and 4% (100 kg additional mass results in 0.03-0.04 kg additional fuel burn per hour). Our performance model calculates by using balance of power a cost of weight of 2.6%, which is slightly lower than empirical values. We assume these differences can be justified by the use of optimum altitudes and minor inaccuracy in fuel modeling.

2.3. Impact and Error of PF and BADA

The airline determines the PF by using a statistical analysis of flight performance for each aircraft for the past few months. Therefore, the individual specific range is calculated and then compared with a reference value. But for each single flight measurement errors occur, which are responsible for fluctuations of the PF. Later, the average of measured PF is calculated which includes statistical errors. These errors are unknown for us at this moment. As a reminder, we assume that the given PF represents exactly the deterioration effect of engine and hull. However, measurement errors must be handled to avoid false assessment and recommendations.

If errors in measurements cannot be excluded completely, then it is interesting what minimum delta PF is needed to do ensure the right assignment decision. We demonstrate different influence parameters in the correctness of decision for our example A320 whose fuel burn is shown in Table 2:

Table 2: Fuel burn deviation as result of deteriorated aircraft efficiency (A320)

Flight time [h]	Fuel PF100 [kg]	Fuel PF106 [kg]	Δ Fuel [kg]
Short: 1.5	3,044	3,236	192
Long: 3.5	9,936	10,624	688
Rotation #1 (5 Flights, 13.8h)	29,145	31,074	1,929
Rotation #2 (7 Flights, 11.1h)	23,046	24,528	1,481

An applied continuous descent approach (CDO) saves for the same aircraft approximately 65-96 kg fuel [31, p. 22]. To reach such fuel savings, a minimum PF of 102-102.9 compared to a PF100 is necessary ('short flight'). For the longer flight a PF of 100.9-101.3 is sufficient due to more flight time. However, normally a saving potential can only be reached, if a change in assignment of flights and aircraft happens. In this case both aircrafts are already planned to flight operations and the saving potential decreases (nearly) to delta flight time. When the short and long flight will be assigned to the related aircrafts, the delta PF between the aircrafts must be greater than 1.5 up to 2.5 to reach the CDO saving potential. Even higher deltas let expect higher potential. Attention should be paid, that this assignment change often results in increased planner's effort. Therefore, imputed costs should be assumed to be sure the assignment change saves costs.

Figure 8 shows the relation of imputed costs to the needed delta of PF to gain profit through reassignment of rotation #1 and #2. For example, imputed costs of 100 € (1kg fuel is set to 1 €) need a minimum delta of 1.5 to balance the costs. Only when delta PF is more than 1, fuel savings in range of CDO can be reached. Should the CDO potential reached for every flight, a delta of 10.5 is necessary. Such deltas in PF are normally not present in airlines fleet and if the rotations are more homogenous, the delta should be even higher.

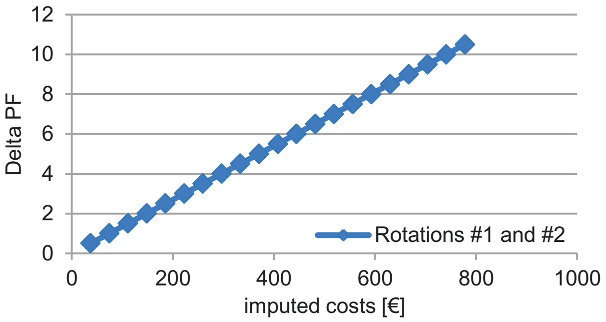

Figure 8: required delta of performance factor to gain profit at given imputed costs for rotation #1 and #2

The measurement and statistical analysis of PFs results in fluctuations and can in bad cases lead to erroneous assignment recommendations. A bigger delta the considered PF can reduce such mistakes by providing sufficient saving potential (in case of the rotations assignment above, a delta of 1 in PF results in 70 kg fuel). If the measurement errors of PF are unknown, we can formulate a recommendation from the planner's view how precise the PF should be.

The used measurement technology for same fleet types should be identical, so that occurring standard variations also should be equal for PFs of the aircrafts. By using this simplification, we can determine a tolerance t for each PF (see (8),(9)). If the actual error is smaller than t the assignment recommendation will result in a probable saving.

$$PF1 = 100 + x1\ [\pm\ t] \tag{8}$$
$$PF2 = 100 + x2\ [\pm\ t] \tag{9}$$

To determine the maximum tolerance t we search the cost factors, at which the assignment decision lead to zero savings. Therefore, we assume that $x2 > x1$ but the same methodology is applied vice versa for $x2 < x$. At this point, the accepted error t is so high that the assignment recommendation is inconclusive (*PF1+t=PF2-t*). By using equations 8 and 9 we get:

$$100 + x1 \pm t = 100 + x2 \pm t \tag{10}$$

With (10): $t = \frac{x2-x1}{2}$ (11)

From planners view, the maximum error must not exceed the half of delta of both PF. If additionally a minimum saving potential is required (e.g. to cover imputed costs and fuel flow errors in BADA) the PF tolerances should be smaller. The cost difference between the two assignment possibilities as saving is 447 € for delta PF of 6 (rotations in Table 1, rotation 1 gets best PF). If a minimum of 20 % initial fuel saving potential should be kept, only a tolerance of *t*=2.4 (50%: 1.5) is acceptable. These tolerances can be calculated iteratively by increasing the error in small steps via parameter study. The saving potential is then reduced in each step and the stop criterion is reached, when the saving is lower than *initial saving*minimum factor*.

The maximum BADA error is for rotation 1 and rotation 2 489 kg and 342 kg. If the full error is included in minimum fuel assignment decision, then there is no saving potential with assigning this rotation. In worst case, the fourfold of delta PF is required to obtain a saving.

3. APPLICATION

In this chapter we demonstrate the fuel saving potential by considering individual tail sign efficiency for an air cargo airline. Cargo airlines provide typically a hybrid strategy between regular scheduled flights and demand-driven air charter operations. We hereby expect, that lesser flight assignment changes are possible than in a typical line carrier with high frequenting their home base (passenger airlines).

3.1. Cost Calculation Parameter

The cost calculation shall take place as described in chapter 2. By modelling the performance factors, we assume a ratio of 80 to 20 for engine and airframe efficiency impact. Typical airline loading factors are modeled for the given flights and increased slightly by longer flight distance.

Differences in operating mass empty are not significant and set to constant for all aircrafts of a fleet series. This is also done for the maximum take-off mass and other DOC. Our optimization objective is then minimizing the total fuel consumption for the given flight plan using modeled individual tail sign performance.

3.2. Flight plan optimization

The investigated flight plan period is one week of September, 2016. The flights are served by two fleet series and in total more than 15 aircrafts of long distance type. There are some fix scheduled maintenance events and operations reserve slots in the flight plan. It is mandatory that maintenance slots are covered by the aircraft planned in origin flight plan. Operations reserves can be served by every aircraft but due to capacity constraints the origin fleet series must be maintained. This applies also to flights: the originality assignment of fleet series keep remained, but can be done by every aircraft within fleet. The minimum turnaround time represents the time between on block and in block and is set to 60 minutes. Scheduled departure and destination times represent the defined time windows.

We apply different optimization steps by successive increasing the degrees of freedom for reassignment. At first, only complete rotations are swapped in the flight time period. Second, single flights and strings of them are reassigned but the first and last flight of each aircraft rotation is maintained. Thereby it is ensured that the optimized flight plan can be better integrated in the existing other plans. At third, we renounce this restriction and reassign also these flights completely free within given time windows. Figure 9 shows an excerpt of the original flight plan for one of the considered fleets. Departure and destination stations are anonymized but the flight and ground time can be identified as colored box.

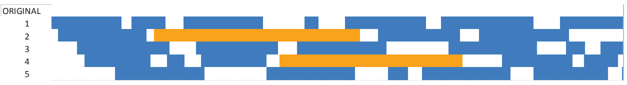

Figure 9: originial flight plan as timeline for fleet 1 (blue are flights, orange are maintenance events)

For the first fleet is a range in delta PF of 2 existing. This rise expectation, that fuel saving potentials by assignment changes will be very small. The second fleet has a widener range in PF of more than 4 points. This will result in higher potential, if modifications in the flight plan and different optimization phases are possible. The optimized solution for each of the planning steps is shown in Table 3. Figure 10 is based on the flight plan of Figure 9 and presents both optimization steps with the visual reassignment of flights (rotation swap is identical to the first illustration). In both fleet types it was not possible to swap the assignment of complete rotations due to scheduled flight restrictions and different departure and destinations of each rotation. So the rotation swap is the easiest modification step but the most limited in saving potential.

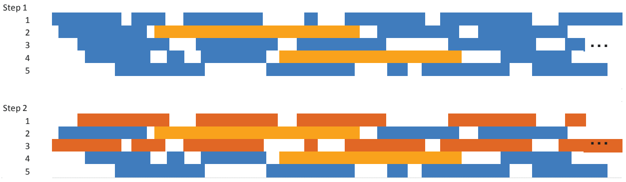

Figure 10: both fuel minimization steps by flight reassignment for fleet 1. red: changes in assignment to original flight plan

Table 3: results of optimization with different degrees of freedom

	Fleet 1	Fleet 2
Number of Flights (ca.)	70	190
Fuel consumption original flight plan [kg]	4,362,500	7,207,800
Saving potential with changed rotations [kg]	0	0
Saving potential with change of flights (first and last remain fix), [kg]	0	12,200
Saving potential with change of flights	1,400	21,000
Saving related to total fuel burn of reassigned flights	0.06 %	0.33 %

Following Table 3, a fuel saving up to 22,400 kg within the investigated week is possible (1,100,000 kg per year). Related to the total fuel consumption of all reassigned flights, the fuel saving is with 0.25 % very low. But in contrast of normally 60 t fuel burn per flight this value results in a saving of 150 kg fuel per reassigned flight. It also has to be taken into account that these savings are substantially lower than the BADA errors for the used aircraft. For example, the aerodynamic component in PF is responsible for 0.3 % of total fuel burn, engine for 1.24 %. The error in BADA for the used fleet 1 is on average 2.64% and thus higher than the measured delta PF. Whereas absolute saving values cannot be given with high precision, the basic methodology represents the additional fuel consumption in percent as PF. So the given relative fuel saving potential appears to be plausible.

4. DISCUSSION AND CONCLUSION

If individual tail sign performance is considered in airline flight planning and aircraft allocation, a significant fuel and cost saving potential can be revealed. Our example shows, fuel savings up to 630-1,100 t per year if flights are reassigned in short term flight planning phase. To gain such high potential, extensive flight plan modification steps are necessary.

Therefore, we modeled engine and aerodynamic related aircraft deterioration as performance factor with the simulation environment TOMATO and COALA. By the help of this, we calculated fuel consumption and other operating costs for flights of a given flight plan and unique aircrafts performance. The modeled performance degradation is based on long-term deterioration effects. Short-time airframe contaminations by dirt etc. are not appropriate for the investigated flight planning phase which has a time horizon of several weeks. Using an assignment optimization model, we reallocated a given flight plan within a time period and minimized the overall fuel burn. The model, based on a vehicle routing problem, connects flights with binary variables to an aircraft and creates strings of flights between time windows. The reassignment was based on departure and destination time, operational reserves and maintenance events. Other restrictions, resulting from airline network or political constraints are not considered.

The delta of given performance factors for two aircrafts affects the saving potential. So it can be stated and recommended to assign aircrafts with good PF to longer flights and with a bad PF to short flights. We proved that other influencing parameters in fuel consumption are smaller than PF impact. The achievable savings depends on the heterogeneity of the flight plan. If it is more homogeneous, the reassignment reveals only low saving potential reasoned by a low delta in flight times.

However, it was shown that the number of flight cycles can also be a crucial factor for the assignment. In case of rotations with a high proportion of short haul flights it can be appropriate to use aircrafts with better PF. This is often the case when a few long hauls are compared with some short hauls (1: 7±1). Then the effect of flying in low altitudes in short distances has an impact in the best assignment. But such flight plan heterogeneity can be found only occasionally in normal flight planning. Furthermore, this altitude effect is very low if it is based on delta PF and assignment cost difference. For these reasons, the recommendation to serve flights and rotations with longer distance by a good PF can be maintained. The number of flight cycles should only be preferred is the number of short flights is drastically higher. The fuel efficiency of short and long-hauls is in our example very similar. If short hauls have significant higher fuel consumption per distance, the optimum cost decision can be occur even earlier.

The loading factor is also an important influential factor and increases the effect of additional fuel consumption through PF. If total distance of candidate rotations for change is really similar, the rotation with higher number of flights should be preferred with best PF. But this depends mainly on loading factor: If the longer distance has a higher SLF than the shorter distance, then the longer distance should be preferred to best PF.

On the other hand, the change of assignments can result in high imputed costs. If assumed 100 € of such costs occur per flight assignment change, the amount of reassigns decreases significantly due to lower saving opportunities. For that reason, a reassignment is often only reasonable when a whole number of flights or complete rotations are changed. Our example rotations need a minimum of 1.5 in delta PF to balance the imputed costs of 100€ out. If the rotations are more heterogeneous, the minimum delta decreases. Attention should be paid that a small delta requires tight error tolerances. In this example (delta PF=1.5) the measurement error must not exceed 0.75 to achieve even a potential. Also errors can occur in modeling aircraft performance and fuel consumption. The gained fuel savings are normally lower than BADA fuel flow error. However, we compared only flights modeled with same model and expect similar fuel flow errors. For this reason, we assume an outweighing error effect and present the relative tendencies in fuel saving.

The given saving potentials and recommendations are only valid for minimum fuel solutions and similar operating empty mass. If other cost factors will be included the cost minimum assignment can be different from fuel minimum. So a detailed and individual calculation is unavoidable.

5. OUTLOOK

For the next steps we apply the tail sign optimized flight planning for schedule carrier with kont and interkont flights. We assume a significant increase in saving potential due to a higher number of flights and aircrafts, widener spread in PF and more possibilities in reassignment of the flight schedule. Also the complexity will increase with more assignment option so we expect the application of a heuristically approach will be necessary. These results will lead to a planner's assignment recommendation for solving individual aircraft and flight assignments.

6. ACKNOWLEDGEMENTS

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