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PROFIT-BASED NETWORK LEVEL EVALUATION OF AIRCRAFT BLOCK TIMES

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Abstract

For the replacement of today´s aircraft, a significant reduction of mission fuel burn and noise is targeted by various future studies to achieve promoted emission targets. A Cruise Speed Reduction (CSR) should result in significant fuel burn savings, however, also leads to network-wide implications. The framework presented in this paper goes beyond an usual aircraft fuel burn trade-off study. For a holistic evaluation of the economic impact of changed block times, different models for aircraft performance, aircraft scheduling, Direct Operating Cost (DOC) and passenger demand need to be applied. Therefore, aircraft designed for cruise speed Mach numbers (M) of M0.66-0.82 based on ducted fan and open rotor propulsion technologies were analysed regarding their impact on block times. Based on an operational evaluation of schedule disruptions, speeds down to M0.70 seem feasible. Echoing this result, DOC analyses demonstrated the lower bound of CSR should be set to around M0.70. In contrast, taking airline yields into account, the results show that for aircraft using open rotor or turbofan propulsion technology an optimized design cruise speed is around M0.78-0.80.

1 Introduction

For the replacement of today´s single aisle short-to-medium haul aircraft like A320 or B737 family, a significant reduction of mission fuel burn and noise is targeted by various future studies to achieve US NASA N+3 [1] or European Commission (EC) Flightpath 2050 goals [2]. To open up the design space, alternative mission specifications, such as reduced design cruise speeds, are considered in these studies. For example, Boeing´s concepts like SUGAR HIGH or VOLT [1] or the D8 Double-Bubble concept from MIT [3] are designed for lower cruise Mach number (M) of M0.70 compared to M0.76-0.78 of typical in service short-to-medium haul aircraft. This Cruise Speed Reduction (CSR) should result in significant fuel burn savings, however, it could also lead to network-wide implications as a consequence of late arrival, i.e. going below the Minimum Connecting Time (MCT) or minimum required ground time for aircraft servicing. Furthermore, discouragement of passengers to longer flight times might influence booking behaviour, and hence, influence demand and airline yields.

In the course of this paper, these network level effects are addressed. Furthermore, a profit-based evaluation of CSR is performed taking into account changes in operating costs, delay cost and passenger yields. Therefore, a number of aircraft designed for a wide range of cruise Mach numbers are analysed regarding their expected benefit for an operator. In order to determine the specific characteristics of eligible alternative propulsion system concepts, the studies are comparatively performed for turbofan and open rotor propulsion technologies.

1.1 Review of Cruise Speed Reduction Studies

Alternative mission specifications, such as reduced design cruise speeds, are considered in future aircraft studies. In the following, an overview of studies assessing the effects of CSR on aircraft and the network is given. A summary of effects generated by CSR is given Table 1. Flight time influences equipment-type utilisation and rotation. Due to reduced ground time, the passenger and baggage flow is impacted, especially for connecting flights. Time dependent costs, such as Cost Of Ownership (COO), crew cost and flight dependent maintenance costs, are also affected. The reduced fuel burn at lower cruise Mach numbers is directly related to the fuel cost. Due to the lower amount of fuel which has to be replenished during the service, also the Minimum Ground Time (MGT) is reduced.

Table 1 Overview of influences by CSR

Direct Effect	Cascading Effects
Flight times	– Aircraft equipment-type rotation – Aircraft utilisation – Time dependent cost (cost of ownership, crew cost, partially maintenance) – Passenger flow (e.g. connections) – Freight and baggage flow
Fuel burn	– Fuel cost – Minimum ground time (MGT)

One study investigated an advanced turbofan with an Open Rotor (OR) concept on operating economics assuming three distinct air traffic scenarios in year 2030 [4]. The evaluation was based on COO and fuel costs taking also lower aircraft utilisation due to CSR per duty day into account. Additional Direct Operating Cost (ADOC) were also captured by Emission Trading Scheme (ETS) and local noise charges. It could be shown that possible future fuel prices and environmental charges have a noticeable impact on the overall cost efficiency of each aircraft concept with these two propulsion technologies. Compared to status quo, an OR concept could result up to 14.3% operating cost savings [4] depending on the chosen scenario.

A review of fuel burn reduction potentials for OR aircraft compared to Turbofan-based (TF) propulsion as predicted in past studies indicating improvements ranging from –7% to –40% [5]. Latest results showed OR integrated block fuel benefits on a typical narrow-body design range of up to 9% relative to a technologically similar two-spool direct-drive turbofan power plant architecture at M0.80 [6]. A reduction to M0.70 yielded an 8% reduced design block fuel for the TF powered aircraft, while the OR technology benefited from the lower cruise speed by more than 20% in terms of design block fuel [6].

It was stated in general [1] that efficient aircraft utilisation, as well as, the value of time might limit the reduction of cruise Mach number based solely on mission fuel. Current speed for medium range aircraft vary between M0.75-0.80. As stated in [1], an upper and lower bound for minimum cruise speed is given and recommendations show that M0.70 is still economically competitive. The drivers for this minimum speed are the desired city pairs, flight crew rules and the aircraft utilisation [1] without showing further analysis.

The impact of cruise speed reductions on airline operations and economics of current short-haul, medium-haul and long-haul aircraft was investigated in [7]; at aircraft level, the resulting fuel savings vary between 4% for regional aircraft and 8% for long-haul aircraft taking the MCT into account. The variation depends upon the aircraft type, the CSR level, fuel price and the airline network structure. In the case of a narrow-body single aisle aircraft, such as the Boeing 737-800, a CSR of 6% results in an average shift of the departure time by 4.0 min affecting 17% of total flights. However, from a passenger view, the flight time increase may be marginal compared to the door-to-door travel time. Furthermore, strategies for mitigating the operational impact of CSR, such as improved cabin layouts to reduce boarding time or optimized buffer times in airline schedules were discussed [7].

Using a re-engined version of the Embraer E190 for non-stop routes in the US, a reduced fuel consumption and operating cost to serve the investigated network could be shown [8].

Besides a CSR from M0.74 to M0.70, also the cruise altitude was reduced. This results in longer trip times and higher crew cost. But due to the shorter stage length considered in this study, the fuel burn benefits compensate the associated cost. A fleet composed of the E190 and B737-800 optimized for operational conditions, showed a 16.3% reduced energy consumption and 4.7% lowered DOC for the served network [8].

2 Profit-Based Framework for Network Level Assessment of Cruise Speed Reduction

To evaluate the impact of changing block-times due to CSR with respect to operating profit, a set of four models was combined into a framework, as depicted in Fig. 1.

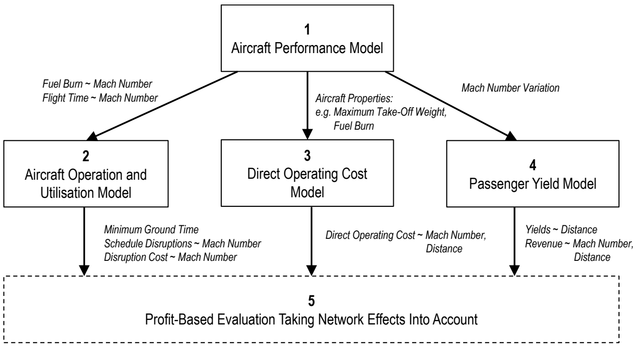

Fig. 1 Framework of models for the profit-based assessment

The “1” in Fig. 1 denotes aircraft integrated performance characteristics of the advanced propulsion technologies modelled using the approach published in Ref. [6]. For each investigated cruise Mach number, combinations of aircraft and power plant systems are sized and mission performances evaluated, thus, providing data about block fuel and block time for a variety of stage lengths.

Using data of contemporary aircraft equipment-type rotation and utilisation in airline networks, “2” in Fig. 1 denotes current aircraft replaced by the concepts incorporating new propulsion technologies. Depending on the cruise Mach number, difference in the buffer time between two flights can be identified. This analysis provides insights into how many flights could not be operated in current flight schedules. The impact of CSR on “3” cost basis upon aircraft performance characteristics can be assessed applying existing DOC methods. In order to analyse the effect of changed block times at network level, “4” airline yields are determined using a microscopic passenger simulation demand model offered in Ref. [9]. Taking the results of the four models, “5”, a profit-based evaluation of design cruise Mach number variations becomes feasible. The following Sections highlight the properties of the methodologies embedded in the framework.

2.1 Aircraft Performance Model

Conceptual sizing and aircraft integrated performance prediction of the investigated propulsion system technologies is used based upon methods given in Ref. [6]. Here, a comprehensive set of multidisciplinary analytical and semi-empirical models is integrated in a fast-responding, iterative aircraft scaling procedure. This includes methods and heuristics for aircraft component geometric description and corresponding prediction of weights, the mapping of skin friction and form drag, wave drag, and, vortex-induced drag, surrogate-based model integration for propulsion system design and off-design behaviour, as well as aircraft balancing and numerical mission performance. Wing loading determination is based upon low-speed performance, i.e. approach speed, requirements, as well as, high-speed buffet onset limits as in Ref. [10]. Within these limits, wing loading is maximised to facilitate optimum aerodynamic efficiency in cruise. Wing sweep determination is based on classical simple sweep theory in order to ensure appropriate wing quarter chord line definition.

The employed propulsion system surrogate models are derived from conceptual sizing and performance models synthesised in the software GasTurb^{TM}11 [11]. In order to ensure meaningful power plant performance, dimensions and weight characteristics against design parametric variation, a comprehensive set of typical heuristics for flow path design as described in Ref. [6] was implemented, and, adequate component temperature and pressure levels were adopted. For the studies presented in this paper, a two-spool boosted direct-drive Turbofan engine architecture is considered as a baseline (TF). In contrast, a two-spool geared counter-rotating Open Rotor (OR) is used as a technological alternative for the targeted application case. Therefore, a stripline code for highly-loaded, counter-rotating propeller design is employed [6].

Technological consistency between the investigated propulsion options is ensured through a maximised extent of model communality and the use of communal methods for flow path loss prediction. The implication of different flow path, i.e. core sizes, of OR and TF engines in the same thrust class are incorporated in the evaluation of turbo component design efficiencies. For all off-design operational characteristics, GasTurb™ standard component maps [11] are used. The integrated, multidisciplinary power plant models, provide full functional sensitivities w.r.t. flow path and power plant overall geometric dimensions, turbo component aerodynamic loading, flow path temperature levels occurring, e.g. during take-off, resultant weight characteristics, and, operational performance in the defined flight envelope.

Aircraft integrated performance simulation is based on a parametric numerical mission simulation including a parameterised 4-segment climb profile and a continuous descent approach [6]. For the studies presented in the following, climb above FL100 was simulated at 290 KCAS until cruise Mach number was reached. Climb to initial cruise altitude was then performed at cruise Mach number. Cruise was simulated at level flight at FL350 in all cases. Typical contingencies for hold, diversion and final reserves were included in the aircraft sizing and operational assessment.

2.2 Aircraft Operations and Utilisation Model

To model current aircraft operation and utilisation, Origin-Destination (O-D) data for the last quarter of 2013 focusing on US air traffic for short-to-medium haul aircraft, such as A320 and B737-800, was examined. Based on the analysis, an average utilisation and a variation of the ground time can be determined for each aircraft type neglecting the business model and network structure of the airline. Using aircraft servicing guidelines from the manufactures, additional on-block buffer times can be identified. During the aircraft ground time, aircraft servicing takes place. Effects of the fuel burn according to the stage length are taken into account in order to determine MGT. The MGT is composed of passenger egress and ingress duration and refuelling time according to the required block fuel [12]. The additional buffer times of a status-quo analysis are an indicator as to how airlines plan and the amount of delay which can be absorbed. Furthermore, they are indicators for network-wide effects of connections.

After analysing current operations, the short-to-medium haul aircraft in today´s airline networks are replaced by aircraft concepts incorporating new aircraft propulsion technologies. For each investigated cruise speed in the range of M0.66-0.82 the simulation of the aircraft equipment-type rotation is performed taking the flight time and the corresponding fuel burn as input variables from the aircraft performance model. Determining the required on-block time for servicing after each flight, differences in the buffer time between flights will emerge. However, the delay propagation in the network is not covered by this model. As a result, the percentage of flights violating the minimum required service time are identified. The monetization of schedule disruptions is achieved using the metric of delay cost per minute.

2.3 Direct Operating Cost Model

Direct costs are defined as expenditures allocated to specific items, and therefore, vary according to the type of aircraft used and the rate of utilisation [13]. The applied DOC model covers COC, COO and ADOC, as illustrated in Fig. 2.

The COO includes depreciation, interest and insurance costs which are mainly based on the aircraft market value and the annual aircraft utilisation. They are also often referred to as fixed costs since these costs are determined on a yearly basis [14]. The aircraft market price is calculated by a parametric cost function based on aircraft parameters known during the conceptual design [15]. To capture the effects of CSR, the variation of the maximum number of daily flights is estimated with the method found in Ref. [16] and compared with the average number of annual trips [17].

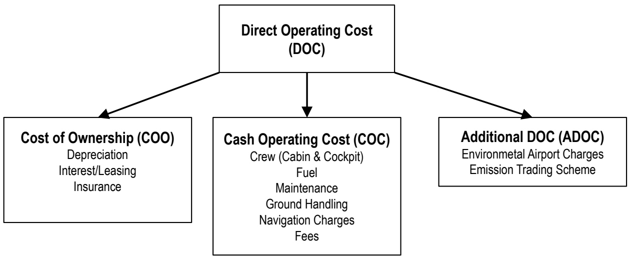

Fig. 2 Overview of the direct operating cost elements

The COC sums up expenditures for fuel, crew, maintenance, airport and enroute charges (see Fig. 2). The fuel costs are determined with mission fuel (excl. reserves) and the fuel price. The principal crew cost model is based the Association of European Airlines (AEA) methodology where the crew hourly rate is a function of aircraft Maximum Take-Off Weight (MTOW) and number of passenger [18, 19]. The enroute charges for the Air Traffic Management (ATM) are reflecting US charges levels [20]. Airport charges vary between airports, region and time. These charges typically cover expenditures such as landing or ground handling fees. They are determined using parametric cost functions based on MTOW and number of passenger [21]. The Direct Maintenance Costs (DMC) cover labour and material cost associated with airframe and engine. Operational dependencies, such as flight cycle and flight time are considered, as well as aircraft aging effects and de-rating of the engines. The airframe DMC are calculated with an analogous costing method [22] and the engine DMC are determined using parametric cost functions [23].

The ADOC cover noise and NO_x-emission charges. The NO_x calculation is based on the pollutants of engine emissions defined by the ICAO engine data base [24]. The modelled TF and OR engines would meet ICAO NO_x-emission standards; hence, the cost effect at the DOC level is marginal. Therefore, the NO_x-specific cost is assumed constant during cost mapping. The noise charge model uses aircraft specific standardized noise values for arrival and departure [25]. Compared to the noise level of the reference aircraft, the open rotor noise is estimated to be 5 EPNdB higher [26].

2.4 Passenger Yield Model

Passenger yields for an airline can be explained as aggregated results from individual booking behaviour or selection from a pool of available flight alternatives which have discrete different attributes. The individual booking decision of each passenger between discrete different flight alternatives is modelled with the help of discrete choice models.

In order to analyse the effect of increased block times on airline yields, a microscopic passenger simulation model for short-to-medium haul airline networks was used [9]. The model is based on Utility Maximization Theory. Each individual flight with its attributes is transferred into generalized cost functions with dependency on individual passenger characteristics. As shown in Table 2, cost functions for local arrival and departure times including the passenger´s personal schedule delay, number and type of stops, total travel time, airline market share, level of offered airline services and ticket price are included in the model based on a summary of available studies found in the literature [9].

Table 2 Implemented flight attributes in passenger yield model affecting flight choice

Flight Attribute	Effect
Ticket	– Ticket price – Frequent Flyer Program
Flight Schedule	– Type of stop – Total travel time – Departure schedule delay – Arrival schedule delay
Airline	– Market share – Service quality and passenger environment

The passenger itself is described by socio-demographic parameters which were identified having an influence on individual booking behaviour. These parameters were age, gender, traveller type or maximum willingness to pay amongst others. Additionally, passengers are further characterized by length of stay, departure day, number of flights per year, the membership and status of frequent flyer programs, preferred cabin class, and travel policy in case of business travellers.

Possible itineraries from origin airport to final destination airport are defined by using path finding algorithms [9, 13] out of single flights from Official Airline Guide (OAG) [27]. In the model, different heuristics have been implemented to derive up to two-stop itineraries in the passenger´s choice set. The heuristics have been derived from analysis of real airline itinerary data [9]. Only at airline-specific hub airports, itineraries with interconnections are included.

The simulation was calibrated and validated with actual O-D data from the US in 2008 using DB1B [28] and T100 [29] databases provided by the Bureau of Transportation Statistics (BTS). The validation was conducted in three steps starting from a global level including overall passenger traffic, transported passengers per airline or O-D traffic [9]. The second step tested the ability to model connections and validated especially the cost functions for stops and travel time. The last step was validation of airline-specific yields and load factors. Only smaller deviations could be observed, mainly driven by the distance-based ticket price model and inability to model airlines offering services for two different airline alliances.

The model was used in [9] to assess the impact of CSR on long-haul routes on airline load factors and yields. For this study, here, the same calibrated model was used. The outcome of this model is the calculation of individual flight load factors and ticket yields depending upon block times and possible market shares from the US market. The derivation of a response function of passenger yields with a change of block times based on 25 flights covering 23 different US markets. The variation in geographical location and market distance is shown in Fig. 3.

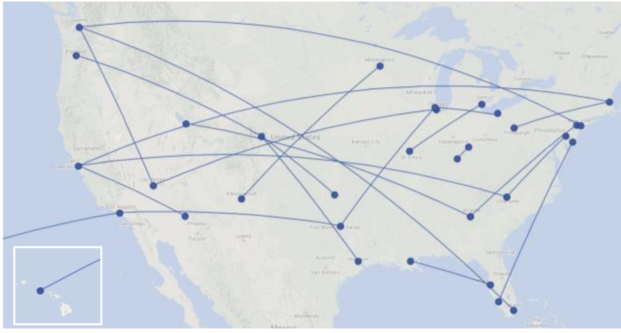

Fig. 3 Visualisation of simulated US aviation markets

The Monte-Carlo based simulation was conducted three times and a mean value was calculated. Each simulation result differs by around 1-2% in load factor and yields. The sample included routes between hub airports and non-hub airports, as well as, hub-hub connections to capture the effect of connecting passengers in the airline network. Furthermore, different airlines were selected. The sample consisted of 11 different airlines, whereas five of them are typical network carriers like American Airlines, United Airlines or Delta Airlines. The remaining six airlines are low-cost airlines like Southwest, Jetblue or Frontier. Flights were also chosen to achieve a wide spread of different departure times throughout the day, the same refers to the market distance. The sample includes flights with a great circle distance of 176 nm (326 km) (Tampa to Miami) up to 2217 nm (4106 km) (Los Angeles to Honolulu) [27].

2.5 Profit-Based Evaluation

In the final step of the presented framework results of the operation, DOC and passenger yield models allowing a profit-based evaluation were processed. The operation and utilisation model delivered a percentage value of schedule disruptions due to the CSR. The average delay due to the late arrival of the aircraft was monetized using the metric of delay cost per minute. This cost element captures the quantified effect of CSR in current airline networks. Further costs occurring during aircraft operation were determined by the DOC model. In relation to the reference aircraft, changes in DOC per trip were calculated for the investigated range of cruise Mach numbers and a variation in stage length. These two cost elements cover the operating cost and the revenues are determined by the passenger yield model. The parametric airline ticket fare equation models current ticket prices. These fares are corrected with block time related airline yields to capture the effects of CSR on airline yields. Assuming the DOC and schedule disruption cost as expenses and the airline yields as revenues, a quasi-profit-based evaluation becomes feasible.

3 Results

This Section presents the results of a quasi-profit-based evaluation of CSR of current short-to-medium haul aircraft in the US market. The economic evaluation of CSR uses DOC per trip as metric and forms together with the passenger demand perspective the basis for the profit-based analysis, which is discussed in the last Section.

3.1 Reference Aircraft Characteristics, Operation and Operating Cost

A generic short-to-medium-haul narrow-body aircraft is taken as reference. The aircraft is designed for a range of 2400 nm (4445km) at 20t maximum structural payload. Power plant specification and design are tailored to reflect Entry Into Service (EIS) 2015 technology. Aerodynamic improvements due to state-of-the-art wing-tip devices is incorporated in the integrated aircraft sizing and performance model using appropriate technology factors for wing induced efficiency. Based on the current operation of the A320 and B737-800, a cruise speed of M0.76 and the accommodation of 160 passengers (PAX) is assumed. The main specifications of the reference aircraft are summarized in Table 3. A typical turnaround process accounts for 30 minutes.

Table 3 Specification of the reference aircraft

Specification	Value
Overall length	35.6 m
Overall height	11.6 m
Wing span	34.0 m
Reference wing area	122.4 m²
Wing Sweep (at 25% MAC)	25.0 deg
OWE	42960 kg
MTOW	78490 kg
Lift-to-Drag (C_L0.55, FL350, M0.78)	18.2
Thrust/Weight (ISA, SLS)	0.314
Max. MTOW/S_{ref}	641 kg/m²
Engine Design Bypass Ratio	11.0
Fan Diameter	1.98 m
Design Mission	2400 nm (4445 km), 20t payload, Cruise at FL350, M0.78

Regarding the current operation of the A320 and B737-800 in the US, the distribution of O-D distances is depicted in Fig. 4. A characteristic of the short-to-medium haul US market is the high share of flights around 2000 nm (3704 km) which are connections between East and West Coast.

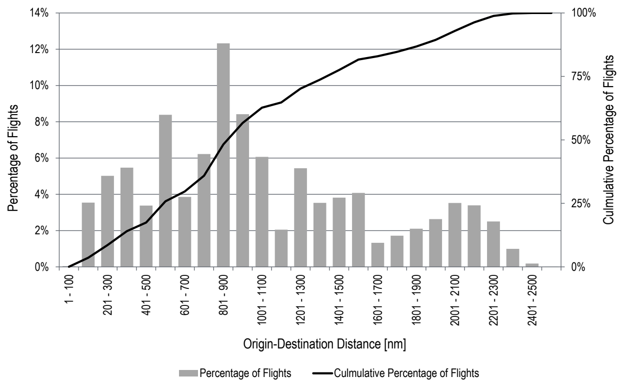

Fig. 4 Utilisation spectrum for flights within the US based on OAG 2012 data [27]

An analysis of the scheduled ground times of the actual US A320 and B737-800 fleets is illustrated in Fig. 5. For around 66% of the flights, a ground time of 40-60 minutes is scheduled; this is aligned with manufacturer data for a full service of the aircraft. For less than 1% of the flights, a time below the minimum required time servicing of 30 minutes is scheduled. This distribution of the available ground time forms the basis for the investigations of schedule disruptions due to CSR performed in Section 3.3.

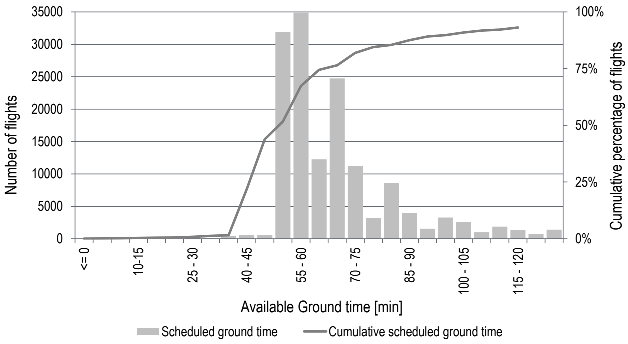

Fig. 5 Scheduled ground time of the A320 and B737-800 fleets for flights within the US

3.2 Aircraft Performance for Cruise Speed Reduction

In a parametric design and performance study, the previously introduced TF powered reference aircraft was alternatively sized for a wide range of different design cruise Mach numbers (DCM, M_{ADP}) and the operational characteristics were comparatively investigated against similarly sized aircraft featuring OR propulsion. Three-views of TF powered reference aircraft and the corresponding OR powered aircraft sized for DCM0.78 are shown in Fig. 6.

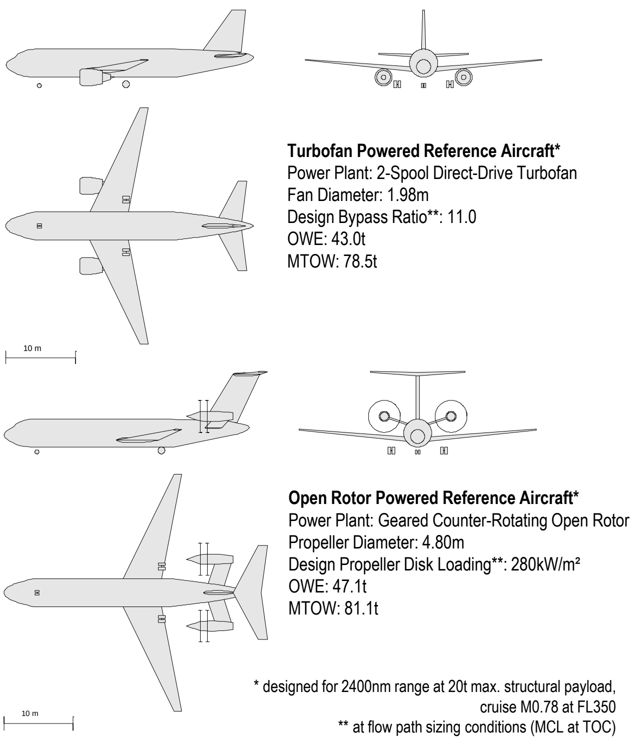

Fig. 6 3-view and attributes of a turbofan and open rotor powered reference aircraft

For each of the aircraft sized for a given DCM, an investigation of essential operational performance characteristics was performed. Therefore, stage lengths between 250 nm (463 km) and 2600 nm (4815 km) were simulated with 16t structural payload. The mission specifications include fuel for 200 nm (370 km) diversion and 30 minutes holding. In Fig. 7, relative change in block fuel is plotted against block time for the domain of TF powered aircraft. Both, fuel burn and block time were normalized for a DCM of M0.76. All ducted power plants studied, feature a design bypass ratio of 11.0.

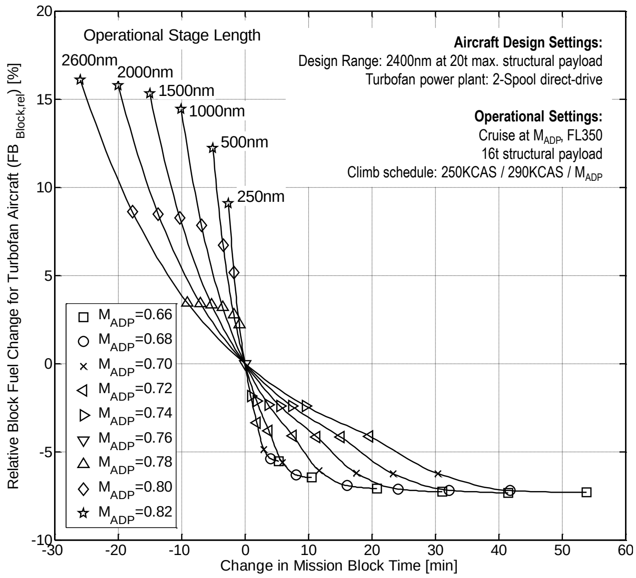

Fig. 7 Relative change in block fuel of a ducted fan powered aircraft vs. block time

As expected, the impact of varying DCM on block time is strongly dependent on stage length. While a reduction of DCM from M0.76 to M0.70 increases block time by approximately 6 minutes for 500 nm (926 km) distance, for 2000 nm (3704 km) this means about 23 minutes. At the same time, block fuel is reduced by 6 % and almost 7 %, respectively. The impact of the OR technology on aircraft block fuel relative to unducted powerplants for the investigated design cruise Mach numbers and operational stage lengths is presented in Fig. 8.

It can be seen that the OR propulsion concept exhibits fuel benefits at all investigated DCM and stage lengths. Driven by the intrinsically high propulsive efficiencies of unducted propulsors, the relative benefits increase as DCM is reduced. On the very short-haul operations, mainly constituted by transversal flight phases, superior propeller efficiency at low speeds dominates the open rotor fuel benefits against turbofan propulsion. The variation of mission block times, however, is only between OR and TF operation, due to the simulated common climb and descent profiles. For the study, propeller design tip speed was set to 200m/s, which is assumed to be a reasonable limit w.r.t. propeller source noise.

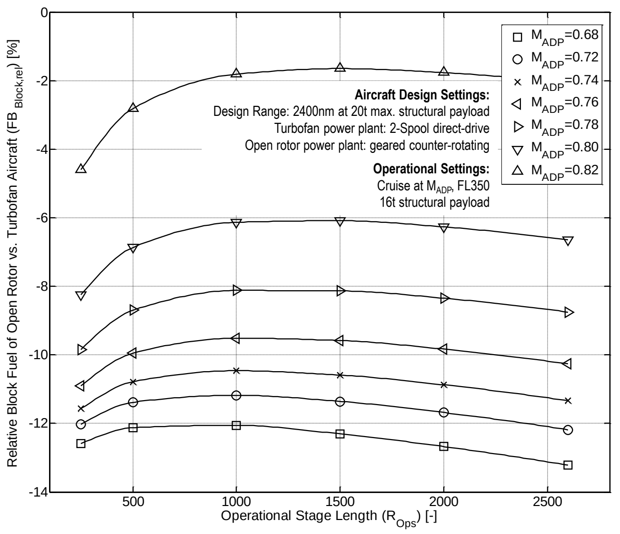

Fig. 8 Comparison of fuel burn between open rotor and ducted fan powered short-to-medium range aircraft

3.3 Schedule Disruptions Due to Cruise Speed Reduction

A delay, is in general reported, if an aircraft deviates from its flight schedule beyond 15 minutes according to DOT standards [30]. Typically, 30% of the delays are caused by delayed incoming flights. In most cases, the delays can be partly compensated by means of improved ground process efficiency [31]. At a network level, the delay propagation of a single aircraft causes system-wide disruptions until the delay can be absorbed by scheduled slack time between flights or the aircraft equipment type is going off rotation [32].

The analysed flight itinerary consists of over 150000 flights. For each flight, the flight time and required block fuel was simulated for the investigated cruise Mach number range. Based on the refuelling quantity for the next flight, the MGT could be determined. The MGT varies for short flight distances around 23 minutes and for increasing stage lengths up to design range between 26-28 minutes (cf. Fig. 9).

Keeping existing schedules intact, the shift of the available ground time for lower cruise Mach number is shown in Fig. 9. The trend shows a decreasing percentage of disrupted flights and average delay with increasing cruise Mach numbers. In the case of a cruise speed of M0.70, 6.9% of the schedule will be disrupted due to an average of 7.0 minutes late arrival of the aircraft. Focusing on the lower bound at M0.66 up to 25.7% flights are delayed 10.7 minutes on average.

The monetization of the average delay is accomplished with the delay cost per minute which account for USD 25.61 in 2012 [33]. In the case of M0.66 and an average delay of 10.7 minutes of this 25.7% of flights, the schedule disruption cost adds up to around USD 70.00 for each flight.

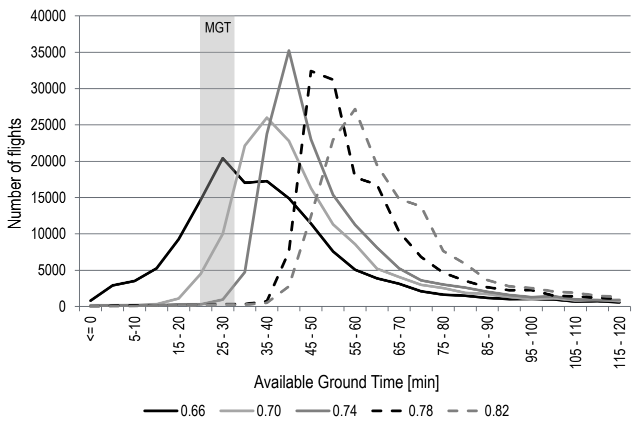

Fig. 9 Shift of the available ground time g due to cruise Mach number variation

3.4 Airline Economics

Additional to the schedule disruption cost, the DOC are also accounted as expenses. The cost elements were calculated for domestic flights in US in year 2012 USD and reflect the region specific cost levels in enroute fees and airport charges, as well as, crew and personnel salaries. The costs are averaged over the expected life span and during the aircraft life-cycle, no inflationary adjustments or cost elevations to, for instance, fuel price, are applied. Due to the assumed constant NO_x-emissions over the Mach number range, the ADOC remains unchanged despite the increased noise level of the OR. A summary of the socio-economic input values is shown in Table 4.

Table 4 Socio-economic input values for the DOC estimation

Parameter	Value	Unit
World region	North America	-
Flight type	Domestic	-
Fuel price	3.00	2012 USD
Depreciation period	20	years
Interest rate	4.00	%/a
Insurance rate	0.2	%/a

The results of the DOC calculation are summarized in Fig. 10. Taking M0.76 as the reference, the percentage variation of the DOC per trip is depicted as a function of the variation of the cruise Mach number and stage length. At the reference design Mach number, the OR is around 5.0% lower in DOC. For Mach numbers above M0.76, the DOC significantly increase. Especially the OR propulsion efficiency drops with higher Mach numbers and thus results in 2-3% higher DOC for M0.80 compared to an OR at M0.76. The TF shows only higher DOC of 0.75-1.5% at M0.80. With an increasing MTOW at higher Mach numbers due to more powerful engines and structural cascade effects, the dependent cost elements, such as airport charges, increase. On the one hand, a trend in rising COC with higher Mach number is noticed, covering amongst others fuel cost and airport charges with a share of around 75-80% of the total DOC. On the other hand, a lowering of COO is observed resulting from the higher aircraft utilisation.

The discontinuity in Fig. 10 of the DOC curve below M0.76 is caused by the variation in the COO resulting from the change in the annual utilisation according to the method in Ref. [16]. Especially for short distances (250 nm, 463 km), the OR has a cost minimum at M0.70 with -0.5% DOC. Focusing on a cost perspective regarding profit-based evaluation, the lower bound of CSR should be set around M0.70 due to the strong slope increase of the DOC curve at slower speeds. This is in line with the observations made in Ref. [1].

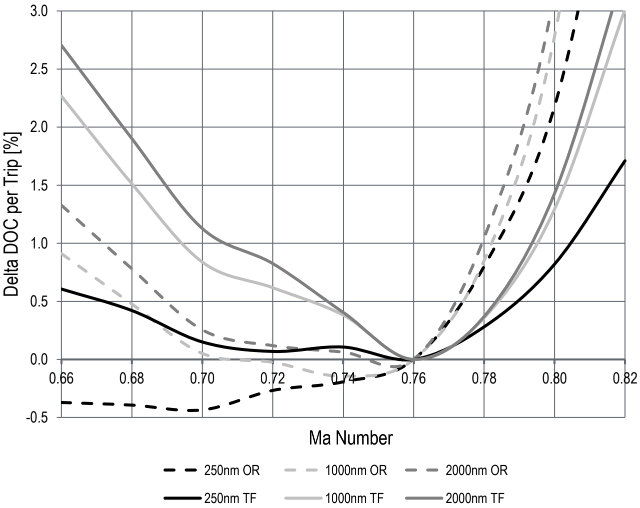

Fig. 10 Delta DOC per trip for different stage lengths in dependence of the design cruise Mach number

3.5 Influence of Cruise Speed Reduction on Airline Yields

To quantify status quo of airline yields for each individual flight without any changes to the cruise speed, a market-distance dependent regression function from real ticket data published by the US Department of Transportation [34] were used. Mean ticket values for each of the published markets and linear regression functions for lower, mean and upper bound are shown in Fig. 11.

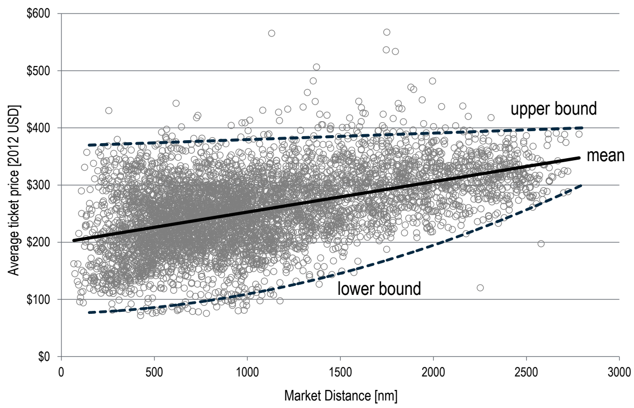

Fig. 11 Average ticket price in dependency on market distance [34] and corresponding lower, mean and upper regression functions

Out of the regressions, a simplified airline ticket fare model was derived for three fare classes: lower bound, mean and upper bound (see Table 5). The fare model is used to quantify flight-specific airline yields.

Table 5 Airline Ticket Fare Model

Specification	Equation
Upper Bound	$TP = 368.3 + 0.0113 \cdot D$
Mean	$TP = 199.60 + 0.053 \cdot D$
Lower Bound	$TP = 75.22 + 2.6 \cdot 10^{-5} \cdot D^2 + 8.41 \cdot 10^{-3} \cdot D$
With: TP = Ticket price [2012 USD] D = Market Distance [nm]	

The determination of changes in passenger booking behaviour and hence airline yields while changing cruise speed, was based on simulation runs for each of the 25 investigated flights with a change of -10%, +10% and +20% in block time according to original schedule data obtained from OAG [27]. Similar to real ticket fare data, the simulations show quite scattered data. This refers to the complexity in real world only partly captured by the simulation. A few simulations especially on shorter market distances show an increase in airline yields through an increase in block times. This mainly refers to the passenger scheduled delay functions in the model [35]. With higher block times and corresponding later aircraft arrivals, primarily between 7 am and 1 pm, increases the probability in lower schedule delays. Especially for private travellers, this promotes a higher demand.

As shown in Fig. 12, an increase in block times mostly affects airline yields negatively. The effects of longer flight times are directly captured by value of time for different passenger types. Leisure travellers are less time sensitive than business travellers [9] which is captured in the simulation model. Other indirect or airline network depended effects are available flight alternatives. A late arrival of an aircraft might lead to a decrease of possible connecting flights for a fixed timeframe, especially if flights are conducted to an airline hub. Furthermore, another indirect effect is the competition on the specific route and airline´s market share at the arrival airport. With an increase in competition on a certain route, the probability of alternative flights for passengers is increasing.

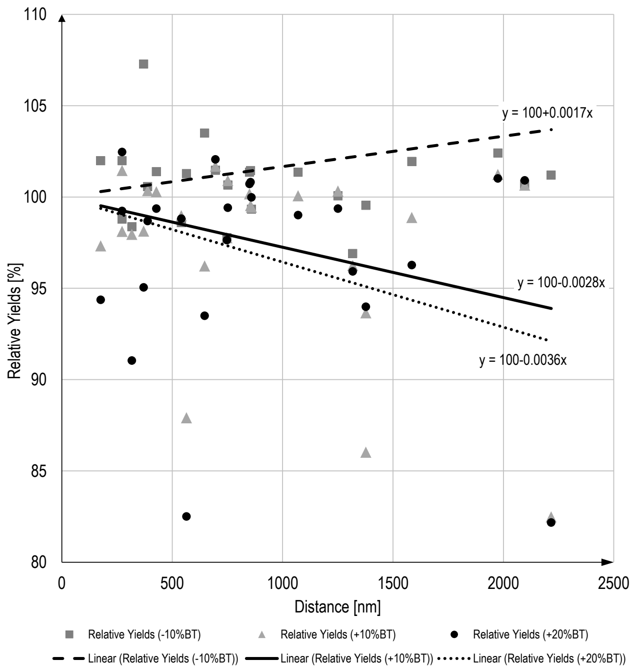

Fig. 12 Relative yields in US markets in dependency on distance and delta block times (-10%, +10%, +20%) according to OAG [27]

The simulation results in dependency on block time changes was consolidated to airline yields regression functions for -10%, 10% and +20% block time changes. The according yield correction factor as a result from regression function can be obtained from Table 6.

Table 6 Block time related airline yield correction model

Block Time	Equation
-10%	$Y = 1 + 1.7 \cdot 10^{-5} \cdot D$
+10%	$Y = 1 - 2.8 \cdot 10^{-5} \cdot D$
+20%	$Y = 1 - 3.6 \cdot 10^{-5} \cdot D$
With: Y = Airline yield correction factor D = Market Distance [nm]	

3.6 Profit-Based Results for Cruise Speed Reduction in Airline Networks

Summarising the results of the operations, DOC and airline yields model, a profit-based assessment of CSR in airline networks was conducted. Fig. 13 illustrates the trend of gained profit based on the Mach number variation for the OR at 1000 nm (1852 km). The revenues show a linear correlation according to the airline yield correction model and diminish with lower Mach numbers. The DOC are characterized by an almost constant gradient between M0.70-0.76, however, above M0.76 the cost are strongly increasing. From a profit-based perspective, earnings increase compared to the reference between M0.76-0.82 with a peak of +0.70% around M0.79.

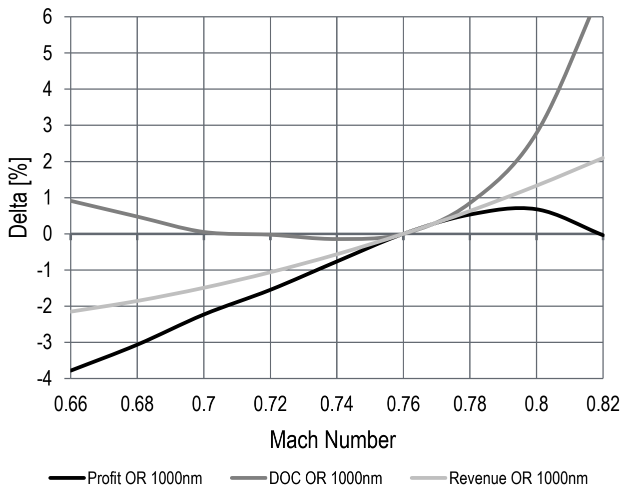

Fig. 13 Composition of the profit for the open rotor and a flight distance of 1000 nm

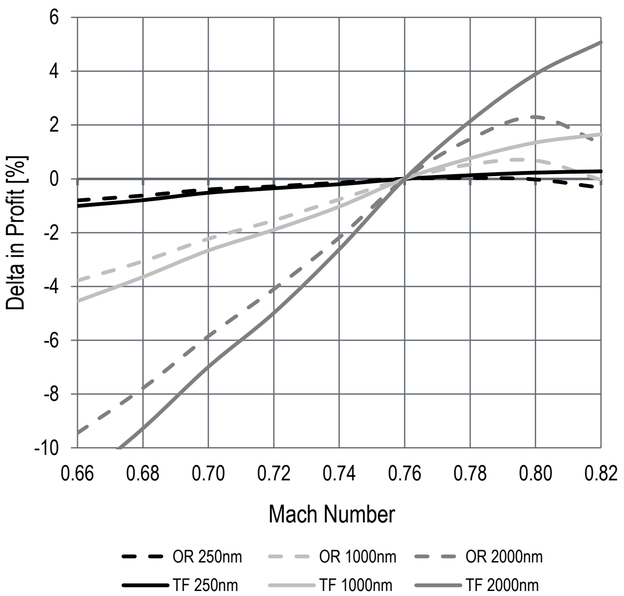

Fig. 14 Profit-based evaluation of open rotor and turbofan for different stage lengths and cruise Mach number

The comparison of different flight distances for OR and TF is depicted in Fig. 14 (above). For Mach numbers under M0.76, the OR and TF show similar downward trends of the profit with advantages of the OR due to the lower fuel burn. For shorter flight distances, the profits are reduced by 1.0% at M0.66, however, for distances around 2000 nm (3704 km) the losses are over 10.0% for the TF. For Mach numbers above M0.76, the earnings increase continuously for the TF flying longer stage lengths. On the contrary, the OR shows a cut in the profit above M0.80. The results show that an optimized design cruise Mach number is around M0.78-0.80 which is consistent with current aircraft in service.

4 Conclusion

This paper presented a framework which goes beyond the assessment of fuel burn trade-offs on aircraft level. To allow a holistic evaluation CSR, different models for aircraft performance, operations, DOC and passenger demand were applied. Therefore, aircraft designed for cruise speed Mach number of M0.66-0.82 based on ducted fan and open rotor propulsion technologies were analysed.

Based on an operational evaluation of schedules disruptions, Mach numbers down to M0.70 seem feasible for implementation into current flight schedules with minor modifications, since only 7.0% of the flights will be affected with an average delay of 7.0 minutes. Focusing on a DOC perspective, the lower bound of CSR should also be set around M0.70 due to the strong increase of DOC below. However, taking also airline yields into account, the results show that for aircraft using OR or TF propulsion technology an optimized design cruise Mach number is around M0.78-0.80 which is consistence with current aircraft in service.

5 Outlook

For further research, the distinction between the airline business models in the flight schedule analysis should be considered. Based on the different network structures operational scenarios for low cost carrier, full service carrier and regional airlines can be derived. These different airline characteristics can be subsequently considered in DOC. Taking the effects of the schedule disruptions, an optimized flight schedule including the deviations in the aircraft rotation should be provided. Hence, the operational impact on airline level can be investigated in more detail.

To open up the design space, the focus could be on regional aircraft, such as Bombardier CRJ or Embraer E-Jet, since the OR promise especially during short O-D distances under 500 nm (926 km) large fuel burn savings. Moreover, different advanced propulsion technologies besides the OR should be investigated.

This study investigated only one aircraft out of each family (i.e. A320 or B737-800). Similar studies for various aircraft family members (i.e. A319 and A321) have to show similar results to prove a robust CSR.

The focus was set on the US market. In the next step, other markets and their socio-economic boundary conditions should also be considered. In previous work, COC optimality of design cruise speed has been presented based on simplified methods [36]. In particular considering the economic feasibility of OR powered aircraft, the mapping of noise charges appears essential. With the comprehensive methodology presented in this paper, these sensitivities should be investigated and the robustness of the conclusion drawn should be reflected w.r.t. to more detailed future scenarios.

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