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BALANCING ECONOMIC AND ENVIRONMENTAL GOALS IN AIRLINE FLEET PLANNING: A MULTI-OBJECTIVE OPTIMIZATION APPROACH

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This work proposes a methodology for systematically balancing economic and environmental goals in airline (long-term) fleet planning. In fleet planning an airline faces a number of trade-offs between economic and – increasingly important – environmental planning goals (e.g., keeping an older, emission-intensive aircraft as long as economically reasonable vs. replacing it earlier to reduce the airline's environmental footprint).

Here, a multi-objective programming model optimizes fleet composition (number and type of aircraft), fleet development (timing of purchases/retirements) and fleet employment (assignment of aircraft to routes in the network) within a 10-year planning horizon. Model inputs include flight plan data, operational, technical and cost parameters, the airline's existing fleet and the availability of new, more efficient aircraft. The model determines trade-offs between an economically and an environmentally optimal fleet plan depending on user-defined weighting factors for both goals. By varying these weighting factors, a series of alternative optimal fleet plans is found (Pareto frontier).

A sample application of the proposed methodology uses data of a major European airline. Results indicate that lowering the environmental footprint comes at high cost for the airline: for example, it would have to sacrifice about 3% of the economic goal's optimum to achieve a 7% improvement in the environmental goal (and 6% to achieve 9%).

Keywords: Airline fleet planning, economic and environmental goals, multi-objective optimization

Classification: "Airline Strategy, Management and Operations", "Environmental Issues in Air Transport Industry", "Operations Research in Air Transport: Modeling and/or Applications"

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1 Introduction

1.1 Research question

(Long-term) fleet planning is one of the most important steps in the airline planning process. In simple terms, it needs to answer two questions: How many aircraft are needed? And: When to acquire them?[1] More specifically, fleet planning needs to determine *the fleet composition and the timing of purchases/retirements within a planning period* while considering constraints such as the escalation of operating costs with fleet age, the availability of new aircraft and the airline's financial situation.

In recent years, environmental goals have become more important for airline fleet planning. First, certain environmental goals now directly impact the cash flow balance. Such goals cause (or save, respectively) costs for the airline and are thus considered when planning the fleet according to economic criteria. One example is the reduction of CO_2 emissions for airlines that are affected by the EU's emission trading scheme (ETS). Second, there are motives to consider environmental goals in fleet planning beyond direct cost impact:

- *Potential future costs:* airlines reckon that stricter environmental policies could punish or even restrict the usage of emission-intensive aircraft in the future.
- *Potential future revenues:* airlines reckon that environmental sustainability could become more important in passengers' booking decision.
- *Public opinion:* airlines want to demonstrate their environmental commitment in light of the increased public awareness of aviation's impact on the environment.

This work proposes a methodology for *balancing economic goals (in monetary units) and those environmental goals (in non-monetary units) that do not (or not yet) have a direct cost impact* and cannot be monetized (i.e., translated into monetary units).

The planning model in this study includes two mechanisms that allow an airline to improve its environmental performance:

- Existing, emission-intensive aircraft are retired (and replaced) earlier than economically optimal
- Low emission aircraft are purchased (or leased) even though this might not be economically optimal (e.g., because of higher purchase prices)

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[1] Fleet planning in the context of this work refers to a planning period of 5-15 years. It is also called "long-term" or "strategic fleet planning" in literature [1, 2].

The proposed methodology is implemented using a major European network carrier as an example. Changes in fleet plan[2] and financial and environmental key performance indicators (KPI) are analyzed. All changes are evaluated with respect to a reference fleet optimized for economic performance.

Airlines can use the proposed model as a “high-level” fleet planning tool. Manufacturers can assess the market potential of future aircraft when operated by an individual airline under different scenarios. “Policy makers” can analyze the impact of environmental (and other) policies (e.g., penalties for old aircraft) on airline fleets.

1.2 Literature review

Morrell has investigated environmental trade-offs in long-term fleet planning using a net present value model [1]. His research explores the economic viability of early aircraft retirements and the introduction of new technology into an airline fleet. By nature of a net present value analysis only a single fleet decision (replacing one aircraft type by one other where timing of replacement is given) can be assessed and neither network nor fleet effects (e.g., fleet composition, commonality with existing fleet) can be considered.

Several authors have published optimization models for long-term airline fleet planning [3-5]. While these models differ in scope, they all optimize according to economic criteria only. None of the publications considers the influence of environmental criteria on fleet planning.

Braun et al. [6] and Koch et al. [7] use multi-objective optimization models to analyze trade-offs between airline operations and environmental impact. Braun et al. [6] illustrate climatological benefits achievable for a single airline from changes in network structure. Koch et al. [7] investigate the effects of variations in flight altitude and speed on operating costs and climate change.

This research draws on Morrell’s study [1] by exploring economic-environmental trade-offs in airline fleet planning. It uses a multi-objective optimization approach similar to those reported in references [6] and [7].

The paper is designed as follows: Section 2 introduces the fleet planning model used in this study. In its basic version, the model has a single, economic objective function. In section 3, the model is extended by a second, environmental objective function (3.1) and a suitable environmental metric is discussed (3.2). Section 4 outlines the implementation of the methodology. Results are presented in section 5.

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[2] In this work, a fleet plan shows the fleet composition and the fleet development over time.

2 Fleet planning model

This section introduces *FLOP*[3] (Fleet Optimization Model), an *optimization model for airline (long-term) fleet planning* that was developed for the purpose of this study.

FLOP determines, for an individual airline, the *optimal fleet composition (number and type of aircraft) for each year of a multi-year planning period.* The model considers (1) deployment of the fleet within flight operations (operating activities), (2) extension or reduction of the fleet over time (investing activities) and (3) selected aspects of fleet financing.

The model inputs include:

- Flight plan data: e.g., number of flights and total seat capacity by “net(work) class” and year. A “net class” is determined by intervals for flight distance and seats per operation. All flights that are within the same intervals are summarized in one “net class”.
- Operational data: e.g., maximum utilization by aircraft type and age, number of seats by aircraft type
- Cost data: e.g., cash operating costs per flight by aircraft type, age and year
- Market data: e.g., market values and lease rates of new and used aircraft by aircraft type, age and year, availability of new aircraft
- Financing data: e.g., interest rates on credit and debit by year, the airline’s credit and investment limit, cash on hand at the beginning of the planning period
- Current fleet: the airline’s existing fleet by aircraft type and age
- Fleet commonality: commonality with existing fleet by aircraft type and family, represented by “setup costs” for the introduction of new aircraft types/families into the fleet
- Airline strategy: e.g., split between manufacturers in fleet, maximum average age of the fleet, maximum leasing quota

Figure 1 summarizes the working principle and input data of FLOP.

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[3] “FLOP“ must not be mistaken for „FLOPS“ (Flight Optimization System), NASA’s aircraft performance calculation and sizing tool.

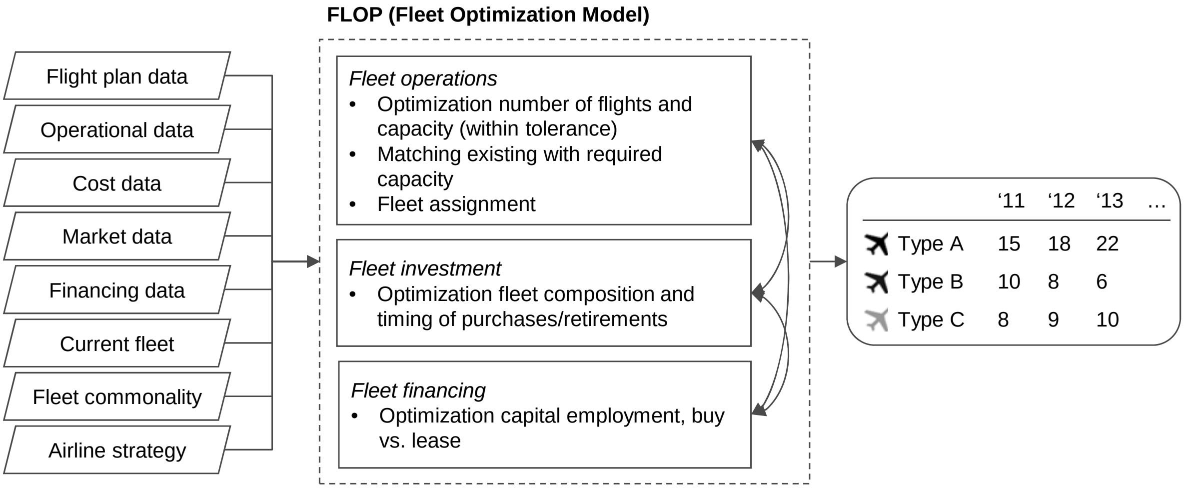

Figure 1: **Working principle and input data FLOP (Fleet Optimization Model)**

FLOP buys or leases new aircraft if (1) additional capacity in existing aircraft types or capacity in aircraft types other than the existing ones is required (expansion investment) or (2) the cost of acquiring new aircraft (purchase price minus salvage value) is smaller than any savings from lower operating costs (replacement investment). Ageing aircraft in the fleet are penalized by higher MRO costs and lower utilization. *An existing aircraft is retired* if (1) less capacity (in the entire fleet or one of its sub-fleets) is required in the future, (2) the return on capital employed in the aircraft (ROCE) in the form of yields is smaller than the return from a fixed-income investment, or (3) the aircraft has reached its maximum age.

The model combines advanced investment appraisal methods (simultaneous investment and production planning, see [8]) with elements of fleet assignment. FLOP is formulated as an optimization problem. *In its basic version, the single objective is to maximize the airline's asset value at the end of the last planning period* $(t = T)$. The asset value at the end of $t = T$ is the sum of any cash surplus (or deficit) at the end of $t = T$ and the (virtual) revenues from liquidating the fleet (i.e., the fleet value):

$$maximize\ (z_{eco} = c_T^+ - c_T^- + LIQ) \tag{1}$$

c_T^+	Cash surplus at the end of $t = T$ $(c_T^+ \geq 0,\ c_T^+ > 0 \leftrightarrow c_T^- = 0)$
c_T^-	Cash deficit at the end of $t = T$ $(c_T^- \geq 0,\ c_T^- > 0 \leftrightarrow c_T^+ = 0)$
LIQ	(Virtual) revenues from liquidating the fleet at the end of $t = T$

A cash surplus/deficit comes from cash generated/lost within the period plus any cash surplus/deficit carried over from the previous period. Following the structure of a typical cash flow statement[4], cash generated/lost within a period comes from 3 sources: operating activities (e.g., revenues and cash operating costs from flight operations), investing activities (e.g., cash for the acquisition of new aircraft and from the disposal of existing aircraft) and

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[4] A cash flow statement is part of a company's annual report.

financing activities (e.g., interest on cash carried over from the previous period or cash taken “out of the system” in the form of dividends). The difference between the asset value at the end of $t = T$ and the asset value at the beginning of $t = 0$ is the change in assets during the planning period. The asset value at the beginning of $t = 0$ is an input to the model. Thus, maximizing the asset value at the end of $t = T$ is equivalent to maximizing the change in assets.

Key constraints of the model cover the balance of cash flows and aircraft in the fleet over time, the number of aircraft and flights required to provide sufficient transport capacity, and the assignment of aircraft to flights. Upper limits are set on the number of aircraft available on the market, the amount of cash that can be invested in new aircraft, and the total number of transactions per year.

For brevity, a mathematical formulation of the constraints is not shown in this paper.

3 Balancing economic and environmental goals

3.1 Multi-criteria optimization

The model is extended by a *second objective function to account for environmental goals.* Thus, FLOP becomes a multi-criteria optimization model. Its two objective functions are:

$$\begin{array}{ll} \textit{maximize}\ (z_{eco} = c_T^+ - c_T^- + LIQ) & \text{economic goal} \\ \textit{minimize}\ (z_{env}) & \text{environmental goal} \end{array} \tag{2}$$

A solution to a multi-criteria optimization model is called Pareto-optimal if there is no other feasible solution that improves at least one objective function while keeping others unchanged [9]. The set of all Pareto-optimal solutions forms the Pareto-front. A schematic Pareto-front for the two-criteria model with z_{eco} and z_{env} is illustrated in Figure 2.

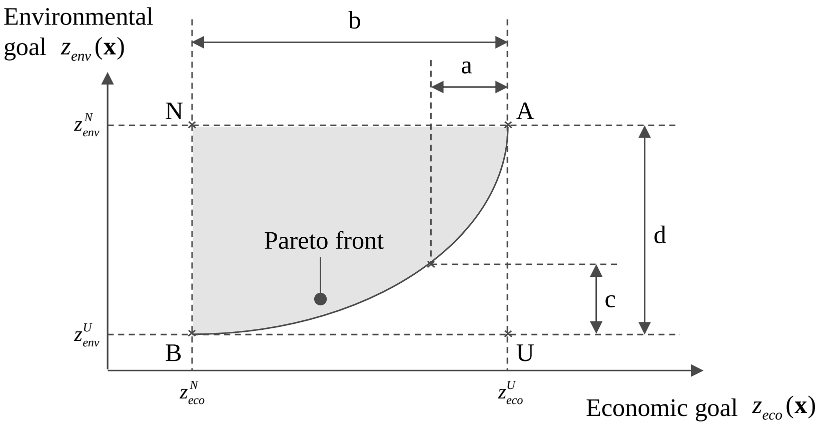

Figure 2: Schematic Pareto front for z_{eco} and z_{env} with Utopia (U) and Nadir (N) points

Point U in Figure 2 is called the Utopia point (or ideal point). It is obtained by optimizing (maximizing for z_{eco} and minimizing for z_{env}) both goals independently. As z_{eco} and z_{env} are conflicting and there is no solution that optimizes both goals at the same time, U is not an achievable solution. Point N in Figure 2 is called the Nadir point. It is determined by the minimum of z_{eco} and the maximum of z_{env}, respectively.

The two goals z_{eco} and z_{env} are combined to a single objective function by normalization[5] and weighting ("weighted sum method", see [10]):

$$minimize\ \left\{ w_{eco} \cdot \frac{z_{eco}(\mathbf{x}) - z_{eco}^{U}}{z_{eco}^{N} - z_{eco}^{U}} + w_{env} \cdot \frac{z_{env}(\mathbf{x}) - z_{env}^{U}}{z_{env}^{N} - z_{env}^{U}} \right\} \tag{3}$$

w_{eco}	Weighting factor economic goal ($w_{eco} + w_{enc} = 1$)
w_{env}	Weighting factor environmental goal ($w_{eco} + w_{env} = 1$)
z_{eco}^{U}	Utopia point ($=$ max.) economic goal (when optimizing for the economic goal only)
z_{eco}^{N}	Nadir point ($= \min$.) economic goal (when optimizing for the env. goal only)
z_{env}^{U}	Utopia point ($= \min$.) value env. goal (when optimizing for the env. goal only)
z_{env}^{N}	Nadir point ($= \max$.) value env. goal (when optimizing for the economic goal only)

The first fraction in (3) represents the difference between z_{eco} and its maximum value, in relation to the distance between maximum and minimum value (a/b in Figure 2). The second fraction stands for the difference between z_{env} and its minimum value, also in relation to the distance between maximum and minimum value (c/d in Figure 2).

Depending on the weighting factors w_{eco} and w_{env}, FLOP determines the best trade-off between an economically and an environmentally optimal fleet plan. There are two ways of dealing with the weighting factors w_{eco} and w_{env} [10]:

- Their values are determined a priori to reflect the fleet planner's clearly defined preferences. In this case, FLOP yields exactly one point on the Pareto front (representing one Pareto-optimal fleet plan).
- Their values are systematically varied. In this case, FLOP yields several points on the Pareto front. The fleet planner's preferences are expressed only a posteriori when selecting one of the alternative Pareto-optimal plans.

This study follows the second approach.

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[5] Normalization is required because z_{eco} and z_{env} differ in unit and scale.

3.2 Environmental metric

The *total nitrogen oxides emissions (*NO_x[6]*) from flight operations in the planning period* are chosen as the environmental metric for this study. This metric is suitable to prove the functional capability of the proposed methodology. There are two reasons for using total NO_x emissions:

- Importance relative to other aviation related emissions: NO_x emissions have the second largest impact on local air and water quality (second only to particulate matters from SO_x emissions) and global climate change (second to CO_2 emissions) [11, 12].
- Ease of computation relative to other environmental metrics: NO_x emissions can be pragmatically estimated using existing and publicly available engine emission data (see further below in this section).

It should be noted, however, that any other single (e.g., noise emissions) or integrative environmental metric (e.g., global warming potential) can be used instead of NO_x emissions, subject to the availability of data.

Total NO_x emissions are a function of fuel consumption and thus reducing fuel consumption leads to lower costs and lower NO_x emissions. Still, “maximizing asset value at the end of $t = T$” and “minimizing total NO_x emissions” are *only partly, not fully complementary goals.* This is due to the fact that both objective values are influenced by other factors, in addition to fuel consumption: The asset value at the end of $t = T$ for example by the purchase price of an aircraft, total NO_x emissions for instance by combustor design. Theoretically, there is even a trade-off between the reduction of fuel consumption and the reduction of NO_x: Higher combustion temperatures and pressures decrease fuel consumption, but at the same time increase NO_x production [11]. New generation jet engines, however, feature both lower fuel consumption and lower NO_x emissions[7].

NO_x emissions impact the environment both at the local and the regional/global level. *At the local level*, NO_x emissions during ground operations, take-off and landing adversely affect local air and water quality. *At the regional/global level*, NO_x emissions contribute to climate change through the enhancement of tropospheric greenhouse gas ozone (O_3) and the depletion of greenhouse gas methane (CH_4)[8].

The total NO_x emissions from flight operations in the planning period are calculated as follows:

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[6] Comprising nitric oxide (NO) and nitrogen dioxide (NO_2)

[7] This is achieved by innovations in engine design such as the twin-annular premixed swirler (TAPS) in GEnx and LEAP-X engines [13].

[8] For details on the impact of NO_x and other emissions on the environment see, e.g., [11, 12].

$$NOX = \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{t=1}^{T} f_{ijt} \cdot NOX_{ijt} \tag{4}$$

i, j, t	Indices for aircraft type (i), "net class" (j) and planning period (t)
f_{ijt}	Number of flights with aircraft type i in "net class" j in t
NOX_{ijt}	NO_x emissions of a flight with aircraft type i in "net class" j in t

When calculating NOX_{ijt}, emissions during landing/take-off[9] and emissions during climb/cruise/descent[10] are distinguished:

$$NOX_{ijt} = a_i + b_i \cdot fuel_{ijt} \tag{5}$$

a_i	NO_x emissions during landing/take-off
b_i	Emission index (mass NO_x/mass fuel) during climb/cruise/descent
$fuel_{ijt}$	Fuel consumption during climb/cruise/descent

The parameter a_i is taken from the “ICAO engine emissions databank” [15]. Values for b_i are estimated using emission data in the “EMEP/EEA air pollutant emission inventory guidebook” of the European Environment Agency (EEA) [16][11]. Emission data for future aircraft have been estimated based on information published by aircraft and engine manufacturers and other literature (see Table 1).

Table 1: Assumptions on fuel burn and NO_x emission performance for future aircraft

Aircraft type	Engine(s)	EIS	Trip fuel burn rel. to ref. aircraft	Trip NO_x rel. to ref. aircraft	Reference aircraft	Sources
A320NEO	CFMI Leap-X	2015	-15%	-40%	A320	[13, 17, 18]
A321NEO	CFMI Leap-X	2017	-15%	-40%	A321	
B737-7MAX	CFMI Leap-X	2017	-15%	-40%	B737-700	
B737-8MAX	CFMI Leap-X	2017	-15%	-40%	B737-800	
CSeries100	PW1500G	2013	-20%	-50%	B737-500	[19, 20]
A350-800	RR Trent XWB	2016	-12%	-30%	A330-200	[21]
A350-900	RR Trent XWB	2014	-11%	-30%	A330-300	
B747-8	GEnx-2B	2012	-7%	-10%	B747-400	[17]
B787-8	GEnx-1B, RR Trent 1000	2012	-15%	-30%	B767-300ER	[17, 21]
B787-9	GEnx-1B, RR Trent 1000	2014	-15%	-30%	A330-200	

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[9] LTO-cycle according to ICAO definition: taxi-out, take-off, climb-out up to ~3000ft, approach/landing from ~3000ft and taxi-in [14]

[10] ICAO definition: climb from ~3000ft up to cruise altitude, descent from cruise altitude down to ~3000ft [14]

[11] Emission data in [16] was calculated using PIANO and a semi-empirical emission model by DLR.

4 Implementation

4.1 Model setup

FLOP is formulated as a *mixed-integer programming model* using IBM ILOG CPLEX Optimization Studio (v12.4). The model instances used in this study have about 27,000 variables and 23,000 constraints. Solution times on a standard PC vary between 5 and 30 minutes per instance at 1% MIP tolerance. 200 model instances are solved with values of w_{env} ranging from 0 to 1 (steps of 0.005).

4.2 Input data

Input data for a major European network carrier featuring ≈270 aircraft and ≈400,000 flights in 2010 is collected. All data is determined using publicly and commercially available sources (e.g., flight plans from OAG data, revenues from MIDT data, number of seats per aircraft from airline websites, financing data from airline annual reports). The planning period ranges from 2011 to 2020 (10 years). An extension beyond 2020 is theoretically possible, but many elements of the input data can hardly be forecasted with sufficient precision. For this study, the number of aircraft types is limited to 20 to keep solution times at tolerable levels.

The model "mechanics" and input data are validated by comparing actual data with model results for the historic time frame 2006-2010. Overall, the agreement between actual and planning data is satisfactory. Deviations are mostly below 5% with regard to aggregate sums, e.g., number of short-/mid-range and long-range aircraft by year, average age of fleet by year, fuel consumption and emissions by year. However, the split in number of aircraft between similar aircraft types (e.g., A319 and A320) is more than 5% off in some cases. One reason for this deviation could be that real data (on cost, utilization etc.) used by airlines slightly differs from input data used for FLOP.

5 Results

The model results are analyzed in 3 categories: *fleet data, economic KPIs, environmental KPIs*. Results are evaluated with respect to a *reference case* where $w_{env} = 0$ (optimization according to the economic goal only). The total number of flights per "net class" is held constant within a tolerance of ±1% for different values of w_{env}. This makes sure that the model doesn't lower total NO_x emissions by simply operating less flights.

Table 2 shows the sample airline's fleet plan for 2011-2020 as calculated by FLOP for the reference case. The total number of aircraft in the fleet increases from 292 to 358, reflecting an increase in the number of flights and capacity needed, with the number of short-/mid-range and long-range aircraft growing at similar rates. Existing aircraft are gradually retired/sold and replaced (e.g., B737-300, B737-500, A340-300, A340-600 and B747-400) as they grow in age and new, more efficient aircraft become available (e.g., A320neo, A350-900, B747-8 and B787-8).

Table 2: Fleet plan reference case (w_{env} =0), values indicate the number of aircraft in the fleet

		Year									
		2011	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**
Short-/mid-range	A319	31	41	44	46	57	70	75	80	83	85
	A320	45	50	53	55	51	41	37	34	34	34
	A320neo	-	-	-	-	6	17	23	29	41	47
	A321	56	61	64	64	64	65	65	65	56	53
	A321neo	-	-	-	-	-	-	1	2	2	3
	B737-300	32	21	21	21	18	7	3	-	-	-
	B737-500	24	14	11	11	3	-	-	-	-	-
	B737-7MAX	-	-	-	-	-	-	-	-	-	-
	CS100	-	-	-	-	-	-	-	-	-	-
Sub-total		188	187	193	197	199	200	204	210	216	222
Long-range	A330-300	19	22	20	20	20	20	20	19	15	15
	A340-300	22	17	17	16	12	7	3	-	-	-
	A340-600	25	24	24	17	14	13	13	9	4	-
	A350-800	-	-	-	-	-	-	-	-	-	-
	A350-900	-	-	-	4	10	16	22	28	34	40
	A380-800	8	10	11	13	15	15	15	16	18	20
	B747-400	30	25	18	13	9	5	-	-	-	-
	B747-8	-	5	12	18	20	21	22	21	21	21
	B787-8	-	3	6	9	15	21	27	33	39	40
	B787-9	-	-	-	-	-	-	-	-	-	-
Sub-total		104	106	108	110	115	118	122	126	131	136
Total		**292**	**293**	**301**	**307**	**314**	**318**	**326**	**336**	**347**	**358**

Values of z_{eco} and z_{env} for the reference case are ≈15,700 (million USD) and ≈690,000 (tons NO_x), respectively. As w_{env} (and thus the relative importance of reducing NO_x emissions) increases, both z_{eco} and z_{env} decrease[12] (see Figure 3 and Figure 4).

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[12] Keep in mind that a decrease in z_{eco} is undesirable, while a decrease in z_{env} is desirable.

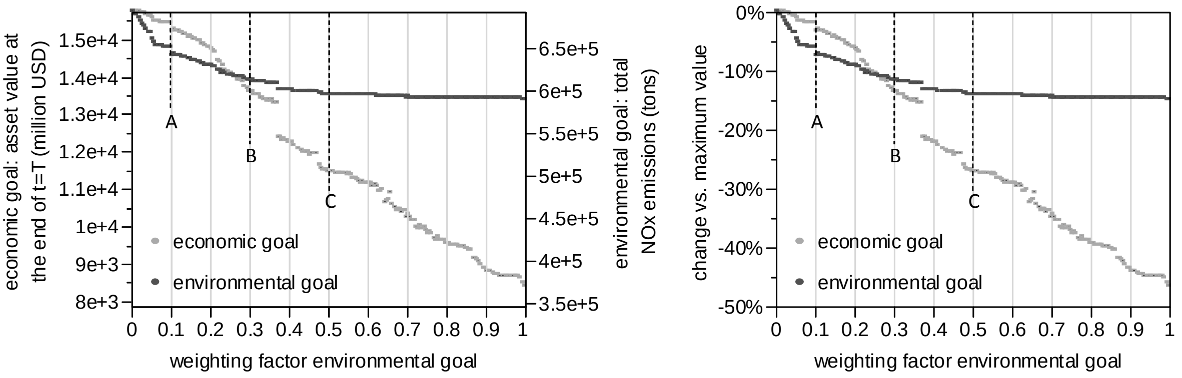

Figure 3: **Values of economic and environmental goal as function of weighting factor, in absolute (left) and relative (right) numbers**

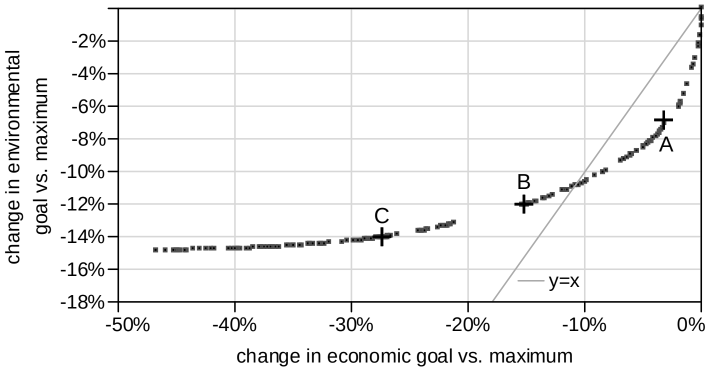

Figure 4: **Pareto frontier with relative changes in goal values (and bisector y=x)**

At $w_{env} = 0.1$ (case A, Figure 3 and Figure 4), total NO_x emissions have dropped by 7% (as compared to the reference case) while the asset value at the end of $t = T$ has decreased by only 3%[13]. At $w_{env} = 0.2$, emissions are reduced by 9% at the cost of a 6% drop in the value of the economic goal. The lines for “change in economic goal” and “change in environmental goal” intersect at about $w_{env} = 0.25$ (Figure 3[14]). From thereon, relative losses in economic performance are greater than relative gains in environmental performance. At $w_{env} = 0.3$ (case B), 14% of the economic optimum have to be sacrificed to achieve 12% lower NO_x emissions, at $w_{env} = 0.5$ (case C), 27% to achieve 14%. Only marginal improvements in environmental performance are possible for greater values of w_{env}.

The large step in the economic value in Figure 3[15] at $w_{env} \approx 0.35$ and smaller steps at $w_{env} \approx 0.1$, $w_{env} \approx 0.45$ and $w_{env} \approx 0.65$ are caused by “setup costs” for the introduction of new aircraft types into the fleet (see input data on fleet commonality in section 2). Setup costs are expenses related to the training of aircrew and maintenance personnel, additional spares

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[13] With the assumptions made on the total asset value at the beginning of $t = 0$ this 3% decrease translates into a 31% decrease in the total growth in assets (from ≈1,700 to1,200 million USD).

[14] In Figure 4 the Pareto frontier intersects the line that bisects x- and y-axis.

[15] This break can also be seen in Figure 4.

inventory and lower aircraft assignment flexibility [22]. At $w_{env} \approx 0.35$, Bombardier's CS100 is added to the fleet, replacing existing A319 and B737-300 aircraft. At $w_{env} \approx 0.1$, the A350-800 replaces a part of the A330-300 and A340-300 fleet. The setup costs for the A350-800 (and thus the size of the break in Figure 3) are smaller than for the CS100, as a member of the A350 family (here: the A350-900) is already part of the fleet when the -800 is added.

The model's main mechanism to reduce total NO_x emissions is the replacement of existing, emission-intensive aircraft by new technology aircraft. This can be seen in the left part of Figure 5: As w_{env} increases, the average age of aircraft at retirement and the average age of aircraft in the fleet decrease[16]. Retired aircraft are replaced by both bought and leased aircraft. The number of aircraft bought remains almost constant for increasing values of w_{env} (right part of Figure 5). The reason for this is that the number of aircraft that can be bought by the airline per year is limited by the airline's investment limit. Thus, the capacity gap left by aircraft sold prematurely needs to be filled by leased aircraft.

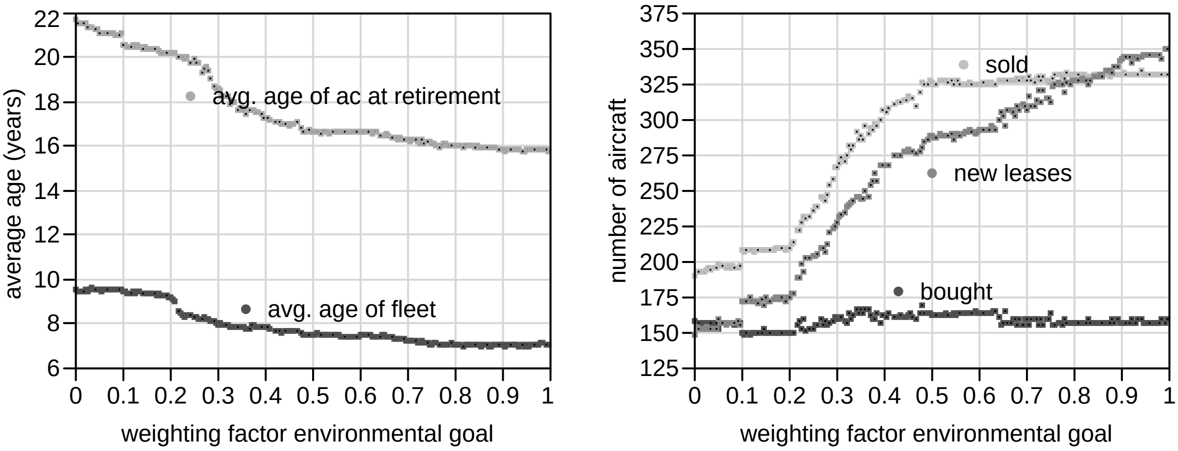

Figure 5: Average age of fleet/age of aircraft at retirement (left) and number of aircraft bought, new leases and aircraft sold (right) as function of weighting factor

Figure 6 illustrates the correlation between fleet composition and fleet deployment using aircraft types A321/A321neo and A320/A320neo as examples. The share of flights <4000 km operated with A321neo increases from 1% (consequently, only few A321neo are in the fleet) to 14-16% at $w_{env} > 0,5$ (left part of Figure 6). In return, the share of flights operated with "standard" A321 decreases from 16% to about 6%. The correlation is less significant for A320/A320neo (right part of Figure 6) as A320neo are added to the fleet in numbers near the maximum (defined by availability on the market) even for $w_{env} = 0$.

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[16] Values in Figure 5 (as well as in Figure 6 and Figure 7) are averages over the entire planning period.

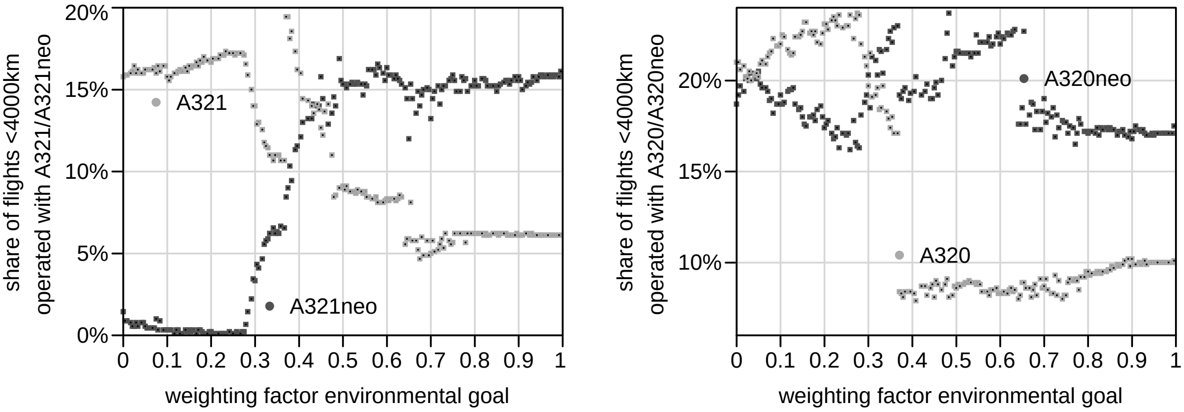

Figure 6: **Deployment of A321/A321neo (left) and A320/A320neo (right) on flights <4000 km as function of weighting factor**

The environmental performance of the fleet, measured by average NO_x and CO_2 emissions per 100 RPK (revenue passenger kilometers), as a function of w_{env} is shown in Figure 7. Specific NO_x emissions can be reduced by 13% at maximum[17], specific CO_2 emissions by only 2%. This is due to the fact that future aircraft achieve greater performance gains for NO_x emissions than for fuel consumption and thus CO_2 emissions (see Table 1).

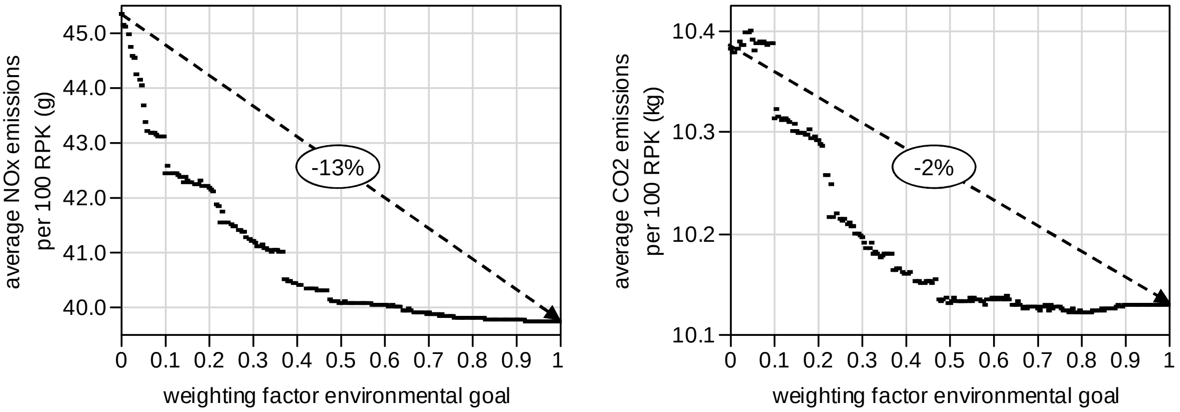

Figure 7: **Average NO_x (left) and CO_2 (right) emissions per 100 RPK as function of weighting factor**

Cases A, B and C (see Figure 3 and Figure 4) are now investigated in more detail and compared to the reference case where $w_{env} = 0$. Fleet plans for cases A to C are shown in Table 3 to Table 5.

In case A, existing long-range aircraft A330-300, A340-300, and A340-600 are retired earlier compared to the reference case (and replaced by A350-800, A350-900 and B787-8). The short-/mid-range fleet is more "stable" compared to the reference with the exception of some minor changes in the number of A320neo and A321neo. In B, retirements of long-range

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[17] Specific NO_x emissions can be reduced by only 13%, not by 15% as total NO_x emissions (see Figure 3). The 1% tolerance on the total number of flights that was mentioned at the beginning of this section allows FLOP to slightly reduce the total number of RPK.

aircraft take place even earlier. Resulting capacity gaps are filled with B787-9 and a higher number of B747-8 aircraft. A considerable number of B737-7MAX are added, mainly as substitutes for less efficient A319s and despite the commonality cost of their introduction. When moving from B to C, only few changes are possible with regard to the airline's long-range fleet. This is mainly because the maximum number of aircraft available on the market has already been exploited in case B. Instead, major changes can be observed for the short-/ mid-range fleet: the number of A320neo and A321neo increases and a large sub-fleet of CS100 is added, facilitating earlier retirements of existing A319, A320, and B737 aircraft.

Table 3: Fleet plan case A (w_{env} =0.1) , values indicate the number of aircraft in the fleet

		Year									
		2011	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**
Short-/mid-range	A319	31	40	42	44	56	69	75	79	82	85
	A320	46	50	55	59	51	41	36	34	34	34
	A320neo	-	-	-	-	9	21	28	34	46	51
	A321	56	61	63	62	62	62	62	62	53	50
	A321neo	-	-	-	-	-	-	1	1	1	1
	B737-300	32	22	21	21	18	8	3	1	-	-
	B737-500	24	15	13	13	4	-	-	-	-	-
	B737-7MAX	-	-	-	-	-	-	-	-	-	-
	CS100	-	-	-	-	-	-	-	-	-	-
Sub-total		189	188	194	199	200	201	205	211	216	221
Long-range	A330-300	19	22	20	20	20	19	11	2	-	-
	A340-300	21	15	15	13	9	-	-	-	-	-
	A340-600	25	13	4	1	-	-	-	-	-	-
	A350-800	-	-	-	-	-	5	9	14	14	14
	A350-900	-	-	-	4	10	16	22	28	34	40
	A380-800	8	10	11	13	15	15	15	16	18	20
	B747-400	30	30	30	22	16	12	8	3	-	-
	B747-8	-	8	15	21	23	23	23	23	23	20
	B787-8	-	3	6	9	15	21	27	33	37	38
	B787-9	-	-	-	-	-	-	-	-	-	-
Sub-total		103	101	101	103	108	111	115	119	126	132
Total		**292**	**289**	**295**	**302**	**308**	**312**	**320**	**330**	**342**	**353**

Table 4: Fleet plan case B (w_{env} =0.3) , values indicate the number of aircraft in the fleet

		Year									
		2011	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**
Short-/mid-range	A319	35	43	51	53	57	70	59	40	30	29
	A320	45	50	57	61	51	41	35	30	23	23
	A320neo	-	-	-	-	12	30	42	54	66	71

	A321	56	61	55	54	54	48	31	26	26	26
	A321neo	-	-	-	-	-	-	12	14	14	14
	B737-300	24	16	14	14	14	8	-	-	-	-
	B737-500	26	17	11	11	9	-	-	-	-	-
	B737-7MAX	-	-	-	-	-	-	19	37	49	53
	CS100	-	-	-	-	-	-	-	-	-	-
Sub-total		186	187	188	193	197	197	198	201	208	216
Long-range	A330-300	19	22	20	20	20	14	8	4	1	1
	A340-300	21	15	15	10	-	-	-	-	-	-
	A340-600	25	10	1	-	-	-	-	-	-	-
	A350-800	-	-	-	-	-	-	-	-	-	-
	A350-900	-	-	-	4	10	16	22	28	34	40
	A380-800	8	10	11	13	15	15	15	16	18	20
	B747-400	30	29	29	20	12	8	4	1	-	-
	B747-8	-	11	18	24	26	26	26	25	22	18
	B787-8	-	3	6	9	15	21	27	33	38	39
	B787-9	-	-	-	3	9	12	14	14	14	14
Sub-total		103	100	100	103	107	112	116	121	127	132
Total		**289**	**287**	**288**	**296**	**304**	**309**	**314**	**322**	**335**	**348**

Table 5: Fleet plan case C (w_{env}=0.5) , values indicate the number of aircraft in the fleet

		Year									
		2011	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**
Short-/mid-range	A319	26	29	29	29	30	27	10	-	-	-
	A320	46	50	59	63	45	36	22	6	-	-
	A320neo	-	-	-	-	21	34	50	67	86	91
	A321	56	61	55	54	51	51	36	25	-	-
	A321neo	-	-	-	-	-	-	14	26	40	41
	B737-300	32	28	24	21	11	2	-	-	-	-
	B737-500	30	24	12	2	-	-	-	-	-	-
	B737-7MAX	-	-	-	-	-	-	12	25	38	50
	CS100	-	-	14	27	39	51	59	59	47	35
Sub-total		190	192	193	196	197	201	203	208	211	217
Long-range	A330-300	20	23	21	21	21	11	4	-	-	-
	A340-300	20	14	14	9	2	-	-	-	-	-
	A340-600	25	10	1	1	-	-	-	-	-	-
	A350-800	-	-	-	-	-	5	8	8	6	6
	A350-900	-	-	-	4	10	16	22	28	34	40
	A380-800	8	10	11	13	15	15	15	16	18	20
	B747-400	30	29	28	18	9	5	-	-	-	-
	B747-8	-	11	19	25	29	29	29	26	22	18
	B787-8	-	3	6	9	15	21	27	33	37	38
	B787-9	-	-	-	3	6	9	9	9	9	9

Sub-total	103	100	100	103	107	111	114	120	126	131
Total	**293**	**292**	**293**	**299**	**304**	**312**	**317**	**328**	**337**	**348**

The gradual diffusion of new technology into the fleet is documented in Figure 8 using aircraft types A330-300, A340-300, and B787-8 as examples. For this study, all three aircraft are competitors, because they feature a similar number of seats[18] and similar ranges. Increasing w_{env} (from 0 as in the reference case to 0,5 as in case C) accelerates the introduction of B787-8 aircraft into the airline's fleet. Note that the total number of aircraft in Figure 8 from 2016 on is higher in the reference case than in cases A-C. Missing capacity in cases A-C is compensated by slightly larger A350-800 aircraft (not displayed in Figure 8 to increase readability).

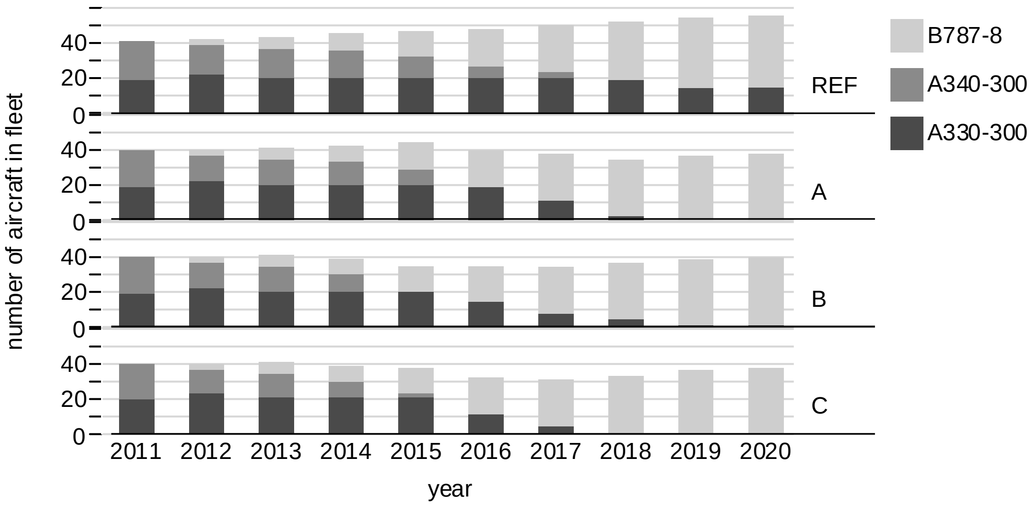

Figure 8: **Number of A330-300, A340-300 and B787-8 in fleet for reference case (row 1) and cases A to C (rows 2-4)**

Figure 9 and Figure 10 illustrate the development of environmental, economic and fleet KPIs within the planning period. Specific NO_x and CO_2 emissions decrease, even for the reference case, as a consequence of increased fuel efficiency and lower emissions for new technology aircraft. Despite lower fuel consumption, cash operating costs (COC) per ASK increase due to growing fuel prices and inflation on other cost items. Higher values of w_{env} generate lower specific COC (because of lower fuel consumption that comes along with lower emissions), but this does not translate into higher values of the economic goal as was shown in Figure 3.

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[18] As opposed to "standard" cabin layouts with 290 (or more) seats, the airline in this study operates both Airbus aircraft with about 220 seats.

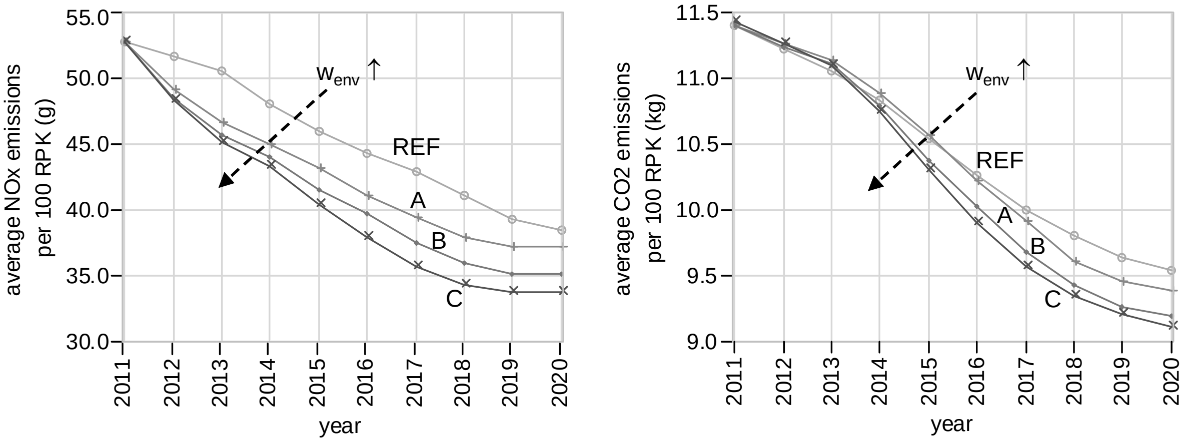

Figure 9: **Average NO_x (left) and CO_2 (right) emissions per 100 RPK as function of planning period**

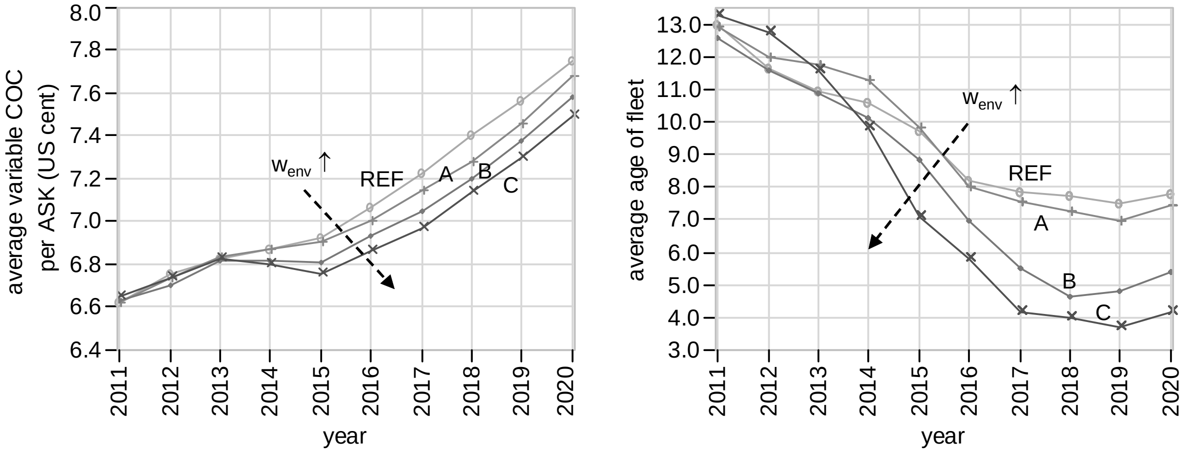

Figure 10: **Average variable COC per ASK (left) and average age of fleet (right) as function of planning period**

6 Conclusions and future work

A methodology for balancing economic and environmental goals in airline (long-term) fleet planning was presented[19]. This methodology was implemented using total NO_x emissions in the planning period as environmental goal and input data for a major European network carrier. Study results can be summarized as follows:

- Despite NO_x emissions mainly depending on fuel consumption (the largest single item of cash operating costs), there is a trade-off between minimizing NO_x emissions and maximizing economic performance.

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[19] The approach presented in this paper is not limited to environmental goals. Theoretically, any other non-economic goal in fleet planning, for example passenger comfort, could be considered.

- Total NO_x emissions could be reduced by 15% at maximum. Economic performance, as measured by the asset value at the end of the planning period, would decrease by 47% in this case (both numbers apply for the specific input data and assumptions on future aircraft used for this study).
- A reduction of NO_x emissions by 7% could be achieved at the cost of 3% loss in economic performance.
- The main lever for reducing NO_x emissions is the early replacement of existing aircraft.
- Due to a limit on the airline’s investment budget the number of leased aircraft increases for more environmentally friendly fleets.
- Given generally low airline profitability, it currently seems unlikely that airlines would voluntarily sacrifice any economic performance. Going forward, policy changes and growing pressure from society and customers might change this.

Further research could focus on two ways of extending the model: First, to integrate more advanced environmental metrics (e.g. global warming potential). This would allow for consideration of the combined effects of different emissions. And second, to consider trade-offs between aircraft size and frequency. The model could then improve environmental performance by deploying larger aircraft at lower frequency. This would require data on the elasticity of demand by service frequency.

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