Foundations of a Technology Assessment Technique Using a Scenario-Based Fleet System Dynamics Model

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In the face of ambitious mitigation policies of the environmental impact of the civil air transport industry, this paper proposes an integrated technique for the assessment of future aircraft technologies in order to determine the impact at fleet-wide level these technologies actually have. With the help of scenario planning methods, three different future scenarios are developed, defining alternative growth rates of the air transport market. The core of the proposed technique is a fleet system dynamics model that is able to dynamically calculate the time and market-specific fleet size, composition, and age distribution, taking the scenario-specific market growth rates as input data. Preliminary results of the study presented reveal the major future aircraft sales markets, as well as the market size for future aircraft generations such as the A320neo/B737max aircraft. In addition, fleet-level performance calculations quantify the increase in fuel efficiency that is required to reach the system-wide CO_2 emission targets set by the Air Transport Action Group.

Nomenclature

$ASKS$	=	Global Available Seat Kilometers
$ASKS_i$	=	Available Seat Kilometers on Flight *i*
$ASKS_j$	=	Available Seat Kilometers on Route Group *j*
$ASKS_{j,a}$	=	Available Seat Kilometers of Aircraft Cluster a on Route Group *j*
D_i	=	Transport Distance provided by Flight *i*
$D_{j,a}$	=	Transport Distance of Aircraft Cluster *a* on Route Group *j*
$f_{j,a}$	=	Number of Flight Operations per Year of one Aircraft of Aircraft Cluster *a* on Route Group *j*
$F_{j,a}$	=	Freight Capacity (in Tons) of one Aircraft of Aircraft Cluster *a* on Route Group *j*
lf_j	=	Load Factor on Route Group *j*
$n_{j,a}$	=	Number of Aircraft of Aircraft Cluster *a* operating on Route Group *j*
$RPKS$	=	Global Revenue Passenger Kilometers
$RPKS_j$	=	Revenue Passenger Kilometers on Route Group *j*
$RTKS_j$	=	Revenue Ton Kilometers on Route Group *j*
S_i	=	Seat Capacity available on Flight *i*
$S_{j,a}$	=	Seat Capacity of one Aircraft of Aircraft Cluster a on Route Group *j*

Subscripts

a	=	Aircraft Cluster
i	=	Flight Operation
j	=	Route Group

I. Motivation

WITH its Flightpath 2050 report, the European Union has set ambitious goals for the European civil aviation industry concerning its future development until the year 2050. Among others, one major mission is to protect the environment and the energy supply by achieving a 75%-reduction in CO_2 emissions as well as a 90%-reduction in NO_x emissions per passenger kilometer relative to the typical values of an aircraft in 2000.[1]

The Air Transport Action Group (ATAG) has also defined challenging environmental targets for the civil aviation sector: (1) a 1.5%-improvement in fuel burn per annum is envisaged between now and 2020. (2) After

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2020, carbon-neutral growth is planned and (3) in 2050, the total quantity of CO_2 emissions of the global fleet is supposed to be mitigated by 50% relative to 2005.[2]

Other major institutions of the civil aviation sector like the International Air Transport Association (IATA) have formulated similar industry goals; all of them contain stringent regulations at a fleet-wide level. IATA has defined a four-pillar strategy that is composed of technological, operational, infrastructural, and economic measures.[3]

In this context, it is required to consider and treat the civil air transport system from a global, fleet-wide perspective and compare its (future) performance and characteristics with the targets that are supposed to be reached (i.e., technology assessment at fleet-wide level). However, describing these future capabilities is a very challenging task. As Tetzloff and Crossley stated correctly, it is a naïve approach to take the status quo fleet of the air transport system and simply replace old or common aircraft technologies (or other measures out of IATA's four-pillar strategy) with new ones.[4]

A much better approach is to take the dynamic nature of the aircraft fleet development into account, *infuse* a new measure into the fleet, let it *disperse* within the fleet with time passing by, and eventually observe the overall system response. One option of how such an approach can be implemented is portrayed in this paper.

II. Approach

A. Schematic Overview

We suggest an integrated, future-oriented aircraft technology assessment technique at fleet-wide level (ATTESST) that fundamentally consists of the six elements illustrated in Fig. 1.

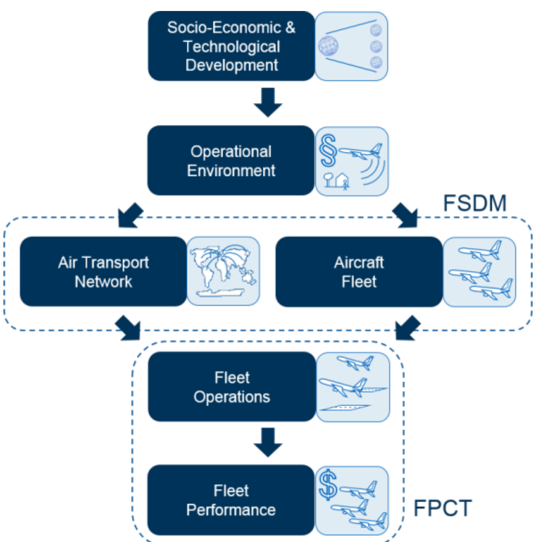

Figure 1. Approach to the proposed aircraft technology assessment technique at fleet-wide level (ATTESST).

With the ultimate goal to quantify the performance of the global future aircraft fleet as a function of the fleet-level impact of technology options (*fleet performance*), the basis and starting point of ATTESST is built on a method of modeling the global *socio-economic and technological future development* that in turn determines the *operational environment* that directly surrounds the air transport system (e.g. noise and emissions regulations, night curfews). Subsequently modeling the *air transport network* is a crucial task in order to be able to allocate aircraft operations and movements to geographical locations and must be done in accordance with the boundary conditions set by the two preceding steps. Determining the size and structure of the globally operating future *aircraft fleet* is the second prerequisite in order to quantify the global fleet performance.

The air transport network model and the aircraft fleet model are numerically united within the fleet system dynamics model (FSDM) that is presented in more detail in this paper. Due to its relevance to the overall mission of the study presented here, the FSDM can be considered as the core of the ATTESST approach.

The FSDM in turn forms the basic input for the *fleet operations* model where performance data of individual aircraft types as well as mission procedure information is contained. The fleet operations module provides input data to eventually quantify and assess the overall *fleet performance*.

B. Development of Future Scenarios

The technology assessment approach proposed here is a well-balanced compromise between input data prerequisites, model complexity, and computational performance requirements. This is especially the case once it comes to the task of predicting the global socio-economic and technological development on a long-term basis (i.e., 2050) in order to be able to extract the future air transport-related operational environment.

Instead of trying to predict the future reality as precisely as possible, we propose a *what-if* approach to enable the description of the system behavior as a function of a wide range of future environmental conditions. Fig. 2 illustrates the corresponding key principle: starting from a well-analyzed status quo situation, several alternative pictures of the future (i.e., *scenarios*) form the basis for a robust extrapolation of alternative operational environments.

We develop these future scenarios by using scenario planning techniques – a bundle of qualitative and quantitative future forecasting techniques that are usually applied to support corporate strategic decision-making processes.[5] Scenario planning techniques are used to develop alternative, consistent, and comprehensive pictures of the long-term future.[6] The future pictures we develop contain statements at macro-social, -technological, -economic, and -political levels as well as at an air transport-related micro-level for all major regions worldwide. Thus, when elaborating these complex scenarios, an interdisciplinary project team of experienced professionals is required.[7,8] In the study presented here, we took the final outcomes of a scenario development project that we had held at our institute in the summer of 2012.[9]

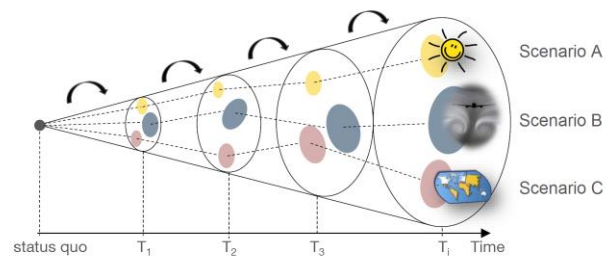

Figure 2. Alternative future scenarios on expanding horizons.

The extraction of operational environments from the elaborated future scenarios is required to generate quantitative input parameters for the FSDM (cf. Fig. 1). In this context, the definition of scenario-specific growth factors of the air traffic volume is especially required. In addition, regulative issues such as the presence of aircraft noise and emission restrictions (e.g. a politically driven cap of overall exhaust emission quantities), and issues related to the air transport infrastructure (e.g. airport capacity and expansion, role of intermodality) are also taken into account.

For this, the mostly qualitatively formulated scenario statements and operational environments must be quantified to a certain extent. This task actually presents a major challenge of the scenario planning methodology and is also a current topic within the relevant scenario-related literature.[8] At the current state, we quantify qualitative scenarios with the help of a *best-guess practice*, using the professional expertise and experience of the project team. A more straightforward, computer-aided method is currently under development at our institute.

C. The Fleet System Dynamics Model (FSDM)

Several authors have presented models of the global civil air transport fleet with the goals to evaluate paths of its future development, emission quantities, and the impact of new technologies on the entire sector. While some highly detailed models require huge amounts of input data and extremely high computer performance, others include a lot of relatively simple assumptions in order to reduce complexity and minimize modeling and computation efforts.[4,10,11,12,13,14]

In principle, the FSDM presented here follows the "macro approach to fleet planning" as described by Clark.[15] The key idea is to model the scenario-specific overall seat and cargo transport capacity of the global aircraft fleet, i.e., the global quantity of available seat kilometers (*ASKS*) and ton kilometers (*ATKS*) offered to the market by all commercial aircraft operators per year.[†] For one flight operation *i*, the corresponding $ASKS_i$ are the product of the number of transported seats S_i on the shortest distance D_i between the origin and the destination airport (i.e., the great circle distance). If the $ASKS_i$ of all commercial flight operations are summed up, the sum *ASKS* can be interpreted as the ability of the global aircraft fleet to offer air transport capacity to the market (cf. Eq. (1)).

For the purpose of reducing complexity, the considered global aircraft fleet, being composed of 198 different specific aircraft types,[16] is grouped into nine discrete aircraft categories (cf. Table 1). Instead of applying a simple payload capacity-oriented method for the grouping of different aircraft types (which is frequently done in similar research projects), the aircraft categories are determined here by using a k-medoids clustering algorithm that groups the 198 aircraft types according to preselected aircraft parameters, including aircraft type-specific seat and cargo capacity, typical distance flown, and type of propulsion. In a later version of the FSDM, this approach will enable the consideration of

Table 1. FSDM aircraft clusters.

ID	Name	Representative Aircraft	Average Retirement Age [Years]	Initial Fleet Size
1	Long-Range Combi	Boeing MD-11	40	83
2	Long-Range Heavy Passenger	Boeing 747-400	30	619
3	Mid-Range Freighter	Boeing 767-300F	45	869
4	Jet Commuter	Embraer 170	30	3,507
5	Long-Range Freighter	Boeing 747-400F	45	411
6	Turboprop Commuter	ATR 72	35	337
7	Mid-Range Passenger	Boeing 767-300	30	2,044
8	Long-Range Passenger	Airbus A340-300	30	1,279
9	Short/Mid-Range Passenger	Airbus A320-200	30	8,843

(Initial Fleet Size as of 2008)

[†] Note that for the purpose of keeping this paper short, only the modeling method of the seat transport capacity is depicted here. The modeling of the cargo transport capacity is done accordingly.

those future aircraft types and technologies that need to be handled separately when assessing them relative to the entire fleet. The clustering method applied here also enables a profound technical characterization of each aircraft cluster. The nine clusters feature specific seat and freight capacities, as well as characteristic operational parameters (e.g. trip length, cf. Table 2).

Each aircraft cluster of the modeled fleet of the FSDM is represented by a currently operating aircraft type (as of 2008). This representative aircraft is determined by the clustering algorithm and is mainly used for flight performance analysis.

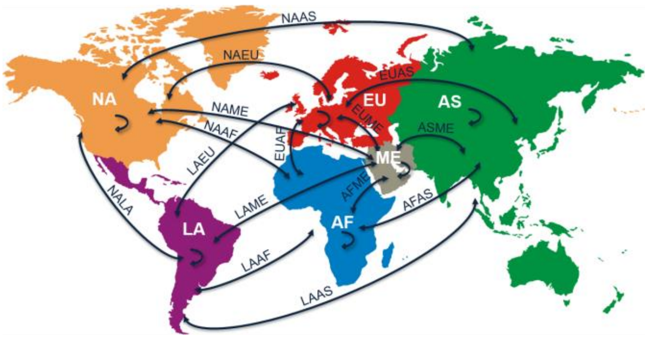

Figure 3. Schematic display of the FSDM air transport network. *The arrows represent the 21 intra- and intercontinental route groups.*

In order to handle the complexity caused by the enormous number of flight operations per year taking place in reality, the global *ASKS* are concentrated here to form 21 air traffic route groups j that intra- and interconnect six predefined world regions (cf. Fig. 3). Every route group is initially characterized by a specific amount of $ASKS_j$ and a specific frequency of flight operations $f_{j,a}$ of an aircraft cluster of the world fleet per year. The $ASKS_j$ and $f_{j,a}$ are directly derived from the Official Airline Guide flight schedules database (OAG)[16] for the initial situation in 2008 which is set as the initial year of the FSDM.[‡] By extracting the fleet data of 2008 from the ACAS aircraft fleet database[17], the initial world fleet can be determined.

In the current version of the FSDM, the initial fleet is assigned to the 21 route groups by distributing all aircraft in proportion to the amount of $ASKS_{j,a}$ of aircraft cluster a on route group j relative to the overall amount of $ASKS_j$ on route group j. A specific seat capacity $S_{j,a}$ and a specific stage length $D_{j,a}$ for each aircraft cluster operating on route group j can then be determined by solving Eq. (2). The values for $S_{j,a}$ and $D_{j,a}$ thus present frequency-weighted average values. In the current state of the model, the values for $f_{j,a}$, $D_{j,a}$, and $S_{j,a}$ are set constant over time. Consequently, additional transport capacity from one year to another can only be generated by integrating more aircraft into the fleet (i.e., increase of $n_{j,a}$).[§]

Table 2. Characteristic operational parameters of a route group.
Example: NA route group (North-American domestic flights).

A/C Cluster ID	Initial Fleet Size	$f_{j,a}$	$D_{j,a}$ [km]	$S_{j,a}$	$F_{j,a}$ [tons]	Daily Utilization [h]
1	0	0	0	0	0	0
2	3	517	4,421	384	14	24
3	163	102	2,131	0	45	2
4	2,036	1,439	844	58	0	16
5	44	547	3,892	0	104	22
6	22	1,361	357	65	0	11
7	429	471	2,719	207	7	14
8	20	526	3017	319	19	17
9	2,844	1,266	1,395	136	2	20

(Initial fleet size as of 2008)

Table 2 shows the data characteristics of a route group, taking the NA route group (i.e., all North-American domestic flight operations) as an example. Note that the daily utilization data is currently used for testing purposes only, but will play an important role in a future version of the FSDM. It is composed of the block time, the turn-around time, and the time for maintenance works of one aircraft of aircraft cluster a on route group j per day.

$$ASKS = \sum_i ASKS_i = \sum_i \left(S_i \cdot D_i\right) \tag{1}$$

[‡] We chose 2008 as the initial year for our fleet model because we think it provides a cleaner image of the actual air transport system performance compared to the years after 2008 when the global financial crisis heavily interfered with the development of the air transport sector.

[§] This implies that the characteristics of *how* an aircraft is operated remain constant over time.

$$ASKS = \sum_{j} ASKS_j = \sum_{j,a} \left(S_{j,a} \cdot D_{j,a} \cdot f_{j,a} \cdot n_{j,a} \right) \tag{2}$$

$$RPKS = \sum_{j} RPKS_j = \sum_{j} \left(ASKS_j \cdot lf_j \right) \tag{3}$$

The 21 route groups become *markets* once a route group-specific load factor lf_j is introduced. The actual *size* of these markets is identified with the revenue passenger kilometers ($RPKS_j$) metric (cf. Eq. (3)). Currently, the seat load factor is set to 83% (cargo load factor set to 69%) on all route groups and is set constant over time. The determination of the growth rates of the 21 markets (i.e., annual growth of $RPKS_j$) is a highly speculative task that is accomplished here with the best-guess practice mentioned above. Obviously, the growth rates must also be defined in accordance with the future scenarios we developed in the preceding steps (cf. Fig. 1).[9]

As mentioned before, the air transport network model and the aircraft fleet model of ATTESST (cf. Fig. 1) are numerically united using a system dynamics approach within the FSDM. This union is realized with the *fleet evolution and aircraft operations module*, the numerical core element of the FSDM. See Fig. 4 for a schematic overview. Modeling the development over time of the global fleet by using system dynamics methods is considered adequate as this approach helps to keep an overview of the complex interaction schemes between the chronological evolution of the fleet and the simulated individual aircraft operations by visualizing the implemented system structure. System dynamics has been used within a similar research context before.[14]

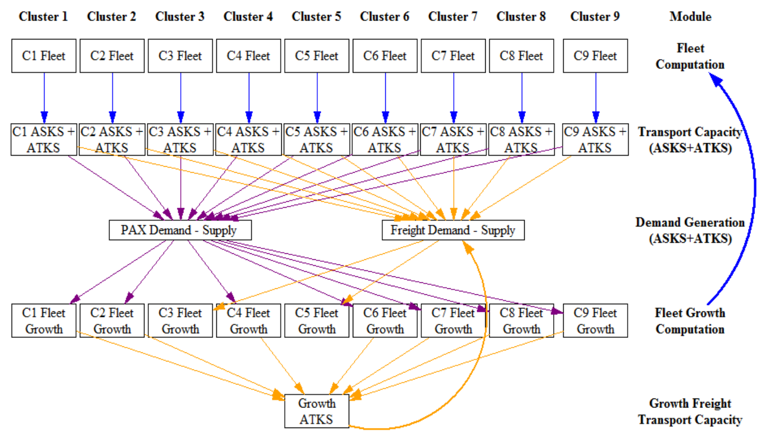

Figure 4. Scheme of the FSDM fleet evolution and aircraft operations module.

Fig. 4 reveals that the fleet evolution and aircraft operations module forms a positive reinforcement feedback loop that is composed of the sub-modules *fleet computation*, *transport capacity*, *demand generation*, *fleet growth computation*, and *growth freight transport capacity*. The loop is controlled by the predefined annual growth rates of $RPKS_j$ that are derived from the future scenarios.** Starting with the computation of the air transport capacity of the initial aircraft fleet on every route group in 2008 (Fig. 4: *Fleet Computation*, *Transport Capacity*), the gap between the transport capacity of the current year and the one that will be required in the subsequent year is calculated, based on the corresponding $RPKS_j$ growth rate between the two years (Fig. 4: *Demand Generation*). This transport capacity gap is then distributed among the nine aircraft clusters. As mentioned before, the fleet-wide transport capacity can only be adapted from one year to another by de- or increasing the number of operating aircraft $n_{j,a}$. However, when doing so, the retirement of currently active aircraft has to be taken into account. Retiring old aircraft and inserting new ones into the fleet in order to satisfy the transport capacity gap is the task of the *Fleet Growth Computation* sub-module (Fig. 4). A special issue arises when it comes to the differentiation between cargo and seat capacity because passenger aircraft are able to transport both seats and cargo whereas cargo aircraft can only transport cargo. In the FSDM, priority is given to passenger aircraft, i.e., the $RTKS_j$ gap is filled with the cargo capacity of newly inserted passenger aircraft at first (cf. Table 2). The remaining rest is then assigned to the cargo aircraft clusters 3 and 5 that represent pure cargo aircraft (Fig. 4: *Growth Freight Transport Capacity*).

The aircraft retirement modeling is a current research area within the ATTESST project and has not ended yet. That is why in the current version of the FSDM, it is still at a relatively simple level: we differentiate between the retirement of the initial fleet of 2008 and the retirement of the fleet that is gradually inserted on a year-by-year basis. While the initial fleet is retired strictly according to the average retirement age given in Table 1, the rest of the fleet is retired while adhering to a normal distribution rule around the aircraft cluster-specific average retirement age.

** The $RPKS_j$ annual growth rates are defined for each of the 21 route groups from 2008 till 2050.[9]

D. Fleet Operations and Performance

With the output of the FSDM available, i.e., the size and composition of the route group-specific aircraft fleet, operational characteristics (i.e., on-ground and in-flight procedures) of the fleet have to be defined in order to eventually calculate technical fleet performance (cf. Fig. 1). Fleet operations definitions and performance calculations are conducted with the Fleet Performance Calculation Tool (FPCT) that is currently being developed within the ATTESST framework. Here, the aircraft performance modeling of the current aircraft fleet is based on Eurocontrol's Base of Aircraft Data (BADA).[18] Performance data input of future aircraft is subject to the results of design studies of future aircraft concepts at our institute and from partner research facilities.

III. Results to Date

Although several modules of ATTESST are still under development, preliminary results could already be produced, especially as far as the scenario-related fleet development and characterization are concerned. In order to enable a better understanding of these results, the underlying future scenarios are briefly outlined. Each scenario describes a possible path of development of the future until 2040 at a socio-economic and technological level.[9] For the study presented in this paper, the quantified statements of the scenarios related to the air transport sector have been extended to the year 2050.

Scenario A "Bright Horizons": This scenario is characterized by a very positive political and economic development. The developing countries of the present have become major players in the world economy. Powerful international authorities have established and enforced a system of equal distribution of wealth in a globalized world, enabling strong economic growth. Because of the continuously rising oil price, research and development activities have been focusing on finding sustainable alternative energy sources. The big steps especially in the flight propulsion industry have eventually been able to provide the air transport system with an entirely new type of aircraft engine. The air transport sector is an integral part of a globalized, intermodal transport chain.

Scenario B "Decoupled Powers": According to this scenario, the emerging countries of today have formed a strong economic and technological counterbalance to the West. This has also enabled moderate economic growth rates at global level. Some countries have even undergone a strong economic development with major infrastructural expansion processes. The air transport sector is benefiting from this development, even though only conventional technologies are available. In this context, drop-in fuels from alternative energy sources play a decisive role.

Scenario C "Rough Air": An increasing number of extreme weather events and the strongly growing energy price cause a volatile political and economic development. As a result, the process of globalization has tremendously slowed down. The industrialized countries of today have successfully defeated their leading role in economy and technology. Yet, they have not been successful in developing major technological game changers yet. In this scenario, the air transport sector faces a strong consolidation process at low growth rates where only the fittest can survive.

To provide a quantitative overview of the scenarios, the corresponding growth rates of RPKS for each scenario are depicted in Fig. 5 for today's industrial countries, the BRIC, and the N11.[††]

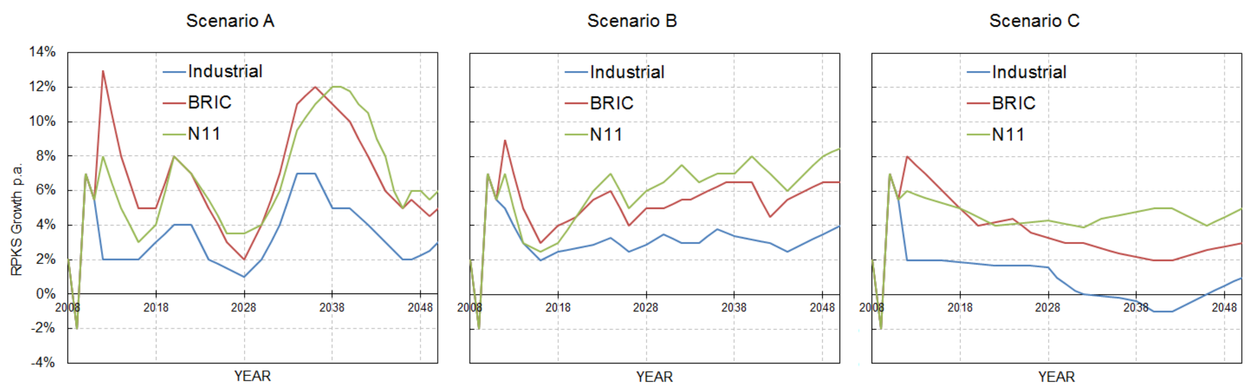

Figure 5. RPKS Growth p.a. corresponding to the three scenarios.[9]

[††] BRIC = Brazil, Russia, India, and China. N11 = Bangladesh, Egypt, Indonesia, Iran, Mexico, Nigeria, Pakistan, Philippines, Republic of Korea, and Turkey.

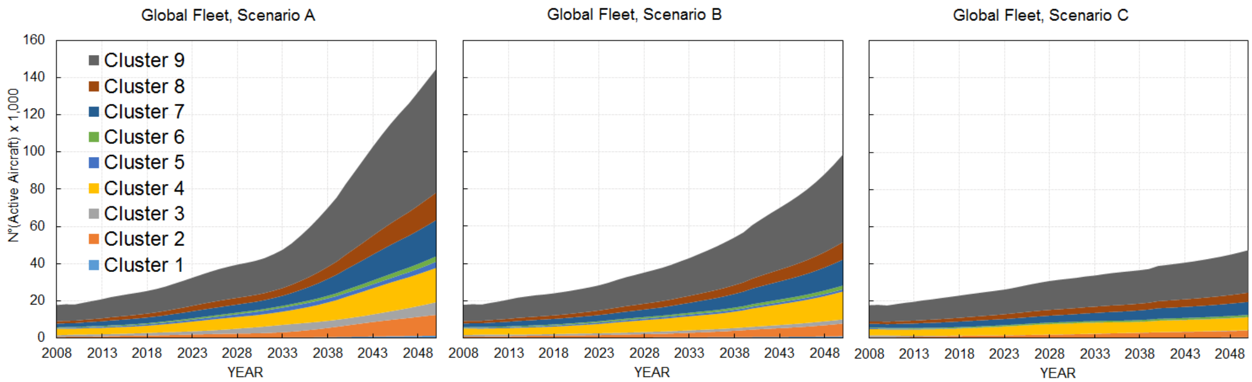

Figure 6. Development of the global fleet mix according to the three scenarios.

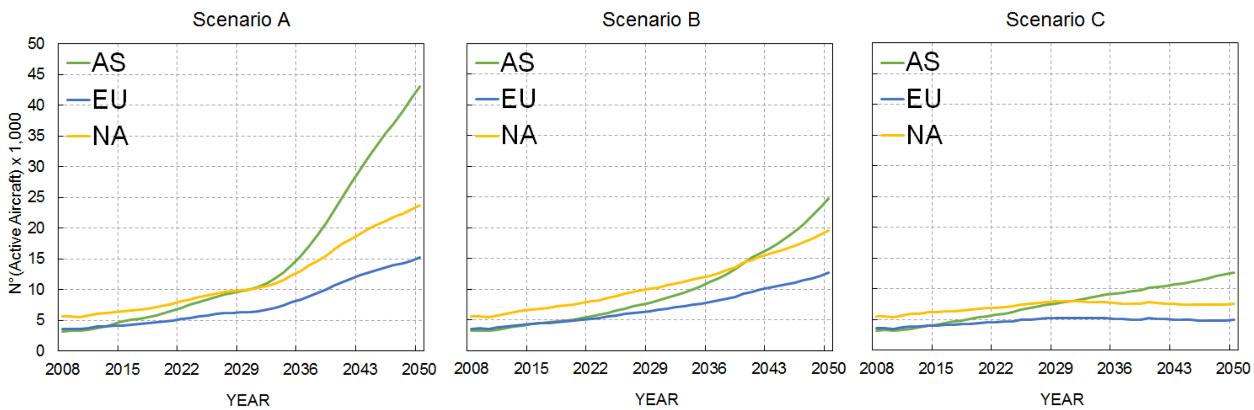

Figure 7. Fleet development on route groups AS, EU, and NA (short-/medium-haul market).

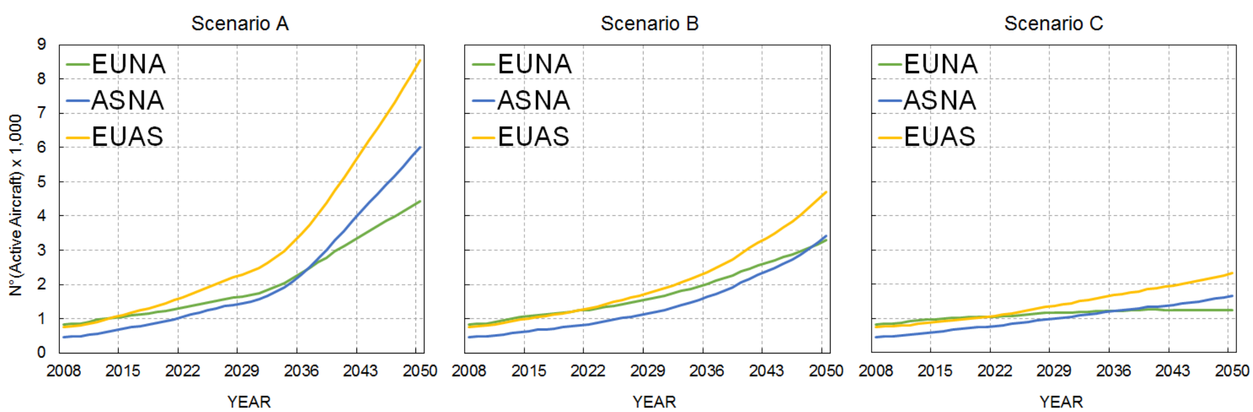

Figure 8. Fleet development on route groups EUNA, ASNA, and EUAS (long-haul market).

A. Scenario-specific development of fleet size and age

As depicted in the previous section, the scenario-specific $RPKS_j$ growth rates are used by the FSDM to calculate the annual transport capacity gap for each aircraft cluster on each route group which in turn determines how many new aircraft are needed in order to fill this gap. With the RPKS growth rates displayed in Fig. 5, global scenario-specific fleet sizes are determined by the FSDM routine as shown in Fig. 6. Note that in order to receive this result, all route group-specific fleet calculation results were summed up.

While in all scenarios, positive growth rates of the air transport sector are predicted, leading to an overall increase in the number of operating aircraft, decisive differences in fleet development and structure become apparent (Fig. 6): in the positive scenario A, a fleet of roughly 144,500 aircraft is operated in 2050, whereas approximately 99,000 aircraft and 48,000 aircraft are in operation in the scenarios B and C, respectively. Once the results at global level are decomposed into statements at a route group-specific level, indications of growing and stagnating markets become evident: Fig. 7 shows the fleet sizes of the EU (European domestic), the NA (American domestic) and the AS (Asian domestic) route groups as an example, representing major markets for short- and medium-haul flights. Fig. 8 reveals the fleet development on the EUNA (flights connecting Europe and North America), the ASNA (flights connecting Asia and North America), and the EUAS (flights connecting Europe and Asia) route groups that present significant long-haul markets. For every scenario, we see a dominating future role of Asia starting from around 2030, both for the short-/medium-haul and the long-haul air transport market segment, whereas today's traditional routes such as the North-Atlantic routes loose market shares.

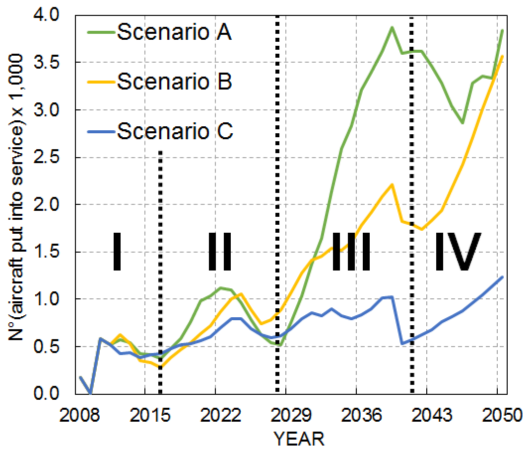

Figure 9. Number of cluster 9 aircraft put into service per year.

The results also provide information about the size of future aircraft markets which may present important data to aircraft manufactures: Fig. 9 displays the number of aircraft per year that are put into service, taking aircraft cluster 9 as an example (i.e., the A320/B737 market). In Fig. 9, four areas are identified: area I can be interpreted as the market size for the current series of the A320/B737 market. The negative influence of the global financial crisis on aircraft deliveries is clearly evident. Until 2016, an average delivery of just under 500 aircraft units per year is determined by the model. This value is smaller compared to reality, where 777 A320/B737 units were sold in 2010 and 870 in 2012.[19,20] In area II, between 2016 and 2028, the market size of the A320neo/B737max aircraft series can be seen. Here, a quantity of 9,853 aircraft units is predicted for scenario A, 9,261 units, and 7,940 units for the scenarios B and C, respectively. These values are also slightly smaller in comparison to the aircraft manufacturers' market forecasts.[21,22] The error of underestimating the amount of new aircraft deliveries is caused mainly by the imprecise retirement modeling of the initial fleet. When considering the total number of aircraft in operation however (Fig. 6), the calculation results of the FSDM seem more realistic. Finally, the areas III and IV depict the market size of a successor aircraft type of the A320neo/B737max aircraft generation. In these areas, the significant differences between the three scenarios becomes evident: while in scenario A, a total of 63,783 units of the cluster 9 aircraft are predicted to be delivered between 2029 and 2050, 44,183 units and 18,695 units are determined for scenarios B and C, respectively.

In addition, the current results include information with regard to the age structure for every aircraft cluster of the fleet and for each scenario. As such, the results provide indications to determine the technology and performance levels of the fleet. Fig. 10 displays the age structure of the global fleet for the three scenarios: for the most challenging scenario C, the average age of the fleet will increase from around 11 years in 2008 to roughly 13 years in 2050 while for the other two scenarios, it will rather swing around 11 years. This indicates that the corresponding aircraft technology level of scenario C will be inferior to the ones of scenarios A and B.

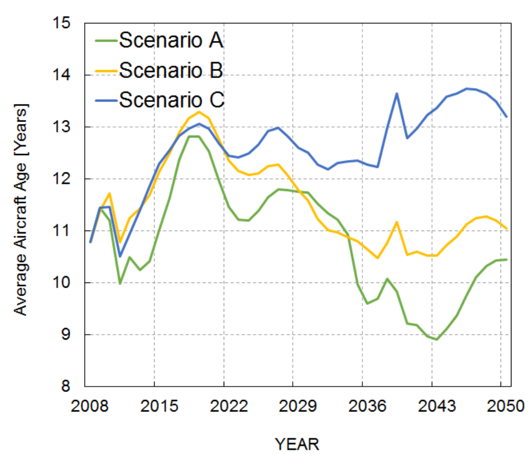

Figure 10. Average aircraft age of the world fleet for each scenario.

B. Fleet-level fuel consumption

Preliminary results with regard to the calculation of the fleet-wide fuel consumption could already be generated for each scenario by using a relatively simple, preliminary version of the BADA-based fleet performance calculation tool (FPCT). In this context, it is especially interesting to study the role of technology-driven efficiency improvements with regard to fuel consumption and related exhaust emission quantities. This can be done by initially setting the technological fleet performance constant over time, analyzing the scenario-specific results, and eventually identifying the gap between the obtained results and a certain target value.

In Fig. 11, the normalized fuel consumption of the world fleet for each of the three underlying scenarios is shown over time, with the fleet-level fuel consumption of 2008 set as the baseline year. In addition, the CO_2

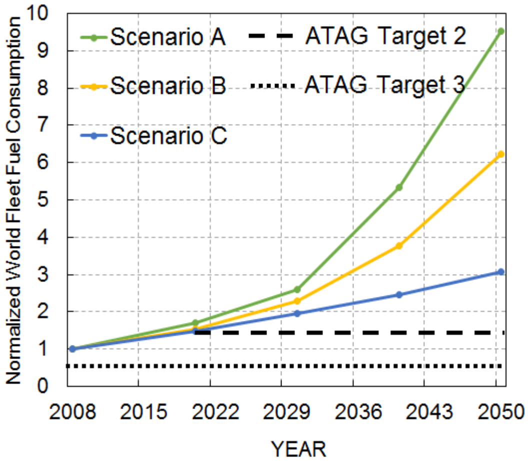

Figure 11. Normalized fuel consumption of the world fleet (2008 = 1). *Note that no technological efficiency improvement is taken into account here.*

Table 3. Required efficiency gain p.a. for ATAG Target 2.

Scenario	Req. Efficiency Improvement p.a.
A	5.9%
B	4.8%
C	2.5%

Table 4. Required efficiency gain p.a. for ATAG Target 3.

Scenario	Req. Efficiency Improvement p.a.
A	7.3%
B	6.2%
C	4.4%

emission targets 2 and 3 of the ATAG are visualized (cf. section I). Although Fig. 11 displays the fleet-level normalized fuel consumption, the results can also be interpreted as normalized CO_2 emission quantities, since fuel burn and CO_2 emission production correlate proportionally with a factor of 3.16.[23] The significant gap between the ATAG targets and the actual values of produced CO_2 emission quantities underlines that, with a more or less strongly growing aircraft fleet in each scenario, the ATAG targets cannot be reached without a major increase in fuel efficiency of the world fleet with the help of technological progress.

Tables 3 and 4 display the rates of efficiency improvement at fleet level per year between 2008 and 2050 that are necessary to reach the ATAG targets 2 and 3, respectively. Because ATAG target 2 is less stringent, the corresponding improvement rates are smaller compared to the ones of ATAG target 3. Yet, a rate of improvement of 2.5% in the case of scenario C to reach ATAG target 2 still presents a challenging task. Achieving a rate of around 7% per year in the case of scenario A in order to cut CO_2 emissions by half until 2050 seems rather unrealistic from today's viewpoint. Decisive technology steps would be required to achieve such a high rate.

IV. Conclusion

The proposed ATTESST approach depicted in this paper presents a consistent way to assess the impact of new aircraft technologies on the performance of the world aircraft fleet as a function of multiple future scenarios. Robust air transport-related trends can be found on the basis of the intended dissimilarity of the underlying scenarios. The proposed method thus presents a way to deal with the high degree of uncertainty of the long-term future and enables to conduct sensitivity analyses to gain a better understanding of the air transport system reaction towards its environment. Although still under development, ATTESST has proven to be able to identify the key markets of aircraft sales and air travel of the future, and to quantify the efficiency improvement steps that are required to reach the system-wide CO_2 emission targets.

A major finding of the study presented in this paper is that even with small growth rates of the air transport market, significant technology improvements in fuel efficiency have to be realized in order to reduce the amount of CO_2 emission quantities and meet the corresponding long-term emission targets. In this context, a part of the future work of this study will be to identify the most promising technology options and relate them to the future fleet performance.

ATTESST may also be used when defining requirements within the design process of future aircraft concepts. Today, the aircraft design process is purely committed to optimize the aircraft performance considering a generic single flight mission. Yet, airlines usually operate a multitude of different aircraft types on multiple routes. They cannot necessarily operate each aircraft of their fleet in the way the aircraft manufacturer had in mind when designing the aircraft. Understanding the aircraft requirements from a fleet-wide perspective may contribute to a more efficient operation of the future aircraft fleet and help aircraft manufacturers to improve their products to better meet customer needs.

Although the fleet system dynamics model has already produced promising results, its development has not terminated yet. Its underlying assumptions will be examined and model elements enhanced in order to improve the overall model accuracy. E.g., an advanced model of aircraft acquisition and retirement is currently being implemented. In addition, the assignment of the fleet to the route groups will be further improved to enable a more realistic response of the model to the scenario-specific input data.

The BADA-based fleet performance calculation tool will also be improved and made more accurate. Besides technology assessment studies related to the aircraft itself, an improved performance model will additionally enable studies with regard to the impact of new operational procedures on fuel efficiency.

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