Impact of a New Long-Range Aircraft Concept Considering Aircraft Sharing on Airline Fleet Scheduling

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Novel aircraft and operational concepts imply changes of important operational parameters and thus of the whole air traffic network structure. Following the introduction of a holistic concept for long-range air travel proposed by Bauhaus Luftfahrt e.V., the paper at hand assesses its impact on airline fleet scheduling. The concept includes a hydrogen powered aircraft operating at reduced flight speeds of M=0.7 as well as the possibility of aircraft sharing. Considering airline flight schedules, the impact of the proposed concept on required fleet counts is estimated. Here, variable turnaround times and maintenance requirements play a central role. The applied method is based on a flight planning tool deriving optimized aircraft flight schedules. Considering different aircraft sharing strategies and turnaround times, the required fleet counts to serve current airline networks as well as shared networks using both traditional and proposed concept aircraft are derived. It is shown that aircraft sharing reduces the total amount of aircraft required to serve a given network under the given conditions. However, fewer aircraft can be saved as a result of sharing than are required to compensate for the increased demand resulting from decreased flight speeds.

I. Introduction

Novel aircraft concepts and operational processes in aviation imply changes in operational parameters. Current regulatory guidelines emphasize the need for such new concepts in order to decrease the climate impact of aviation (e.g. Flightpath 2050 [1]). One possibility for decreasing the use of energy and thus emissions during flight is a reduction of cruise speeds [2]. This can further facilitate the introduction of new technologies in aircraft design, e.g. Natural Laminar Flow wing designs [3] or High-Bypass Turbofan engines [4].

In practice however, such flight speed reductions are limited by operational and financial considerations. Aircraft operating at reduced cruise speeds are still required to fit into the existing air traffic network in order to avoid system capacity limitations and to ensure network efficiency, e.g. through good connectivity between flights via established peak structures at hub airports. Since current flight schedules are tailored for current aircraft, new aircraft should, as far as possible, be able to be integrated into the existing network and flight schedules when operating in parallel with conventional and possibly unchanged short- and mid-range aircraft. A further central goal is to reduce the increase in

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fleet sizes and required production capacities associated with the described lower cruising speeds. In order to keep costs at a minimum, an airline is interested in acquiring as few new aircraft as possible for fulfilment of the envisaged flight program.

The new long-range aviation concept Hy-ShAir developed by Bauhaus Luftfahrt e.V. focuses on the analysis of operational and technological improvements and innovation potential across the long-haul network that enable a significant reduction in emissions and would be an important building block for reaching environment protection targets. Such a reduction would be significant since long-range aviation is currently responsible for up to 40 % of aviation fuel consumption. At the same time, there is room for operational improvements by bundling capacities. Bauhaus Luftfahrt e.V. therefore follows a two-fold strategy within the context of a holistic view on long-range aviation [5]. On the technical side, this led to the design of a concept aircraft using liquid hydrogen (LH_2) as energy source in order to avoid the emission of CO_2 [6]. A reduced flight speed of Mach=0.7 should reduce total energy consumption and enable the introduction of efficiency improving aircraft technologies. On the operational side, optimized operational procedures such as network related aspects and business models can further reduce emissions [5]. The resulting aircraft concept is described in detail in Troeltsch et al. (2019) [7]. The effects of introducing the proposed concept into the long-range air transport network are investigated in terms of required fleet sizes given the existing flight schedules. In order to cope with an otherwise strong growth in the number of aircraft required for the performance of schedules due to the decrease in flight speed, we focus on different aircraft sharing strategies for selected airlines. These sharing models also promise to bundle passenger flows on fewer flights with higher load factors, eliminating low capacity parallel flights conducted by the sharing partners. The scope of this paper is limited to long-range flights and current flight schedules. Furthermore, only selected airline fleets that represent regional differences as well as different levels of fleet utilizations are analyzed. Possible adjustments of load factors or flight frequencies are part of the airline's fleet and schedule planning. The connection between these different airline planning steps is highly complex and was outside of the scope of this first investigation.

One of the main aims of the paper at hand is therefore the quantification of the effects of the introduction of the above described new long-range aircraft concept with lower cruising speeds into the existing air traffic network. Furthermore, effects of operational changes in the form of aircraft sharing and reduced turnaround times for counteracting deteriorations in the resulting aircraft utilization as well as increases in the required fleet counts will be examined as well in regard to their ability to improve network efficiency. We want to address operational problems and possible solutions thereby for the service introduction of an aircraft concept ready to enable a significant step towards decarbonization of aviation.

In the following Section II, the utilized approach of the Aircraft Maintenance Routing Problem as well as concepts of aircraft sharing are shown. Section III deals with the description of the use case, the input definition and results, whereas Section IV further discusses the obtained results. The paper closes with a conclusion and outlook in Section V.

II. Approach and Basic Concepts

Aircraft Route Assignment is a mathematically complex task, requiring detailed data on air traffic demand and supply, and substantial computational resources. In practice, it follows other airline planning steps like fleet and schedule planning and fleet assignment to respective routes [8]. In this paper, we concentrate on the Aircraft Maintenance Routing Problem, the decisive step for the assignment of aircraft to a flight schedule in the Airline Planning Process. Further steps of the Airline Planning Process are not considered in this paper. The basic Aircraft Maintenance Routing algorithm has been covered to a great extent in literature, usually addressing profitability measures (as in [9]), or other network design-specific research questions (as for example in [10] and [11]) as optimization variables. However, optimum fleet sizes as required in this work can be derived with the model described by Ben Ahmed et al. (2018) [12] and Haouari et al. (2013) [13], forming the core of the calculations within this study. Further advantages of this tool make it especially useful for considerations involving long-range flight plans. On the one hand, these advantages include the representation of so-called wraparound flights extending beyond the given time horizon, such as overnight flights. While short-range flights often only require daily periods with no flights occurring during nighttimes, overnight flights are a common procedure for long-range services. On the other hand, the model's time horizon is easily adaptable to a multiple-day timeframe, allowing for the consideration of flights that are not operated on a daily basis. For a detailed description of the model, see [13].

The described model comprises a mixed-integer model making use of a polynomial-sized formulation [12, 13]. It allows for the determination of the minimum fleet size needed in order to accomplish a given flight schedule. On this basis, we will conduct investigations regarding the introduction of the proposed long-range aircraft concept operating at lower cruise speeds and its resulting effects on airline schedules and required fleet sizes. Sensitivities in terms of varying turnaround times and aircraft sharing strategies will be evaluated with regard to their potential impact on fleet size and aircraft utilization. This includes fleet pooling for various subfleets within an airline's fleet (intra-airline-sharing) and among different airlines (inter-airline-sharing). The required input flight schedules and flight times are derived from OAG [14]. Furthermore, aircraft data in the form of cruise speed as well as maintenance requirements in terms of number of flights until returning to a defined maintenance base are considered. Flight times are adapted according to the lower flight speeds by adding the additional time to the arrival time of the given schedule. This is achieved by means of a simplified mission analysis. The basic flight plan structure is kept for the concept aircraft in order to resemble current traffic peaks at hub airports and thereby fit these aircraft into the current air traffic network.

The case of intra-airline sharing should therewith depict the benefits of utilizing fewer subfleets in the fleet of an airline in the form of increased flexibility [8] and reduction of fleet counts. An aircraft that is easily adaptable to different passenger demands would enable such an approach, however is difficult to realize in an economically feasible manner. The idea of pooling aircraft of different airlines to create some sort of inter-airline fleet sharing is not new. Such ideas were already investigated by European airlines such as KLM, Sabena and Swissair in the 1950s. These ideas were, however, never implemented owing to missing agreements about the routes to be covered with such a concept [15]. Many different forms of cooperation among airlines have been introduced since then, ranging from interline and codeshare agreements to airline alliances. The high costs for operating the respective airlines' global networks can be reduced by this and new customers can be acquired thanks to improved connectivity in an environment where legal constraints often prevent mergers of airlines of different nations [16]. The concept of aircraft sharing might therefore follow these goals and further enhance the efficiency of global network operations, expanding the list of existing airline joint-activities, as for example depicted by Oum and Park (1997), who already included the exchange of aircraft as a possibility for cooperation [16].

Necessary preconditions for such partnerships are cost benefits on the one hand, e.g. reduction of capital costs for new aircraft, and increases in load factors. On the other hand, benefits of the partners should be balanced and a high overlap of the markets served should be avoided. In this respect, the connection of different continental markets seems especially promising for opening new markets through the establishment of codesharing agreements [16, 17, 18]. This is in contrast to the efforts for the aircraft pooling strategy described by Wassenbergh (1963), where the partners often served similar markets and the cooperation was limited to few routes [15]. Therefore, airlines participating in an inter-airline fleet sharing model should serve their unique continental markets and avoid competition with each other in these markets. Fleet sharing benefits arise when using synergies at the connecting arcs between those markets that are unique to the different airlines are used. These synergies come in the form of an ability to switch aircraft easily between the partner airlines' route networks and the possibility to reduce frequencies on such routes by using larger aircraft and by increased load factors. The former mechanism is investigated in this study; the latter is open for future consideration. Inter-airline fleet sharing aspects with three airlines from three different continents with only a small overlap of served routes will therefore be chosen for this investigation. Furthermore, the chosen airlines are already involved in different levels of partnership with each other in their membership in Star Alliance and in joint ventures. This follows the findings reported by Li (2000) [19], who formulated different categories of inter-airline cooperation and reported that implementation of joint operations, such as fleet sharing alone does not usually lead to a long-lasting cooperation.

III. Analysis and Results

The described procedures will be used in the following for the evaluation of the Hy-ShAir concept. Important study parameters as well as the selection of the study fleet are shown in this section. Subsequently, the results for fleet counts and utilization considering reduced cruise Mach numbers, the introduction of aircraft sharing strategies and the turnaround time variations are depicted.

A. Study Parameters

This section describes the influence of different factors on fleet size and utilization. One factor of high importance in this case is the concept aircraft's flight speed which is significantly lower than cruise speeds of conventional long-range aircraft. Current long-range aircraft are assumed to travel at average cruise speeds of Ma = 0.84. This is based on a survey of wide-body aircraft utilized on long-range routes according to OAG 2016 data [14]; the respective cruise speeds were derived from BADA [20]. Future conventional reference aircraft in related studies were expected to have cruise speeds in the range of Ma = 0.82. The concept covers flights longer than 2500 nm (design range 6400 nm), a segment responsible for about 30 % of aviation CO_2-emissions today [7]. A mission analysis conducted for both an aircraft flying at Ma = 0.82 and at the cruise speed of the new concept aircraft (preliminary) of Ma = 0.7, reveals that the flight takes about 20 % longer in the case of the slower cruise speed. For long-range flights, the cruise phase is the defining flight phase in many respects, e.g. for the required flight times. Therefore, we assume that all flights using the new aircraft type will take 20 % longer. For shorter range flights, however, the difference in flight times between new and old aircraft types is probably well below the 20 % owing to the higher importance of the climb and descent phases.

Further factors influencing optimum flight schedules and therefore fleet counts are related to ground operations, with the main ones the maintenance intervals required as well as the turnaround time between flights. The latter, often discussed in the context of utilization improvement (see e.g. Belobaba et. Al (2016) [8]), promises the highest improvement potential of all ground operations factors. For baseline calculations, we assume a turnaround time of 70 minutes [13]. In addition, we set the duration of a maintenance event to 360 minutes per check and the intervals between two maintenance events to either 3900 minutes of flying time or six takeoffs according to Haouari et al. (2013) [13]. This resembles the values for overnight checks. C- and D-Checks are not considered owing to the long intervals between them (usually one or more years, [8]).

B. Selection of Study Fleet Parameters

For the described use case of comparing long-range aircraft with different flight speeds, only the consideration of aircraft in the same size category (passenger capacity, take off mass) that perform long-range flights is relevant. This describes the category of wide-body aircraft, which is why the selection of data is not based on flights, but on aircraft types. However, the same kind of aircraft is still often used for short range flights as well. The flight plans of these aircraft for long- and short-range flights are therefore highly intertwined in order to reach a high aircraft utilization. Consequently, the flight plans with these different kinds of ranges for wide-body aircraft cannot be treated independently when analyzing current air traffic networks in the present study.

The study is based on data from the OAG 2016 database as input, which reports reliable flight schedule data. We selected flights performed by the wide-body fleets of three airlines. As introduced in Section II, fleet sharing approaches are expected to be most realistic for airlines already cooperating, provided this proves to be operationally and economically beneficial. We consequently chose airlines that are part of the same alliance and that have established joint ventures with each other. Finally, the chosen airlines should be from different continents to avoid competition in core markets and to investigate the global impact fleet sharing concepts have on long-range flights. The three airlines chosen, Air China (CA), Lufthansa (LH) and United Airlines (UA) operate flights between their home regions (and hubs) that follow mainly East-West directions and vice versa, resembling the dominance of East-West bound (+/- 45° heading) long-range flights, which is also evidenced by Fig. 1.

Figure 2 further shows the distribution of long-range flights globally as well as for the three chosen airlines. It can be seen that the most important long-range routes in the global network departing from North East Asia, Western Europe and North America are covered by the three investigated airlines owing to their respective home bases. The selection of investigated flights in this study is therefore considered representative of the global long-range network.

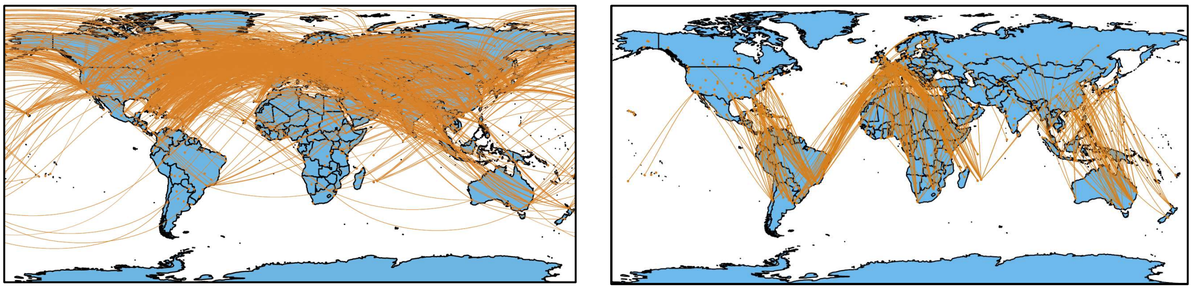

Figure 1 – Visualization of East-West bound (left) and North-South bound (right) flights, based on OAG data [14].

For our investigation, we chose data of the second week of June, one of the months per year with the highest amount of traffic [21]. Owing to calculation time restrictions we chose a two day schedule, including flights on Monday and Tuesday of the selected week data, enabling us to depict flights occurring daily and every second day.

In order to consider inter-airline sharing, three aircraft clusters are defined as shown in Table 1. They are defined according to the size of the respective aircraft as well as their function in the airline network. Complexity in the form of many different subfleets is thereby reduced. Furthermore, on the basis of the resulting clusters, similar subfleets of different airlines are defined which might be subject to replacement by a single fleet of new type long-range aircraft incorporating inter-airline fleet sharing. Additionally, Lufthansa's A380-subfleet was not considered in the clustering owing to the high seating capacity (509 seats), which is well above the numbers for the Large cluster.

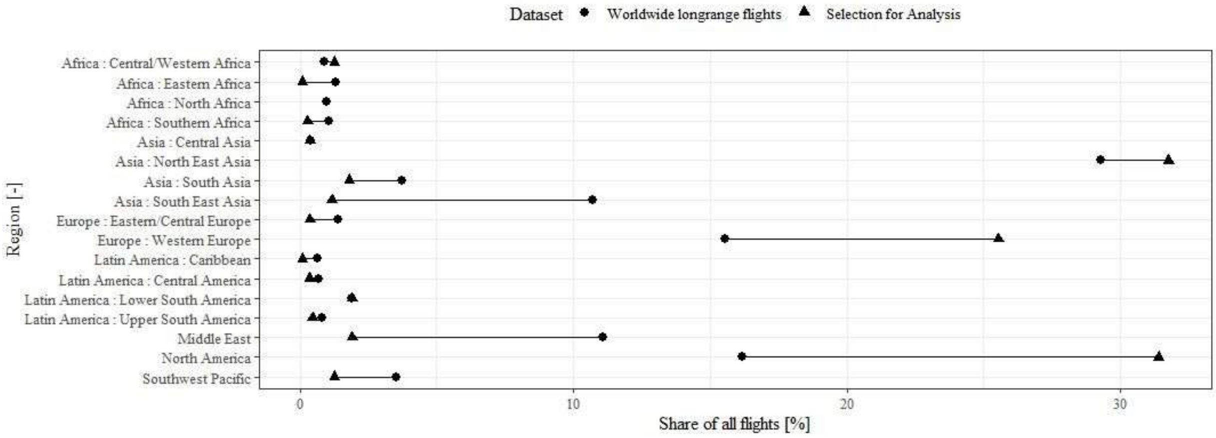

Figure 2 – Distribution of worldwide long-range flights – total and for the three airlines chosen for investigation.

Table 1 – Clustering of aircraft into three cluster according to size and network function.

Cluster	Subfleets	Network Function	Seats [14]	Fleet Count
Small	- CA: A330 - LH: A333 - UA: B763, B764, B788, B789	relatively small aircraft for routes with low demand, often connecting hubs with airports that are not hubs in the airline's and its partner's network or operating additional frequencies	183-301	144
Medium	- CA: B772, B77W - LH: A343, A346 - UA: B772	aircraft of size between Small and Large cluster, operating on main routes	269-364	120
Large	- CA: B748 - LH: B744, B748 - UA: B744	aircraft with the highest seat capacity for routes with high demand, often connecting the airline's hub with other big hub airports	340-393	54

Table 2 shows further details about the subfleets used for the calculations in this paper. The fleet counts represent the results of the calculation of the optimal fleet sizes given the respective subfleet's real flight schedule according to OAG. The Long-Range Share indicates the share of inter-regional flights in all flights of a cluster. From this data, it can be seen that especially Air China uses its wide-body fleet for short-range, usually domestic, flights as well. The A330 and B772 subfleets are mainly used for short flights.

Table 2 – Investigated subfleets and their fleet count, average utilization, long-range share and seat capacity.

Airline	Aircraft type (ICAO)	Fleet Count	Utilization [%]	Long-Range Share [%]	Seat Cap.
CA	A330	54	42.78	29.31	237/284/301
CA	B748	6	47.83	62.50	365
CA	B772	9	23.88	14.29	310
CA	B77W	20	59.09	65.63	311
LH	A333	25	38.91	78.38	255
LH	A343	13	61.23	100.00	279/298
LH	A346	16	67.85	100.00	281/297
LH	A388	13	69.76	100.00	509
LH	B744	12	68.40	100.00	371-393
LH	B748	18	64.70	100.00	340-364
UA	B744	18	54.98	100.00	374
UA	B763	25	65.56	89.80	183/214
UA	B764	14	63.68	92.31	242
UA	B772	62	64.78	100.00	267/269/364
UA	B788	12	58.23	77.78	214
UA	B789	14	66.90	84.21	252

In order to obtain network improvements through aircraft sharing, the respective route networks of participating airlines need to have some overlap to have sufficient connecting points and synergies between the subnetworks. As shown by Fig. 3, the three representative airlines chosen in this study fulfil that requirement with about 30 % of airports being served by at least two, in many cases even all three airlines.

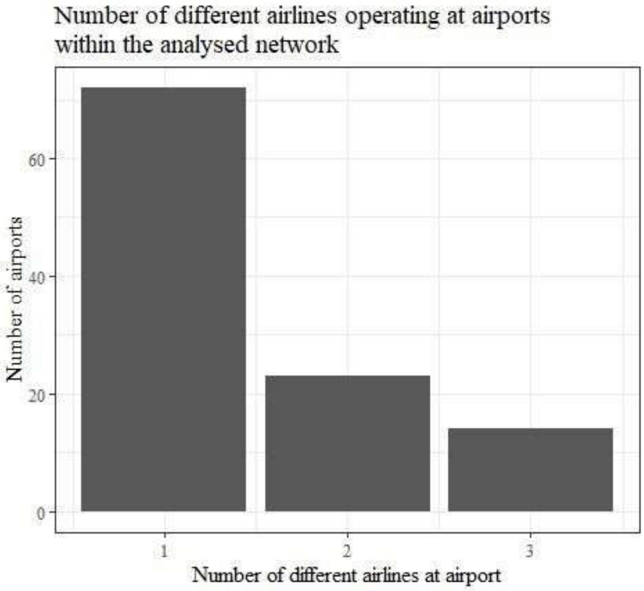

Figure 3 – Number of different analyzed airlines operating at airports within the analyzed network

In the course of the current study, calculations were performed for intra-airline aircraft sharing, for inter-airline-sharing and finally for all subfleets of the three airlines merged into a single fleet. Flight time increases owing to lower cruise speeds of the novel aircraft concept were incorporated by adding 20 % of the original flight time to the arrival time as given by the OAG flight schedules. Stroh (2020) found no significant differences in fleet sizes and utilization for different strategies of uniform addition of the prolongation to the original schedule (e.g. moving the departure and arrival times or only moving arrival times with fixed departure times) [22].

C. Results

The results are divided into three different sections according to the investigated influence factor. First, the general effects of reduced cruise speeds are shown, followed by the introduction of the described aircraft sharing strategies and finally the variations in turnaround time.

1. Effects of lower flight speeds

To begin with, we will show the effects of a 20 % longer flight time (in the following Slow flight case), corresponding to a full substitution of the respective current wide-body subfleet by the new concept aircraft type. While departure times remained the same as in the dataset drawn from OAG 2016 (in the following Reference flight case), arrival times were delayed to account for increased travel times, which is illustrated in Fig. 4. The arrival part on the right side of Fig. 4 shows the shifted arrival times for slower flight speeds (blue curve) as compared to the Reference flight case (green curve). All other parameters remain unchanged when compared to the Reference case described above. Furthermore, important effects for fleet size and network considerations for the Slow flight case can be determined.

Figure 5 shows the fleet sizes and utilizations achieved by the considered subfleets of Air China (CA), Lufthansa (LH) and United Airlines (UA) in the Reference as well as the Slow flight case. The respective differences between both cases are depicted as well. Observing the left side of Fig. 5, it can be concluded that an extension of the flying times leads to a high increase in required fleet sizes in all cases. However, the extent of that increase is very different for each subfleet, ranging from 33 to 92 percent in our example. This shows that with lower flight speeds and hence later arrival times, many connections between flights in today's flight schedules can no longer be accomplished, requiring an increase in fleet count. This directly translates into significantly lower utilizations in the Slow flight case, as indicated on the right side of Fig. 5.

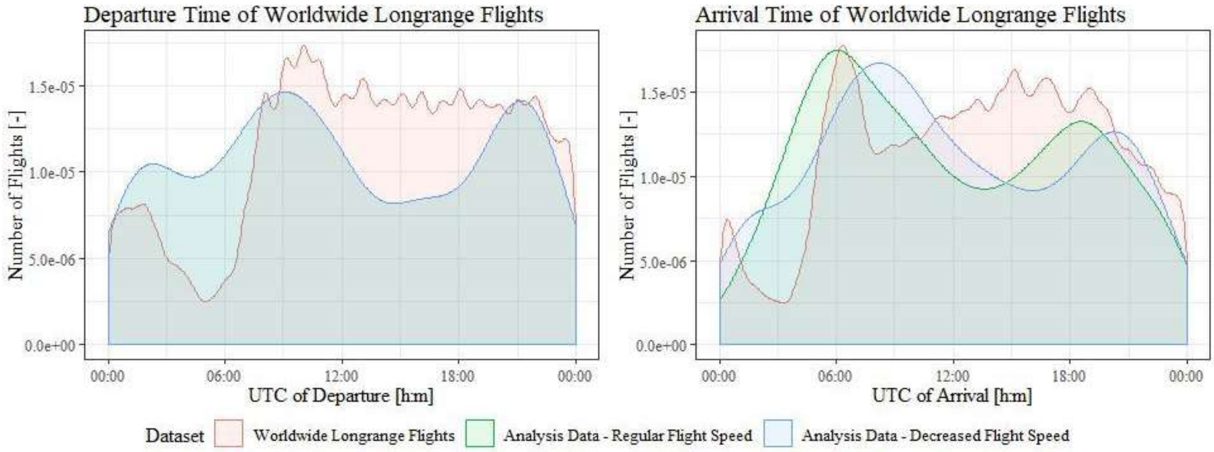

Figure 4 – Departure and arrival times of worldwide long-range flights (red), of the Reference dataset of the three airlines chosen (green) and for these three airlines with 20 % longer flight times (blue).

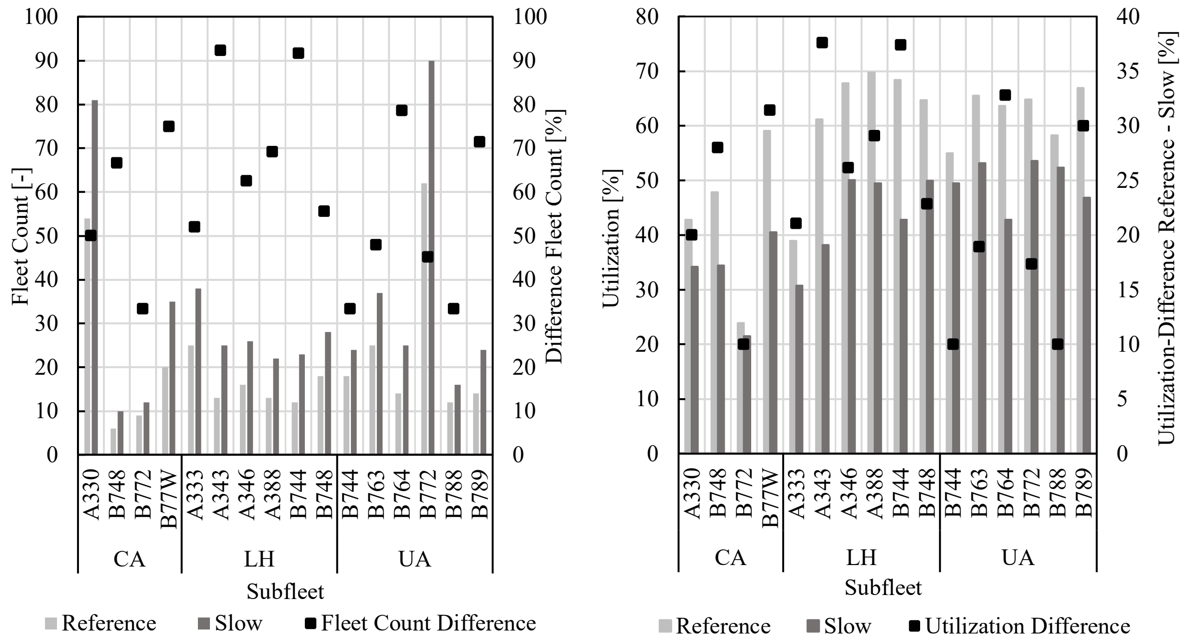

Figure 5 – Left: Fleet count for the Reference and the 20 % slower flight case, right: Utilization for the Reference and the 20 % slower flight case.

2. Effects of aircraft sharing strategies on required fleet size and utilization

In order to avoid disproportional increases in fleet counts as seen in Fig. 5, new flight plans would require to be implemented, which is outside of the scope of this paper. In the following section, we summarize the effects of aircraft sharing on fleet count and utilization.

Figure 6 shows the differences in fleet counts and utilization for intra-airline-sharing for the three investigated airlines. As illustrated on the left side of Fig. 6, fleet sharing leads to reductions of between 0 and 7 percent in the required fleet sizes for the Reference case. In the Slow flights case, higher fleet size reductions in the range of 11.5 to 15.5 percent can be observed through aircraft sharing. Part of that effect can be attributed to the fact that the given flight schedules are not optimized for the slower cruise speeds. It should be noted that for the Reference case of Lufthansa (LH), there is no advantage through aircraft sharing; the existing schedules cannot be further optimized in this case. The same observations can be made regarding the utilization improvement on the right side of Fig. 6.

The inter-airline sharing models have similar effects on fleet count and utilization. The results of that investigation are presented in Fig. 7 for all three functional aircraft clusters. For Reference flight speeds, fleet count reductions through aircraft sharing are in the range of 1 to 4 percent, whereas they lie between 8 and 11 percent for the Slow case, corresponding to tendencies and values for intra-airline sharing. The same applies to utilization improvement. Furthermore, it can be observed that the Small aircraft cluster has the lowest advantages through sharing, while the highest values count for the Large cluster. In general, it can be seen that neither sharing strategy is able to prevent significant increases in required fleet counts and deteriorations of utilization in case of the envisaged cruise speed reduction.

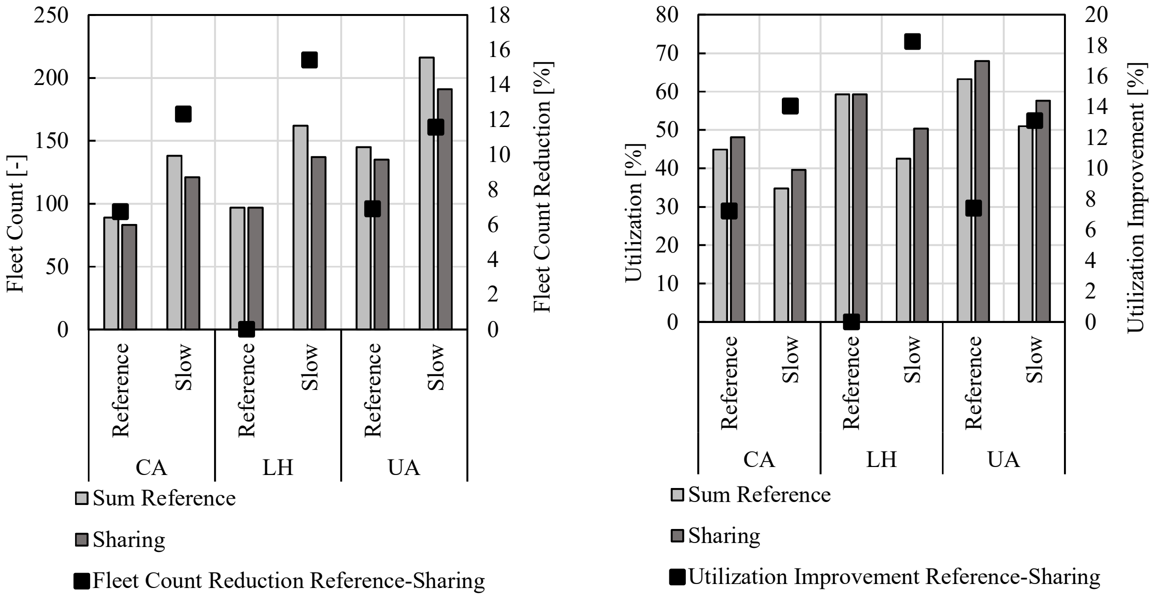

Figure 6 – Fleet count reductions (left) and utilization improvements (right) through intra-airline aircraft sharing for three airlines.

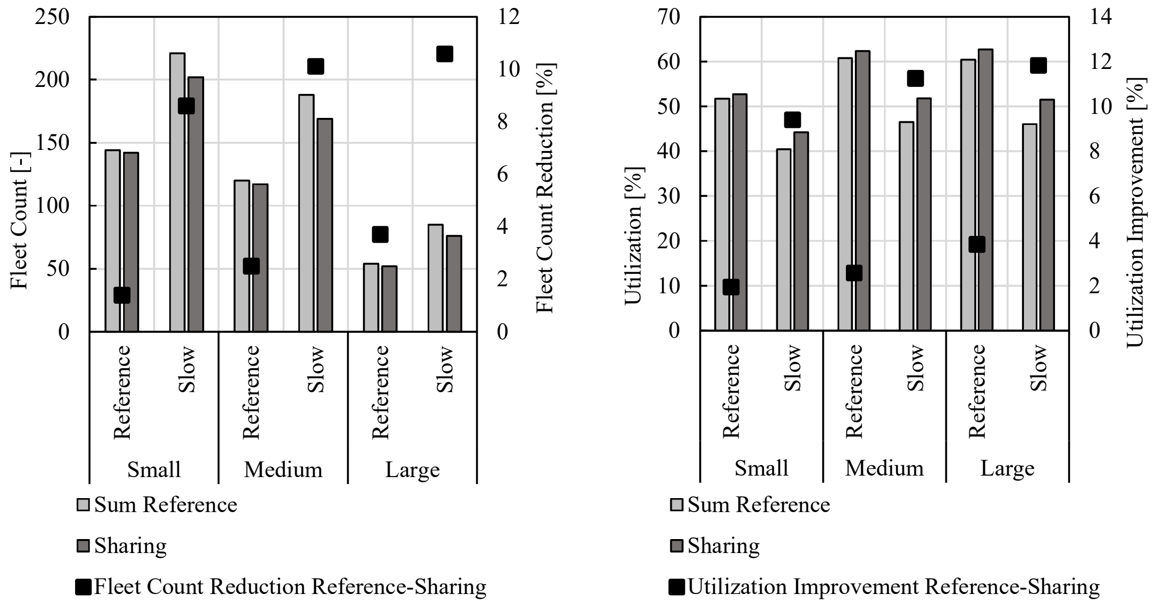

Figure 7 – Fleet count reductions (left) and utilization improvements (right) through inter-airline aircraft sharing for three long-range aircraft clusters.

3. Variations in turnaround times

Another parameter that was extensively investigated for its influence on fleet count and utilization is the turnaround time. Varying minimum turnaround times between 40 and 90 minutes are considered in 10-minute intervals. The upper limit counts for a turnaround efficiency reduction compared to the current turnaround process, e.g. through not carefully incorporating turnaround considerations into the design process of new aircraft. The lower limit is derived by consideration of the minimum turnaround times for the investigated aircraft as stated by the manufacturer. In our dataset, the lowest scheduled turnaround times existed in the Airbus A330 and Boeing 767-300 subfleets which are frequently used on domestic flights with low turnaround times (see Table 2). Minimum turnaround times for these aircraft in transit conditions are specified by the respective manufacturers at 34 minutes for the A330 [23] and 40 minutes for the 767-300 [24]. According to Sefain (2006) [25], LH2-fueled aircraft like the Hy-ShAir aircraft concept investigated in this study do require only minor changes of turnaround times compared to conventionally fueled aircraft. The rest of the changes introduced in this concept do not have any influence on turnaround times. Therefore, minimum turnaround times of 40 minutes are expected to be achievable for a high number of connections considering the use of new technologies and processes.

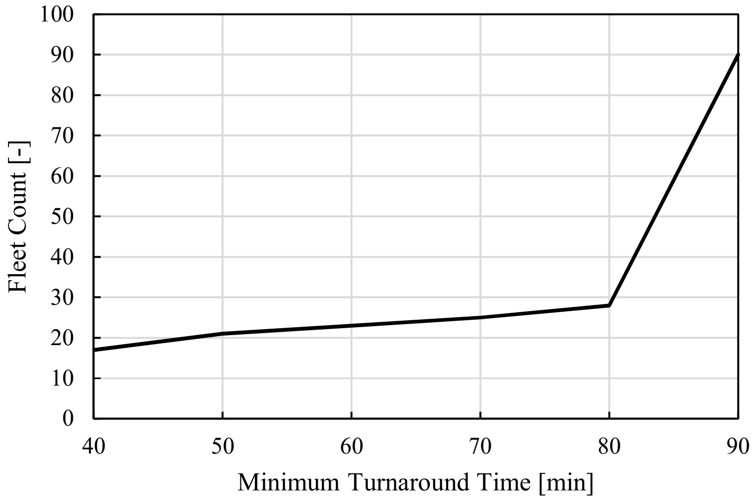

Figure 8 – Exemplary fleet count for the Lufthansa Airbus A330-300 subfleet over minimum turnaround times from 40 min to 90 min, Reference case.

In a first study we investigated the general influence of minimum turnaround time variations on Reference case subfleets. A representative result is shown in Fig. 8 for the Airbus A330 fleet of Lufthansa. For minimum turnaround times longer than the Reference turnaround time of 70 minutes, a rapid increase in fleet numbers with an increase in turnaround time is noticed. This observation could be made for most subfleets included in the study. When considering turnaround times lower than 70 minutes however, the decrease of fleet counts with a decrease in turnaround times is significantly lower. Similar observations could only be made for a minority of subfleets. In three cases, no significant changes in fleet sizes are noted across the entire range of turnaround times. These fleets almost exclusively exhibit turnaround times greater than the maximum investigated time of 90 minutes. Accordingly, in the Reference dataset of current flight schedules, one connection arc with a turnaround time of less than 90 minutes was found for Air China’s 747-8 fleet, while for Lufthansa’s 747-400 fleet, there was no connection of less than 100 minutes, and for United Airlines’ 747-400 fleet there was one connection arc of less than 100 minutes. Furthermore, not all fleet sizes for the Reference case correspond to real fleet sizes. Higher fleet counts occur in the optimized calculation as compared to real fleet sizes for various subfleets with considerable shares of short haul flights. For example, Lufthansa utilized a fleet of 19 Airbus A330-300 in 2016, while an optimum fleet size of 25 aircraft was calculated for the given schedule in Reference conditions. This discrepancy occurs since various short haul flights are included in the schedule, e.g. in order to cover multiple destinations in Nigeria. Before the departure of such flights, often only very short turnaround times between 40 and 50 minutes occur. Calculations with 70 minutes of minimum turnaround time would therefore require additional aircraft for such short connections. The definition of a Reference turnaround time of 70 minutes thus is only suitable for comparison purposes, such as in this paper. To better resemble reality, turnaround times have to be chosen independently for each subfleet, considering the different schedules performed.

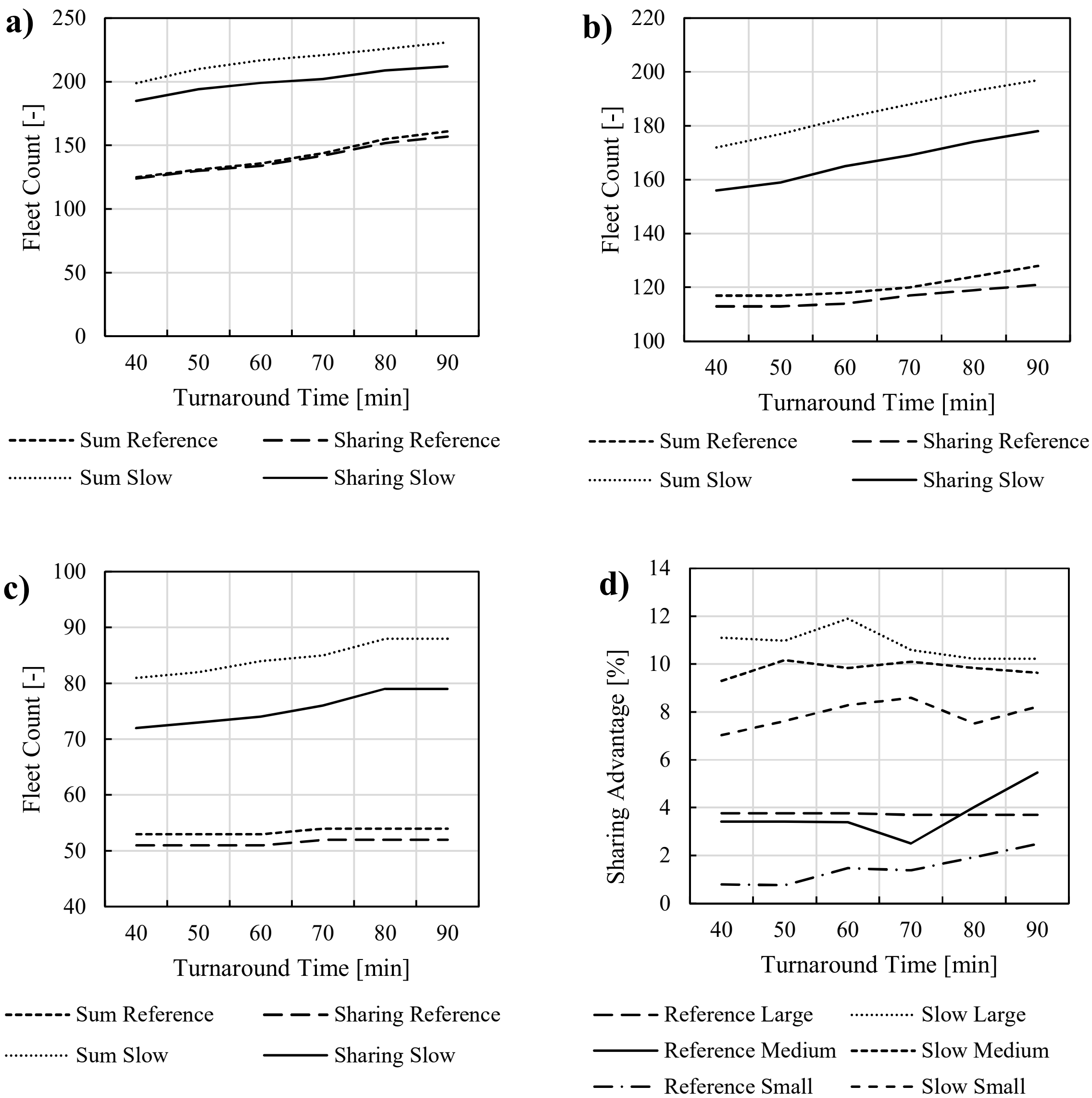

Figure 9 – Development of the fleet count with turnaround times for the inter-airline aircraft sharing clusters a) Small, b) Medium and c) Large as well as sharing advantage for the fleet count (d)).

Figure 9 shows the results of the optimization calculation for all three aircraft clusters with and without inter-airline sharing over the chosen range of turnaround time variations in parts a) (Small), b) (Medium) and c) (Large). The tendencies regarding the effects of aircraft sharing reported in Section III.C.2 for a Reference turnaround time of 70 minutes hold true for turnaround time variations. Again, the advantage of aircraft sharing is lower for the Reference than the Slow case. Figure 9 d) indicates that this difference between the sharing advantages of Reference and Slow cases is present over the entire range of turnaround times. The Reference cases thereby correspond to the observations made above for the single subfleets: The sharing advantage increases significantly for turnaround times above the reference time of 70 minutes for Small and Medium fleets. The reason for this is that for such long turnaround times, many connection arcs cannot be accomplished by one aircraft anymore and the amount of connections favorable for aircraft sharing increases. At the same time, there is no such variation in advantage visible for higher turnaround times and the Large cluster. This is due to the above-mentioned long turnaround times present in the flight schedules of those subfleets that make up the Large cluster, e.g. Lufthansa's 747-400 fleet. However, at most turnaround times, the fleet count advantage of inter-airline sharing is highest for the Large cluster and lowest for the Small cluster. This applies to the Reference as well as the Slow case and is attributed to the share of short-range flights that is highest for Small aircraft and lowest for Large aircraft (see Table 2). The higher that share, the lower the average turnaround times, leaving fewer possibilities for a rearrangement of flights through sharing.

This picture changes for the investigation of fleet counts for the Slow case. While sharing advantages are again lowest for the Small aircraft cluster and highest for the Large cluster as seen in most cases above, no conclusive development for the sharing advantage over different turnaround times can be identified. The development of utilization shows an increase with a decrease in turnaround times. Otherwise it follows already mentioned patterns and is therefore not further elaborated.

4. Combined Strategies

Conclusively, we compare aggregated results for different strategies of utilization increase and fleet count minimization for the proposed long-range aircraft concept with 20 % lower flight speeds.

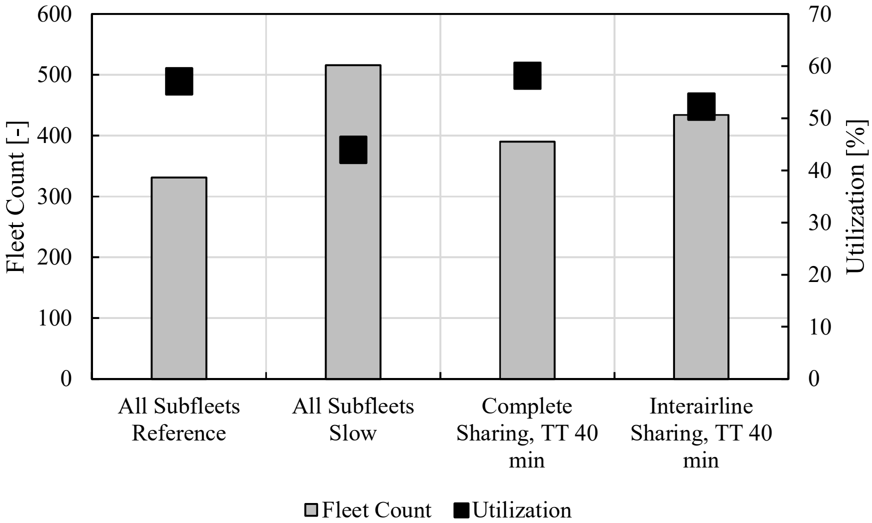

Figure 10 – Aggregated fleet counts for Reference and Slow cases as well as sharing strategies.

Figure 10 shows the aggregated sum of the fleet counts of all investigated subfleets and the aggregated utilization for the Reference and the Slow flight cases as well as for two different operational strategies utilizing the abovementioned aircraft sharing methods and a reduction of the minimum turnaround time to 40 minutes. As can be seen in Fig. 10, a flight speed reduction of 20 % without further changes, e.g. in turnaround times, leads to an increase in fleet count from 331 aircraft in the Reference case to 516 aircraft (see “All Subfleets Slow” in Fig. 10). This equals an increase of about 56 %. The average utilization likewise declines by 23 % from 57 % in the Reference case to 44 % for the Slow case.

These general figures are compared to results of two strategies for utilization increase and fleet count minimization in the Slow flight case, comprising a combination of elements of the elementary strategies mentioned above. The first strategy includes a complete sharing of the total fleets of all three airlines and a reduction of minimum turnaround time to 40 minutes. Compared to the Slow flight case without further changes, the utilization can be improved to 58 % and the fleet count can be reduced to 390 aircraft. Compared to the Reference, this means an increase in fleet size of about 18 % and an increase in utilization of 2 %, constituting a significant improvement when compared to the simple Slow case. The second strategy utilizes the three inter-airline aircraft sharing clusters (and an additional fleet of 21 A380 of the original Lufthansa fleet) as well as a turnaround time of 40 minutes. Compared to the simple Slow flight case, improvements can again be seen: in utilization up to 52 % and in fleet count down to 434 aircraft. Although these effects are not as pronounced as for the complete sharing case, they still lead to significant improvements in fleet count and utilization as compared to the simple Slow case. When adding changes in the flight plan not described in this paper, we might expect further considerable reductions in aircraft numbers leading to the conclusion that the envisioned decrease in flight speed can be possible without disproportionally high increases in aircraft production capacities.

IV. Discussion

As seen in the previous section, the presented aircraft sharing strategies in combination with reduced minimum turnaround times led to significant reductions in fleet size and increases in utilization. While the case of total sharing exhibited a higher utilization than the Reference case and the highest reduction in fleet counts, the inflexibility of a single-type fleet replacing a fleet with different aircraft types of different sizes operating in a variety of missions makes the introduction of such a strategy unrealistic. More realistic is the introduction of sharing strategies for aircraft clusters comprising aircraft which perform similar missions. Such a strategy was shown to still lead to significant improvements in fleet size and utilization, although not as high as for complete sharing.

In connection with the introduction of fleet sharing strategies, further implications of resulting flight chains connecting the partner airlines' networks are investigated. When it comes to flight times, it can be stated that short range flights usually take place during daytimes, corresponding to passenger travel habits and night curfews at airports. On the contrary, long-range flights take place during day- as well as nighttimes since only departure and arrival should normally occur during daytimes. Long-range flights therefore often follow East- or West-bound patterns while connecting the main markets of the airlines investigated in the paper at hand. For example, flights between Europe and North America usually perform West-bound legs during daytimes, while flights in the opposite direction are most often operated during nighttimes. With the introduction of flight sharing mechanisms, it might now be expected that the participating airlines are able to introduce East- as well as West-bound chains of multiple flights. If that assumption holds true, the average number of consecutive East- or West-bound flights should increase for cases of flight sharing as compared to single airline operations.

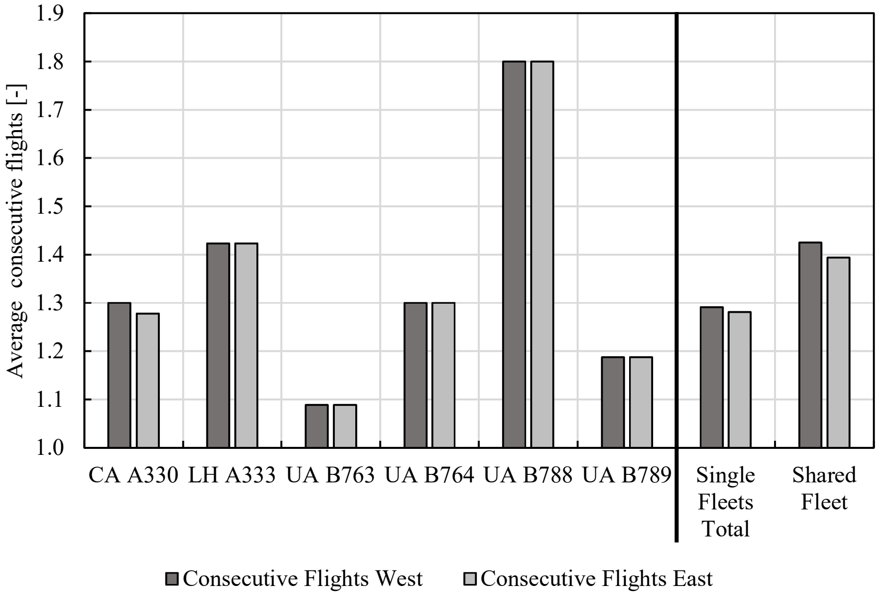

Figure 11 – Average number of consecutive flights on West- as well as East-bound routings for the Small aircraft cluster, shared case (far right) as well as single subfleets of participating airlines.

In order to determine whether aircraft sharing leads to the build-up of such chains of consecutive flights into one direction, we investigated results of the Small aircraft cluster for the Slow case and minimum turnaround times of 40 minutes. The results of that study are presented in Fig. 11 for the relevant single airline subfleets, their aggregated average as well as for the shared fleet. The numbers reflect the average consecutive East- and West-bound flights. All considered flights are classified this way even if they primarily follow a North- or South-bound direction. It should be noted that the numbers given for the single subfleets already represent results of the optimization tool. The optimization's result for the shared fleet included an arc of flights consecutively passed by an aircraft that comprised almost all flights; therefore no specific East- or West-bound routings could be identified. However, the numbers in Fig. 11 show significant increases in consecutive East-bound flights of 8.7 % and in consecutive West-bound flights of 10.4 % for the shared fleet as compared to the aggregated results of single subfleets. The aggregated results should only be used as a reference because the numbers for the single subfleets show significant variations depending on their individual peculiarities. The most noteworthy of these peculiarities are described in the following. First, those subfleets used on a variety of destinations throughout the entire network show the highest numbers of consecutive directional flights. One example is United Airlines' Boeing 787-8 fleet which is comparably small (16 aircraft) and operates only a limited, however widespread number of destinations. These often enable routings e.g. beginning in Asia, leading to North America, where a further East-bound short-range flight to another North American hub takes place before the flight chain is completed by a final East-bound flight to Europe or South America. Similar observations can be made for Lufthansa's Airbus A330-300 fleet. The aircraft are used for a wide range of destinations, including relatively short long-range flights to Western Africa and Central Asia. Second, subfleets mainly operated on specific parts of the network, e.g. on domestic flights within China or transatlantic services, usually exhibit frequent changes in route directions between East- and West-bound flights. Examples are the two biggest subfleets investigated – Air China's Airbus A330 and United Airlines' Boeing 767-300 subfleets.

As described, Fig. 11 shows that the results for a shared fleet contain elongated directional flight chains. Examples for such chains can be found in the main arc of flights resulting from the route optimization tool, e.g. the consecutive West-bound routing Mumbai (BOM) – Munich (MUC) – Denver (DEN) – Tokyo (NRT) – Shanghai (PVG) – Beijing (PEK) – Chengdu (CTU) – Lhasa (LXA), consisting of seven flights. The first two of these flights are originally operated by Lufthansa, the third by United Airlines, and all others by Air China. Although indications for more specific West- and East-bound routings are present in our results, future studies have to be conducted in order to substantiate these findings. If this is the case, aircraft might be introduced that can be configured more easily for day- or night-time flights.

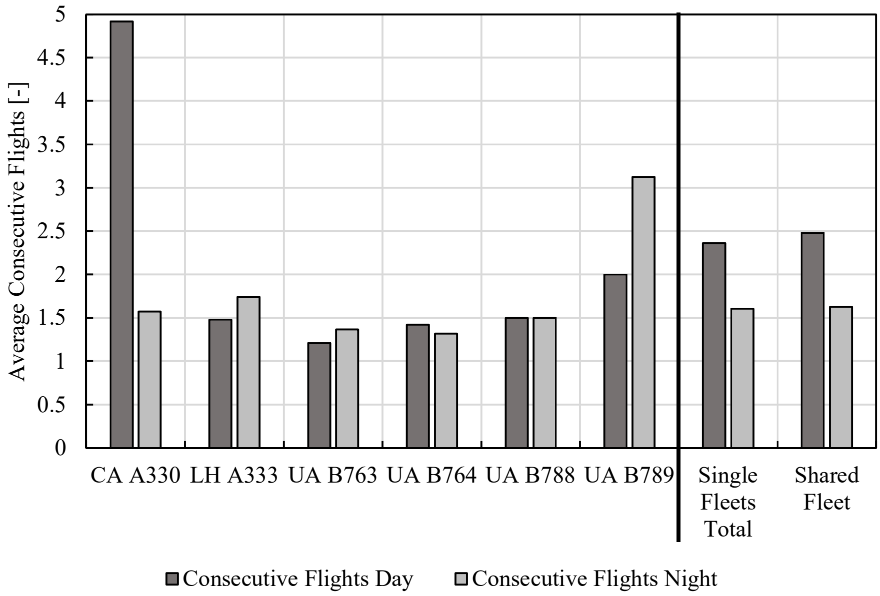

Figure 12 – Average number of consecutive day- as well as night-flights for the Small aircraft cluster, shared case (far right) as well as single subfleets of participating airlines.

This is supported by the observation of at least a small increase in the number of consecutive day and night flights for a shared fleet in the Slow flight case, as indicated in Fig. 12 for the Small aircraft cluster when comparing the shared fleet results with the aggregated numbers of the single subfleets. Night flights are such flights arriving on another day than the day of departure (except for West-bound flights across the International Date Line) or departing between 22:00 p.m. and 04:00 a.m. It should be noted that the high number of consecutive day flights for the Air China A330-subfleet are related to domestic short-range flights operating during daytime.

V. Conclusion

In this study, the impact of using aircraft operating at decreased cruise speeds on long-range flight schedules and required fleet sizes is investigated. Current flight plans are utilized to represent the current long-range air traffic network structure. We use these flight schedules in order to depict a network structure which already takes into account the fit of long-range with mid- and short-range services, which are otherwise not in the scope of the presented long-range aviation concept and, therefore, this study. As anticipated, the introduction of the novel aircraft leads to a significant rise in required fleet counts and, at the same time, to a degradation of aircraft utilizations. As a countermeasure, two different types of aircraft sharing strategies and reductions in minimum turnaround times were investigated. Both strategies were shown to be able to significantly reduce fleet sizes and improve utilization in the case of slower flight speeds, in other words, in a case with non-optimum flight plans. Thereby, the realization of the complete sharing case is, if at all, only an option in the long term. This approach has shortcomings when considering traffic performances on single routes as well as fleet-wide. It would imply the use of aircraft of the same size on all routes. As a consequence, for example on routes only served by one airline, no synergy effects can be used. Furthermore, there is a risk of demand spill when the standardized novel long-range aircraft is too small. On the other hand, there might as well be too low load factors if that aircraft is too big on other routes. It can therefore be expected that such an approach can lead to fleets lacking the flexibility of mixed fleets with different aircraft sizes. The described approach of inter-airline sharing within distinct aircraft clusters might be seen as a compromise between the use of synergies through aircraft sharing and the required flexibility to achieve the demanded traffic performances at high load factors. The three airlines shown serve unique networks with few overlaps of their main markets. The still not negligible number of connections between these networks might hold synergies for the efficient use of fleet sharing strategies.

The model used in the paper at hand should be improved by the introduction of individual adjustments of departure and arrival times for each flight. Such an approach would allow for a better adjustment of connection arcs between two flights, yielding further considerable potentials for fleet reductions and utilization improvements. The required flexible departure times can be implemented in the form of time windows around the original times. Such an approach could build upon research conducted by e.g. Dunbar et al. (2014) [26], Levin (1971) [27], Rexing et al. (2000) [28] or Sherali et al. (2011) [29]. Further future improvements require the connection with other airline planning steps, such as fleet assignment. With respect to aircraft sharing considerations, effects of increasing load factors, consolidation of currently parallel flight services among the partner airlines as well as frequency adjustments can then be considered. This would lead to completely new flight schedules. Aircraft sharing strategies with their before mentioned advantages of utilization and fleet sizes might help to ease such a development.

As this paper has shown, re-organizing the aviation network in a way to efficiently include the described new concept aircraft with lower cruise flight speed is not an easy task, and meaningful improvements will need conviction for vast operational changes by all stakeholders. Considering, the major challenge to decarbonize aviation however, every promising option should be considered. Slower flight speeds and aircraft sharing might very well be one of these options and should thus be investigated further.

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References

[1] European Commission. *Flightpath 2050 – Europe's Vision for Aviation.* Report of the High Level Group on Aviation Research, Luxemburg 2011.

[2] Lovegren J. A., Hansman R. J. *Estimation of Potential Aircraft Fuel Burn Reduction in Cruise via Speed and Altitude Optimization Strategies.* Report No. ICAT-2011-03, MIT International Center for Air Transportation, USA 2011.

[3] Holmes B. J., Croom, C. C., Hastings Jr. E. C., Obara C. J., van Dam C. P. *Flight Research on Natural Laminar Flow.* NASA, USA 1986.

[4] Daidzic N. E.: *Estimation of Performance Airspeeds for High-Bypass Turbofans Equipped Transport-Category Airplanes.* Journal of Aviation Technology and Engineering 5:2, 2016.

[5] Paul A., Engelmann M., Koops L., Steinweg D., Troeltsch F., van Wensveen J. and Hornung M.: *Emission reduction Potential across the Long-haul Network.* Deutscher Luft- und Raumfahrtkongress, Darmstadt, Germany 2019.

[6] Penke C., Falter C. and Batteiger V.: *Pathways and environmental assessment for the introduction of renewable hydrogen into the aviation sector.* In Albrecht, S. et al. (eds.). Progress in Life Cycle Assessment. Springer International Publishing, 2019. DOI:10.1007/978-3-030-50519-6

[7] Troeltsch F, Engelmann M, Peter F, Kaiser J, Hornung M and Scholz A.: *Hydrogen Powered Long Haul Aircraft with Minimized Climate Impact.* AIAA AVIATION Forum 2020.

[8] Belobaba P., Odoni A. and Barnhart C.: *The Global Airline Industry.* 2nd edition, Wiley 2016.

[9] Kölker K., Lütjens K.: *Using genetic algorithms to solve large-scale airline network planning problems.* 18th Euro Working Group on Transportation, EWGT 2015, Delft, The Netherlands, 14-16 July 2015.
[10] Kepir B., Koçyiğit Ç., Koyuncu I., Özer M. B., Kara B. Y., Gürbüz M. A.: *Flight-Scheduling Optimization and Automation for AnadoluJet.* Interfaces 46(4), 315-325, INFORMS, USA, 2016.
[11] Tang C.-H., Yan S., Chen Y.-H.: *An Integrated Model and Solution Algorithm for Passenger, Cargo and Combi Flight Scheduling.* Transportation Research Part E: Logistics and Transportation Review, Volume 44, Issue 6, 2008.
[12] Ben Ahmed M., Zeghal Mansour F., Haouari M.: *Robust Integrated Maintenance Aircraft Routing and Crew Pairing.* Journal of Air Transport Management, Vol. 17, 2018.
[13] Haouari M., Shao S., Sherali H.D.: *A Lifted Compact Formulation for the Daily Aircraft Maintenance Routing Problem.* Transportation Science 47(4), 508-525, 2013. http://dx.doi.org/10.1287/trsc.1120.0433
[14] OAG Aviation Worldwide Limited: *OAG (Official Airline Guide): Database of Scheduled Flights.* 2016. https://www.oag.com/airline-schedules-data
[15] Wassenbergh, H.: *Interchange of Aircraft on International Routes and the Philippine—U.K. Conflict.* Nederlands Tijdschrift Voor Internationaal Recht, 10(3), 275-283, 1963. DOI:10.1017/S0165070X00028114
[16] Oum T.H. and Park J.-H.: *Airline alliances: current status, policy issues, and future directions.* Journal of Air Transport Management, Vol. 3, No. 3, pp. 133-144, Elsevier Science Ltd., 1997.
[17] Kleymann B. and Seristö H.: *Levels of airline alliance membership: balancing risks and benefits.* Journal of Air Transport Management 7, 303-310, 2001.
[18] Gerlach M., Cleophas C. and Kliewer N.: *Codeshare-Allianzen bei Fluggesellschaften.* Wirtschaftsinformatik: Vol. 55, No. 3., 147-158, Springer, 2013. DOI: 10.1007/s11576-013-0361-7
[19] Li M.Z.F.: *Distinct features of lasting and non-lasting airline alliances.* Journal of Air Transport Management 6, 65-73, 2000.
[20] Base of Aircraft Data (BADA). European Organization for the Safety of Air Navigation (EUROCONTROL), 2013.
[21] Schinwald C. and Hornung M.: *Identification of Capacity Constrained Airports: A Review of Indicators and a Case Study of Major European Airports.* 18th ATRS World Conference, Bordeaux, France 2014.
[22] Stroh F.: *Development of a Flight Scheduling Tool Optimizing for Fleet Utilization.* Bachelor's Thesis, Institute of Aircraft Design, Technical University of Munich 2020.
[23] Airbus S.A.S.: *Airbus A330 Aircraft Characteristics – Airport and Maintenance Planning.* AC, Rev Jun 01/20, Airbus S.A.S. 2020.
[24] Boeing: *767 Airplane Characteristics for Airport Planning.* Document D6-58328, Boeing Commercial Airplanes 2011
[25] Sefain M.J.: *Hydrogen Aircraft Concepts & Ground Support.* PhD Thesis, Cranfield University 2006.
[26] Dunbar M., Froyland G. and Wu C.-L.: *An integrated scenario-based approach for robust aircraft routing, crew pairing and re-timing.* Computers & Operations Research 45, 68-86, 2014.
[27] Levin A.: *Scheduling and Fleet Routing Models for Transportation Systems.* Transportation Science 5, 232-255, 1971.
[28] Rexing B., Barnhart C. and Kniker T.: *Airline Fleet Assignment with Time Windows.* Transportation Science: Vol. 34, Issue 1, 2000.
[29] Sherali H.D., Bae K.-H., Haouari M.: *A Benders decomposition approach for an integrated airline schedule design and fleet assignment problem with flight retiming, schedule balance, and demand recapture.* Annals of Operations Research, Vol. 210, Issue 1, Springer, 2013.