Influence of Airport Capacity Limitation Mitigation on Air Traffic Networks and Fuel Consumption

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The reduction of its environmental footprint is crucial for aviation to achieve its own goals and, ultimately, meet the expectations of society and its customers, especially toward the Paris Agreement. The current discussion regarding measures toward that goal includes operational levers for reducing fuel consumption through improved procedures and the reduction of inefficiencies in the aviation system. One of these inefficiencies results from infrastructure capacity limitations, especially at airports. This paper builds on previous research on the integration of airport capacity limitations and their mitigation with an evolutionary fleet development model. Thus, it presents the effects of these mitigation strategies on air traffic fleets and networks and derives estimations of additional fuel consumption they might imply as compared to a use case without infrastructure limitations. In this context, we introduce a new modeling approach for describing changes to fleet-wide average flight distances in shifting traffic within Multi-Hub and Multiairport systems. We thus aim to contribute to the further discussion of operational fuel and emission saving potentials.

I. Introduction

The reduction of emissions is one of the most prominent requirements for aviation in the next decades to come. The consensus is that no one measure is able to provide enough effect to reach the ambitious goals of the industry. Besides many technological options and alternative fuels, operational measures are widely acknowledged as an important means to reduce aviation emissions [1]. These operational improvements account for a wide range of measures, e.g., regarding climate-optimized flight trajectories or operational procedures in the air (e.g., [2-4]) and on the ground (e.g., [5,6]) as well as airline operations (e.g., [7]). Most of these operational approaches foresee a reduction of inefficiencies in the air traffic system. This paper proposes that infrastructural limitations add inefficiencies in average fuel consumption at the airports concerned, ultimately yielding further emission reduction potential.

A model integrating the scenario-based simulation of global air transport fleet development with airport congestion and strategies for its mitigation (in the following "mitigation strategies") was introduced in preliminary work [8]. The implemented mitigation strategies comprise shifting traffic to uncongested airports and using aircraft with higher passenger capacity. Using this basis, this paper introduces improvements to the previous work and details on the network effects and the optimal application of these mitigation strategies. These improvements enable aircraft operators to cover rising demand, although capacities at the corresponding airports are exhausted. As such, these

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strategies inherently imply inefficiencies in the air transport system which would not be present without airport capacity shortages. This paper will discuss the effects of the mitigation strategies in detail. Adding assumptions on additional fuel burn these strategies entail makes it possible to compare fuel consumption among use cases with and without considering airport congestion and its mitigation on the fleet and the flight level. This paper aims to unveil some of the basic mechanisms behind airport capacity limitations, their mitigation, and subsequent additional fuel consumption. It thus contributes to the discussion of operational emission reduction potentials.

II. State of Affairs

A. Integrated Model

The system view of airport congestion effects requires an integrated approach to modeling future fleet development and airport capacity constraints (“integrated model” in the following). Such an approach was described by Michelmann et al. [8], using an evolutionary fleet development model after Randt [9] to derive scenario-based estimates of future global fleet development. Important simplifications in this modeling approach include the clustering of routes into route groups between and within six air transport network (ATN) regions (as of OAG 2016 [10]) and of aircraft into aircraft clusters. The former are represented by frequency-based average routes per aircraft cluster, the latter by a representative aircraft type. Current technology aircraft clusters can be complemented by new and future technology clusters, e.g., to investigate the fleet uptake of novel aircraft designs (see [8] for more information on the clusters used). Different airlines are not modeled, as the focus is on technology assessment and global network aspects. Thus, for example, the addition of new, so far unserved routes cannot be depicted [9].

The fleet development model generates projections of movement demand at airports. Additionally, the capacity supply at all relevant airports globally is estimated according to current runway system capacity, capacity utilization and future capacity growth [11]. Capacity growth is introduced at the level of ATN regions and airport clusters (APC) as data for single airports is often difficult to obtain. The APC used for assigning airport infrastructure growth factors are described in Table 1. The cluster of Global Hubs (APC1) includes the largest airports with the most central network function in the air transport network. APC2 includes mostly smaller, still important, airports. APC3 serves mostly large urban centers without a hub function. APC4 includes airports of various sizes with a high share of long-range flights and no pronounced hub function. APC5 and 6 are small airports with usually limited regional significance. [8] By comparing demand and supply, we can identify surplus traffic at congested airports as demand which cannot be accommodated by the airport. As airlines usually still want to cover that additional demand, strategies for mitigating capacity constraints are implemented [8], as shown in the subsequent section. Surplus traffic which cannot be accommodated despite using mitigation strategies is called *remaining surplus*.

Table 1 Airport cluster (APC) names.

Airport Cluster (APC)	APC name
APC1	Global Hubs
APC2	Large Airports
APC3	Medium Airports
APC4	Long-Haul Airports
APC5	Regional Airports
APC6	Small Airports

Preliminary results using this approach showed a significant amount of unaccommodated traffic [8], accounting for about 22 % of movements in 2040. This is roughly in a similar range as described by [12], reporting up to 16 % of unaccommodated movements in Europe by 2040 owing to airport capacity limitations. However, newer studies expect much lower surplus traffic shares, especially following the COVID-19 pandemic, see section D. This emphasizes the high uncertainty in scenarios for airport capacity influences on air traffic [13].

B. Airport Capacity Limitation Mitigation Strategies and System Efficiency

The mitigation strategies considered in this work include shifting traffic to uncongested alternative airports or to aircraft with larger passenger capacity as described in the following. Michelmann et al. [8] further detail the functionality of both strategies. The selection of mitigation strategies to be applied is based on a two-step optimization approach. The first step optimizes for minimum remaining surplus RPK (Revenue Passenger Kilometers), see the next section for changes to previous version [8]. In case multiple solutions to this first step exist, a second step selects the solution implying the lowest fuel consumption.

1. *Use of aircraft with higher passenger capacity*

As described by [13,14], the use of aircraft with larger passenger capacity is a common strategy for mitigating airport capacity issues. In our model, this includes the seating densification of current aircraft (in the following "*densification*"), operating larger aircraft types, or a combination of both [8,15]. Owing to computing limitations, these mitigation mechanisms are derived on the route level, accounting for fixed shares of aircraft clusters operating on that route and their ability to be upgraded or replaced by larger aircraft. Only one of the strategies for higher passenger capacity is selected for each congested airport per simulation year. [8,15]

Densification increases the number of seats on board either to the maximum seat number that a cluster achieves on any route (old technology aircraft clusters) or by 20 % for new technology aircraft clusters. There is no change in fuel consumption as the freight mass is reduced by the additional passenger mass. A densification can occur only once for a flight on a given route. The introduction of larger aircraft is limited to the next-larger aircraft cluster as defined a priori for all current clusters. If several larger aircraft clusters are available, the one with the lowest fuel consumption is chosen. To avoid unrealistic operations of large aircraft at small airports, only aircraft up to the size of the largest aircraft operating at the airport as of OAG 2016 data [10] can be introduced via this mechanism. [8,15] Each of these modifications is presented in the model with its own cluster, a so-called upgrade cluster of a basic aircraft cluster.

2. *Airport Shifting*

The shifting of unaccommodated traffic to uncongested airports accounts for the operation of Multi-Hub [16-18] and Multiairport systems [19]. The options available for shifting depend on whether the congested airport is classified as a hub airport. If this is the case, first an alternative hub within the network of the congested airport's dominant carrier is searched. If such an alternative hub is not available, a new hub can be introduced at an alternative airport where the hub carrier already has a strong presence. In both cases, the shifted traffic resembles the congested airport's traffic structure. Furthermore, traffic can be shifted to non-hub alternative airports, either within a Multiairport system or to a nearby regional alternative (in the following "*Nearby Airport*"). This method is also used to find alternative airports for congested non-hub airports. In both cases, mostly short- and mid-range traffic is shifted to the alternative airports, which often lack the infrastructure to support significant long-haul operations. [8,20]

C. Improvements to the Integrated Model and Use Cases

As compared to the integrated model presented in [8], multiple improvements are introduced. First, the first optimization step for the mitigation strategy choice was changed to minimize remaining surplus RPK instead of remaining surplus movements. The previous approach led to unwanted changes in fleet composition, with narrow-body aircraft operating short-range routes being preferably substituted by larger aircraft for congestion mitigation [8]. In contrast, minimizing remaining surplus RPK better accounts for long-range routes operated by wide-body aircraft. This better resembles airline behavior, as otherwise movements and revenue on usually high-yield long-range routes would be lost. Second, an improved modeling of airport infrastructure capacity development has been introduced. Besides different airport clusters [8] it considers regional differences. The resulting airport capacity growth factors are derived through data research on runway system extensions accomplished between 2000 and 2016. More details on these new growth factors and underlying data are given in [11]. Third, the fleet development model was better integrated with the modules simulating airport capacity development and congestion mitigation strategies, directly incorporating it in the modeling chain of each simulation year. Fourth, debugging eliminated still-existing errors.

In this work, the development of global air traffic is simulated in the timeframe 2016-2040. Main air transport input data is derived from the OAG 2016 database [10]. The influences of the COVID-19 pandemic on air traffic development are disregarded. As this work covers long-term developments, such an assumption seems justified considering the rebound in air traffic starting in 2022 and the subsequent recurrence of congestion problems at airports [21]. For the simulations with the updated model, four cases are distinguished:

- ***reference case***: no-congestion reference case, integrated model with infinite airport infrastructure capacity growth factors, thus, no airport congestion and no usage of mitigation strategies (used in sections III.A-D).
- ***no action case***: airport congestion appears and remains unmitigated ("worst case." used in section III.A).
- ***use case***: integrated model accounting for airport congestion and mitigation strategies, airport infrastructure capacity growth factors as of [11] (used in section III.A-D).
- ***use case fuel***: like use case, additionally incorporating new module for estimation of additional fuel burn owing to airport shifting (used in section III.D).

The cases investigated in this work show the basic functionality and effects of congestion and mitigation modeling. For a proper forecast, however, it would be inevitable to consider different scenarios for capturing the inherent significant modeling uncertainties and range of possible future developments.

D. Comparable Research in the Field

This section shortly describes two fleet modeling approaches including airport capacity limitations and mitigation strategies. For detailed literature, e.g., on specific mitigation strategies, please refer to [8]. First, EUROCONTROL published fleet development studies considering airport capacity limitations in its *Challenges of Growth* reports. Based on different scenarios for air traffic and airport infrastructure growth, numbers of movements unaccommodated owing to airport congestion in Europe are derived. The *Challenges of Growth 2013* report expects an unaccommodated movement share of 12 % for Europe in 2035 in the most probable scenario, increasing up to 20 % for strong growth scenarios. Additionally, congestion mitigation strategies are considered, such as operating larger aircraft, smoothing flight schedules or using local alternative airports. These, however, are expected to mitigate less than half of the surplus movements. [22] The subsequent *Challenges of Growth 2018* report observes more effective airport capacity expansion enabling a reduction of surplus traffic. For 2040, an unaccommodated movement share of 8 % is expected in Europe in the most likely scenario, increasing to 16 % in a high growth scenario. Again, mitigation strategies are expected to reduce surplus traffic by less than a half. [12] The newest EUROCONTROL *Aviation Outlook 2050* reports a significant reduction in airport congestion following the COVID-19 pandemic, see section IV.A [23].

Further, research on the influence of airport congestion on air transport (fleet) development is performed at the German Aerospace Center DLR. A comprehensive composition of this work is given in Gelhausen et al. [13]. In a recent publication, research on airport congestion and its mitigation within fleet modeling was introduced in Clean Sky 2. Scenario-based forecasts of global fleet mix development between 2014 and 2050 estimate the impact of new technology aircraft on air transport emissions. Airport congestion and its mitigation by using larger aircraft are mainly modeled by data envelopment and regression analysis. As a result, half of the traffic growth is covered by additional flights, while the other is accounted for by larger aircraft. This leads to a 1.6-1.9 % annual increase in average seat numbers per flight. In 2050, 4-7 % of passenger demand remain unaccommodated owing to airport congestion. [14]

III. Sources for Additional Fuel Burn in Mitigation Strategies

The functionality of the mitigation strategies described in sections II.B and II.C is basic to the understanding of possible sources for additional fuel burn, a central parameter for mitigation strategy choice in the integrated model. This section details on the estimation of additional fuel burn resulting from each mitigation strategy and introduces a new method for estimating fuel burn changes when shifting airports.

A. Sources for Fuel Burn Increase

Changes to fuel consumption can be measured on different levels. First, for global environmental considerations, the aggregate fuel consumption of aviation is important. For more detail, e.g. the average fuel used per single flight is of interest to better understand smaller scale saving potentials. Airport capacity limitations usually lead to a reduction in global fuel consumption owing to flight movement reductions using larger aircraft and remaining surplus traffic. In contrast, the broad use of mitigation strategies might result in inefficiencies in the form of additional fuel burn per flight. These changes as compared to a case without considering airport congestion and its mitigation have various sources, shown in the following for each implemented mitigation mechanism:

- ***densification***: No change in per flight fuel consumption appears, assuming constant load factors and additional seats leading to a likewise reduction in freight load. This implies a cost-free method in this regard [15].
- ***larger aircraft***: Using a larger aircraft on the same route often implies that this aircraft flies on routes shorter than its design mission, leading to higher fuel consumption per passenger kilometer (e.g., [14]). In our model, an example is an Airbus A330-300 taking over a route previously operated by an Airbus A320. The additional fuel consumption might surpass the amount of fuel saved through a lower number of flights. Contrarily, using a larger aircraft from a subsequent aircraft generation with lower fuel burn per passenger might hide this effect due to comparison of different levels of technology [15]. This, however, depends on the availability of such newer aircraft and might lead to the increased use of older generation aircraft elsewhere.
- ***airport shifting***: So far, it was assumed that shifting yields an increase in route length on some routes while others likewise decrease in length, averaging out any effect on global fuel burn [20]. Considering the uneven distribution of airports across the globe, especially of hubs in Multi-Hub systems, this assumption might not hold true, implying changes in fuel burn owing to shifting.

The first two variants are already implemented in the integrated model [8], while the identification and estimation of possible additional fuel consumption owing to airport shifting is introduced in this work as described below.

B. Fuel Consumption Changes due to Airport Shifting

Additional fuel burn due to airport shifting highly depends on the position of the congested airport in relation to its alternatives as well as the route structure and fleet mix of the shifted flights. Thereby, shifting leads to changes in average flight distances, as alternative airports and route shares are not equally distributed. This may either increase or decrease flight distances and, subsequently, fuel consumption.

Fig. 1 Schematic illustration of airport shifting between MUC and SZG, image created with http://www.gcmap.com/

Figure 1 schematically illustrates distance changes owing to airport shifting. Here, short- and medium-range traffic on routes within Europe and from Europe to the Middle East and Africa is shifted from Munich (MUC) to the nearby non-hub alternative of Salzburg (SZG). The route to the Middle East gets shorter while the intra-European one increases in length and the one to Africa sees almost no change. With a high share of intra-European traffic, this implies an overall increase in average fuel burn per shifted flight. The global fuel consumption change due to shifting highly depends on the set of congested and alternative airports, changing with every different use case.

This change is added to the current model with the following generic calculation approach: For each combination of aircraft and route clusters the frequency-based average route length of all flights operating at the congested airport is calculated from OAG data [10]. These averages are more specific to the airport under investigation compared to the representative route lengths of the route groups. For these flights, the same calculation of average route length is performed, substituting the congested by the alternative airport. Then, for both flight sets the fuel burn is estimated. The difference between both fuel burn values is the additional or saved fuel for airport shifting.

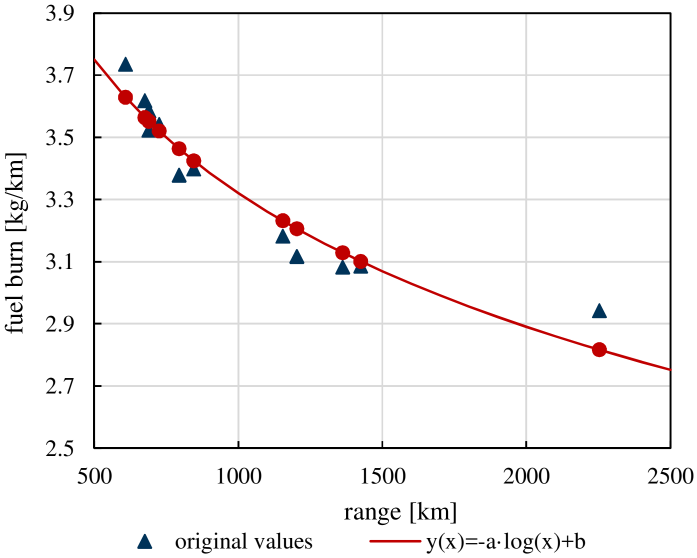

Fig. 2 Fuel burn per km of an Embraer 190, original integrated model input values and estimated representative function.

The estimation of fuel burn on the airport-specific distances starts with the given basic fuel burn on each combination of aircraft and route cluster. These reference values were calculated through a mission evaluation tool as input for the current integrated model's route groups [8]. Due to the variety of different route lengths involved in shifting, this method would take too long to compute, thus requiring a simple approximation method. Assuming similar cruise flight conditions and unchanged payloads, the fuel burn per kilometer is obtained for every aircraft cluster's flights on any given route group. To estimate the fuel consumption for any other range this value must be fitted to a representative function. Figure 2 exemplarily represents these considerations for an Embraer 190 over its usual flight range. The chosen logarithmic function with two aircraft cluster-specific variable coefficients is shown in red. It fits the reference input values for current route groups with sufficient accuracy. This was investigated by calculating the residual of the sum of squares by comparing the values from the estimated function with the given reference values. This approximation method is used for all aircraft clusters of the integrated model.

To further evaluate whether the approximation results lie in a realistic range, these are compared to the values reported by Steinegger [24]. He performed research on fuel economy as function of weight and distance, and introduced the concept of marginal fuel burn. The results from the research are based on analysis of operational flight plans of different aircraft types. Assumptions, e.g., for cruise altitude and extra fuel, are similar to this work. According to [24], the fuel burn per kilometer for an A320 with 150 passengers lies between 2.9 and 3.3 kg/km. The values obtained for this work's narrow-body aircraft cluster represented by the A320 of 3.2 kg/km is within this range. The same accounts for the cluster of small wide-body aircraft represented by the A330-300 which consumes about 6.8 kg/km of fuel in our approximation. [24] shows a comparable range of 6.2-7.5 kg/km for the same aircraft type. Hence, the fuel burn values obtained with the new model are coherent with studied literature.

IV. Results and Discussion

This section first presents the updated integrated model's results for airport congestion and its mitigation. It starts at global level further detailing to the use of single congestion mechanisms, fleet mix development, and, ultimately, shows effects at level of selected exemplary airports. That way, the functioning of the implemented mechanisms and their plausibility are illustrated. Second, the resulting implications on fuel burn on different levels of consideration are shown, including the new module for estimating additional fuel burn in airport shifting within the use case fuel.

A. Air Transport Performance Effects

This section presents the effects of airport congestion and its mitigation on global air transport performance data by comparing the use and no action cases with the reference case, followed by an overview of mitigation mechanism deployment and the number of congested airports. An example overview of air traffic movement development in the ATN region Europe is shown for comparison with available literature data.

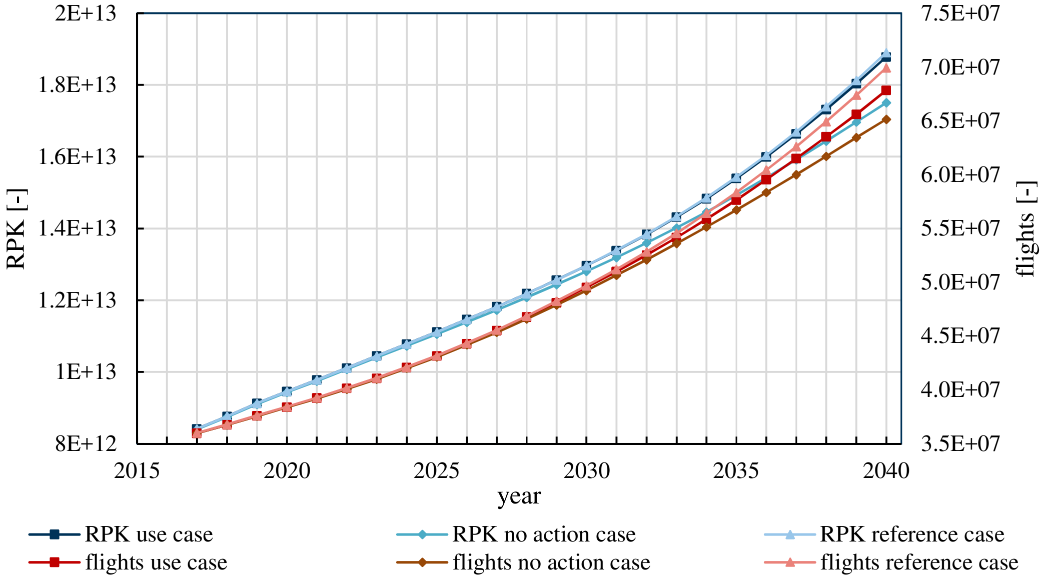

Fig. 3 Development of RPK and flights in the use case, no action case, and no-congestion reference case, simulation years 2017-2040.

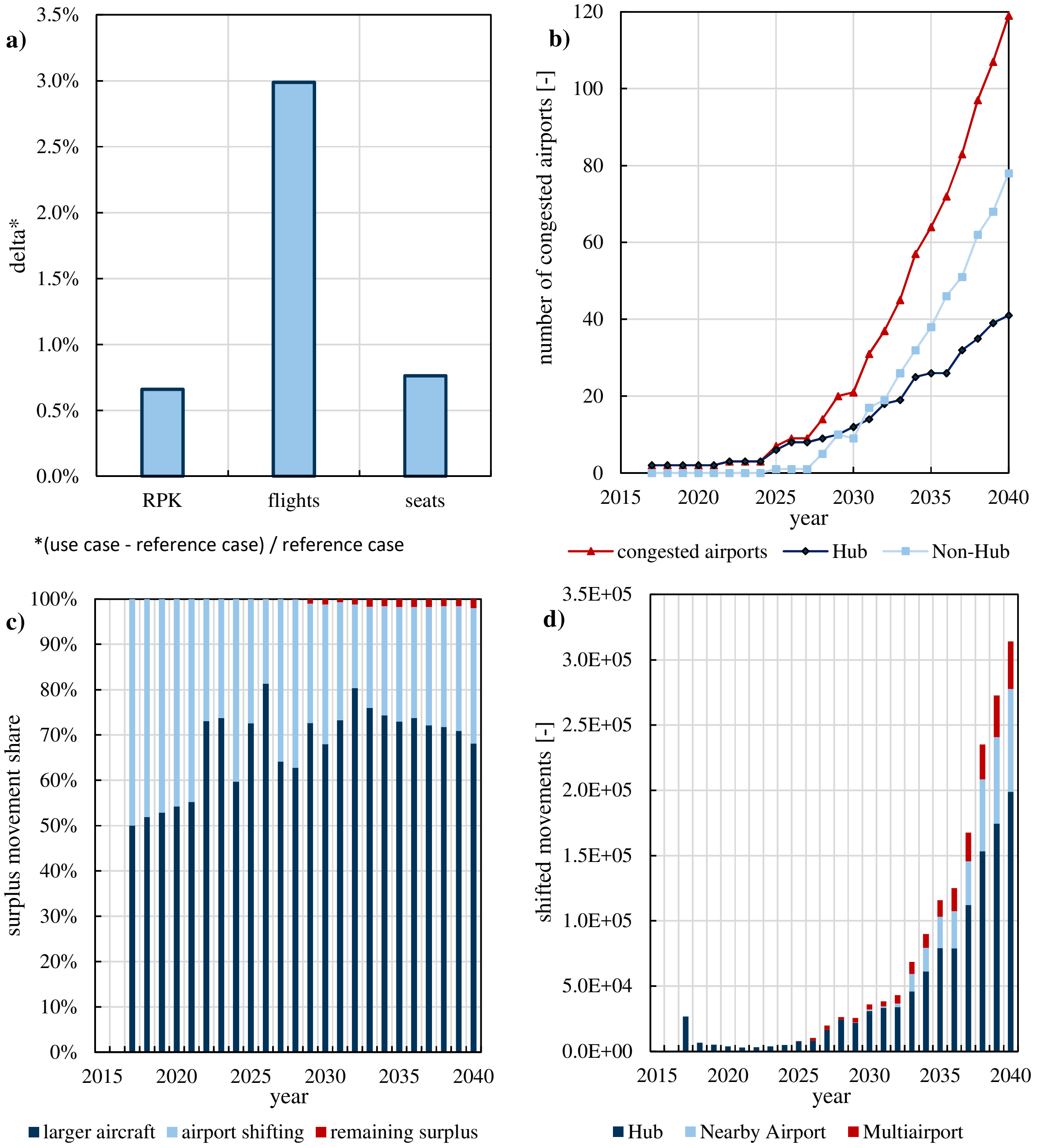

Fig. 4 a) Deviation of use case results from reference case in year 2040 for RPK, flights and seats; b) Development of number of congested airports throughout simulation period; c) Surplus movement shares of mitigation strategies and remaining surplus; d) Usage of hub-, Nearby Airport-, and Multiairport-alternatives in shifted movements.

Basic global results for the updated integrated model are shown in Fig. 3 and 4. The changes introduced to the model allow for an RPK CAGR (Compound Annual Growth Rate) of 3.58 % and an increase in the number of flights up to 70 million in simulation year 2040. This is in line with the RPK CAGR expected by the current *Boeing Commercial Market Outlook (CMF) 2022-2041* of 3.80 % [25] and the *Airbus Global Market Forecast (GMF) 2022-2041* of 3.60 % [26]. As depicted by Fig. 3 and 4a), the updated model is able to accommodate surplus traffic via mitigation strategies almost completely, leaving 0.66 % of 2040 RPK from the unconqested reference case as surplus traffic in the use case. If no congestion mitigation mechanisms were applied, remaining surplus amounts to 7.4 % of RPK. Both is lower than reported in the previous model [8] and other research such as [12, 22], but similar to more present literature (see end of section). Comparing the uncongested and no action cases, significant capacity shortages set in at about 2030, coinciding with a strong increase in congested airports in Fig. 4b). The difference in flights between both cases in 2040 is 2.99 %, significantly higher than the RPK difference. This behavior is expected, as this difference accounts for remaining surplus as well as surplus movements mitigated by larger capacity aircraft. If no mitigation was applied, 6.8 % of unconstrained movements would remain unaccommodated. The difference in 2040 seat numbers between both cases is slightly higher than for RPK at 0.76 %. This hints at the model preferring longer routes for congestion mitigation owing to the new optimization algorithm.

Figure 4b) shows a continuous increase in the number of congested airports with 119 airports being ultimately congested in 2040. In the no action case (not shown), 97 airports are congested in 2040. This smaller number is expected, as congestion cannot reach the same spread via airport shifting (see section C). For reference, a similar study reports significantly fewer congested airports (36 congested airports in 2050) [14], indicating that this work assumes a wider spread of congestion. However, the number of 17 congested airports in Europe in 2035 is near the value given in [22] (about 20 congested airports). This constitutes a major improvement over the previous model [8], which showed fluctuations in the number of congested airports: A constant CAGR for air traffic demand can intuitively be expected to keep congested an airport which already experienced congestion in the past year. Furthermore, the division of congested airports into hubs and non-hubs is shown. For the definition of hubs within the integrated model please refer to [8]. Until 2030, hubs account for the majority of congested airports, while afterwards congestion levels are so high that they lead to rapid congestion at smaller airports as well. Interestingly, the number of congested non-hubs decreases by one between 2029 and 2030, as Ho Chi Minh City Airport (SGN) changes to hub status.

With the number of congested airports the number of surplus movements rises throughout the simulation period – from a minimum of 6356 movements in 2021 to a maximum of more than one million in 2040 in the use case. As Fig. 4c) indicates, in the first simulation years larger aircraft capacities and airport shifting are likewise used to mitigate congestion. With subsequent years, the share of airport shifting overall decreases as not enough suitable, uncongested alternatives are available. Additionally, a small share of remaining surplus starts to appear from 2029 onward as the implemented strategies are not able to entirely mitigate the rising surplus. The usage of larger aircraft overall mitigates a higher share of surplus traffic in this model than expected for Europe in [22], where a potential 15 % reduction in movement surplus is estimated. Within airport shifting, Fig. 4d) shows that a majority of shifted movements accounts for traffic being shifted to hub airports. In the first simulation years this is in line with Fig. 4b), as only hubs are congested. In following years, hubs still account for a majority of surplus traffic as they in general experience significantly higher movement numbers as compared to non-hubs. The rising number of congested non-hubs, however, enables further shifting mechanisms. While shifting within Multiairport systems takes place first, this measure soon reaches limits, necessitating the use of Nearby Airports.

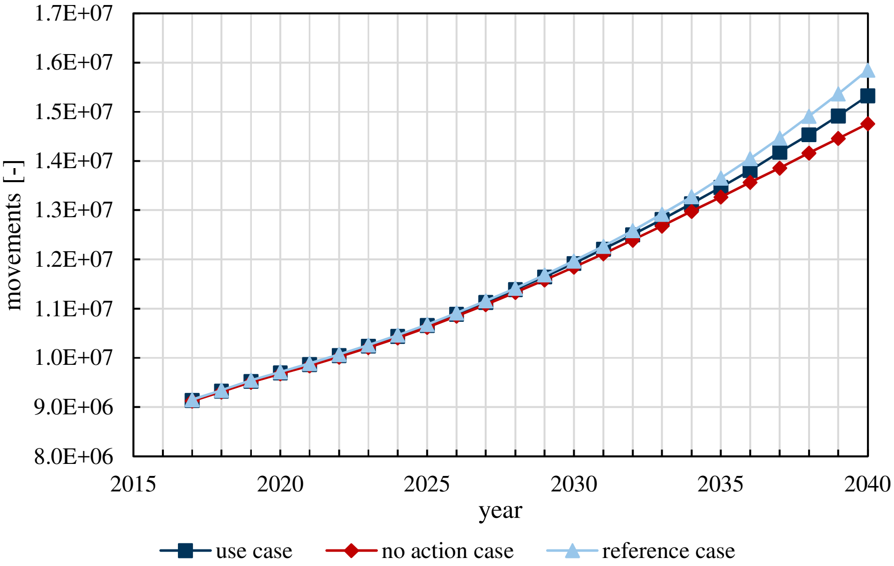

Fig. 5 Movement development in ATN region EU, 2017-2040. Dark blue: use case, light blue: no-congestion reference case, red: no action case.

Figure 5 presents the development of movements originating or arriving (or both) in the ATN region EU for the use case, the no-action case, and the no-congestion reference case. This figure serves for comparison with results published in the EUROCONTROL *Aviation Outlook 2050* [23], which presents traffic forecasts for Europe for both an uncongested case and a congested case without mitigation. In Fig. 5, the three different cases exhibit between 14.8 and 15.8 million movements in 2040.The congested use case achieves 3.3 % and the no action case 6.8 % less movements than the reference case. The slightly above-average value for the use case (compare to Fig. 4a)) indicates the significant airport congestion within Europe. The movement numbers lie between those of the "Base" and "High" forecasts described by EUROCONTROL with the movement difference for the no action case slightly above the share of unaccommodated movements in the "High" forecast [23]. Within this work's use case, however, surplus mitigation works rather efficiently in Europe, with a share of 0.01 % of unaccommodated surplus in 2040. This, like Fig. 4c) as well, shows a significant change compared to the previous model version and use case presented in [8]. There, considerable shares of unaccommodated traffic were expected. Furthermore, this work expects higher traffic growth than EUROCONTROL [23] by disregarding COVID-19 influences. Nevertheless, the results in this section show sufficient agreement with available literature to assume the validity of its results. Further descriptions of regional congestion developments taking into account regional peculiarities are presented in [11].

B. Fleet Mix Development

Airport congestion and its mitigation also have influence on the fleet mix, especially via the use of larger capacity aircraft at congested airports. This is reflected in the rise of average seat numbers per flight, mainly in those APC which experience most capacity limitations. The section starts with a comparison of fleet mixes in the reference and use cases in the final simulation year 2040, as shown in Table 2.

Table 2 2040 fleet mix for no-congestion reference and use cases, number of upgraded aircraft (use case).

Aircraft Cluster	Fleet reference case	Fleet use case	Upgrade aircraft use case
C01 AT75	840	830	25
C02 E190	1335	1299	95
C03 A319	61	58	16
C04 A320	1726	1590	154
C05 A333	156	141	20
C06 B77W	35	33	10
C07 763F	0	0	0
C08 744F	0	0	0
C09 A21N (XLR)	3329	3152	341
C10 A20N	5400	5085	787
C11 A359	3158	3299	682
C12 AT76	543	538	18
C13 E290	2801	2735	105
C14 A339 (Regio)	2644	2774	513
C15 A321 (F)	0	0	0
C16 748F	1982	1955	0
C17 A21N	23030	22314	1834
C18 B789	4296	3909	382
sum	**51337**	**49713**	**4982**

The overall fleet size in the use case is about 3.2 % smaller compared to the reference case. Similar differences appear at the aircraft cluster level, with notable exceptions being wide-body clusters represented by the A350-900 (C11) and the A330-900 (C14). This follows the expected broader use of these aircraft in congestion mitigation via larger capacity ("upgraded") aircraft. Further, Table 2 shows the number of these upgrade cluster aircraft (included in use case fleet). All aircraft clusters contribute to upgrades, yielding a fleet share of 10 % of upgraded aircraft in the 2040 overall fleet. Thereby, the model selects only current or larger aircraft with densification, as upgrades by larger aircraft without densification have the highest fuel burn per seat. They are thus omitted in the mitigation strategy choice. The resulting fleet counts are in line with current forecasts by Airbus and Boeing. In 2041, Boeing predicts a global fleet size of 47,080 aircraft [25], while Airbus expects 46,930 aircraft [26]. Deviations mainly result from different fleet bases: Airbus disregards aircraft with less than 100 seats and Boeing omits turboprop aircraft. The latter alone account for more than 1400 aircraft at simulation start in this work.

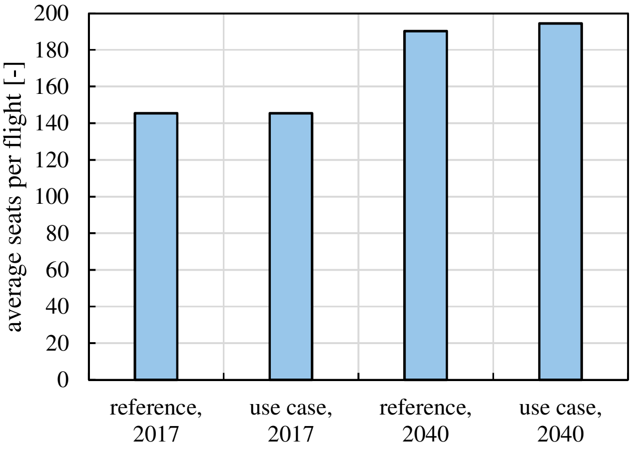

Fig. 6 Average seats per flight, no-congestion reference and use cases, 2017 and 2040.

Figure 6 depicts a general increase in average seat numbers per flight in the simulation period of about 30.8 % for the reference and 33.8 % for the use case. This follows the observation of a persistent growth in aircraft seat capacity also described by Will et al. [27] and Gelhausen et al. [14]. Such a growth in seats per flight might already hint at the implicit way in which the air transport system reacts to infrastructure constraints and is also inherently implemented in the available aircraft clusters used in this work. This can be observed in Table 2 with the significant numbers of A321neo and even A330-900 aircraft serving short- and mid-range flights in 2040. These flights were previously served mostly by smaller aircraft such as the A320. Finally, a difference of 2.3 % between the average seat numbers per flight of the reference and use cases in 2040 reflect the operation of upgraded aircraft clusters with consequently increased passenger capacities as depicted by Table 2. However, the average growth in seats per flight of 1.27 % p.a. (constant load factor of 86 %) is lower than reported by a similar study [14]. Among others, a reason might be the additional use of airport shifting for congestion mitigation.

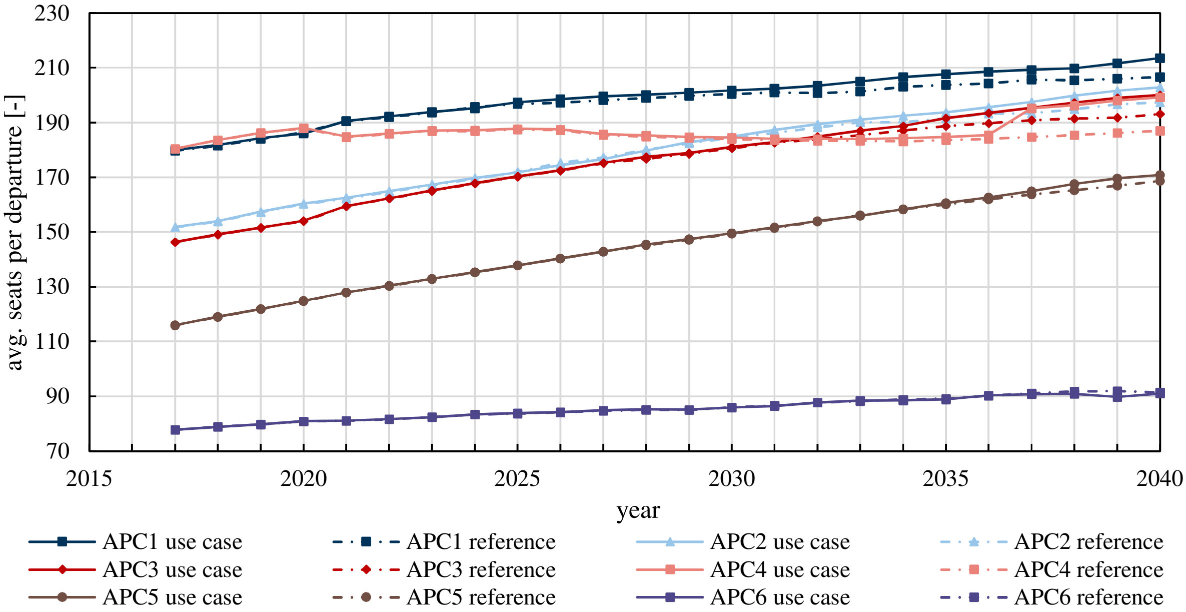

Fig. 7 Development of average seat numbers per departure for all APC, 2017-2040, solid lines: use case; dashed lines: no-congestion reference case.

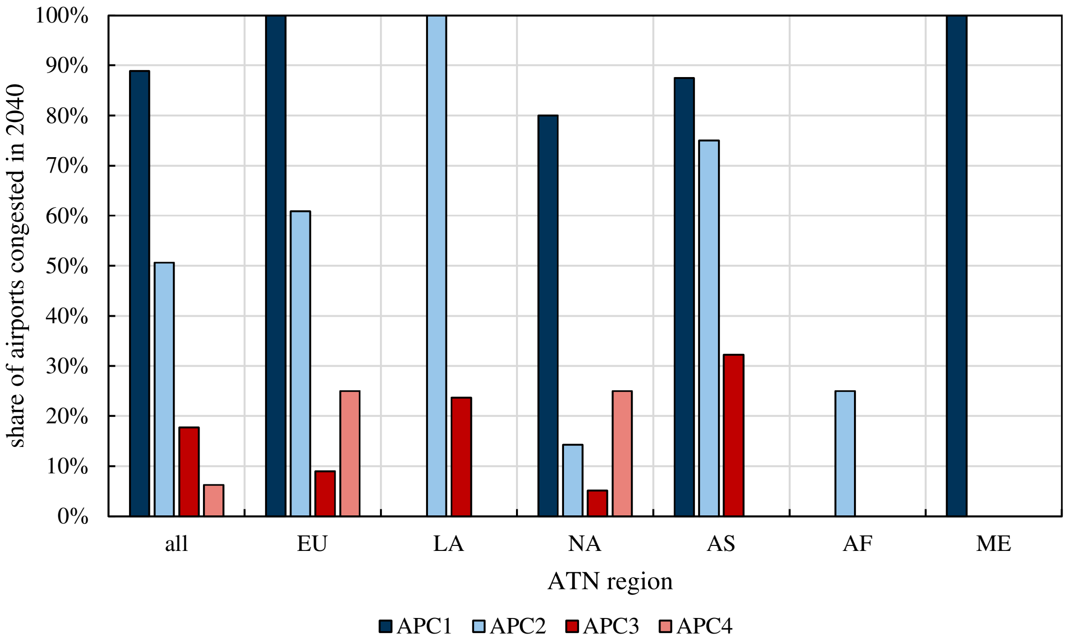

Fig. 8 Share of airports congested in the use case in 2040 for APC1-4.

The differences in average seats per flight mainly result from those APC containing congested airports, as shown in Fig. 7. Congested airports can be found only in APC 1-4. An exception is the Latin American ATN with three congested APC5 airports in 2040. APC1-3 and 5 roughly follow the growth in per-flight seat numbers shown in Fig. 6. For APC1-4, Fig. 8 presents the shares of airports congested in the use case in 2040 for all ATN regions. The highest levels of congestion are reached by Global Hubs (APC1), with 89 % operating at their capacity limit in 2040. In the European ATN, all APC1 airports are congested; the same applies to the only APC1 airport in the Middle East ATN, Dubai (DXB). Few APC1 airports still have capacity reserves in the North American and Asian ATN region, where large infrastructure is either readily available or under construction. This congestion level can also be observed in Fig. 7 with a 3.3 % increase in average seat numbers per departing flight from the reference to the use case, indicating substantial use of congestion mitigation by larger aircraft. Large Airports (APC2) see a lower level of congestion with 51 % of airports operating at capacity limit globally. Strong regional differences can be seen with a high share of APC2 airports congested in the Latin American and Asian ATN. Especially in Latin America, the region's largest and most congested hubs are part of this cluster, there is no APC1 airport (same in Africa). APC2 airports thus show a high difference (2.8 %) in average seats per departure between use and reference case. This difference becomes notable in Fig. 7 starting shortly after simulation year 2030, when the first of these airports become congested. Similar observations can be made for Medium Airports (APC3), although their share of congested airports is relatively small with 18 % in 2040 globally. The highest share of congested APC3 airports is seen in the Asian ATN region, indicating the wide spread of congestion there. Long-Haul Airports (APC4) show a behavior different from the other clusters. As seen in Fig. 8, congested APC4 airports appear only in the European and North American ATN, leading to a low congested share of 6 % globally. Their appearance as congested mainly results from a modelling weakness in the airport clustering: Both the use and reference cases see a decline in average seat number per departure for this cluster after 2020. This is connected with changes in clustering: Between 2020 and 2021, Tokyo Narita (NRT) moves to Global Hubs APC1, while the comparably small airports of Cayenne (CAY) and Freetown (FNA) are now members of APC4. Both airports feature high shares of turboprop and regional jet traffic. The appearance of congested APC4 airports is strongly connected with the change of the highly congested airports London Heathrow (LHR) and New York (JFK) from the Global Hubs (APC1) cluster to this group between 2036 and 2037. This is evidenced by a jump in average seat numbers per departure as compared to the reference case. The reason for the latter change might lie within the very high shares of long-haul traffic at these airports, leading to such an unexpected classification. APC5 and 6 do not experience (significant) congestion, as evidenced by the very low differences between use and reference case seat numbers per departure in Fig. 7. Aircraft size at both airport clusters is lower than at all other clusters due to their importance for regional traffic only. It should be noted that, despite what Fig. 7 might suggest, no infinite growth in average aircraft size is possible. The growth limits are given by the implemented aircraft clusters.

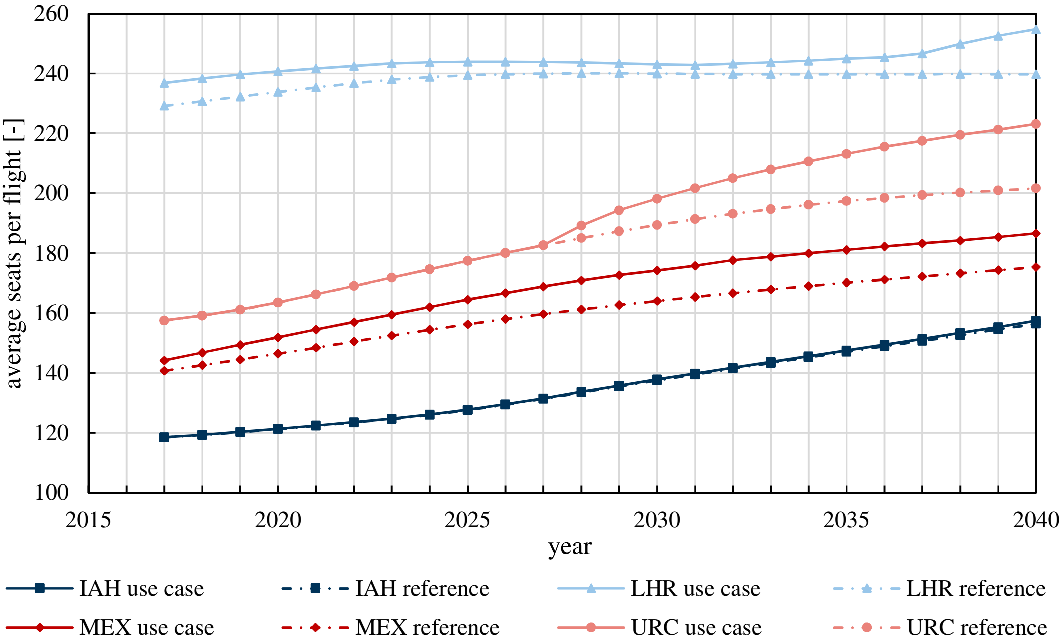

Fig. 9 Development of average seat numbers per flight at IAH, LHR, MEX, and URC, 2017-2040, solid lines: use case; dashed lines: no-congestion reference case.

On a more detailed level, Fig. 9 shows possible consequences of congestion mitigation via larger-capacity aircraft at single airports throughout the simulation period. Houston Intercontinental Airport (IAH) does not experience any congestion; small differences between use and reference case average seat numbers result from surplus traffic shifted from Chicago O'Hare Airport (ORD). Still, the average seat number per flight rises by 32.8 %, roughly resembling the network-wide average. The reason for this increase is the relatively small aircraft size operating at the airport at simulation start with just 118 seats per flight. Contrarily, LHR has very high average seat numbers, over 235 seats per flight, right from the start, resulting from the airport being congested for many years already (see, e.g., Gelhausen et al. [13]) and being an intercontinental hub rather than offering many regional flights, such as IAH. Consequently, the average seat number at the airport has little room for increase, resulting in a change of only 7.6 % until 2040. Still, after the major shifting alternative, Madrid (MAD), becomes congested in 2037, the average seat number in LHR increases at a higher rate as seen in the comparison between use and reference case. Mexico City (MEX) is congested from the first simulation year, similar to LHR. As shown below, surplus traffic is constantly shifted to other airports in Mexico, not solely relying on larger capacity aircraft. Thus, average seat numbers grow at a rate slightly below average at 29.4 %, roughly following the development in the reference case. In contrast, Urumqi (URC) has no shifting alternative. Here, congestion mitigation entirely depends on introducing larger aircraft. This leads to an above-average growth in seat numbers starting from the onset of congestion in 2028. It amounts to 41.7 % in 2040, as compared to 28.0 % in the reference case. Not all surplus traffic can be mitigated, leaving remaining surplus at the airport.

C. Congestion Network Propagation

An important effect is the propagation of congestion through a network of shifting alternatives. Obviously, the likelihood of reaching congestion significantly increases for any airport receiving traffic shifted from another airport. This can be observed in the results of the use case, with 25 out of 119 congested airports in 2040 having received shifted traffic from other congested airports in previous years. On the airport level, a prominent example for this issue are the hubs of the Lufthansa Group throughout central Europe. The integrated model first identifies Munich (MUC) as congested in simulation year 2029, necessitating traffic shifting to Frankfurt (FRA). When the latter becomes congested in 2031, surplus traffic from both airports is shifted to Zurich (ZRH). ZRH is first congested in simulation year 2034, leading the operator at all three airports to shift traffic to Vienna (VIE). However, one year later, VIE is congested as well. Now traffic is shifted from all four congested hubs to the last remaining Lufthansa Group hub in Brussels (BRU), which additionally receives surplus traffic shifted from Dusseldorf (DUS). Consequently, BRU becomes congested in 2039, leaving only smaller airports such as Cologne (CGN) or Hanover (HAJ) as shifting alternatives. These results resemble the description of the Lufthansa Multi-Hub system in Burghouwt [16] in the sense that secondary “overflow” hubs are built up in order to accommodate additional traffic when primary hubs are congested. In this work, however, congestion doesn’t start at the airline’s dominant hub in Frankfurt but at MUC, which since outgrew the role as a simple overflow hub.

Another example of congestion spread can be found in Mexico. Starting with the first simulation year, MEX is one of only two airports identified as congested by the integrated model. This is not surprising given the importance of this airport, the above-average air traffic growth rates in Latin America and the runway layout with two dependent parallel runways with very limited possibilities for expansion.

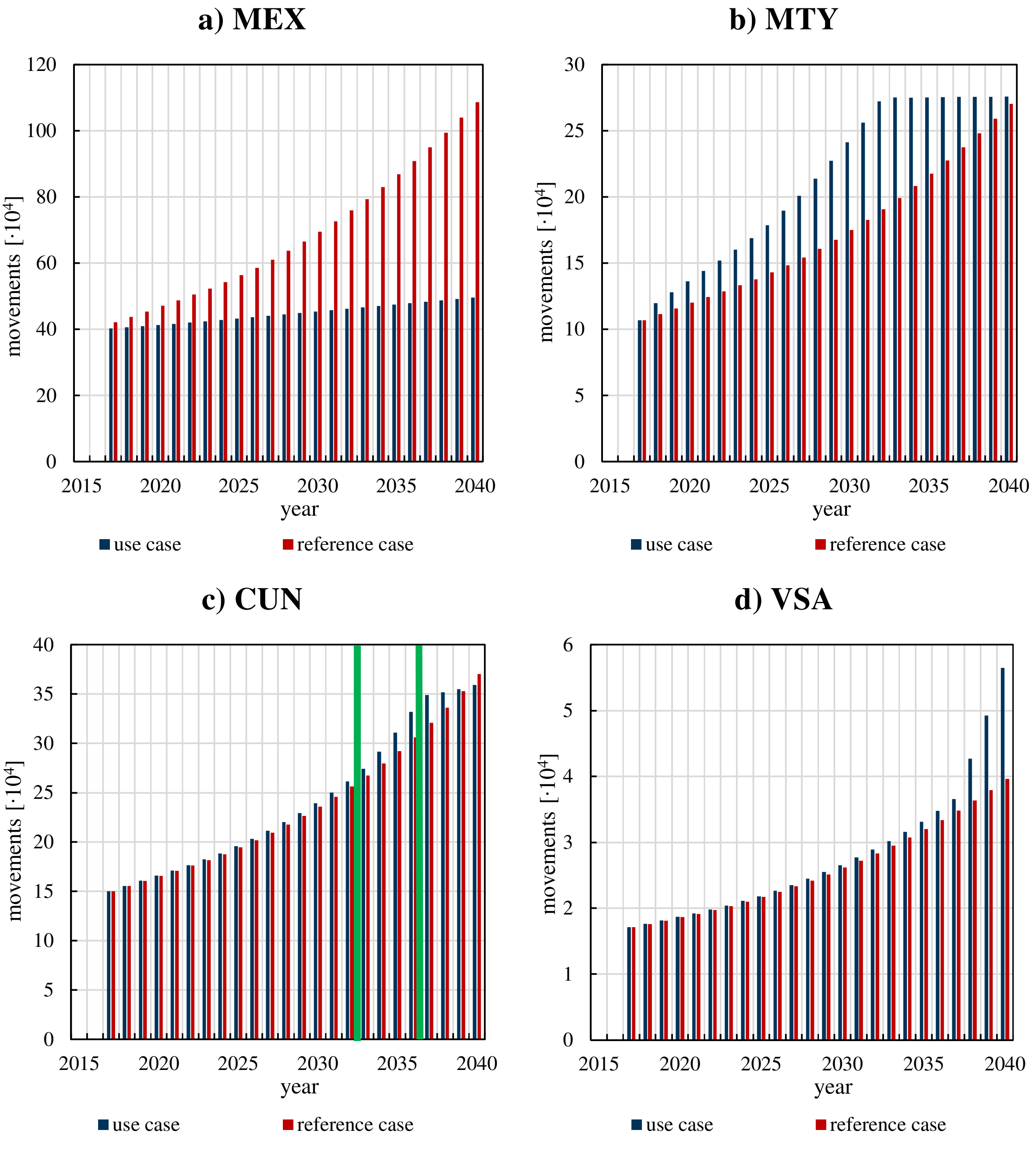

Fig. 10 Movement development at a) MEX, b) MTY, c) CUN and d) VSA airports, use case (blue), reference case (red), and indication of period of shifting flights to CUN (green).

Figure 10 presents the movement number for the use case (blue) and the reference case (red) at MEX and all three airports which receive surplus traffic shifted from MEX in the use case. As Fig. 10a) shows, in the reference case air traffic at MEX is predicted by the integrated model to grow to more than one million annual movements by 2040, following the region's high RPK growth factors (red bars in Fig. 10a)). Considering the aforementioned runway layout and limited expansion prospects of MEX, as well as its already persistent congestion (see OECD [28]), such a development seems highly unlikely. In fact, before being put on hold in 2018, construction for a new airport with six runways was already initiated. However, the model's capacity growth factors allow for a 23 % increase in movements between 2017 and 2040 in the use case (blue bars in Fig. 10a)). This yields more than 213,000 surplus movements over the entire period. A substantial share of these (43.9 %) is shifted to other Mexican airports.

The first of these is Monterrey (MTY) between the years 2017 and 2032 as shown by Fig. 10b). MTY is identified as a hub alternative thanks to its traffic mix, containing even long-range flights in 2016 OAG data, and thanks to the dominant role of Aeromexico, the hub carrier of MEX, with a movement share of 36.3 % in 2017. Similar to MEX, movement growth in the reference case follows the region's air traffic growth. The additional movements absorbed from MEX in the use case further increase movement growth at the airport (blue bars in Fig. 10b)). Consequently, the airport reaches its simulated capacity limit in 2033. This prohibits further shifting from MEX and requires the use of mitigation strategies for MTY itself (larger aircraft only in this case). As a result, the use case movements barely experience any increase after that year. Interestingly, in the uncongested reference case, movement numbers at MTY would not have reached the use case capacity limits until 2040. The next shifting alternative receiving movements from congested MEX is Cancún (CUN, Fig. 10c). CUN serves as a shifting alternative in the period 2033-2036 (indicated by green lines in Fig. 10c)) before reaching its capacity limit. As such, it is operated already near to this limit without additional traffic from MEX. Surplus traffic from CUN is shifted to nearby Cozumel (CZM), adding a "second generation" of shifting alternatives. In parallel, the final airport receiving shifted traffic from MEX is Villahermosa (VSA, Fig. 10d)) from 2037 onwards. This additional traffic means a rapid movement increase for this small airport. For comparison, in the no action case, besides MEX only CUN reaches congestion levels in the final simulation year. This shows the importance of traffic shifting for spreading congestion over a wide network of airports.

Both above examples illustrate that the integrated model mostly finds alternative airports which would be expected intuitively, taking into account geographical proximity and predominant carriers. This, however, is not always the case – especially if the first shifting alternatives become congested. As such, after MAD becomes congested, both MAD and LHR shift traffic to Santiago de Compostela (SCQ), probably owing to the high share of IAG group airlines operating there. However, taking into account the broad modeling approach in this work, such errors are acceptable.

The presented results show an overall expected, explainable, and plausible behavior of the implemented congestion and mitigation mechanisms. On the most detailed level, it became possible to follow the development path of specific simulated airports throughout the simulation period. This detailed view of congestion mitigation builds the foundation for considerations regarding fuel consumption in the following section.

D. Effects on Fuel Consumption

This section presents first results on the influence of congestion and mitigation on fuel consumption. In the first part, only the use case is investigated, thus the only source for additional fuel burn is the deployment of larger aircraft. With this approach we aim to develop a first understanding of the interplay between congestion, its mitigation and fuel burn considerations. The second part introduces results for the use case fuel in comparison with the use case. That way, effects due to the new module accounting for flight distance changes in airport shifting become apparent.

Figure 11a) depicts the difference in global fuel burn and average fuel burn per flight between the use and the reference cases. In the first simulation years until 2025, both values are slightly negative (smaller fuel burn in reference than in use case), around -0.5 %. In this time period, only few hub airports are congested and either shift traffic to other airports (no additional fuel burn in this case) or deploy larger capacity aircraft. As these airports usually already operate a comparably high share of wide-body aircraft, mainly densification without employing overall larger aircraft is used in the latter case. This means no additional fuel burn but a reduction in the number of flights and, thus, in fuel burn. With the onset of widespread congestion after 2025, the difference in global fuel burn increases steadily. In 2040, 2.51 % less fuel is consumed in the use case due to fewer flights being performed. However, compared with the decrease in the number of flights of 2.99 % (Fig. 4a)), it becomes apparent that the fuel burn per flight rises in the use case. This behavior can be followed in Fig. 11a). With more and more smaller airports becoming congested after 2025, upgrades to larger densified aircraft increase. The subsequent operation of relatively large aircraft on short routes leads to the increase in average fuel burn per flight. In 2040, 0.5 % more fuel is used per average flight in the use case.

The developments leading to these global values are very diverse on the airport level. This is shown in Fig. 11b) for six example airports. LHR follows the observation described above for congested hub airports. Until 2037, traffic is shifted from LHR to MAD while deploying larger aircraft is difficult due to the high average seat numbers per flight at LHR. When MAD becomes congested in 2037, however, LHR has to make extensive use of larger densified aircraft, raising the average fuel burn per flight. MAD sees a consistently higher fuel burn per flight from the start year. This is due to traffic shifted from LHR, which accommodates a high share of wide-body long-range flights. The fuel burn per flight for Lima airport (LIM) sees almost no deviation from the reference case until 2031, when the airport is first congested. Afterwards, per flight fuel burn rises quickly: The reason is that LIM has to rely solely on larger aircraft as a congestion mitigation. Alternative airports are not available. For MEX, additional fuel burn per flight continuously rises until 2040 as, besides traffic shifting to alternative airports, congestion mitigation through larger aircraft is also employed. Still, MTY receives considerable amounts of traffic from MEX. This includes a fleet mix with longer-range flights and larger aircraft than previously operating at this airport, leading to a strong increase in per flight fuel burn of 23.7 % until 2032. As the airport becomes congested afterwards, this value again rises strongly to 29.6 % in 2040 owing to the use of larger aircraft. Finally, Xian airport (XIY) consistently uses both its shifting alternatives from the onset of congestion in 2028. Still, these do not provide enough surplus mitigation potential so that larger aircraft are used as well. Consequently, fuel burn per flight increases by 2.2 % in 2040.

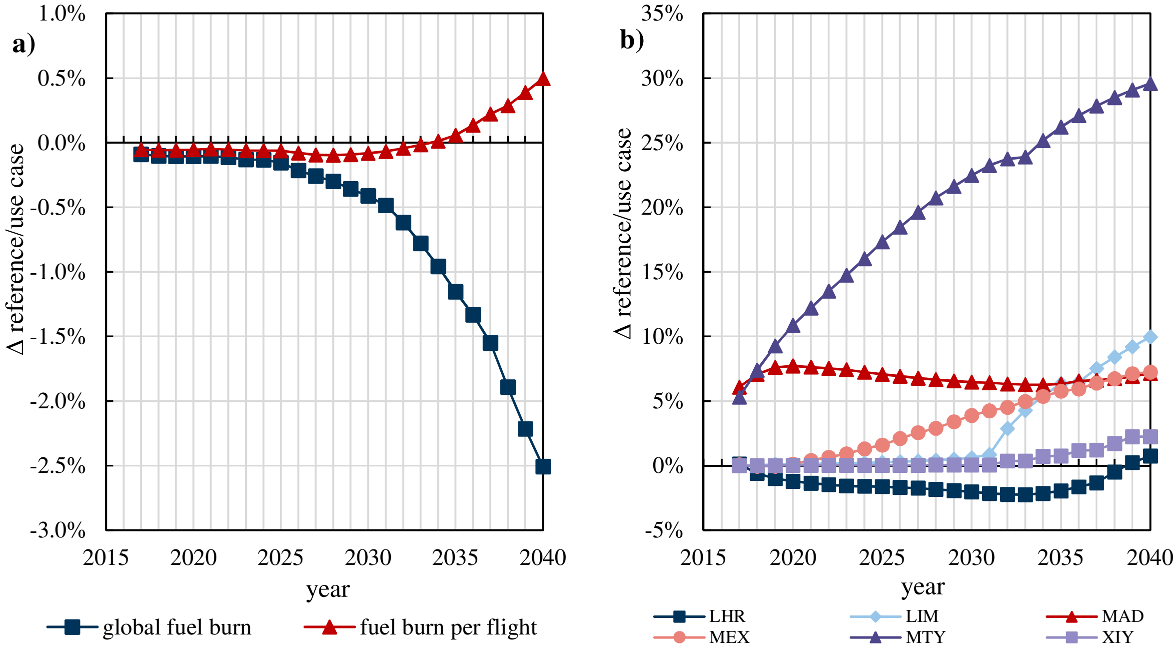

Fig. 11 **a) Difference in global fuel burn (blue) and average fuel burn per flight (red) between use case and reference case, simulation period 2017-2040; b) Difference in average fuel burn per flight between use and reference cases, simulation period 2017-2040, for airports LHR, LIM, MAD, MEX, MTY and XIY.**

The observations made in Fig. 11a) and b) show that, despite lower global fuel burn owing to remaining surplus and fewer flights following airport congestion, inefficiencies are still present following the use of mitigation strategies. These appear on the level of per flight fuel burn and reach significant values for some example airports.

In the final part of this section, the results of the additional generic approach for calculating changes in distances and fuel burn due to airport shifting are investigated. Therefore, we compare the use case and the use case fuel on the airport level to illustrate important effects and work out the occurrence of additional fuel burn step by step. As mentioned above, the integrated model identifies LHR as congested from simulation start. The surplus movements are shifted to the alternative hub MAD until 2036. The year 2019 is taken as the sample year to study, so it can be compared with historic data.

The integrated model identifies 3399 surplus movements in 2019 for LHR, 1793 of which are shifted to MAD. The objective of the study is to analyze the impact of the subsequent changes in flight distance and fuel burn modeled for these flights. Two aircraft clusters are dominant in LHR in 2019. The narrow-body cluster represented by the A320 (C04) operates 36 % and the large wide-body cluster represented by the Boeing 777-300ER (C06) 16% of the flights at LHR. Figure 12a) shows the sum of the flown distances of the shifted movements in the narrow-body cluster by flown route. Values for the original airport LHR are depicted in blue, those for the shifting alternative MAD in red. Figure 12b) displays the change in fuel burn when shifting these movements.

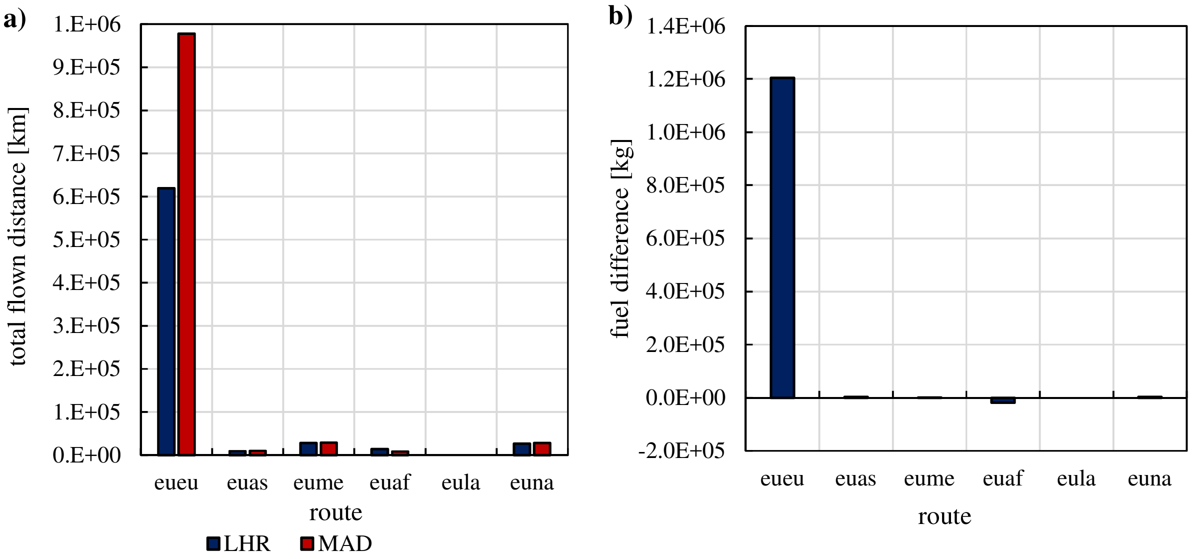

Fig. 12 **Shifting from LHR to MAD; a) Total flown distance of shifted movements for narrow-body aircraft; b) Fuel difference due to shifting for narrow-body aircraft.**

According to modeling results, 63 % of narrow-body movements at LHR operate intra-European routes. The results from Fig. 12a) show that almost all additional flight distance due to shifting in this cluster is attributable to these routes. MAD is located in southwest Europe, whereas LHR has a more central position within the European ATN. Between these airports there is an approximate flying distance of 1243 km. In 2018 the shares of passengers on intra-European flights at LHR who had either their origin or destination in the UK was 18 %, 16 % in Spain, 13 % in Germany, and 10 % in Italy [29]. With that route mix, an average intra-European flight to LHR is shorter than to MAD. Accordingly, the total flown length of the shifted movements increases if shifted to MAD instead of remaining at LHR. On the contrary, for movements to or from Africa, shifting to MAD implies shorter average flight distances since Spain is nearer to the African continent than is the UK. Consequently, in Fig. 12a) routes between Africa and Europe have a larger total distance for LHR (blue) than those for MAD (red). Figure 12b) shows the difference in fuel burn for all shifted movements between operating to the alternative airport MAD and the original airport LHR. As a consequence of the flight distance changes in Fig. 12a), shifting intra-European narrow-body flights from LHR to MAD results in an increased fuel burn. In 2019, this alone yields an extra fuel burn of $1.2 \cdot 10^6$ kg. That same year, seven movements connecting Europe to Africa are shifted, which implies a fuel saving of 2800 kg. This shows the importance of the exact route mix for these considerations.

On the airport level, the modified fuel burn calculation has to be implemented for all movements shifted in the current and in all previous years. This includes additional movements due to demand growth on previously shifted movements. Figure 13 presents the annual movement numbers in MAD for the reference case (red) and the additional movements due to shifting from LHR (blue). Despite being congested and shifting movements from 2036, MAD has a decreasing but significant share of flights in 2040, which can be traced to previous shifting from LHR. The results presented in Fig. 12 and 13 can now be aggregated for an estimation of additional fuel burn due to shifting on the airport level. For all flights at MAD, the corresponding Fig. 14 displays the average fuel burn per flight of the use case in blue. The fuel burn per flight of the use case fuel including the estimation of additional shifting fuel burn is shown in red. Both cases thus include the movements originally present at MAD as well as those shifted from LHR to MAD.

In both cases, Fig. 14 shows an increase in fuel consumption per flight until 2023. This is connected with stronger demand growth on inter-regional flights as compared to shorter intra-European flights. In subsequent years until 2034, fuel consumption per flight declines. In this time older-generation aircraft are rapidly substituted by new aircraft with lower specific fuel consumption. After most of the fleet is exchanged that way, average fuel consumption per flight increases due to higher demand growth and increasing share of longer inter-regional routes. Comparing both use cases in Fig. 14, the additional fuel burn owing to shifting increases its share in the first simulation years until around 2025 to about 0.7 %. In that period, MAD receives large amounts of surplus traffic from LHR. The amount of newly shifted surplus movements shrinks to relatively small numbers in subsequent years, not significantly increasing that share. With congestion and its mitigation at MAD after 2037, the share of additional fuel burn likewise decreases.

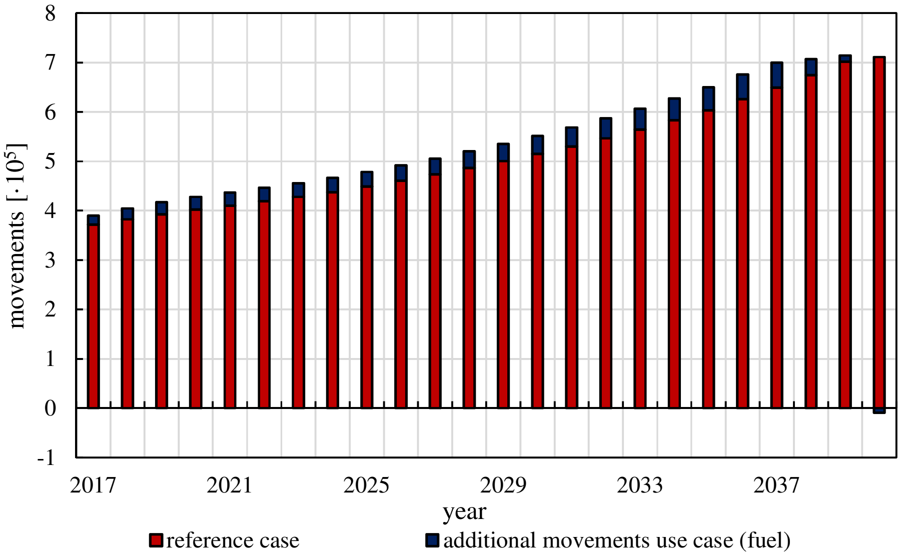

Fig. 13 Additional movements at MAD due to shifting strategies (blue) and total movements without capacity constraint (red).

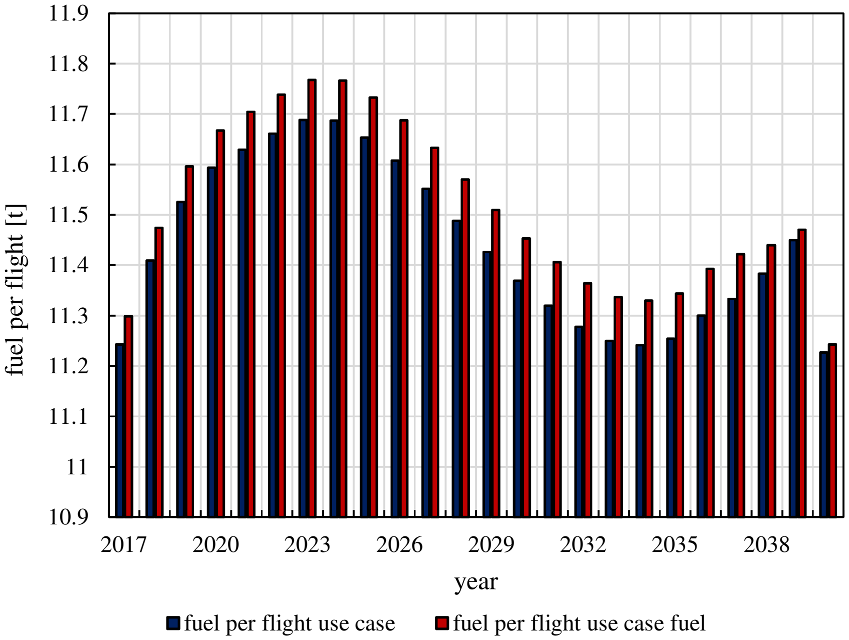

Fig. 14 Fuel burn per flight at MAD: use case (blue) and use case fuel (orange).

The above example illustrates the potentially unignorable impact of additional fuel burn due to airport shifting. It should be noted, however, that for close-by shifting alternatives additional fuel burn becomes insignificant, while for some alternatives there might be fuel savings. It will be up to each airport to consider if the extra calculation is worth the computational effort. If the user of the tool needs highly accurate results, the use of the new fuel burn module would be recommended.

V. Conclusion and Outlook

This paper presented an update with substantial modifications to the fleet model incorporating airport capacity limitations and their congestion as presented in previous work [8]. Besides debugging, these changes included a higher fidelity airport capacity development modeling, optimization of mitigation strategy use toward minimum remaining surplus RPK and a higher level of system integration. First results show congestion and amounts of surplus traffic similar to values reported in the literature. However, the implemented mitigation strategies are able to mitigate most of that surplus. The remaining surplus RPK after mitigation reaches only about two percent in 2040, when more than 100 airports are already congested. The results further show a wider spread of congestion than comparable literature. This first concerns many Medium airports without hub function, especially in Asia. Second, mitigation by shifting traffic to uncongested airports accelerates congestion at these airports. Exemplary cases for this issue were presented for Lufthansa hubs in Europe as well as for Mexican airports. Congestion mitigation by larger aircraft leads to notable changes in average seat numbers per flight. This could be traced back to a diverse set of different behaviors at different airports. The results of the presented use cases were shown to be consistent and plausible.

Basic results indicate a decrease in global fuel burn in a comparison of a congested use case with a reference case disregarding capacity limitations and their mitigation. Reasons for this are the small amounts of remaining, unaccommodated surplus movements as well as fewer flights due to use of larger aircraft at congested airports. At the airport level, however, significant increases in fuel burn per flight could be observed at constrained airports with the wide use of larger aircraft. The introduction of a new module for estimating additional distance and fuel consumption of movements shifted to uncongested airports allows for a more accurate calculation of congestion and mitigation influence on fuel consumption. This gain in accuracy, especially at the airport level, has to be traded against an increased computational effort. For different airports, the per flight fuel consumption shows a clear difference from previous results in a range up to a few percent due to significant changes in the route length of shifted movements. At the global level, however, the effects of this issue are barely notable.

In future work, further improvements are to be added to the integrated fleet model. First, different scenarios for air traffic development in general and for assumed parameters in detail have to be considered. This work depicts only one scenario out of many possible. A view of future developments without depicting the range of possible alternative scenarios, however, would not be suited for sustainable planning [30]. For example, the general post-pandemic air traffic growth should be further investigated, as this work does not account for the high uncertainties in demand development after COVID-19. Second, the ATN region of Asia especially was still identified as being defined too broadly. This led to significant inaccuracies in assigning single values for air traffic growth and airport cluster capacity values for the entire region. A higher-fidelity ATN region division, as proposed by [31] and [32], splitting up Asia into subregions, would yield the desired modeling improvement. Third and last, the current model assumes no limitations owing to OEM aircraft production capacities when using the larger capacity aircraft mitigation strategy. This, however, is neither intuitive nor in line with the fleet model, already accounting for production capacity limitations. A first solution will be to include shares of single- and twin-aisle production capacities available for quick production ramp-up if required by congestion mitigation. This wouldn't concern simple seating densifications, as these are assumed to be possible within short notice (the model doesn't account for cost aspects). Such a limitation of mitigation possibilities implies a higher amount of shifting surplus movements to uncongested airports and, ultimately, remaining surplus traffic. On a general note, the presented mitigation strategies should be investigated toward their own limits. An example is the use of larger aircraft which is constrained by the available fleet. This raises the question what the benefit of deploying even larger aircraft not used in these simulations could mean for the air transport system.

Despite these issues, this paper nevertheless introduces significant improvements to the integrated modeling of airport congestion and fleet development, for the first time making possible an assessment of additional operational parameters such as the additional fuel burn owing to congestion mitigation.

References

[1] Destination 2050, "A Route To Net Zero European Aviation," NLR, Netherlands, 2021.

[2] S. Matthes, B. Lührs, K. Dahlmann, V. Grewe, F. Linke, F. Yin, E. Klingaman, and K. P. Shine, "Climate-Optimized Trajectories and Robust Mitigation Potential: Flying ATM4E," Aerospace, vol. 7, 156, 2020. https://doi.org/10.3390/aerospace7110156

[3] S. Matthes, L. Lim, U. Burkhardt, K. Dahlmann, S. Dietmüller, V. Grewe, A. S. Haslerud, J. Hendricks, B. Owen, G. Pitari, M. Righi, and A. Skowron, "Mitigation of Non-CO2 Aviation's Climate Impact by Changing Cruise Altitudes," Aerospace, vol. 8, 36, 2021. https://doi.org/10.3390/aerospace8020036

[4] C. A. Wells, P. D. Williams, N. K. Nicholls, D. Kalise, and I. Poll, “Reducing transatlantic flight emissions by fuel-optimised routing,” Environmental Research Letters, vol. 16, 2021.
https://doi.org/10.1088/1748-9326/abce82

[5] A. Abbenius and P. Roling, “Flexible Runway Scheduling for Complex Runway Systems: Using a Multi-Objective Optimization,” AIAA Aviation Forum, Chicago, USA, 2022.

[6] M. Groot and P. Roling, “The Potential Impact of Electric Aircraft Taxiing: A Probabilistic Analysis and Fleet Assignment Optimization,” AIAA Aviation Forum, Chicago, USA, 2022.
https://doi.org/10.2514/6.2022-3919

[7] L. Tabernier, E. C. Fernández, A. Tautz, R. Deransy, and P. Martin, “Fuel Tankering: Economic Benefits and Environmental Impact for Flights Up to 1500 NM (Full Tankering) and 2500 NM (Partial Tankering),” Aerospace, vol. 8, 37, 2021.
https://doi.org/10.3390/aerospace8020037

[8] J. Michelmann, B. Gruber, F. Stroh, and M. Hornung, “Evolutionary Fleet Development Considering Airport Capacity Limitations and their Mitigation,” AIAA Aviation Forum, 2022.
https://doi.org/10.2514/6.2022-3315

[9] N. Randt, “Aircraft technology assessment using fleet-level metrics,” Dissertation, Chair of Aircraft Design, Technical University of Munich, 2016.

[10] Official Airline Guide (OAG). 2016 Flight Scedules, Available: https://www.oag.com/ (retrieved 23. September 2022).

[11] J. Michelmann and M. Hornung, “Influence and Sensitivities of Airport Capacity Limitations Modeling in Air Transport Fleet Development,” 26th ATRS World Conference, Kobe, Japan 2023, unpublished.

[12] EUROCONTROL, “European aviation in 2040 – Challenges of growth,” EUROCONTROL, October 2018.

[13] M. C. Gelhausen, P. Berster, and D. Wilken, “Airport capacity constraints and strategies for mitigation – A global perspective,” Academic Press, Elsevier, 2020.

[14] M. C. Gelhausen, W. Grimme, A. Junior, C. Lois, and P. Berster, “Clean Sky 2 Technology Evaluator—Results of the first air transport system level assessments,” Aerospace, vol. 9, 204, 2022.
https://doi.org/10.3390/aerospace9040204

[15] B. Gruber, “Investigation on the Increase in Aircraft Size as an Airport Capacity Limitation Mitigation Strategy,” Semester thesis, Chair of Aircraft Design, Technical University of Munich, Garching, Germany 2021.

[16] G. Burghouwt., “Airport Capacity Expansion Strategies in the era of Airline Multi-hub Networks,” Discussion Paper No. 2013-5, International Transport Forum, OECD, Paris Cedex, France 2013.

[17] J.-C. Düdden, “Multi-Hub Network Configurations – A Temporary or Permanent Outcome of Airline Consolidation?” Review of Network Economics, Vol. 5, Issue 4, 2006.
https://doi.org/10.2202/1446-9022.1106

[18] A. S. Karaman, “Simulating air transportation networks under capacity constraints: Transforming into a multi-hub infrastructure,” Kybernetes, Vol. 47, No. 6, pp. 1122-1137, 2018.
https://doi.org/10.1108/K-01-2017-0022

[19] P. A. Bonnefoy, R. de Neufville, and R. J. Hansman, “Evolution and Development of Multiairport Systems: Worldwide Perspective,” Journal of Transportation Engineering, 2010, 136(11): 1021-1029.
https://doi.org/10.1061/(ASCE)0733-947X(2010)136:11(1021)

[20] T. Kleinheinz, “Optimal Use of Airport Capacity Limitation mitigation Strategies within an Evolutionary Fleet Development Model,” Master thesis, Chair of Aircraft Design, Technical University of Munich, Garching, Germany 2021.

[21] M.C. Gelhausen, P. Berster, and D. Wilken, „Post-COVID-19 Scenarios of Global Airline Traffic until 2040 That reflect Airport Capacity Constraints and Mitigation Strategies,” Aerospace 2021, 8, 300.
https://doi.org/10.3390/aerospace8100300

[22] EUROCONTROL, “Challenges of Growth 2013. Summary report,” EUROCONTROL, June 2013.

[23] EUROCONTROL, “Aviation Outlook 2050,” EUROCONTROL 2022.

[24] R.Steinegger, “Fuel economy for aircraft operation as a function of weight and distance”, Dissertation, Zürcher Hochschule für Angewandte Wissenschaften, Germany 2017.

[25] Boeing, “Commercial Market Outlook 2022-2041,” The Boeing Company, USA 2022.

[26] Airbus S.A.S., “Global Market Forecast 2022-2041,” Blagnac Cedex, France 2022.

[27] F. Will, T.-O. Wunderlich, and M. Hornung, “Flight Plan Modelling with an Approach to Assess Impacts on Future Airport Noise Exposure: A Test Case,” Deutscher Luft- und Raumfahrtkongress (DLRK), Garching, Germany 2017.

[28] OECD, “Effective Delivery of Large Infrastructure Projects: The Case of the New International Airport of Mexico City,” OECD Public Governance Reviews, OECD Publishings, Paris, France 2015.

[29] Eurostat ,“Overview of EU-28 air passenger transport by Member States in 2018: passengers carried (in 1000)”, 2018

[30] J. Gausemeier, A. Fink, and O. Schlake, “Szneario-Management,” Carl Hanser Verlag, Munich, Germnay 1995.

[31] G. Tay, J. Michelmann, H. Roß, and M. Hornung, “A Quantitative Scenario-Based Fleet Evolutionary Framework for the Assessment of the Global Air Transportation Network,” proceedings of the 18th AIAA Aviation Technology, Integration, and Operations (ATIO) Conference, Atlanta, Georgia, USA 2018.
https://doi.org/10.2514/6.2018-4233

[32] G. Tay, “Applying Complex Network Theory to Technology Assessment in Early Conceptual Aircraft Design,” Dissertation, Chair of Aircraft Design, Technical University of Munich, Garching, Germany 2022.

[33] OECD, “Effective Delivery of Large Infrastructure Projects: The Case of the New International Airport of Mexico City,” OECD Public Governance Reviews, OECD Publishings, Paris, France 2015.