# Evolutionary Fleet Development Considering Airport Capacity Limitations and their Mitigation

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**Limited airport capacities pose a constraint on future air traffic growth. Although the current pandemic eased this problem for some years, with growing post-crisis air traffic it will probably return and with it the demand for solutions. This paper aims to integrate airport capacity limitations as a constraint to air traffic growth into an evolutionary fleet development model for global commercial airline fleets. Two operational mechanisms to mitigate such constraints are introduced, both leading to changes in fleet and network structures as compared to unconstrained development. The first strategy foresees the use of aircraft with larger seating capacities. The second one focuses on shifting traffic to unconstrained airports. Both strategies already find use in aviation to different extents. Finally, the actual mitigation strategy to be applied is selected via an optimization function.**

**The results of this modeling approach are shown on a global level. They indicate the buildup of significant reductions in revenue passenger kilometers, flown passengers and movements as compared to unconstrained airport capacities. In future work, the proposed methodology is intended to quantify possible effects of limited airport capacities on the air transport network and fleet. At the same time, the various assumptions made and the scenario-based nature of the model require the derivation of sensitivities toward these uncertainties.**

## Nomenclature

| | | |
|---|---|---|
| *AS* | = | Available Seats |
| *ASK* | = | Available Seat Kilometers |
| *ATM* | = | Air Traffic Management |
| *FSC* | = | Full-Service Carrier |
| *FSDM* | = | Fleet System Dynamics Model |
| *IFR* | = | Instrument Flight Rules |
| *LCC* | = | Low-Cost Carrier |
| *OAG* | = | Official Airline Guide |
| *OD* | = | Origin-Destination |
| *OEM* | = | Original Equipment Manufacturer |
| *RPK* | = | Revenue Passenger Kilometers |
| *SESAR* | = | Single European Sky ATM Research Programme |
| *TUM* | = | Technical University of Munich |

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# I. Introduction

Many aviation industry stakeholders expect air traffic to continue its growth path in the next decade after the shock induced by the COVID-19 pandemic. The growth rates, however, might be smaller as compared to pre-pandemic projections. This growth is fueled by a still rising demand for air travel, especially in regions with both strong economic growth and a growth in population, therefore holding a reservoir of new customers.

At the same time, limitations for further air traffic growth become apparent. As an example, production rates for commercial airliners might not be sufficient to cover demand. Waiting times for newly ordered narrow-body aircraft might lie in the range of some years, while OEM (Original Equipment Manufacturers) are currently struggling to align their supply chain for post-crisis production ramp-up, see for example Ryan [1]. Another field of limitations arises from the infrastructural side of the air transport system, especially from airport capacities. Accordingly, this work focuses on the effect of limited airport capacities on global air transport fleet development. To this end, airport capacity limitations are introduced into an in-house evolutionary fleet development model (Fleet System Dynamics Model - FSDM). Different strategies for mitigating airport capacity limitations are reviewed and applied. As a result, we investigate the subsequent effects on global air traffic parameters while taking into account the effects from limited production capacities. Impacts of the current pandemic are omitted, as previously expected growth in air traffic demand is foreseen to be only shifted for some years while general growth trends remain valid [2]. Gelhausen et al. [3] indicate that after recovery from COVID-19 effects, air traffic will again face similar airport capacity constraints as existed before the crisis. This paper presents the status quo of work still in progress. Its goal is not to claim any form of forecast or make detailed statements about, for example, developments concerning specific airports, but rather to shed light on general interrelationships and dependencies between airport capacity limitations and their mitigation and the global air transport system. To this end, we aim to establish a better understanding of this system's sensitivities, ultimately enhancing the estimation of the system-wide impact of the introduction of new technologies on new aircraft types. Knowledge about these systemic effects can in turn improve requirements passed back to the conceptional aircraft design process. Accordingly, we develop our approach from the viewpoint of fleet development, as opposed to, for example, the viewpoint of airports which might want to develop strategies of optimal capacity limitation mitigation for their own facility. Thus, the main underlying assumptions of this work include the infrastructure extension at airports being limited to levels not satisfying air transport demand at congested airports [4,5] and the concentration on issues directly impacting network and fleet structures. While we acknowledge the driving character of economic considerations, we omit purely economic issues. These are not within the scope of this work and would imply adding further complexity, which limits the ability to clearly work out the wanted effects.

In the following, Section II describes the state of the art of the different building blocks of this research, including the fleet model, airport capacity limitations and their mitigation. Section III introduces the chosen modeling approach and Section IV shows the investigated test cases. Finally, Section V gives a short validation and discusses the results and limitations of the test cases, leading to further action points depicted in the conclusion.

# II. State of Affairs

The literature review starts with a description of studies with a similar field of research. Thereafter, we depict the state of the art in the different research fields contained in this work starting with the basic evolutionary fleet development model FSDM and continuing on airport capacity limitations and their mitigation.

## A. Airport Capacities in the Fleet Modeling Context

Similar studies investigating the influence of airport capacity on global fleet development are rare to find. According to their scope, they take different views on the problem field. Furthermore, they often quantify a range of demand unaccommodated due to capacity restrictions and thus estimate their influence on air traffic growth.

This work follows research on airport capacity influences on various elements of the air traffic system conducted for several years at the Technical University of Munich (TUM). Böck [6] investigated the interrelations of aircraft parameters and airport capacities. By setting up simulation tools for specific airports, he estimated the influence of the introduction of new aircraft types on these airports' capacities [6]. Öttl [7] extends this view to a global influence analysis of new aircraft concepts on runway capacity. He mapped the variety of different airport types via a cluster analysis and depicted the range of possible air traffic developments at these airports through various scenarios [7].

EUROCONTROL [5] gives a comprehensive overview of air traffic growth scenarios for the year 2040, showing the implications of airport capacity limitations at European airports in the form of unaccommodated traffic demand and movements from the view of an ATM (Air Traffic Management) service provider. The report estimates 8 % of unaccommodated demand or 1.5 million unaccommodated flights in the year 2040 for the growth scenario deemed as most likely, while numbers for the scenario with strongest growth even exceed these values [5]. The study makes use of data on airport capacity expansion plans available to EUROCONTROL as network manager. In contrast, similar data for global airport expansion assessment is not available to the study at hand. Furthermore, EUROCONTROL considered the impact of various capacity limitation mitigation strategies on the aforementioned results, including local alternative airports, larger aircraft and measures related to SESAR (Single European Sky ATM Research Programme) [5]. Those considerations, however, included no investigation of the respective underlying mechanisms.

Gelhausen et al. [4] describe a comprehensive modeling approach for identifying airport capacity constraints on a global level. They show that although such limitations only exist at a few airports worldwide, those airports belong to the most important hubs, which handle a significant share of global air traffic. Possible mitigation strategies are also viewed in detail, concentrating on the expansion of airports and the utilization of larger capacity aircraft. Many modeling steps thereby use statistical methods. The authors, rather, follow an airport view, giving recommendations on optimum mitigation strategies for specific types of airports depending on airport parameters such as aircraft movements and average aircraft size [4].

This work transfers the introduction of air traffic bottlenecks due to capacity constraints into an evolutionary fleet model. Accordingly, we take a different viewpoint on the problem field and follow an approach centered on fleet development aspects and the influence of mitigation strategies on the fleet mix.

### B. Fleet Development Model FSDM

This section gives an introduction to FSDM, the evolutionary fleet model of the Chair of Aircraft Design at TUM. For further details please refer to the work of Randt [8]. The tool is implemented in Matlab, although its name bears reference to its origin in a system dynamics environment. Recently, the model was used in the works of Tay [9] and Scholz et al. [10], e.g., for investigating the development of fleet structures and aviation emissions when introducing hybrid electric aircraft as compared to a completely conventional reference fleet. In the following, we give a short overview of the FSDM's functionality in its current basic version, starting with Fig. 1 which displays the basic program sequence.

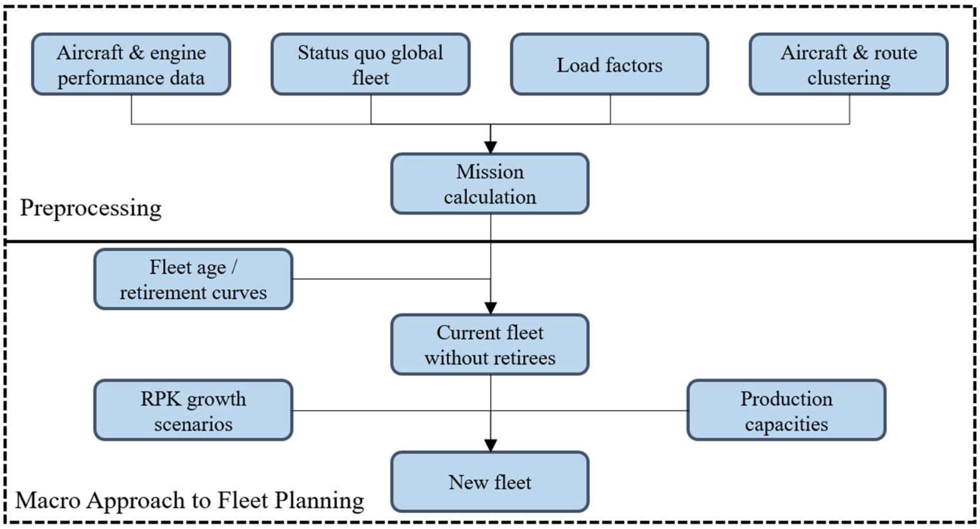


**Fig. 1 Basic program sequence of current FSDM, adopted from [8] and [10].**

The FSDM uses aircraft type and route clusters (route groups) in order to reduce complexity. Thereby, aircraft clusters depict current aircraft types as well as new technology aircraft, which are introduced in the course of later simulation years [8]. Route groups connect different regions or represent intraregional flights. In a preprocessing step, a mission calculation for the aircraft representing the clusters determines the fuel burn of those clusters on their respective missions. Data for route length as well as passenger and freight capacity are retrieved from the OAG 2016 database [11]. Further inputs for the mission calculation include aircraft performance data as well as passenger and freight load factors (see e.g. [12]).

The FSDM itself simulates the annual fleet development up to a simulation end year specified by the user. Thereby, the fleet development follows the Macro Approach to Fleet Planning [8]. This approach will not be elaborated on further, the interested reader is referred to [13] for a comprehensive description. The FSDM bases the fleet introduction of additional aircraft on an approach of fuel burn optimization. The fuel burn per ASK (Available Seat Kilometers) is calculated for each combination of route group and aircraft cluster. Preferably aircraft from the cluster with the lowest such value are introduced into the fleet. Fleet retirements follow given retirement curves as described in [8], which were updated for the influence of the current pandemic crisis on fleet retirement of current aircraft types [14]. The fleet growth is derived from input RPK (Revenue Passenger Kilometers) growth rates based on demand growth scenarios. These can either be given by forecasts, as typically published by various aviation stakeholders (see e.g., [2] or [15]), which might, however, only represent views of that stakeholder, or by own scenarios as shown by Randt [8].

The final calculation of the fleet development in respective simulation years can, according to user input, incorporate a limitation to air traffic growth in the form of limited OEM production capacities for narrow-body and wide-body aircraft. The resulting fleet is depicted on the level of aircraft clusters operating on route groups. The FSDM, thus, is able to perform global analyses of air transport development as well as to give indications on a regional level. Precise information, e.g., on the development of fleet structures and flight frequencies on specific routes, cannot be given. Furthermore, the scenario-based setup of the FSDM enables the impact evaluation of different input settings on the global aviation system. Forecasts, however, are not intended to be developed with such a tool.

### C. Airport Capacity Considerations

As mentioned above, with airport capacity limitations we add a further constraint on air traffic growth to the fleet model. In this section we focus on a short review regarding airport capacity calculations before the subsequent section introduces airport capacity limitation mitigation strategies (in the following "mitigation strategies") in more detail.

Although very specific conditions apply for each individual airport, their capacities are most often limited by the runway system [4,16]. Therefore, in this study the airport capacities are defined by runway capacities. Different methods exist for their calculation, depending on the desired level of abstraction. If very detailed operational investigations of airports and the surrounding airspace are aimed at, simulation programs usually deliver quite precise results. An example for that is Simmod [17]. Such a level of detail is not necessary for the work presented in this paper. In addition, simulations would be time-consuming to set up and would require individual configuration data for each airport. A more general calculation can be pursued by analytical runway capacity estimation methods, as first formulated by Blumstein [18] and further developed by Harris [19]. These methods mainly depend on parameters such as the runway configuration, fleet mix, operational sequence, and approach, as well as climb speeds. These models are especially suitable for simple runway layouts like single runways or parallel independent runways and can easily be used for calculating infrastructural capacities of underutilized airports. However, they reach limits when dealing with complex runway layouts, such as those which are often found at some of the most frequented airports in the world. In these cases, a calculation methodology based on operational data, which does not require the detailed analysis of a complex runway system, might be more suitable. Here, the flight frequencies of an airport under investigation are usually analyzed under the assumption that the airport has reached its capacity limits at least during a specific time interval. Examples for such calculations, often using OAG data, can be found in Gelhausen et al. [4] or, in a more general form for determining the degree of capacity utilization, in Schinwald [20].

### D. Airport Capacity Limitation Mitigation Strategies

Various options for the mitigation of airport capacity limitations can be found in literature. Such strategies range from operational improvements in the current air transport system, only accounting for the symptoms of capacity limitations, to strategies implying changes in fleet and network structures. In this work we cannot give an exhaustive list of all proposed measures, the interested reader might be referred to Gelhausen et al. [4] for an extensive literature review on proposed mitigation strategies as well as their expected impact. They distinguish measures requiring considerable investment into infrastructure, such as airport expansions and high-speed rail systems, from those requiring no infrastructure investments [4]. In the following, we refer to some of these measures in order to motivate the choice of investigated mitigation measures in this study.

Due to the basic assumption of expected infrastructure expansion in general not being sufficient to cover growth in air traffic demand, this option is not considered in detail as a mitigation strategy in this work. It is rather accounted for by airport capacity growth factors. Operational measures include, for example, improved ATM procedures and changes to wake turbulence separations. The latter category is widely covered in literature, for example by Kolos-Lakatos [21], who investigated the airport capacity benefit of various such measures for the busiest airports in the U.S. This included the re-categorization of aircraft into a higher number of wake turbulence categories (RECAT) and the adoption of pairwise separation minima depending on the specific aircraft type. The results show significant capacity benefits up to about 30 %, while also accounting for limitations such as limited benefits of a too high number of wake turbulence categories or the increasing relevance of runway occupancy times [21]. Further studies in this field examine the impact of single measures on specific airports, such as Sekine et al. [22] for the benefits of RECAT for runway capacity at Tokyo Haneda airport. However, the projected high, long-term air transport demand growth mostly surpasses these measures' capabilities to enhance airport capacities [4]. The same is true for the strategy of filling off-peak times at hub airports. However, at some hubs such a strategy might already be used and exhausted, while at others airlines refuse it due to scheduling constraints. This questions its suitability for a long-term relief of capacity limitations. Finally, regulatory intervention is a way of influencing airport capacity utilization. This type of measure comprises many different types of regulations, often depending on regional aspects. For example, schedule coordination is widely used in Europe [16], whereas airports in the U.S. are often facing significant resistance to measures such as congestion pricing schemes, as shown for different examples in [23]. The findings of Givoni and Rietveld [24] and Pai [25] indicate that slot control might not always lead to the use of larger aircraft and a subsequent reduction of frequencies, but could have opposite effects as hub airlines try to secure market share. Furthermore, the capacity situation of many slot-controlled airports, e.g., in Europe, hints at this system not being able to satisfy air traffic demand in the long-term, but rather to manage the symptoms of a tense capacity situation [26]. The same counts for rising load factors, which in pre-COVID times might already have reached levels hard to increase further [4]. Finally, pricing and regulative measures would not directly influence this study's key parameters of the fleet mix and air transport network, and are thus omitted.

We therefore focus on two mitigation strategies directly connected to the aforementioned parameters. These are the use of aircraft with higher passenger capacity and the shifting of traffic to underutilized airports. At many airports recent decades brought a rise in the average seat numbers per flight (see, e.g., the work of Will et al. [27]). The increase in aircraft size is one reason for the number of air traffic movements growing much slower as compared to air transport demand [4], at least delaying capacity constraints at some airports. Berster et al. [28] unveiled direct links between aircraft size increase and capacity utilization at airports using statistical analysis. While airport capacities are not the only factor affecting the increase of average aircraft capacity over the past decades (see extensive literature research in [3] and [4]), they still play an essential role.

Shifting of traffic from capacity-limited to underutilized airports is also often used to mitigate capacity limitations. However, it has much broader reasons and implications than just the capacity aspect. This strategy is often disputed as being accompanied by additional costs and customers not willing to transit to another airport at a more inconvenient location [4]. Still, there are indications that different variations of this strategy are already used by airlines. Therefore, in this study, this mechanism is being investigated as a mitigation strategy with potentially considerable impact on network structure and fleet mix. We distinguish between traffic shifting from hub and non-hub airports. Accordingly, different shifting options can be seen in the real world. These include Multi-Hub and Multi-Airport Systems. A Multi-Hub System denotes the strategy of a hub carrier focusing operations on at least two hub airports. While being contradictory to the advantages of economies of density sought by single-hub operations [29, 30], various Multi-Hub Systems are in operation today, for example Lufthansa Group's system with hubs in Frankfurt, Munich, Zurich, Vienna, and Brussels. Such systems often emerged through consolidation in the airline industry. Burghouwt [29] gives an overview of the reasons for airlines operating Multi-Hub Systems. Besides economic factors, capacity constraints at primary hub airports are most often named as such by various authors [29, 30, 31]. A Multi-Airport System describes a set of airports in spatial proximity to each other, serving the same market. Usually, such systems are neither required to include a hub airport, nor do smaller airports receiving shifted traffic take over any hub functions. This is well described in Bonnefoy et al. [32], showing that smaller airports in such systems often emerged due to use by Low-Cost Carriers (LCC) and the share of such carriers in general well exceeds the one of Full-Service Carriers (FSC). This is in contrast to the bigger system airports with only low shares of LCC service [32]. The basic concepts for the implementation of these two alternatives as mitigation for capacity limitations in fleet modeling are elaborated on in the following section.

## III. Methodology

The aforementioned capacity limitations at airports are to be introduced into the FSDM as a further restriction to air transport growth. Significant differences in simulated fleet structures as compared to a case neglecting the influence of airport capacities are expected, especially by the parallel implementation of mitigation strategies. Due to the complexity of the involved airport-related considerations and interdependencies with elements of the FSDM requiring feedback loops, the fleet model itself will only be an integrated part of the overall model.

### A. Airport Capacities and Clustering

For the introduction to the FSDM, baseline airport capacities and their utilization are determined for the simulation start year 2016. In this step a mixed calculation method containing elements of the aforementioned analytical and operational data-based methodologies is used. The airport capacities are determined analytically [16,18,19] as practical hourly capacity in IFR (Instrument Flight Rules) conditions. Complex airport layouts are treated as a composition of multiple simpler runway layouts. This results in an error for these airports which is, however, accepted as rough estimates in this study. The hourly utilization is the ratio of movements and capacity. For our calculations, the hour with the $30^{th}$ highest utilization is selected.

While airport capacity growth usually does not cover demand growth in many world regions [4,5], a part of additional demand can still be accommodated by extended infrastructure. Investigating this infrastructure growth specifically for every single of the 4000 airports in the OAG 2016 database [11] would be too work-intensive considering the system level-view of the fleet model. Furthermore, data on planned capacity increases is only available for a few airports worldwide. Thus, the airports are divided into six groups by clustering according to three parameters, as described by Richter [33]. One clustering parameter covers the airports' absolute size in the form of the total number of available seats (AS). The other two, the long-haul share and hub-factor, describe the airports' function in the air transport network. The long-haul share relates the share of long-haul movements to the total number of movements at the airport. Long-haul is defined as any route length over 4000 km following EUROCONTROL [34]. The hub-factor, as introduced by Braatz [35], is the ratio of the number of connections the investigated airport offers to the average number of its neighbors' connections. A clustering solely based on airport size parameters would yield misleading results, since size and network function are not clearly coupled, owing to regional network differences. The resulting airport clusters are shown in Table 1, including the medians of the clustering parameters per cluster.

**Table 1 Airport clusters and medians of cluster parameters per airport cluster, from [33].**

| Airport Clusters | Total number of AS [-] | Long-haul share [%] | Hub-factor [-] |
|---|---|---|---|
| Global Hub Airports | 75,493,000 | 13.39 | 2.7104 |
| Big Airports | 31,838,000 | 3.33 | 1.9853 |
| Medium Airports | 7,395,950 | 0.51 | 0.8456 |
| Long-haul Airports | 2,549,100 | 19.91 | 0.4116 |
| Regional Airports | 894,090 | 0.00 | 0.1592 |
| Small Airports | 41,567 | 0.00 | 0.0744 |

Hub airports are found in the clusters of Global Hubs and Big Airports, exhibiting high values of all three clustering parameters and depicting the world's largest and best-connected airports. Big Airports, with lower long-haul share and hub-factor compared to Global Hubs, also include large airports without distinct hub function. While Medium and Regional Airports are self-explanatory, Long-haul Airports have the highest long-haul shares and low hub-factors indicating marginal regional connectedness, which stands in contrast to hubs. Examples of such airports are holiday destinations in the Caribbean, served by a high share of long-haul holiday connections from Europe. Most airports fall into the category of Small Airports. These, however, are usually omitted for further investigation because of their small available seat numbers and their infrastructure which is often insufficient for regular operation of commercial airliners. For a more detailed description of the airport clusters, the reader is referred to Richter [33].

For the further study of infrastructure growth, infrastructure growth factors for every airport cluster are retrieved from literature. In future work scenarios will be developed for infrastructure capacity growth on airport cluster-level in different world regions. Now airport capacity limitations can be defined and added as a constraint to air traffic development in the FSDM. This follows two steps: First, the capacity reserve of all airports is determined on an annual basis, taking into account the current capacity utilization and air traffic demand increase as well as the infrastructure growth factor of the relevant airport cluster [33]. Second, if the airport capacity is exceeded as a result, the corresponding amount of surplus traffic which cannot be handled is calculated [36].

### B. Airport Capacity Limitation Mitigation Strategies

This surplus traffic represents the unaccommodated demand, compare e.g., with EUROCONTROL [5]. Thus, the question arises of how to avoid lost revenues due to unaccommodated demand, leading to the topic of mitigation strategies. As a result, as elaborated in Section II.D, this paper focusses on the two mitigation strategies of utilizing aircraft with a higher passenger capacity and shifting traffic to an unconstrained airport. The following sections describe the implementation of capacity limitations and the two mitigation strategies into the fleet development model FSDM, starting with the resulting program structure.

#### *1. Integration into the FSDM*

The basic submodels of the accordingly updated FSDM are shown in Fig. 2. A program run starts with preprocessing steps, including processing of OAG data, mission calculations for fuel burn estimation and the determination of network metrics. The following integrated model covers the program loop passed for every simulation year. It is started by the clustering model, allocating airports to predefined airport clusters and identifying Multi-Airport Systems at the start of the simulation. The fleet model comprises the functionality of the current FSDM as described in Section II.B (compare with Fig. 1). Finally, a development model is added, integrating airport capacity limitations and the two abovementioned mitigation strategies.

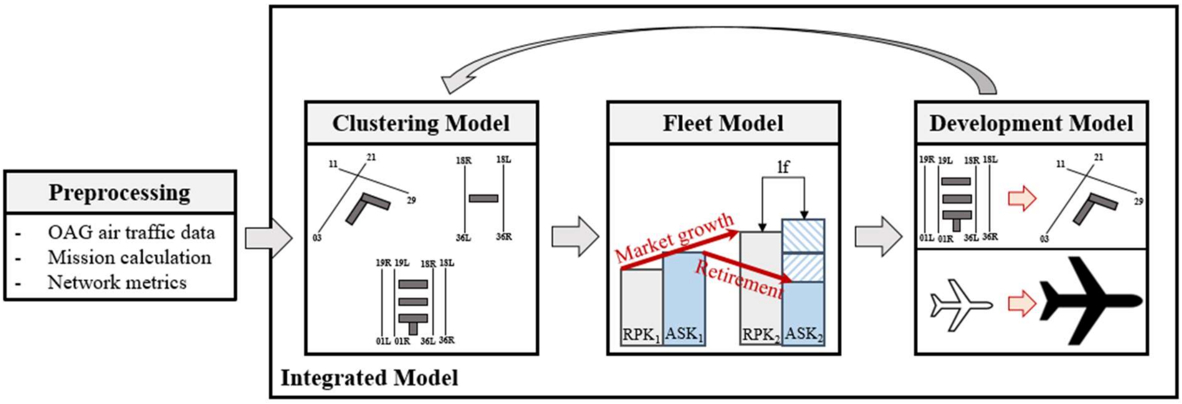


**Fig. 2 Basic updated FSDM program structure.**

This development model is shown in more detail in Fig. 3. It first updates traffic metrics according to the results of the fleet model in Model 1. Then Model 2 determines neighboring airports which lie in the catchment area of a constrained airport but are not part of a Multi-Airport System. This step is required as input for Model 4. Model 3 determines possible surplus traffic at airports according to the different airports' capacities and their utilization. Model 4 introduces the first mitigation strategy by calculating the number of movements that can be shifted to other airports in the form of a "shifting potential". Model 5 deals with mitigating capacity limitations by the use of aircraft with higher passenger capacity, calculating a "larger aircraft potential". Both potentials are fed into Model 6, which searches for an optimum utilization of these mitigation strategies by following a two-step single-objective optimization. First, the mitigation should satisfy as much of the surplus air traffic demand as possible. Different solutions might equally fulfil this requirement. Therefore, in a second step, the solution implying the lowest fuel-burn is identified [37]. With this information, the extent of use of the mitigation potentials is determined for different route groups and airports.

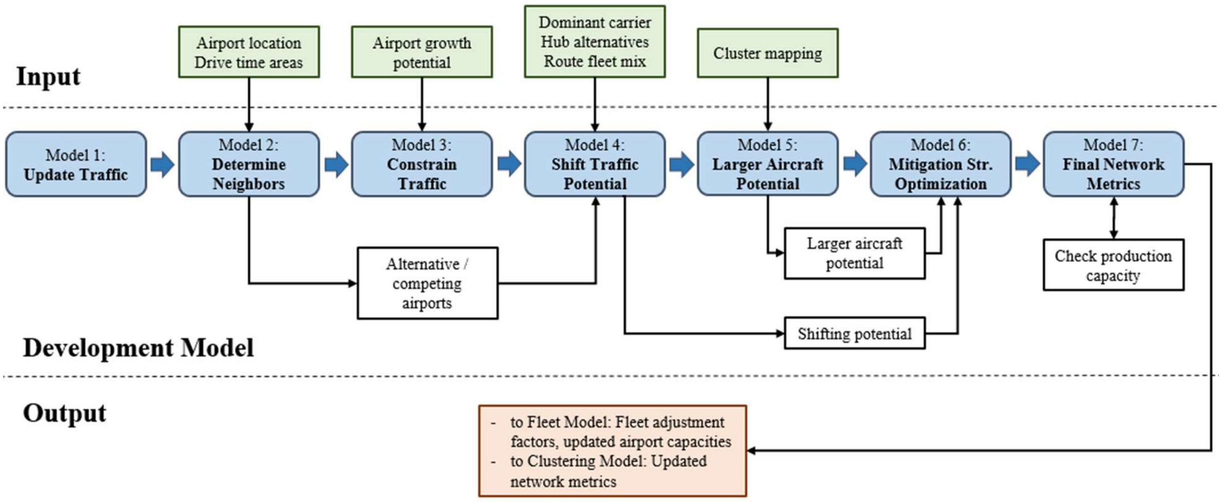


**Fig. 3 Basic development model program structure, adopted from [38].**

The application of Models 4 and 5 leads to a different use of aircraft production capacities. This requires the update of those production capacities and, consequently, a feedback loop to the fleet model. Furthermore, for both mitigation strategies, the capacities for the affected airports have to be updated due to possible changes in the fleet mix and the corresponding wake turbulence separation minima. This is achieved by a simple analytic estimation of the capacity change for a single runway [38] servicing only arrivals. The calculation follows the typical analytical path as described by de Neufville and Odoni [16], based on wake turbulence separation minima and aircraft approach speeds. The approach sequence is assumed to start with the slowest aircraft cluster and to end with the fastest, resulting in the omission of opening cases. As the reference point for the capacity calculation is the runway threshold, closing cases are disregarded either. With these assumptions we can calculate the time required for every movement to land at the airport and subsequently the time for the total fleet mix. This calculation is done twice for each relevant airport—once before applying mitigation strategies ($t_{total,old\ fleet\ mix}$), and once after applying them ($t_{total,new\ fleet\ mix}$). The resulting ratio allows calculation of the new airport capacity ($capacity_{new}$) from the old airport capacity ($capacity_{old}$) according to the following equation [37]:

$$capacity_{new} = capacity_{old} \cdot \left(1 + \left(1 - \frac{t_{total,new\ fleet\ mix}}{t_{total,old\ fleet\ mix}}\right)\right) \tag{1}$$

This simplified approach is justified since it delivers a method usable for all airports for a rough estimation of the impact of fleet mix changes. However, that update will only be introduced in the following simulation year, implying a small but acceptable simulation error. The following sections further detail the two mitigation strategies.

*2. Shifting of traffic to unconstrained airports*

The first mitigation strategy describes the shifting of traffic from a capacity-constrained airport to an unconstrained airport. It differs from the general description in Section II.D with local non-hub alternatives also being taken into account as shifting alternative in addition to pure Multi-Airport Systems. To understand which local alternative airports are available to a congested airport, a logic must be created to find the neighboring airports. This step takes place in the Determine Neighbors sub-model (Model 2 in Fig. 3). Thereafter the calculation of the shifting potential follows according to the two different variations of this strategy introduced in Section II.D.

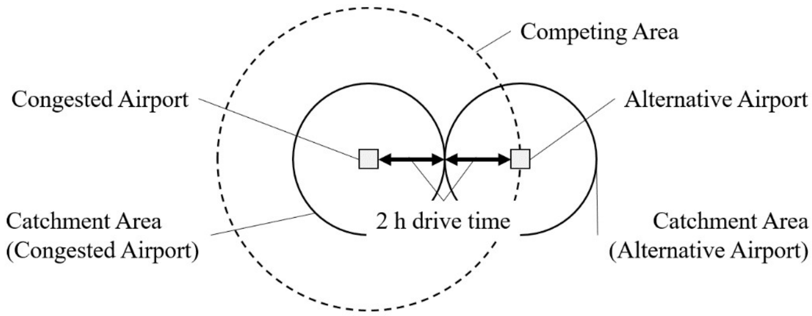


**Fig. 4 Catchment and competing areas for constrained and alternative airport. Circular shape for illustrative purpose, adopted from [37].**

The determination of nearby alternative airports searches for airports competing with the congested airport for local demand. Thus this process step involves the definition of a competing area where the airports involved compete for passengers, representing their market power. This area is based on the catchment areas of congested and alternative airports. Figure 4 illustrates the distinction between the two areas. For calculating catchment areas, drive time areas of about 2 h around an airport are often used in literature [39], which is also followed in this work, using the ArcGIS Drive-time Areas Tool [40]. Compared to a static radius around an airport, this has the advantage of accounting for local differences of airport accessibility [39]. Regional differences in the validity of the drive time area definition and their development over time [39] are beyond the scope of this work. Due to high computational costs, drive time areas could only be calculated for the world's 189 largest and most congested airports. The remaining airports are significantly less likely to require capacity mitigation at all, justifying the simplified use of a radius of 200 km for catchment area definition. While alternative airports may not necessarily lie within the catchment area of the congested airport, they can still compete with it. This situation is illustrated by Fig. 4, showing that a passenger living at the point where both catchment areas meet, thus has an equal choice for the two airports. Consequently, the drive time defining the competing area is double the drive time defining the catchment areas.

The tasks of the Shift-Traffic Potential sub-model are to now find all possible alternative airports and to recommend which of those are most attractive to shift traffic. Attractivity in this sense means the best combination of high market share and capacity reserves of all alternatives. The market share of a local alternative airport is based on the total number of seats offered at an airport and takes into account all airports in the competing area. The market share of hub airports describes the ratio of movements of the hub carrier at the alternative and at the congested airport to ensure a high connectivity level at the alternative. Other factors, such as accessibility, play no role in the calculation owing to lack of data for all airports. [37]

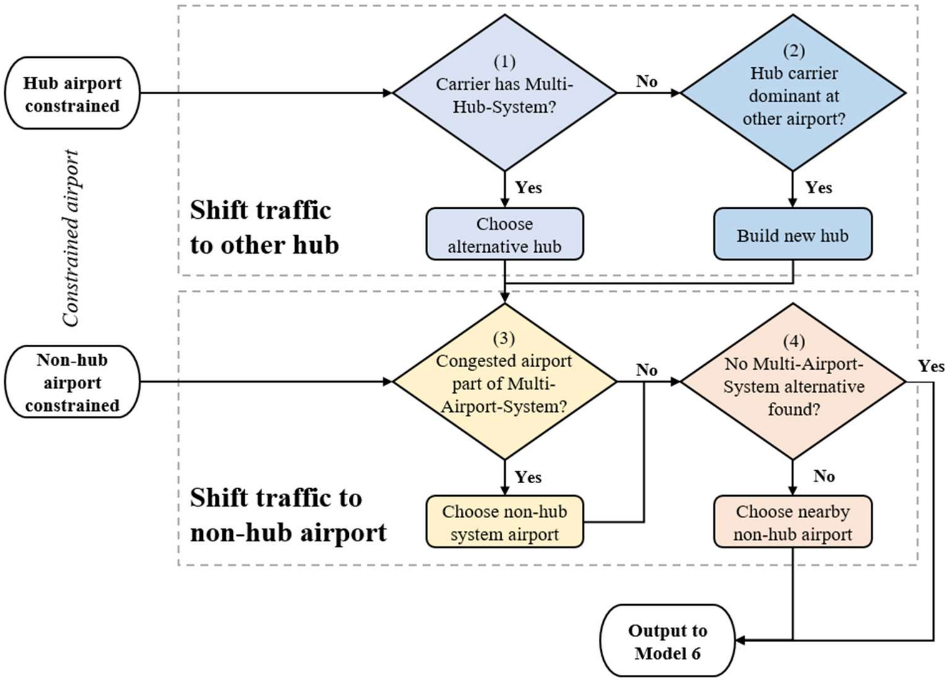


**Fig. 5 Structure of the Shift Traffic Potential model, adopted from [37].**

Figure 5 presents the two abovementioned options for traffic shifting implemented in our model, depicting Model 4 of the development model (Fig. 3). The first shifting alternative deals with shifting traffic to other, unconstrained hub airports, being rather suited for hub carriers. Thereby, it is assumed that passengers affected by this shift only intended to use the respective airport as a transfer hub. That means that ideally, they do not suffer from any notable disadvantage in travel time or comfort due to the shift. The traffic structure moved to alternative hubs resembles the traffic structure of the hub carrier at the congested airport. The second alternative, shifting traffic to a non-hub airport, clearly targets passengers who have their origin or destination at the affected airport. It is assumed that the shift to an airport in close proximity would likewise not impair their travel plans. This second alternative also includes Multi-Airport Systems as described above. In any case, it would be the decision of airlines to choose such a shifting method, also based on economical reasoning beyond capacity considerations and the acceptance of possible losses in market power at important airports. These factors are, however, beyond the scope of this study.

Kleinheinz [37] introduced both methods into the FSDM, building on preceding work of Önder [41]. In total, four possibilities of shifting traffic from a capacity-constrained hub to other, unconstrained airports emerge from these considerations [37], as shown in Fig. 5:

(1) A carrier moves traffic to another of its hubs within a Multi-Hub-System.
(2) A carrier builds a new hub at an airport where it already has a strong presence. Such a situation arises, e.g., in case the hub airline has no other (uncongested) hub airport.
(3) Airlines move traffic to another non-hub airport inside the same Multi-Airport-System. A Multi-Airport-System comprises several airports in the same metropolitan region and being not further apart than 80 km.
(4) Choose an alternative non-hub airport within the congested airport's competing area and not being part of the congested airport's Multi-Airport-System.

If the congested airport is not a hub airport, the first two alternatives are omitted. The decision of whether an airport can be classified as hub follows information on the airport cluster it belongs to, the existence of a dominant carrier at this airport with a movement share ≥ 20 % and a high share of long-haul flights. The airports of the Global Hub cluster can be used directly as hubs, except for Los Angeles International Airport. Contrary to the typical nature of a hub, this airport offers a high proportion of OD (Origin-Destination)-flights and has more than two major network carriers which all equally compete for market share [42]. In case the congested airport is part of the Big and Medium Airport clusters and is the largest airport by number of seats in its country, the airport is also classified as a hub. The same is assumed, if the congested airport is its country's biggest airport, but a member of the Big Airport cluster with the share of flight movements by a major network airline exceeding 20 % and the long-haul share exceeding 4 %. Therefore, the largest network airlines and their countries are defined in the input. All congested airports not fulfilling these criteria are not determined as hubs because they are only serving a regional or purely leisure market. In total, a maximum of two alternative airports are chosen for subsequent optimization. One airport alone might not have sufficient capacity to shift traffic, while more than two alternatives would potentially imply shifting traffic to rather unattractive airports, which is not the intention of the Shift-Traffic Potential sub-model. [37]

Several limitations to this approach exist. First, traffic can be shifted only to specific airport clusters, depending on the cluster of the congested airport. Thus, the aim is to avoid unrealistic traffic structures at some, especially small, airports. Regional peculiarities are also considered when it comes to the formation of Multi-Hub Systems, depending on geographical factors (hubs at the east or west coast of the U.S.) and airline alliances (for example, Lufthansa Group or IAG hubs). Finally, the congested airport determines the structure of shifted traffic, which has an equal fleet and route mix to the congested airport. In case of hub airports, this resembles the operations of the hub carrier shifting traffic, otherwise the traffic mix is similar to the OD-traffic at the congested airport. As a limitation to this approach, owing to infrastructural constraints, Regional Airports can only receive wide-body aircraft clusters already serving the airport. [37] Effects of changed fleet structures on the airport capacity are considered according to the manner described in Section III.B.1.

*3. Use of aircraft with higher passenger capacity*

In this paper we use two different ways to implement increases in passenger capacity per flight: the use of larger aircraft types, and the densification of seating on current aircraft types. This approach was implemented by Gruber [38], thus the following section is derived from [38].

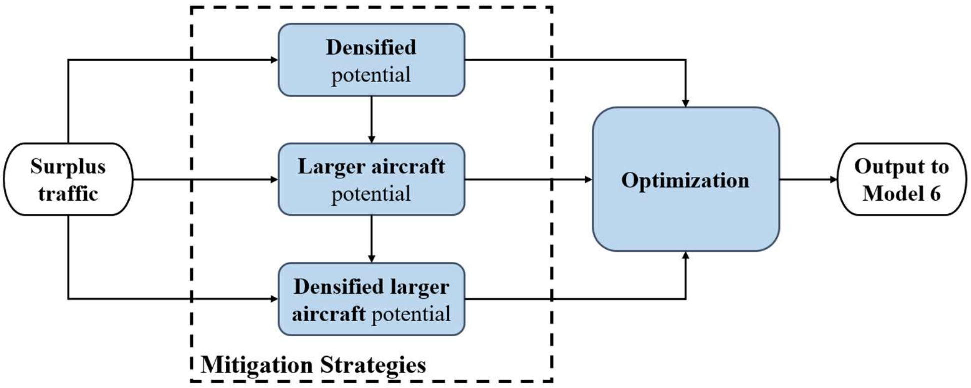


**Fig. 6 Structure of the Larger Aircraft Potential model, adopted from [38].**

The implementation of this mitigation strategy into the FSDM is conducted within Model 5 of the development model (see Fig. 3); the corresponding program structure is shown in Fig. 6. The densification adds seats to the cabin of an already existing aircraft cluster. The second method of using larger aircraft is implemented by allowing the FSDM to switch a current aircraft to the next larger one, retaining the current route distance and flight frequency. Finally, this type of larger aircraft can receive a densified seating arrangement. A densified aircraft cluster can also be upgraded to a larger aircraft cluster, which in turn can be densified. The extent of use of this strategy's variations is determined by a two-step single-objective optimization, similar to the one in Model 6 of the development model. Other factors, economic for example, which might drive an airline to increase seat capacity on a flight (see e.g., [25]) as well as market-driven effects on singular routes are beyond the scope of this simplified model.

The number of movements to be upgraded is correlated to the seat ratio, i.e., the ratio of upgraded seat capacity to current seat capacity (SNOR). Fig. 7 shows this correlation. For a seat ratio of 1.2 and a surplus of 300 movements, at least 1500 movements must be upgraded. This implies that this number of movements must be serviced at the airport. If the airport has less movements than the needed number, the surplus cannot be fully mitigated, resulting in a remaining surplus. The upgrade to a larger aircraft relates to a change in fuel consumption. There could be an increase or decrease in fuel efficiency per flight and seat, depending on the upgrade.

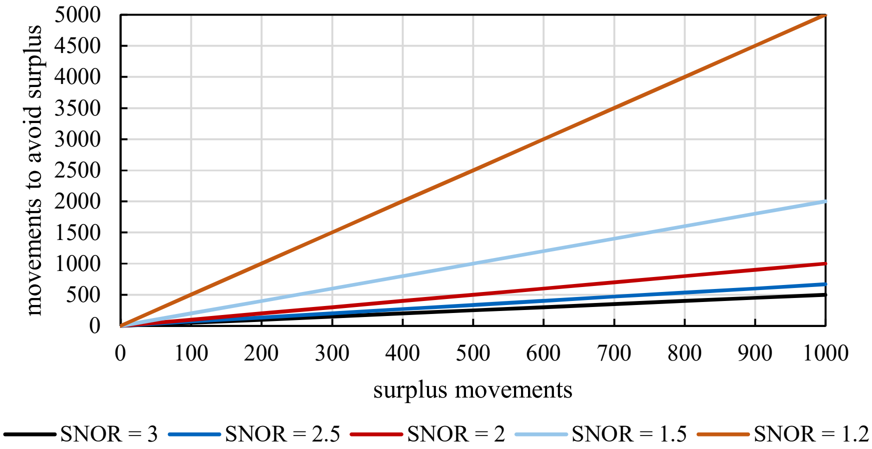


**Fig. 7 Movements needed to avoid surplus for different seating configurations.**

Fig. 6 shows the implementation of the Larger Aircraft Potential's variations. Switching a current aircraft to the next larger one retains the smaller cluster's route distance and flight frequency while increasing the seat capacity. Thus, a new mission calculation for the larger aircraft cluster needs to be performed. This upgrade only considers the next larger aircraft size category. Due to the definition of the aircraft clusters, several aircraft clusters can belong to this larger size category. Thus, the aircraft cluster with the lowest fuel consumption per seat kilometer is selected. If two or more aircraft clusters have the same fuel consumption, the newer type of aircraft is chosen. Taking the infrastructural limits of the considered airport into account, it is assumed that the current largest aircraft cluster at the airport describes the maximum possible size of an aircraft for this airport. Most of the congested airports are large hub airports accommodating all possible aircraft sizes. Therefore, this assumption only affects small and medium airports, where such a limitation is reasonable. The use of larger aircraft is typically connected to higher fuel consumption. So, this approach increases the total fuel consumption for the selected route. The upgrade to a larger aircraft category in general, for example from a narrow-body to a wide-body aircraft, increases the fuel consumption per seat kilometer, while a decrease can again be achieved through the use of a newer technological standard.

The densification of seating arrangements is implemented by increasing the number of seats per aircraft. Thus far this has been given by OAG data on a per-route group basis, up to the highest value existing for the respective aircraft cluster on any route group. This follows the assumption that the resulting number of seats can in any case be realized on the respective aircraft. New technology aircraft clusters feature only one value for the seating capacity on all route groups in the basic simulation case. Within an assumption, this value is increased by 20 % for seat arrangement densification, roughly resembling the average addition rate of seats for current aircraft clusters. In the model, seating densification can be applied only once to an aircraft cluster. The densification is considered as a cost-free approach since the model assumes that the fuel consumption does not change compared to the undensified cabin. This is achieved by an equal loss in cargo capacity if more passengers are seated in the cabin.

Combining the two previously mentioned approaches results in a larger densified cabin. This yields the highest possible capacity increase, followed by the upgrade to a larger aircraft and with cabin densification as the method with the least added capacity. All three variations are simulated to find the best possible way to apply larger aircraft capacities. Then, a two-step linear optimization is conducted, similar to the optimization process for selecting overall mitigation strategies. In the first step, the methods are optimized regarding the highest possible surplus avoidance. The second step optimizes the results toward lowest fuel consumption. Since the upgrade to larger aircraft requires the usage of new aircraft, the production capacities of single-aisle and twin-aisle aircraft is used as a constraint. Furthermore, only one of the three mentioned methods can be applied to a route at one time. The optimization process ensures the selection of the approach with the highest surplus avoidance by minimizing additional fuel consumption.

*4. Optimization of mitigation strategies*

After defining shifting and larger aircraft potential, the optimum combination of these two mitigation strategies has to be identified for each airport. Therefore, the same optimization process is used, as applied for the larger aircraft capacities. The two-step linear optimization finds the maximum surplus avoidance at minimal fuel consumption. Both mitigation strategies can be applied at the same airport. Depending on the needed surplus avoidance, different shares of larger aircraft capacities and traffic shifting can occur at the same airport. If both mitigation strategies do not have enough potential to completely solve the capacity problem, unaccommodated demand is left as remaining surplus.

## IV. Test Cases and Simulation Results

With this paper describing work in progress, only the following three cases could be analyzed so far with the proposed model, based on OAG 2016 data [11] and simulating fleet development up to the year 2050:

1) *"unconstrained case"*: fleet model without limitation in annual infrastructure growth
2) *"basic case"*: fleet model with basic limitation of annual infrastructure growth
3) *"75 % airport growth"*: (limited) annual infrastructure growth reduced to 75 % of basic case values

The two constrained test cases 2 and 3 both include the use of the implemented mitigation strategies. The goal of the test cases is to get a first indication of the resulting effects of the modeled airport capacity limitations on simulated air traffic development. Furthermore, changes due to variations in infrastructure growth are also investigated. Airport infrastructure growth factors for the basic case are derived from the work of van Rest [36]. The results of these test runs on a global scale are described in the following.

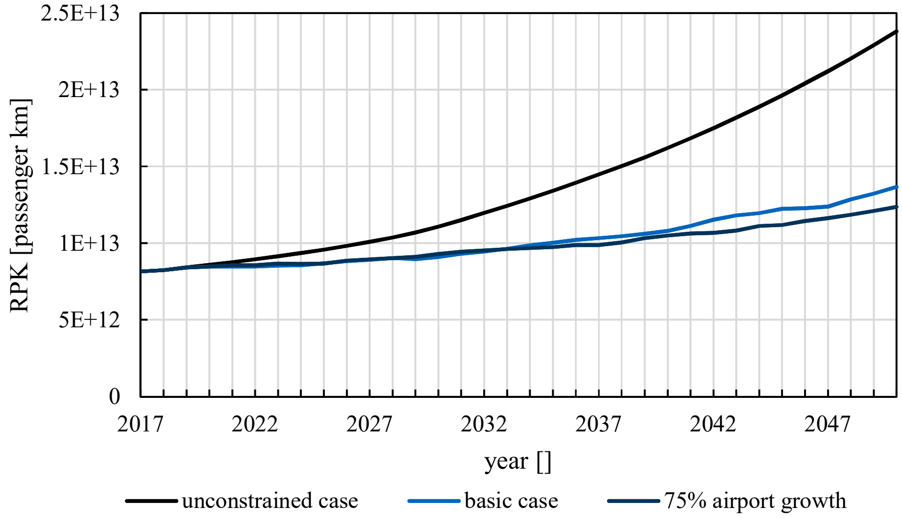


**Fig. 8 RPK development up to 2050 for the three test cases.**

Figure 8 shows the simulated development of global RPK for the three test cases. The black curve depicting the case of no capacity limitation (unconstrained Case 1) shows a near-exponential rise of global RPK as often described by studies in literature and from aviation stakeholders. This reflects the constant annual growth factors allocated to each route group in the fleet model. The light blue curve reflects the development of global RPK in the basic Case 2. It starts at the same RPK value in the year 2017 and at first follows the unconstrained curve until around 2020. Afterwards, it exhibits slower RPK growth, constantly increasing the gap to the unconstrained curve. In the year 2040 it reaches RPK values about 33 % below the unconstrained level. This rapidly increases to a difference of about 42 % in the year 2050. The basic test case, thereby, follows a less smooth course than the unconstrained curve. The curve for reduced infrastructure capacity growth (Case 3, dark blue) follows the basic case until the year 2034. Thereafter, its increase is lower than for the basic case. This leads to RPK values about 35 % lower compared to the unconstrained case and about three percent lower compared to the basic case in 2040. In 2050, these differences increase to about 48 % compared to Case 1 and about 9 % compared to Case 2. In all other respects, the RPK development for Case 3 shows similar peculiarities as described for Case 2.

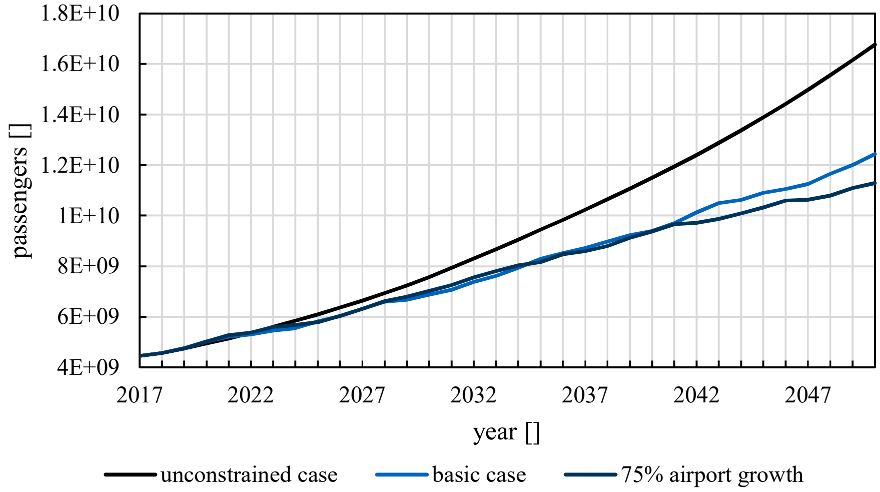


**Fig. 9 Development of global passenger numbers up to 2050 for the three test cases.**

Additionally, the parameters included in the RPK development are shown in more detail. First, this concerns the number of passengers depicted in Fig. 9. Similar to the RPK development in Fig. 8, the unconstrained case exhibits a near-exponential growth in passenger number with an increase by a factor of 3.78 from about 4.45 billion passengers in 2017 up to 16.8 billion in 2050. Again, the light blue curve for the basic case follows the unconstrained curve in the first simulation years, here up to the year 2023. Then the annual growth lies constantly below the one of Case 1 for all subsequent simulation years. This yields an increasing gap between both passenger numbers, reaching about 18 % of the unconstrained case in 2040 and about 26 % in 2050. The curve representing reduced airport growth in Case 3 follows the basic case up to the year 2041. Previously, passenger numbers of this case even surpassed those of the basic case in some simulation years. Afterwards, they show the expected behavior and fall below the passenger numbers of Case 2. This yields a gap of about 19 % compared to the unconstrained case in 2040 and about 33 % compared to the unconstrained case as well as about 9 % compared to the basic case in 2050.

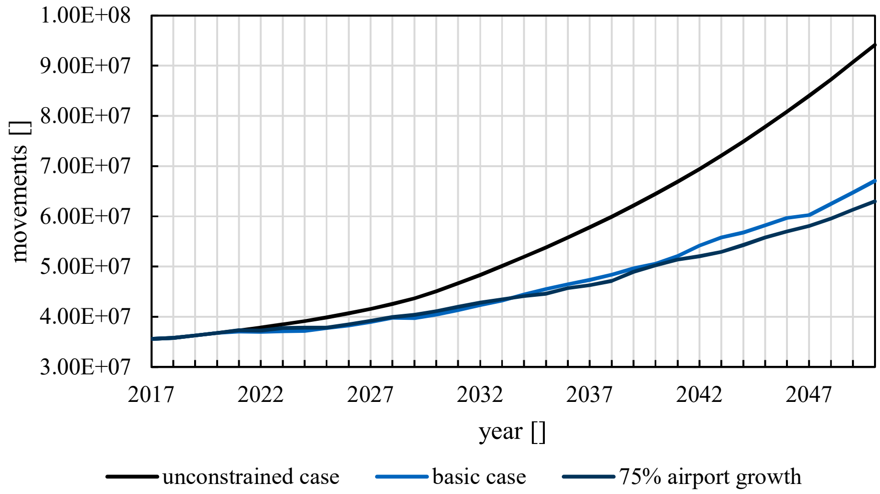


**Fig. 10 Development of global movement numbers up to 2050 for the three test cases.**

The other investigated parameter is the number of global movements, shown in Fig. 10. In the unconstrained case these grow by a factor of 2.65 throughout the simulation period. Both constrained cases follow the same observations as made for the number of passengers, showing a similar development up until the year 2041. In the year 2040, the difference between both constrained cases and the unconstrained case is about 22 % of the unconstrained case's movement number. This increases to about 29 % for Case 2 and about 33 % for Case 3 (about 6 % compared to Case 2) in 2050.

The described differences between the unconstrained curve and the constrained cases are an expression of unaccommodated demand in terms of the different measures investigated. It is noteworthy that there is a significant difference between these unaccommodated demands for passengers or movements and RPK, with the latter being much larger than the former two.

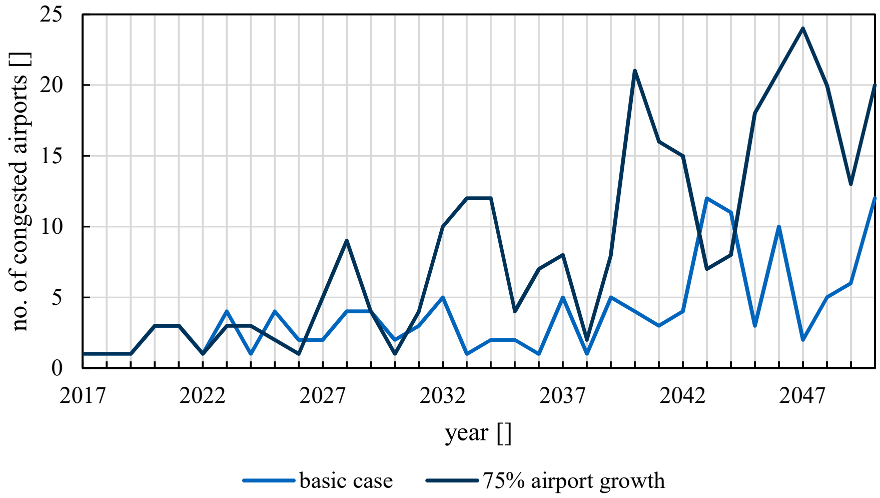


**Fig. 11 Number of congested airports in all simulation years for the basic case and the case of reduced airport growth.**

Additionally, Fig. 11 shows the number of congested airports in all simulation years for Cases 2 and 3. As in the above observations, both cases follow paths within a similar range of values, here up until the year 2026. Thereafter, the dark blue curve representing Case 3 expectedly indicates in many years significantly higher numbers of constrained airports than the light blue curve representing basic Case 2. Furthermore, both curves show pronounced peak structures, e.g., for Case 3 with peaks in 2028, 2033-2034, 2040, and 2047. The years in which peaks and valleys occur in each of both cases usually do not correlate as the airports reach congestion levels in different years according to the given infrastructure growth. In any case, the congestion at an airport automatically yields the implementation of mitigation strategies with subsequent influence on the air traffic parameters shown above.

## V. Validation and Discussion

### A. Validation

As compared to ICAO data [43], the calculated values for the first simulation year 2017 are 6 % higher for RPK, about 3 % lower for the number of movements, and about 9 % higher for the number of passengers. RPK growth factors slightly lower than those of the Boeing Commercial Market Outlook 2019 [44] are used for the simulation. Over the entire simulation period, the case resembling unconstrained airport capacities still achieved only about 3.3 % p.a. RPK growth as compared to a global growth factor of 4.6 % as reported by Boeing [44] for a timeframe between 2019 and 2038. This is related to limitations in OEM production capacities. Gelhausen et al. [4] calculated similar values for the passenger volume growth of 4.1 % p.a. between 2016 and 2030, reducing to 3.1 % p.a. in the decade thereafter.

The number of global movements grows by a factor of 1.8 between 2017 and 2040 in the unconstrained case. This can be compared to an unconstrained movement growth with a factor of roughly 2.2 between 2016 and 2040 as expected in the high growth case by EUROCONTROL [5]. This difference is considered as acceptable to allow for a comparability of this study and EUROCONTROL's *Challenges of Growth 2018 report* [5]. Thus, we compare the capacity gap of 16 % of movement demand in 2040, as forecast for this high growth case in [5], with the 22 % for the constrained cases in this study as reported in the previous section. Considering the global approach and the intended rough estimate in this study, both values show a difference acceptable to assume comparability. Reasons for this difference lie, for example, in the static airport infrastructure capacity factors, defined only on airport cluster, but not additionally on region-level in this study. While these factors might well capture airport capacity growth in Europe, they might be rather low for fast developing regions like Asia. In these regions higher air traffic growth takes place compared to Europe at the same time, filling up slowly growing airports faster and yielding the described higher difference between movement demand and supply. Further research has to substantiate these conclusions. It should also include infrastructure growth factors accounting for regional differences.

Furthermore, we compare the results of the basic case with those of Gelhausen et al. [4] for the year 2040. In this case, significant differences appear in the unaccommodated passenger volume, with the results in this study about one order of magnitude above those reported in [4] (2.6 % of passenger demand unaccommodated). However, values for total passengers and movements are in the same range as reported in this paper. The significant differences for the unaccommodated demand result from different airport infrastructure growth assumptions, modeled mitigation strategies, and focus areas of the models. Thus, they, underline the high uncertainty connected with global air transport modeling.

Nevertheless, especially the comparison with the reference study of EUROCONTROL [5] allows for the conclusion that the proposed model can simulate air traffic growth under airport capacity limitations with sufficient accuracy for a global view of the related effects. More in-depth studies of the use of different mitigation strategies and the developments at the simulated airports are required to further substantiate these findings.

### B. Discussion

The discussion of results starts with observations made for the three air traffic performance indicators RPK, seats and movement numbers before turning toward airport-specific observations.

In Figs. 8-10 we observed considerable differences in air traffic parameters between unconstrained and constrained cases. However, in both constrained cases the maximum annual amounts of remaining surplus traffic after applying mitigation strategies remained rather low (up to about 2 % p.a. of total movements). This issue is related to the modeling logic and can be explained with the help of an exemplary airport. Let's suppose this airport has some amount of remaining surplus traffic in simulation year 1. Then the accommodated traffic of year 1 including changes due to airport capacity limitations and mitigation strategies is used as baseline value for the calculation of the traffic demand in the following simulation year 2. This disregards the initial traffic demand in year 1 before applying airport capacity limitations. The resulting gap between demand and supply in year 1 is thus affecting the entire subsequent simulation. Over time, such seemingly small amounts of unaccommodated traffic at many congested airports lead to the described significant deviations in air traffic parameters on a global level, resembling some sort of a snowball effect.

The abovementioned example is even more relevant to the interpretation of the result, considering that most congested airports belong to the biggest hub airports in the network. Decreases in, for example, movement numbers at congested airports as compared to demand levels can also result from other causes. One of those is the change in fleet mix owing to the application of mitigation strategies. This especially accounts for the operation of more wide-body aircraft through switching from smaller aircraft. The subsequent update of airport capacities (see Section III.B.1) might even lead to a significant decrease in absolute allowable movements at the concerned airport in the subsequent simulation year. The other cause lies in the number of aircraft required to be updated when using the larger aircraft strategy. According to the seat ratio (see Section III.B.3), this might influence far more movements than just the number of surplus movements. Especially the first issue needs further research and possibly significant refinement in subsequent studies, as it leads to unrealistically high reductions in movement capacities.

As discussed in the previous section, the share of unaccommodated movements lies in a range as expected by EUROCONTROL [5]. The number of unaccommodated passengers shows comparable values. At the same time, the share of unaccommodated RPK is significantly higher. We find the reason for this behavior is the mitigation toward aircraft with higher passenger capacity. This strategy optimizes for maximum avoidance of surplus movements, automatically implying a change in traffic structure not accounted for by the model: Long-range flights are usually operated by wide-body aircraft. Besides one loop of seating densification, the change to larger aircraft quickly reaches its limits for these parts of the global fleet. On the contrary, short- and mid-range flights are mostly operated by narrow-body aircraft. By switching to various clusters of larger aircraft available, this mitigation strategy has much larger implications for this segment of the fleet. Thus, at an airport with traffic surplus, mainly movements with shorter route lengths originally operated by narrow-body aircraft are subject to mitigation changes. This also results from the optimization within the Larger Aircraft Potential model which favors those mitigation solutions with lowest fuel burn. As a result, the share of short- and mid-range traffic increases with application of this strategy. This in turn leads to a decrease in average route length in the calculation of RPK and, thus, the observed effect.

A peculiarity of the results shown in Section IV is that the air transport parameter curves (Fig. 8-10) of larger airport capacity constraints (Case 3) surpass the values for the basic Case 2 in some early simulation years. This counter-intuitive behavior is related to small differences in the utilization of mitigation strategies. In the year 2041, Case 3 reaches the limits of the mitigation strategies. Surplus remains at some airports and the air transport parameter curves of Cases 2 and 3 diverge in the expected manner.

Regarding more detailed observations of congested airports, Figure 11 shows that the effect of a reduction in airport infrastructure growth yields a significant increase in the number of congested airports compared to the basic case. Furthermore, as expected, the number of congested airports grows over the course of the simulation. The peak structure occurring in Fig. 11, however, so far could not be explained conclusively. It seems to be associated with mitigation by using larger aircraft and occurs when secondary airports also become congested. Whether this results from previous traffic shifting to these airports is still to be clarified. In any case, the vast majority of congested airports can be found in Asia, which also suggests an underestimation of airport capacity growth in this region.

### C. Limitations of the Model

The various assumptions made in deriving this model as described in Section III constitute the main limitations of this work. However, as for any model describing complex systems, such assumptions are indispensable. Therefore, future research will focus on identifying the model's sensitivity toward these parameters and to verify their validity. This was not in the scope of this first global investigation. Still, first more specific limitations are mentioned in the following.

The first of these is the assumption of no change in fuel consumption when shifting movements to other airports. The basis for that assumption is the expectation that shifting reduces some of the distances flown while extending others, averaging out in a global view. This has a direct influence on the choice of mitigation strategies in our model, usually leading to a preference for solutions including larger passenger capacities. Although this generally might resemble actual airlines' behavior, further research into the validity of this assumption and the influence of different levels of additional fuel used for shifting traffic is planned. Such calculations, however, would require extensive demand and passenger data not available to this project. A solution would be an estimation via OAG data, implying the introduction of further assumptions.

Furthermore, the assumption of global infrastructure growth factors for airports only differentiating airport clusters does not resemble the significant differences in the pace of airport expansion programs in various regions. Especially for Asia, the current factors might significantly underestimate airport expansion. This in turn leads to an overestimation of surplus traffic and related fleet changes due to mitigation strategies. The dominance of Asian airports experiencing surplus increases with every simulation year, supporting this observation.

Finally, the mitigation by larger aircraft passenger capacity includes various limitations. First, the above observed preference for utilizing this strategy for narrow-body aircraft performing comparably short flights can be corrected by optimizing for maximum avoidance of surplus RPK instead of movements. This is expected to better resemble actual airline behavior. Second, up until now this strategy is only limited by OEM production capacities and current fleet structures. However, airlines might not be willing to shift a large share of their operations at an airport to another type of aircraft. This would imply significant investments in aircraft fleets and far-reaching scheduling changes, especially if an alternative hub airport would be available. Thus, future work can investigate the influence of an artificial limitation to larger aircraft use on the model's results, for example.

## VI. Conclusion

### A. Summary

In this paper we propose a modeling approach to map the influence of limited airport capacities on global air traffic and aircraft fleet development within an evolutionary fleet development modeling environment. In addition to calculations of unaccommodated demand, the introduction of mitigation strategies also induces significant influences on the aircraft mix. These strategies include shifting of surplus traffic to uncongested airports, while differentiating between hub and OD-traffic. The alternative airports are selected according to a calculated attractiveness measure. The second mitigation mechanism introduces aircraft with larger passenger capacity to the fleet, allowing for the transport of a higher number of passengers with a low number of movements. This method includes the two fundamental paths of increasing the seating capacity of existing aircraft by densification and of using larger aircraft types.

In the scope of this paper, results are presented on the air transport level for the simulation of air traffic development up to 2050. These show a growing influence of airport capacity limitations on air traffic parameters, rising to significant levels in the medium- to long-term. A simulation with reduced airport infrastructure growth further increases remaining traffic surplus. Thus the observed global values correspond to the results of comparable studies. Even at a global level, interdependencies between the mitigation modeling approaches and different air traffic parameters can be identified and initial implications for different fleet sections can be drawn.

### B. Conclusion and Future Work

Future work will include the investigation of the limitations and their evaluation as suggested in Section V.C Furthermore, different elements of the required input data can be updated or derived with more detail. This includes air traffic growth factors incorporating the influence of the COVID-19 pandemic and scenario-based airport infrastructure growth factors covering a wider range of airport capacity development and its regional variability.

Moreover, the model can be used to its full ability with further in-depth investigations of the different mitigation strategies applied at the simulated airports. The fleet uptake and subsequent fleet structure development, taking into consideration the introduction of new technology aircraft, can then be mapped. The implications of hydrogen or hybrid powertrains on the calculation logic of the FSDM have to be considered for the possible inclusion of future technology aircraft in the long term. A simple fuel-burn optimization is not sufficient in such cases. These changes would further widen the applicability of the FSDM and support investigations on many urgent issues in the aviation sector.

In this manner the authors aim to establish a better understanding of some of the complex mechanisms driving and constraining the development of the air traffic system. This research, on the one hand, gives an idea of the significance of limited airport capacities. On the other hand, the introduction of these limitations to fleet modeling improves the understanding of the uncertainty range connected with estimations about future fleet developments. Despite the shown limitations, the methodological approach presented in this paper builds a basis for these future investigations.

## Acknowledgments

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