Future Passenger Air Traffic Modelling: A theoretical Concept to integrate Quality of Travel, Cost of Travel and Capacity Constraints

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Abstract

In order to model possible future evolutions of the global air transportation system (ATS), not only the assumptions on external socio-economic conditions are relevant to estimate the future realized air passenger demand on city pair level. The internal scenario concerning the air transportation system (ATS), i.e. how the ATS is changing over time with the introduction of new technologies or new operational concepts has a non-neglectable feedback on realized demand. Also, the effect of infrastructural changes concerning airport and airspace capacities have to be considered. That means, the forecast of realized demand and thus realized air traffic depends equally on the supply offered by the air transportation system. There are three essential kinds of feedback on realized air passenger demand and air traffic, the supply provided by the ATS may have. We present a theoretical concept to integrate these three kinds of feedback (1) quality of travel, (2) cost of travel, and (3) constraints of the supply side of the air transportation system on modelling global future scheduled air traffic. The 4-layers approach of modelling future evolutions of the ATS is a basic prerequisite to model these feedbacks, especially the consistent derivation of an aircraft movements network with information on aircraft generations.

Introduction: Generic build-up of the future ATS

In the DLR project "WeCare" climate mitigating effects of operational and technological changes are investigated in the context of the future air transportation system (ATS) on a global scale with a time horizon until 2050. Therefore, at first, a generic model forecasting future air traffic, on network and fleet basis, is required. This will be implemented in a modular environment, called AIRCAST (air travel forecast), including 4435 cities worldwide. A generic approach as depicted in Figure 1 is necessary to assess a multitude of possible changes from the introduction of a single technology to growth of air travel demand. Pure passenger aircraft fleet models used to assess the global climate impact of aviation and the introduction of new technologies as in [2], [3], [4], [5], and [6] have no spatial quality. This is why we combine a fleet scenario analysis with the modelling of global ATS network evolutions. The spatial distribution of flights is relevant to assess the climate impact of the ATS and the evaluation of potential mitigation strategies and revolutionary new concepts. The climate impact of aviation highly depends on the amount, species, altitude and latitude of emission.[7] We introduce the 4-layer philosophy for a generic build-up of the passenger air traffic system of the future. A similar approach to decompose the air transportation system in general and the application by analyzing data of the US air transportation system without a forecasting methodology can be found in *Bonnefoy et al.* [8]. *Bonnefoy et al.* emphasize the importance of not only analyzing present networks, but also the future structure of ATS networks. The research conducted in building the AIRCAST environment focuses on the structural evolution
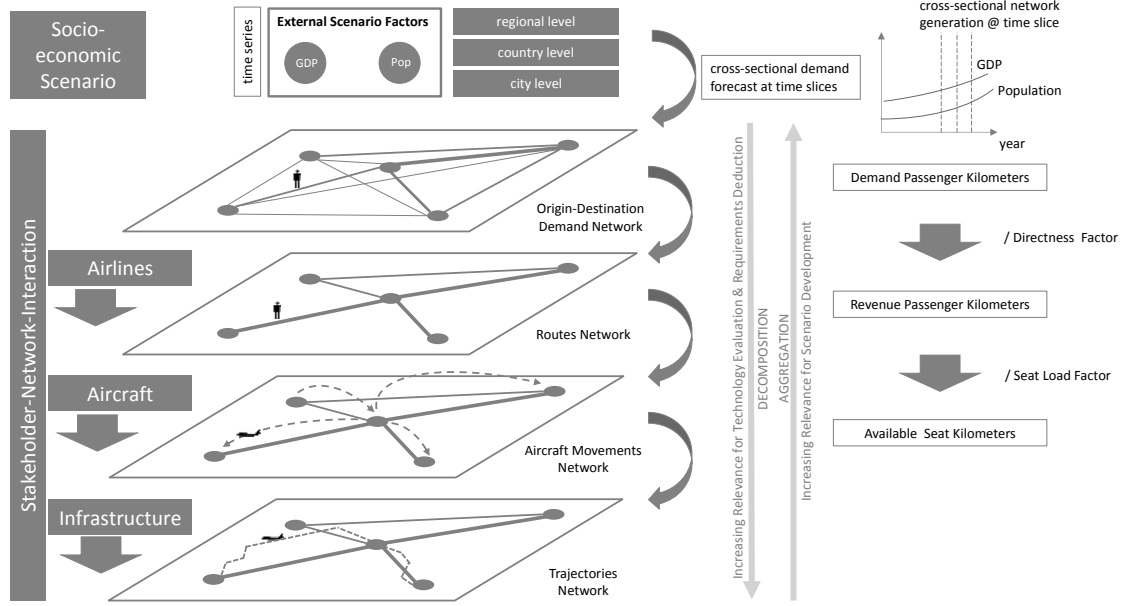
Figure 1: Generic build-up of the future ATS in 4 layers [1]

of global air passenger and aircraft networks until 2050. One goal is the derivation of implications by structural changes of ATS networks on shifts in global mission range frequency distributions and the proportional shift of deployed aircraft sizes over time. The four layers (see Figure 1) consist of (1) the origin-destination (OD) demand network, (2) the routes network, (3) the aircraft movements (ACM) network, and (4) the trajectories network. Each lower layer builds on the information on the above layers. While the first and the second layer forecast passenger flows purely from a passenger perspective, the third and forth layer simulate aircraft movements. By demand here, we mean actual realized demand as described in [9], since our forecasting algorithms are based on global ADI-data[1], which may be interpreted as realized demand. Thus, realized demand are passengers who intended to fly and actually flew in a given year from one origin to a destination because the travel conditions (e.g. time, airfare, number of transfers, etc.) were right for them. Our model environment forecasts at first an undirected demand network on city level (in contrast to airport level), which may be called "city pair air passenger demand". Starting with the theoretically ideal demand network gradually more information concerning the "operational reality" of aircraft deployment is included, e.g. effects of hub structures, categories of aircraft used on segments, and airspace-related trajectory inefficiencies. With the advancement in the derivation process to each lower layer, there is an increasing relevance for technology evaluation and derivation of requirements for new concepts. Interfaces with conceptual aircraft design can be found on the aircraft movements layer concerning the future evolution of flown distances and the number of flights by aircraft sizes. The trajectories network has an interface with conceputal aircraft design concerning flight times, fuel consumption and emissions. On the other hand, there is an increasing relevance for scenario development when results and assumptions are more aggregated. This will allow assessing the growth of the ATS against efficiency and technology improvements dynamically until 2050 on a network and fleet basis. In addition, feedbacks of alterations of the supply side of the ATS on the estimation on realized demand are incorporated in the ATS modelling concept. The overall theoretical framework of systems design, consisting of a systems analysis and a concept design part, with an inherently quantitative philosophy of scenario development has been published in [10].

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[1]Sabre Airport Data Intelligence

The combination of dynamic network and fleet evolution information is considered to be highly valuable for systems analysis, technology assessment, policy planning, and master planning of aviation infrastructure. The scientific results of the AIRCAST environment and the associated methodologies in development are especially interesting for [1]:

- market forcasts of manufacturer

- strategic planning of airlines (insight in the dynamics of realized demand on city pair level)

- airport and airspace capacity evaluation

- aviation-related policy making of city governments, national governments, international organizations (UN, ICAO, IATA)

- dynamic global climate impact assessment of aviation, especially the impact of non-CO2 climate change agents

Exogenous socio-economic scenarios

The AIRCAST 4-layers approach starts with exogenous socio-economic scenarios from external insitutions as does the AIM^2 modelling approach [11]. The exogenous socio-economic scenarios are available at different aggregations: global, regional or county level. For the modelling approach of the AIRCAST environment time series of the parameters GDP and population are required on *city level* as an essential input for the city pair air passenger demand forecasting model, named D-CAST, which directly forecasts demand networks on city pair level in time slices every five years. Here, a specific breakdown methodology for GDP and population was developed and incorporated in the tool CITYCAST. The socio-economic inputs used (see Figure 2) are self-consistent scenarios that rely on global system dynamics models. The data is publicly available. AIRCAST uses the forecast published by Jorgen Randers "2052" [12] and the five scenarios of the International Futures Global Modeling System (IFs) [13] as main inputs.
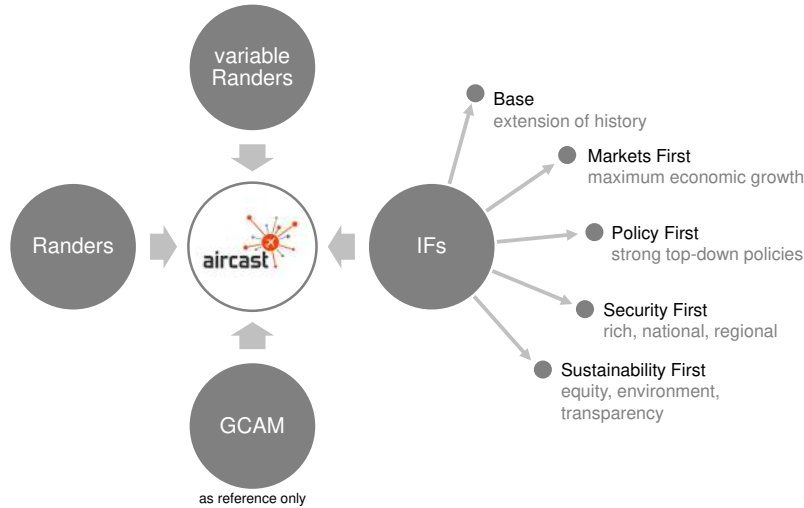

Figure 2: Socio-economic scenarios based on system dynamics models serving as input for AIRCAST

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^{2}Aviation Integrated Modelling Project

The Randers scenario is valuable since the methods and assumptions of forecasting GDP and population are described with great detail. The results and assumptions are discussed in [12] and assumptions critically analyzed and extended with useful qualitative scenario information. The CITYCAST tool further allows a country specific manipulation of the Randers scenario concerning for example birth and death rates or urbanization factors retrieved from United Nations scenarios. Additional desirable information would be a an oil price development which is consistent with the scenarios. This is given for the IF-scenarios, but not for the Randers scenario. The Global Change Assessment Model (GCAM), developed by the Joint Global Change Research Institute (University of Maryland) is integrated as a reference and for comparison purposes to other environments that use this socio-economic scenario for climate change assessments. GCAM is not included in the AIRCAST environment for forecasting future ATS networks because essential information for the methodology to decompose those scenarios to city level is not available. A scenario capability exists for 4435 cities in 215 countries worldwide, meaning that required forecasts on city level of socio-economic parameters are available in addition to the availability of ADI data in the base year 2012. 574 cities in 12 countries existing in the 2012 ADI data set could not be included in the CITYCAST model because of missing socio-economic data. In order to use the time series of socio-economic parameters more effectively for city pair demand forecast algorithms and to handle calculation times, a cluster dynamics methodology of cities has been developed. The cities included in AIRCAST have been grouped in 9 clusters, and thus 45 cluster pairs. The socio-economic condition of a city in terms of GDP, population, and GDP per capita defines its cluster membership. The cluster membership is calculated for each time slice every five years according to its changing socio-economic conditions over time. [14] The cluster dynamics of cities is important to increase the precision of forecasting a global city pair demand network.

Demand Network

The forecast of the air passenger demand network in future time slices follows two steps as depicted in (Figure 3): (1) topology forecast and (2) forecast of the number of passengers on an edge.
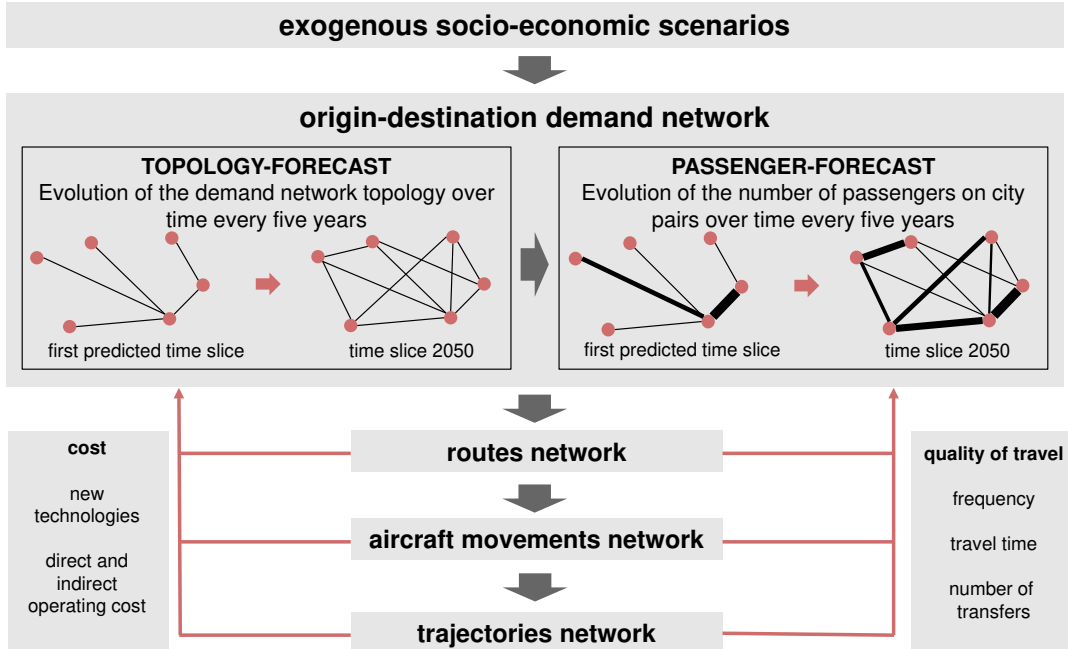

Figure 3: A two steps process of forecasting air passenger demand evolution: topology and number of passengers on city pairs worldwide

Since we forecast an undirected network which does not know the direction of origin and destination, we call one connection demand city pair. A detailed approach to the applied demand forecasting methodology can be found in [9] and [15]. The basic demand network topology is defined by the data of the base year 2012. The step of topology forecasting estimates the appearance of new demand connections for each time slice using weighted similarity-based algorithms according to a socio-economic scenario. Subsequently, passengers on the defined demand connections (edges) are forecasted. We defined metrics to measure the quality of travel in order to quantify feedbacks of the introduction of concepts like flying slower or Intermediate Stop Operations (ISO) on realized demand. Feedbacks on realized demand due to alterations by the introduction of new aircraft with a given aircraft price and a given fuel efficiency or airline business model trends resulting in changing direct and indirect operating cost need to be modeled through a detailed estimation of airfare.

Routes Network

The routes network is forecasted based on the previously generated air passenger demand network in time slices on city pair level. In order to model the global routes network every city pair of the demand network and the associated weight on an edge in terms of passengers is analyzed individually. That means, the routes passengers take, are modelled for each demand city pair seperately. The probabilities for routes are defined by analyzing historical ADI data. Figure 4 depicts the overall process.
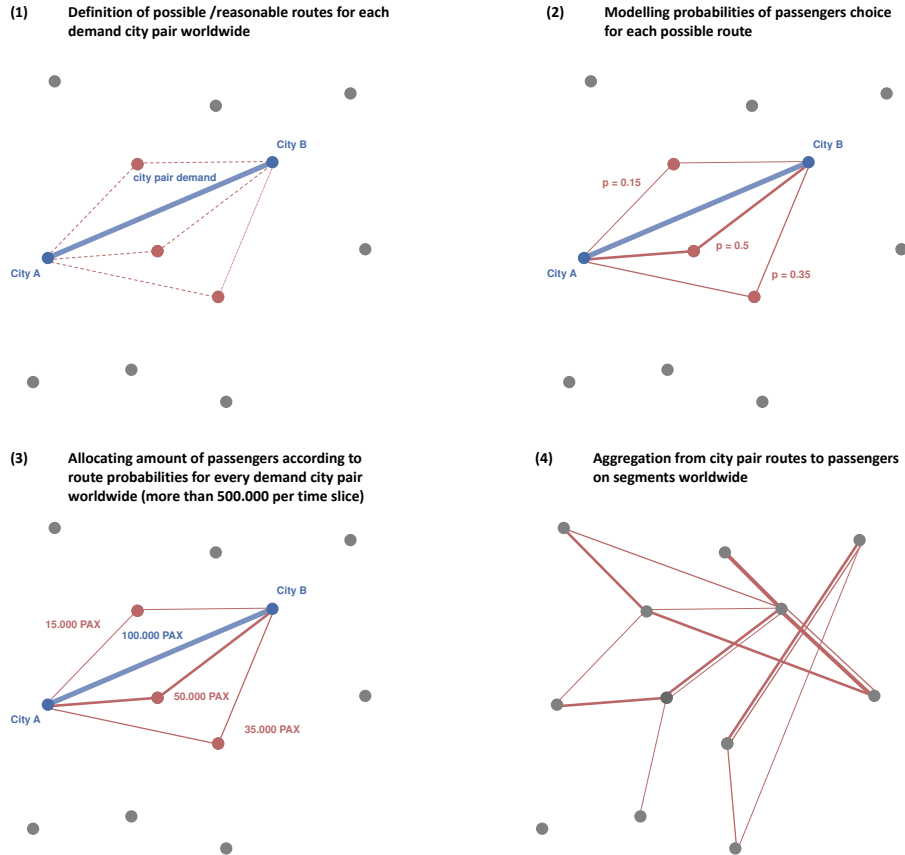

Figure 4: Process of forecasting a routes network: deducing passengers on segments

At first, for each demand city pair, possible or reasonable routes have to be defined. We apply the following criteria to select possible routes:

- list of possible transfer airports (ca. 500 worldwide)

- minimum segment distance (below which there is probably no flight taking place)

- maximum number of transfers

- maximum detour factor (sum of great circle distances of segments relative to great circle distance on demand city pair)

All of the above mentioned criteria have to be met so that a route is defined as a resonable option from a passenger-airline-perspective. In a second step, the probabilties for a passenger to take a certain route is estimated. The probabilities for the distribution of passengers from a demand city pair on different routes, calculated from ADI data, can be looked at as a blurred combination of passenger and airline perspective. In the future, more research is needed concerning the adequate definition of a boundary condition for the forecast of direct routes. The crucial point in this matter is that we have to define probabilities of routes for demand city pairs that have not existed in the historical data since our demand forecast methodology (D-CAST) is forecasting appearing links in future time slices. If that would not be the case, the routes probabilities from past data could be used. Since this is not the case, a model is needed that is able to estimate probabilities for the choice of routes by using segment probabilities. In a third step, the forecasted number of passengers on a demand city pair is distributed according to the previously estimated route probabilities. This routes modelling process is conducted individually for each demand city pair worldwide and applied to all demand city pairs. In a forth step, the number of passengers on routes are aggregated to passengers on each segment worldwide, because the portions of deployed aircraft sizes are empirically a function of segment distances and passenger volumes on these segments.

Aircraft Movements Network

After the estimation process of passengers on segments worldwide, the frequency-capacity-model FOAM (Forecast of Aircraft Movements) [16] is applied to each segment to estimate the portion of flights per aircraft size expressed in seats and abstracted in seat categories as depicted in Figure 5. The analysis of global ADI data of the last 10 years shows that the proportions of aircraft sizes deployed statistically depend on segment distance and the number of passengers on a segment. Segment great cirle distances are known by the city geographical coordinates. Thereafter, the absolute number of flights in a given time slice by seat categories on an individual segment is calculated. This procedure is applied to all segments to derive a global aircraft movements network by seat categories for each time slice until 2050.
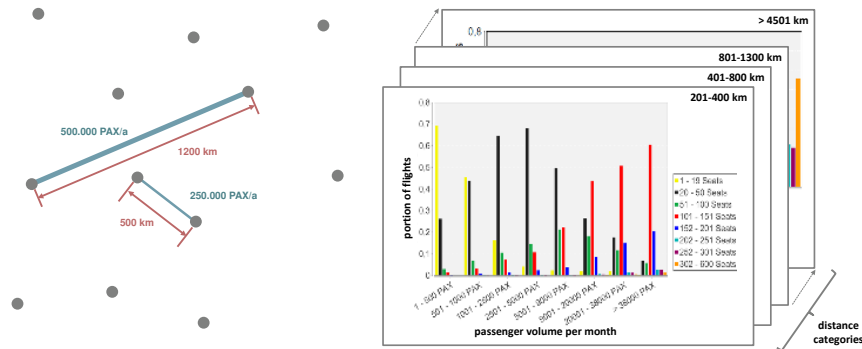

Figure 5: Forecasting aircraft movements on segments [16]

The foundation of being able to integrate Quality of Travel, Cost of Travel, and Capacity Constraints is capability of modelling an aircraft movements network with generation information on aircraft deployed (Figure 6 B). The previously deduced aircraft movements network (Figure 6 A) only gives an information about the number of flights conducted by seat categories on segments whereas the information how many flights are produced by which generation of aircraft in each seat category is missing. Figure 6 shows the interface between the aircraft movements layer and the fleet renewal model FFWD (Fast Forward) [3]. The fleet renewal model requires the global absolute Revenue Passenger Kilometer (RPK) development and absolute RPK developments by seat categories as an input from the AIRCAST networks. Additionally, a consistent seat load factor scenario by seat categories is needed. Subsequently, an introduction pattern of new aircraft considering all seat categories is modelled with technology timelines. FFWD simulates the introduction of new generic aircraft in the future and forecasts shares of aircraft generations for each seat category according to the introduction scenario of a new aircraft program with a certain Entry Into Service (EIS) by using FESG[3] retirement curves. This information is required to forecast an aircraft movements network with generation information of aircraft.
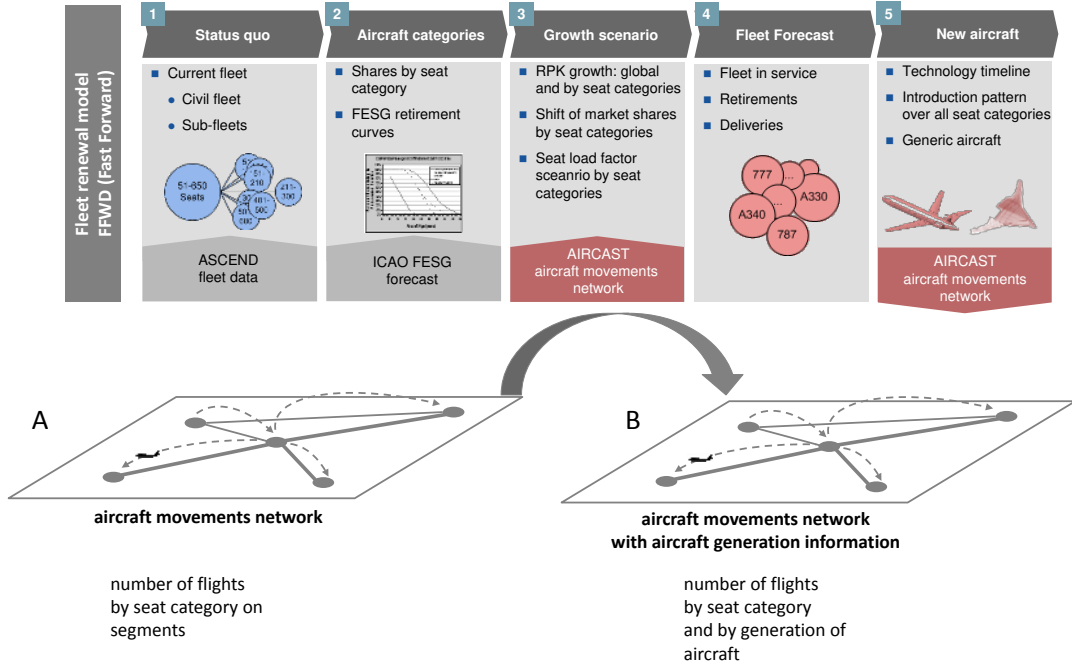

Figure 6: Forecasting an aircraft movements network with aircraft generation information: Interfaces between the aircraft movements layer and the fleet renewal model FFWD [3]

A theoretical concept to integrate Quality of Travel, Cost of Travel and Capacity Constraints

Estimations of segment-based alterations of the three essential kinds of feedback Quality of Travel, Cost of Travel, and Capacity Constraints (see Figure 7) and associated feedbacks on realized demand by the simulated introduction of new aircraft into the ATS are only possible when the generation mix of aircraft is considered. Various generations in one aircraft seat category, for example, will be in utilization in parallel on given segments. The overall cost will be a mix of the operating cost of various aircraft generations that may differ by factors as aircraft price, fuel

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[3]Forecast and Economic Analysis Support Group of the International Civil Aviation Organization (ICAO)

efficiency, and maintainability. The overall cost also depends on external scenario factors as the oil price development and possible charges on CO_2 emissions or by noise certifications. The same applies for assessing alterations of Quality of Travel, for example to simulate the introduction of a slower flying aircraft. A segment-based aircraft movements network with generation information builds the basis of assessing feedbacks of these sorts of quality and cost alterations of the supply side on total ATS evolution.
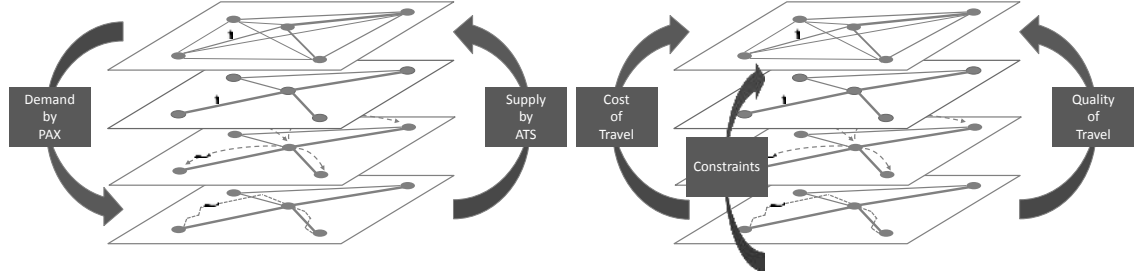

Figure 7: The three essential kinds of feedback on the evolution of the ATS

The feedback effects of changes of the Quality of Travel are quantified by frequency, travel time, and number of transfers. The Quality of Travel Index (QTI) [17] links the quality of air travel as one part of the value proposition of the ATS to the estimation of realized demand. Thus, the negative or positive feedback of new concepts like intermediate stop operations or flying slower on realized demand may be assessed globally through these metrics as shown in Figure 3. The reference QTIs for each demand city pair have been defined using the base year 2012. The QTI will be recalculated for future time slices with new aircraft technologies and operational measures incorporated. Afterwards, the number of passenger forcasting step in D-CAST is recalculating realized demand in a second iteration based on the changed Quality of Travel from a passengers perspective.

Airfares are an essential input to forecast air passenger demand. In the model environment AIR-CAST, within the first iteration, demand is estimated using a simplified airfare model which forecasts OD-pair-based airfares solely as a function of the great circle distance between demand city pairs and the scenario-related oil price.[1] In order to model feedbacks by changing Cost of Travel on realized demand while simulating the introduction of new aircraft, a detailed segment-based cost and airfare model is required. The segment-based airfare model needs to include worldwide aircraft generation information, an estimation of opreating cost as a function of newly introduced aircraft and assumptions of the global development of indirect operating costs reflecting future developments of airline business efficiencies. From the aircraft movements network, segment-based information concerning the aircraft size and the generation mix of aircraft by seat categories needs to be included to estimate a segment-based cost of travel that considers the simulated introduction of new aircraft and their gradually growing impact on airfares over time under a given oil price development in a socio-economic scenario. The modelled segment-based Cost of Travel will be an average of all Costs of Travel from a mix of seat categories and aircraft generations. The segment-based Cost of Travel will be used to deduce an origin-destination-based cost of travel for a passenger travelling on a given demand city pair. Demand city pair airfares might be a weighted average of airfares on routes. Cost of Travel on routes may be derived from Cost of Travel on segments.

We distinguish two kinds of traffic-related capacity constraints: airport and enroute. They relate to the available infrastructure capacity, i.e. airport capacity and airspace capacity. The forecasted realized demand needs to be contrasted to the capacities available through aviation infrastructure according to their master planning. Evans emphazises the importance of modelling airline operational responses because this describes the adjustment process of the supply side of the ATS in

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changing conditions. Evans states that "flight delays result when growth is constrained by the air transportation system capacity".[18] The derivation an aircraft movements network relates to airspace and airport airside capacities whereas the routes network has an interface airport landside capacities. Evans considers only flight operation, but for an overall concept terminal capacity should be as well mentioned, even if this is often not the limiting capacity factor at an airport.[18] Quality of travel and Cost of travel depict the value proposition of the ATS from a passengers perspective. Constraints directly affect airlines and indirectly passengers over the intermediate step of airlines, since the value proposition an airline is able to provide to customers is affected by constraints. These constraints might be physical caps of aircaft movements or airport noise. Constraints need in some circumstances be transfered into alterations of Quality of Travel and Cost of Travel and modeled as such. Environmental capacities for instance concern limitations due to climate impact, local air quality and noise. These constraints may have as well an influence on the Quality of Travel and Cost of Travel. Cost of Travel may for example be altered due to additional noise or emission charges. For instance, Quality of Travel may be altered through capacity constraints if operations are close to the infrastructure capacities. Delays will increase significantly and thus travel time will increase as well, if capacity extensions cannot be realized. In clonclusion, there are complex interaction *between* the three kinds of feedback. The assessment of new aircraft and political or operational measures in the context of future ATS evolution relates in most cases to more than one specific kind of feedback.

Conclusion

The starting point of modelling the future air transportation system in AIRCAST - developing scenarios of network evolutions - are exogenous socio-economic scenarios. In a first iteration all networks (4 layers) in all time slices are forecasted without applying any future alteration to the system. After that, a scenario of the introduction of new aircraft programs over all seat categories and the introduction of operational measures that should be evaluated needs to be defined until 2050 with all relevant assumptions concerning alterations of cost of operation and quality of travel. Especially modelling the feedback of such changes from the supply side of the ATS on the forecast of realized demand and the iterative calculation of all networks is expected to give valuable quantitative insights in the connection between intentional alterations, e.g. to achieve climate targets, and unintended feedbacks of those decisions on the evolution of networks. An essential foundation is modelling the evolution of aircraft movements networks with information on aircraft generations deployed. We expect more realistic insights in how new technologies, aircraft designs and operational measures influence the structural evolution of global ATS networks being valuable for decision making processes of policy makers, manufactures, airlines, and air navigation service providers. Future research is required on the interactions between the aspects Quality of Travel, Cost of Travel and Capacity Constraints in modelling the future air transportation system.

References

[1] R. Ghosh and I. Terekhov. Future passenger air traffic modelling: Trend analysis of the global passenger air travel demand network. 53rd AIAA Aerospace Sciences Meeting, Kissimmee, Florida, USA, 2015.

[2] International Civil Aviation Organization (ICAO). FESG CAEP/9 traffic and fleet forecasts - methodological paper. CAEP/9-IP/11, 2013.

[3] A. Apffelstaedt, S. Langhans, and V. Gollnick. Identifying carbon dioxide reducing aircraft technologies and estimating their impact on global CO2 emissions. Deutscher Luft- und Raumfahrt Kongress (DLRK), Aachen, Germany, 2008.

[4] P. Nolte, T. Zill, A. Apffelstaedt, E. Stumpf, S. Dufresne, S. Briceno, C. Raczynski, and T. Rötger. Technology screening, selection and modelling for an environmentally sustainable aviation. 11th AIAA Aviation Technology, Integration, and Operations (ATIO), Virginia Beach, USA, 2011.

[5] P. Nolte, A. Apffelstaedt, V. Gollnick, and T. Rötger. Quantitative assessment of technology impact on aviation fuel efficiency. Air Transport and Operations Symposium 2012, Delft, Netherlands, 2012.

[6] R. Ghosh and V. Gollnick. The 2° target revisited: Climate-ecological assessment loop and conceptual foundation for air transportation system re-engineering. Deutscher Luft- und Raumfahrt Kongress (DLRK), Stuttgart, Germany, 2013.

[7] Koch et al. Climate impact assessment of varying cruise flight altitudes applying the cats simulation approach. The International Conference of the European Aerospace Societies (CEAS), 2011.

[8] P. Bonnefoy and R. Weibel. Project air transportation system analysis. EDS.342 - Advanced System Architecture, 2006.

[9] I. Terekhov, R. Ghosh, and V. Gollnick. A concept of forecasting origin-destination air passenger demand between global city pairs using future socio-economic development scenarios. 53rd AIAA Aerospace Sciences Meeting, Kissimmee, Florida, USA, 2015.

[10] R. Ghosh, T. Schilling, and K. Wicke. Theoretical framework of systems design for the air transportation system including an inherently quantitative philosophy of scenario development. 29th Congress of the International Council of the Aeronautical Science, St. Petersburg, Russia, 2014.

[11] T. Reynolds, S. Barett, L. Dray, A. Evans, M. Köhler, M. Morales, A. Schäfer, Z. Wadud, R. Britter, H. Hallam, and R. Hunsley. Modelling environmental & economic impacts of aviation: Introducing the aviation integrated modelling project. 7th AIAA Aviation Technology, Integration and Operations Conference (ATIO), Belfast, Ireland(AIAA-2007-7751), 2007.

[12] Jorgen Randers. 2052: A Global Forecast for the Next Forty Years. Chelsea Green Publishing, 2012.

[13] B. Hughes and E. Hillebrand. Exploring and Shaping International Futures. Paradigm Publishers, Colorado, USA, 2006.

[14] Ivan Terekhov and Volker Gollnick. Clustering of airport cities and cluster dynamic for the air passenger demand forecasting model based on a socio-economic scenario. The International Conference of the European Aerospace Societies (CEAS), Delft, Netherlands, 2015.

[15] I. Terekhov, R. Ghosh, and V. Gollnick. Forecasting global air passenger demand network using weighted similarity-based algorithms. 19th ATRS World Conference, 2015.

[16] K. Kölker, P. Bießlich, and K Lütjens. Foam - from passenger growth to aircraft movements. 18th World Conference of the Air Transport Research Society (ATRS), Bordeaux, France, 2014.

[17] K. Kölker, R. Ghosh, and K. Lütjens. Assessing quality of air travel using the impact of frequency, travel time and transfers on passenger demand. 19th ATRS World Conference, 2015.

[18] Anthony D. Evans. Simulating Airline Operational Responses to Environmental Constraints. Clare College, University of Cambridge, 2010.