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MODELLING THE EUROPEAN AIR TRANSPORT SYSTEM: A SYSTEM DYNAMICS APPROACH

M. Urban*, U. Kluge*, K.O. Plötner*, G. Barbeito**, S. Pickl**, M. Hornung*

*Bauhaus Luftfahrt e.V., Willy-Messerschmitt-Str. 1, 82024 Taufkirchen, Germany

** University of the German Federal Armed Forces, Werner-Heisenberg-Weg 39, 85577 Neubiberg, Germany

Abstract

The air transport system is characterised by a highly complex structure with multiple causalities and interactions between its stakeholders, such as passengers, airlines, airports, and aircraft manufacturers. In addition, external effects, e.g. the development of the fuel price or the population growth, influence the air transport system significantly. In order to gain a deeper understanding of the dynamics within the system and to analyse external effects on it, a comprehensive methodology is required to model such a complex structure. Thereby, the quantification of measures is essential.

System Dynamics has been applied first to corporate processes as well as larger systems such as urban and global models in order to derive qualitative conclusions of how complex systems operate. The paper presents a specific System Dynamics model, representing the key relations between passengers, airlines, airports, and aircraft manufacturers. These four aviation stakeholders will be described based on their functions and objectives as well as on their interactions between each other in detail. This description includes, for example, decisions for airport runway and terminal expansions or decisions regarding the aircraft acquisition considering the operational performance of an airline. Furthermore, first numerical simulation results will be presented, including the development of revenue passenger kilometres and the number of aircraft required. The model focuses on air traffic within Europe as well as to or from Europe. Its overall structure enables an extension to a global level including all major aviation markets. The paper concludes with an overview of these next development steps.

Nomenclature

$\bar{A}$	*actual data (Actual)*
a/c	*aircraft*
ASK	*Available Seat Kilometres*
CO_2	*Carbon Dioxide*
f	*nonlinear vector-valued function*
GDP	*Gross Domestic Product*
MATS	*Modelling the Air Transport System*
p	*set of parameters*
p.a.	*per annum*
RPK	*Revenue Passenger Kilometres*
$\bar{S}$	*simulated model results (Simulation)*
SD	*System Dynamics*
SLF	*Seat Load Factor*
x	*vector of state variables or stocks*

1. MOTIVATION

The air transport system is constituted on a complex structure of interactions between different stakeholders. Among others, passengers, airlines, airports, and aircraft manufacturers are the key stakeholders within the air transport value chain. In order to predict future trends and developments within this complex system and to assess the external influences, it is crucial to gain a thorough understanding of its interrelations in the current state. Besides statistical models, there are previous studies who have chosen an alternative approach to model complex systems [1]. Many of these studies consider specific aspects or distinct stakeholders, e.g. the airport subsystem [2] or the commercial aircraft market [3].

The paper presents the development of a model comprising the key stakeholders' interactions. The development and structure of this model, "Modelling the Air Transport System" (MATS), as well as first simulation results of defined output variables connecting two or more stakeholders will be described.

After an introduction of the System Dynamics (SD) methodology, an overview of previous studies on SD application to the air transport system is given. The paper continues with a section on causalities and interrelations between different stakeholders of the air transport system. Interrelations that are implemented in the MATS model will be derived. The subsequent section presents the development approach and structure of the MATS model, including a detailed description of the four subsystems for the stakeholder's passengers, airlines, airports, and aircraft manufacturers. First simulation results on the output factors revenue passenger kilometres (RPK) and the fleet development as well as validation aspects will be presented. In particular, RPK is a common metric in the aviation industry for expressing the number of kilometres travelled by passengers. The growth rate of this metric is predominantly used in air traffic forecasts [4], [5]. The paper concludes with a summary of the MATS model capabilities and an overview of future work related to the further development and enhancement of the model.

2. INTRODUCTION OF SYSTEMS THINKING

The objective of this paper is to develop and provide a reliable model of the air transport system, which represents the major dynamics and interrelations between the key stakeholders. Systems Thinking and SD are well-established methodologies to model such dynamics as they are based on a holistic approach to investigate complex and dynamic systems. The methodology SD has been initially developed in the 1960s at the Massachusetts Institute of Technology by Jay W. Forrester [6]-[8] and has been further developed and extended in order to cover a wide range of application cases. The basic objective of a SD model is to comprehend the structure of a system as well as its behaviour and the drivers of this behaviour [9].

The methodology SD has been selected for the development of the MATS model since it enables a high-level analysis of the studied system using a simple yet effective modelling approach, in which interrelations between several stakeholders can be represented quantitatively. The form of representation allows to quickly getting an overview of the relations between the different model components. The following section introduces the general methodology of SD and presents results from a literature review on application cases of SD to different aspects of the air transport system.

2.1. System Dynamics methodology

SD is a modelling technique used for the study of complex systems and their evolution over time. As a bridge between the high-level managerial perspective and lower-level operations, the SD methodology allows the study of sufficiently aggregated structures [10], [11].

Mathematically, a SD model is a system of coupled, non-linear, first order differential equations, as shown in Equation 1 [12]:

$$(1) \qquad \frac{x(t)}{dx} = f(x, p)$$

X is a vector of state variables or stocks, *p* is a set of parameters, and *f* is a nonlinear vector-valued function. On a practical level, the mathematical concepts are simplified by discretising the temporal dimension and are hidden behind a highly intuitive graphical approach, using a combination of stocks and flows as basic constitutive elements of a model [11], [13]. An intuitive explanation of SD metaphorically compares the basic elements of a SD model to a bathtub being filled with water. According to this metaphor, systems are modelled using a combination of the following elements as depicted in Figure 1.

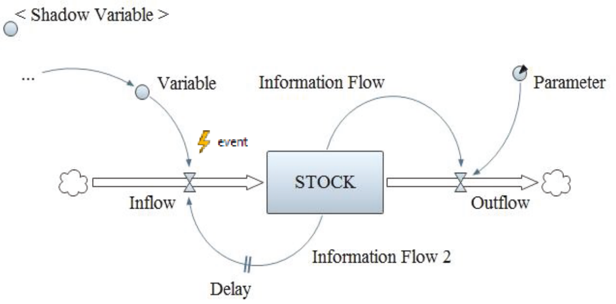

Figure 1. Schematic of basic constitutive elements in a System Dynamics model

Stocks or levels are the equivalent of the bathtub; they accumulate or deplete over time and describe, at any moment, the condition of the system. In this analogy, the content of the stock is the volume of water contained in the bathtub. The material flows represent the faucets that fill the stocks (inflows), or the drainages emptying them (outflows). The net result of adding all inflows and outflows affecting a stock is the rate of change observed in that stock. An information flow transmits information between elements, indicating that the value of one element depends on that of another. In this example, the outflow value is conditioned on the height of the water column in the bathtub and the inflow is corrected according to the volume of water in the bathtub. A delay indicates a waiting period between the event triggering the need for control, and the correcting action. With an event, specific actions can be scheduled within the model during simulation.

Given that, the outflow is not a function of the water in the bathtub, but its height, a conversion is required for the outflow. This conversion is included in a constant factor called parameter that translates water volume into height. When this element changes its value over time, it is referred to as variable.

Moreover, a model contains shadow variables, which are identical copies from other variables within the model. Changes in the original variable will automatically change the shadow variable in the same way.

2.2. Application cases in the air transport system

Several studies have been conducted applying the SD methodology to investigate research questions in the field of air transport, as seen in Table 1 overleaf. Within a literature review, the objective was to identify studies or models, which focus on a holistic view and contemplate more than one air transport stakeholder. The following section provides an overview of the literature review results.

Some models, which have been identified, focus on the interaction of two or more air transport stakeholders. Lyneis [1] has developed a model to analyse the commercial jet aircraft and aircraft parts industry in order to better understand the airline purchase behaviour from an aircraft manufacturers' perspective. His comprehensive SD model includes airlines, aircraft manufacturers, leasing companies, the used aircraft market, and the passenger demand side [1]. The focus of his SD model is on forecasting the aircraft order behaviour of airlines. Capacity aspects related to the airport infrastructure are not included in this analysis.

A second comprehensive model of the air transport industry, developed by Csala and Sgouridis [14] comprises the interactions between airlines, aircraft manufacturers, and passengers. Different technology scenarios are defined from the perspective of Airbus and Boeing. The simulation results are evaluated with respect to the economic performance of both manufacturers as well as the CO_2 emissions of the resulting global aircraft fleet. One major finding is the fact that the stakeholder who is innovating its aircraft technologies generates more profit than the competitor does, especially when the competitor does not invest in research and technology of new aircraft technologies. However, interactions with airports are not considered in this model.

Another SD model addresses the same issue, namely the competition between Airbus and Boeing as well as the impact of macro-economic influences, e.g. the development of the fuel price, on their medium- to long-term development strategies for new aircraft technologies. Pfaender and Marvis [3] note that the most important element to develop a feasible and trustworthy SD model is the calibration against actual data. The model presents simulation results from the purchase of Airbus A330-200 and Boeing B767400ER in a competitive market and under consideration of the fuel price development. The model provides guidance when investigating potential new aircraft technologies and their market acceptance.

Hustache et al. [15] contribute a SD model, which simulates the economic development of the European air traffic development in order to assess the air traffic services supply required. Costs for recruitment and education of the air traffic controllers as well as operational costs are considered. The model provides a tool for strategic management of the European infrastructure investments in air transport. Two publications were identified which investigate airport aspects such as landside as well as airside capacity and overall airport operations. Suryani et al. [16] present a forecast model for air travel demand, influenced by the gross domestic product (GDP) and the population development. From this, the capacity required to meet the demand for air trips, expressed as average number of flights per day, is calculated. Furthermore, the terminal capacity is simulated with the model considering all regular processes for departing and arriving passengers. The model supports airport officials in their decision-making process on capacity development. The second SD model on airport operational aspects simulates aircraft movements and passenger flows at one airport and combines these processes with economic aspects of the airport, i.e. its cash flows [2]. The model captures the perspective of one airport, taken Hamburg Airport as example for the simulation. Some weaknesses in the application of the SD methodology to the case of airport operations were identified in this context, e.g. the difficulty to implement delays of certain variables for a defined period during simulation in order to simulate aircraft operation breaks during a night curfew. Nevertheless, the methodology proves to be a useful tool to better understand dynamics and interrelations within a complex system [2].

Liehr et al. [17] analyse a different air transport stakeholder, the airline, and present an airline market model that provides support in strategic management of fleet planning and long-term capacity from an airline perspective. They raise awareness for business cycles in the air transport market and address the airlines' business cycle management within their model. The SD methodology is combined with a statistical forecasting model in this approach. A similar SD model of the airline industry investigating business aspects is presented by Pierson and Sterman [18]. Differently to the previous model, they focus on airline yield management and optimisation of capacity utilisation.

Yang and Miao [19] provide a model, which connects interactions between different transport modes in an urban environment. It is applied to a use case in the city of Shanghai. Population is the key driver for mobility in this model. Car, coach, motor cycle, taxi, bus, and rail are provided and can be selected as potential transport modes. This model is included in this overview to provide insights on how to model intermodal aspects, e.g. for the application case of the interface between airports and other transport modes.

Author(s)	Application case	Model
Lyneis [1]	- Identification of important structural changes to avoid unnecessary capacity expansion - Strategies to overcome business downturn	Jet aircraft industry model
Hustache et al. [15]	- Tool for long-term economic assessment - Model of the supply for air traffic services	PAMELA (Eurocontrol)
Liehr et al. [17]	- Airline market model for fleet planning and long-term capacity strategy development - Airline business cycle management	Airline market model
Pfaender & Mavris [3]	- Competition analysis of two aircraft types - Application of scenarios defining macro-economic market conditions (fuel price)	Commercial aircraft market model (aircraft manufacturer perspective)
Suryani et al. [16]	- Air passenger demand forecast for airport capacity (terminal and runway) - Application of policy scenarios	Airport capacity model
Yang & Miao [19]	- Evolution of urban passenger transport structure including all modes of transport - Use case: Shanghai	Urban passenger transportation model
Csala & Sgouridis [14]	- Analysis of impact of technology innovation on environment and economy - Competition between two aircraft manufacturers	GAIDT (Global Aviation Industry Dynamics Transition) model
Pierson & Sterman [18]	- Endogenous capacity expansion - Demand, pricing, and other feedbacks - Yield management	Behavioural dynamic model of the airline industry
Bießlich et al. [2]	- Link of operational aspects of an airport with economic development - Single airport perspective	Airport operations model

Table 1. Overview of studies applying the SD methodology to the air transport system

The scientific contribution of this paper complements the rather specific research activities in modelling the air transport system with a holistic approach of developing a model which provides relations and interactions between air transport system stakeholders from an overarching perspective.

One major outcome of the MATS model is the capability to forecast passenger demand for air transport driven by the development of population growth rates and GDP growth rates.

3. MODELLING THE AIR TRANSPORT SYSTEM

Global air traffic can be characterised as a system of trans-national operations where many stakeholders are involved. Wittmer et al. [20] describe this system with a value chain logic where upstream and downstream connections between the different actors are included. The air transport system provides services to the customers or air transport passengers. The general characteristics of the service industry, e.g. the perishability and intangibility of the goods produced, can be transferred to the product of the air transport system, i.e. a flight from one starting location to a final destination. Seats, which are not sold, are perishable and cannot be stored for a later flight and the service of a flight is an intangible good [17], [20]. The air transport system is constituted on the demand for air travel. Thus, it is important to understand what drives and expedites this demand. Several studies on air passenger demand have been conducted in the past. For the development of the MATS model, presented in this paper, the outcome of these studies was utilised and a regression analysis was conducted in order to identify factors having a significant effect on air passenger demand. Details on this are presented in a companion paper [21], which focuses on the methodological steps within the development process of the MATS model.

One major influence is the price for a flight [17]. The aspect is included in the MATS model with an elasticity describing the ratio between the ticket price for a flight and the preference for other mode shares. This relation expresses how many travellers choose the transport mode air as preferred choice over the other options, e.g. travelling by train, car or bus. A second important aspect driving air travel demand is the frequency of flights contained in the schedule of an airline [17]. The frequency of connections provided is one elementary input when measuring connectivity. An increase in frequency has a positive effect on the connectivity provided to the customer [22], [23].

The System Dynamics air transport model presented in this paper aims at providing a system-wide perspective on the interactions between airlines, airports, passengers, and aircraft manufacturers. Figure 2 presents the conceptual structure of the model.

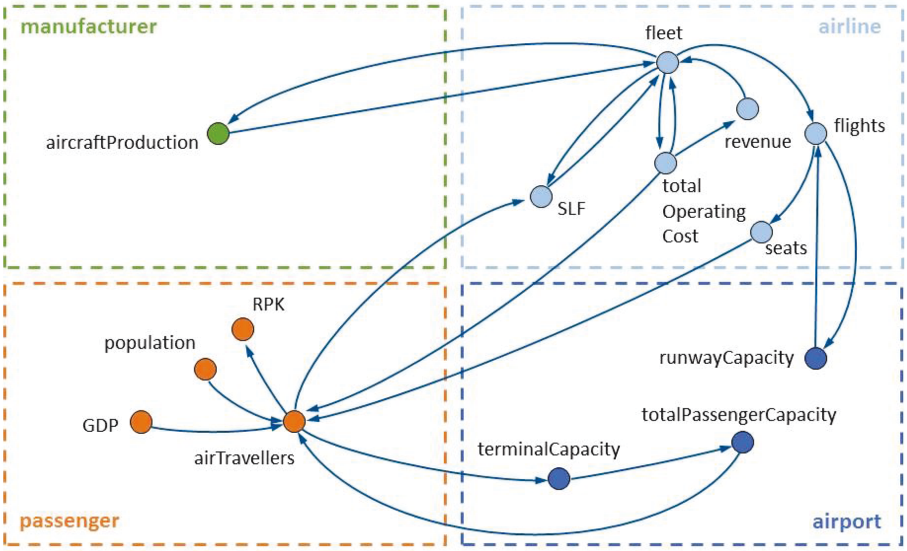

Figure 2. Conceptual graph of major interactions between passengers, airlines, airports, aircraft manufacturers, and external influences

The model structure comprises several major feedback loops. Three of these feedback loops link the airline respectively the airport subsystem with the passenger subsystem. These connections facilitate an impact of capacities generated, i.e. the total *seats* offered by the airline and the *totalPassengerCapacity* at the airport, on the development of air transport demand. The first loop couples the air transport demand, represented as *airTravellers*, with the seatLoadFactor *(SLF)* which, in turn, affects the *fleet* size of the airline. From the *fleet*, the *flights* and *seats* offered by the airline can be derived. The number of *seats* complete the feedback loop since they are linked with the number of *airTravellers*, used as input together with the average distance flown to calculate the *RPK*. Thus, this link back couples capacity changes on the airline supply side, i.e. when the *fleet* size or the frequency of *flights* increases, more *seats* will be offered. The second loop resembles the interrelation between the *flights* offered by the airline and the *runwayCapacity* provided by the airport. Thus, influences from a changing *runwayCapacity* on the *flights* are indirectly considered in the first loop. The third loop connects the *airTravellers* with capacity provided by the airport. From the number of *airTravellers* generated in the passenger subsystem, the required *terminalCapacity* can be derived and converted to the *totalPassengerCapacity* that the airport can provide. This factor is linked back to the passenger subsystem with the *airTravellers*.

Between the aircraft manufacturer and the airline, a fourth loop exists between the *fleet* of an airline and the *aircraftProduction*. This loop is delayed by the aircraft production time. Additional time, e.g. for research and development for improvements of existing as well as initiation of novel aircraft technologies are not considered at this stage of the model.

A fifth loop connects the passenger subsystem with the airline subsystem. The demand, represented as *airTravellers*, has an impact on the *fleet* development, linked through the *SLF*. Interrelations between the *fleet* development, the airline *revenue* and the *totalOperatingCost* affect the demand. Thus, the loop is closed with a connection from the *totalOperatingCost* to the demand through adjustments of the ticket price over time. The ticket price is not represented in Figure 2 but will be explained in more detail in the following descriptions of the subsystems.

The MATS model subsystems will be described in more detail in the following sections, including graphical illustrations. Different colours indicate if an element is obtaining data input (white, such as GDP or number of airports), is calculated within the model (grey, such as runway capacity or number of ordered aircraft) or represents a main output of the model, used, for instance, for the formal validation procedure (black, such as RPK or number of flights).

3.1. Passenger

Passengers are pivotal stakeholders of the air transport system and generate the demand for air transport services. Various factors influence travel demand, both in respect to travellers of all modes and specifically air transport passengers [24]. Two of the main demand drivers constitute the input for the passenger subsystem. *GDP* has been identified as an influential factor within a large amount of studies, such as Chèze et al. [25], Clewlow et al. [26], and Lyneis [27].

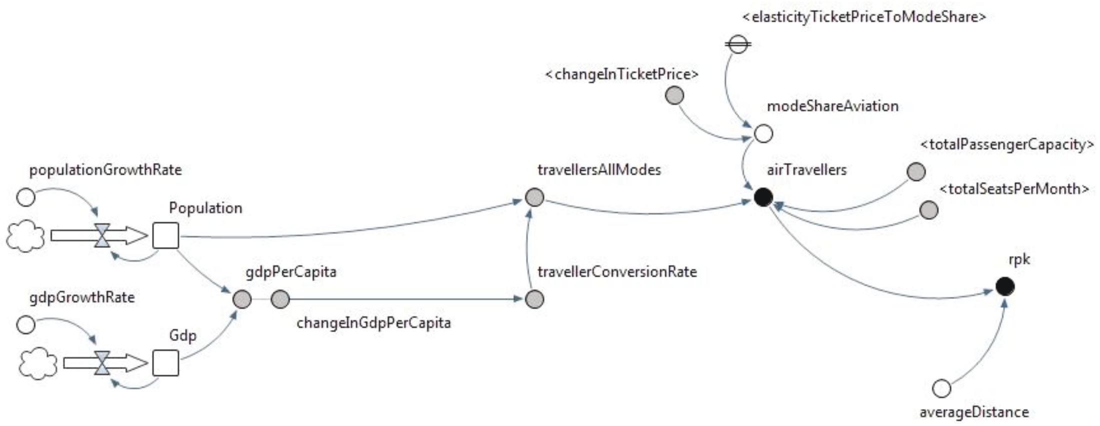

Figure 3. Passenger subsystem

The initial *GDP* value for the base year 2000 and annual *GdpGrowthRate* feed the passenger subsystem. The overall Population numbers [26], [28] as an increasing *Population* indicates an increase in demand for transport, also influences *TravellersAllModes*, including air transport. Hence, as can be seen in Figure 3, the initial *Population* and the annual *populationGrowthRate* are driving the passenger subsystem, as well. Travellers considered in the subsystem are European citizens only, since the model is based on the European population and, then, calculates the percentage of travellers in general using all modes of transport, *travellersAllModes,* as well as *airTravellers* in particular. Hence, passengers with a nationality other than European are excluded at this stage. Moreover, the subsystem distinguishes between *travellersAllModes* and *airTravellers*, which are generated using a *travellerConversionRate* and a mode share for aviation. The *modeShareAviation* is a function of a general mode share for Europe as well as of the *changeInTicketPrice* and the respective elasticity. *RPK* is calculated multiplying *airTravellers* times *averageDistance* (in kilometres). This is one of the main output factors of the MATS model. In Section 4, these *RPK* outputs will be presented and compared with historical and forecast data.

3.2. Aircraft manufacturer

The manufacturer subsystem exhibits the lowest level of complexity at the current stage of the model compared to the other subsystems since it represents the production of one aircraft type based on the number of *airlineAircraftOrders* by the airline and returns aircraft produced considering a defined production rate, included as an event delaying the delivery, and *aircraftBuildingDuration* as depicted in Figure 4. Specific aspects of the aircraft production process, e.g. research and development activities to investigate novel aircraft technologies or the introduction of other aircraft types with different performance and capacity characteristics, are not considered in the current model. Extensions of the model, which will contain these aspects, become necessary when more than one aircraft type will be introduced into the system and when several clusters of different airlines are established in the MATS model in a subsequent step of model development. Other models, which include the aircraft manufacturer perspective, show a similar setup. Manufacturing capacities and lead times for production and delivery are considered in these models [1], [14], as well.

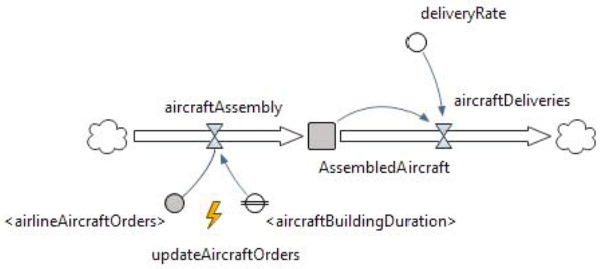

Figure 4. Aircraft manufacturer subsystem

When focussing on competitive aspects, i.e. the competition of two aircraft manufacturers in one market segment, or more precise one aircraft type, factors such as attractiveness and compatibility effects of a specific aircraft type become crucial [3]. Competition between aircraft manufacturers or specific aircraft types is another aspect worthy to be introduced to the MATS model at a later development stage.

3.3. Airline

The airline subsystem, presented in Figure 5, comprises major functionalities of a generic airline providing all scheduled *flights* within and outbound respectively inbound Europe for the base year 2000. Input on the number of *airTravellers* is provided from the passenger subsystem. In turn, the airline subsystem generates the number of *flights* required as an output, which feeds into the airport subsystem and drives the development of *runwayCapacities* over time. A feedback loop to the passenger subsystem, as described before in Section 3, results from aircraft purchase decisions influencing the *Fleet* stock and inducing a change in the number of *totalseatsPerMonth* offered by the airline. The decision to purchase a new aircraft in order to increase the *Fleet* is driven by the *seatLoadFactor* achieved by the airline in comparison to a *seatLoadFactorThreshold*, which has been defined based on the available literature and expert assumptions. An average *aircraftRetirementRate* is applied in order to include the reduction of the *Fleet* due to the aging of aircraft in operation besides the aircraft purchase activities, which increase the *Fleet*. For the calculation of the *totalSeatsPerMonth* available, average values for the *averageFlightFrequency* as well as for the *seatsPerFlight* are defined for all flights within Europe as well as outbound Europe, based on scheduled flight databases [29]-[34].

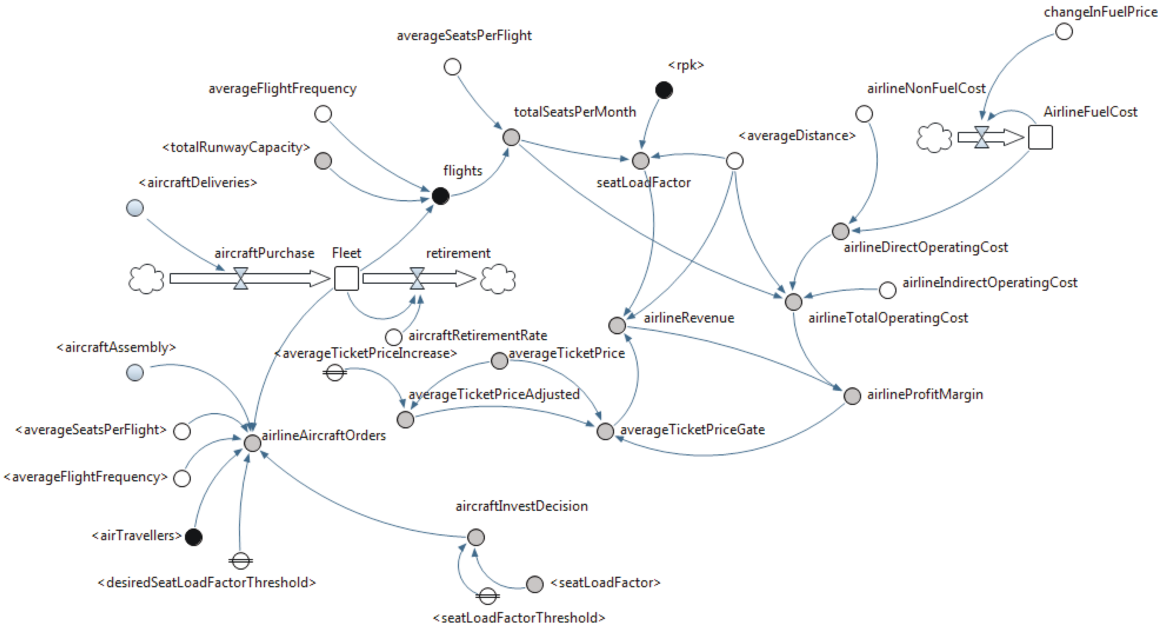

Figure 5. Airline subsystem

Operating cost of an airline are included and divided into *airlineDirectOperatingCost* and *airlineIndirectOperatingCost*. The cost component for fuel is separated from the rest of the *airlineDirectOperatingCost* in order to include the effect of changes in the fuel price, *changeInFuelPrice*, over time on the overall operating cost. Other external influences on the cost structure of the airline are not included at this stage. The ticket price is adjusted in case of a negative *airlineProfitMargin* with an *averageTicketPriceIncrease* of one per cent, elaborated based on expert judgement. In the case of a positive *airlineProfitMargin*, the ticket price is not changed.

3.4. Airport

The airport subsystem, depicted in Figure 6, provides the capacity required for meeting the demand from *airTravellers* and airlines. Capacity is disaggregated into terminal, runway, and airport capacity. The terminal capacity expresses the total number of passengers that the airport is capable of handling. The runway capacity relates to the number of *flights* required from the airline in order to meet its demand, which in turn gratify the demand of *airTravellers* for airline services. The airport capacity is resulting from the stock *Airports* in the subsystem, which represents the total number of airports, operated in Europe.

The three capacities are modelled as stocks since they are expected to accumulate or deplete over time because of the upstream and downstream interactions in the subsystem. In the current version of the MATS model, the rationale for capacity expansion presumes that a new *Airport* will be built if both new *requiredTerminalCapacity* and *requiredRunwayCapacity* is demanded at the same time and if a positive investment decision has been achieved. The subsystem contains several aspects, which act as investment drivers, i.e. the number of *flights* required and the number of *airTravellers*. If a certain *capacityThreshold*, which describes a desired load factor of the infrastructure, is reached, the decision for both, the terminal and the runway capacity, results in favour of the invest. In the current calibration setting, this threshold is defined as 0.72, based on expert judgement. In the rest of the cases where additional capacity is required, either terminal or runway capacities are adjusted to the demand for *airTravellers* or *flights*. In the case of no demand for additional capacity, no action is taking place for the respective simulation step.

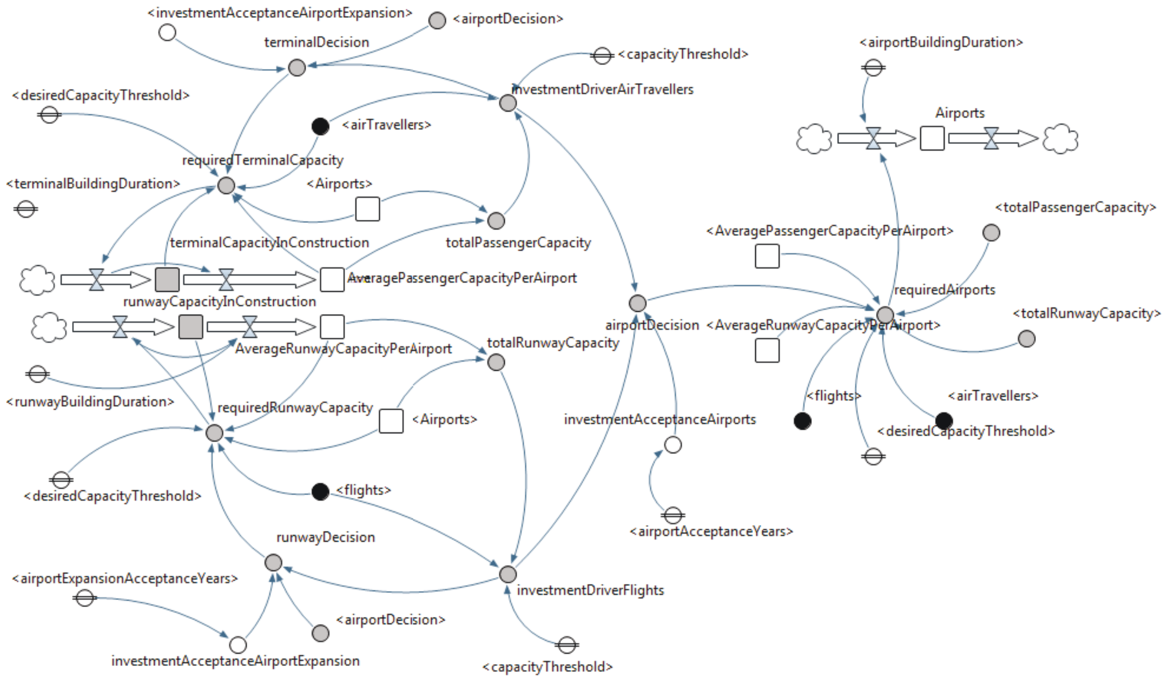

Figure 6. Airport subsystem

For each capacity adjustment, i.e. terminal, airport, and runway, a *buildingDuration* is implemented, based on expert judgement for a representative airport in Europe. These building durations induce a time delay in the provision of additional capacity.

Financial relations, e.g. between the airport and the airline as in previous models [2], [16], are currently not included in the airport subsystem. Furthermore, all threshold values, which currently steer the capacity adjustment activities at the airport, are elaborated according to expert assumptions and available literature.

4. FIRST RESULTS

The model was calibrated to historical data for the European air transport market between 2000 and 2016. The following section will give an overview of the simulation results in comparison with the historical data. Besides the development of RPK absolute and RPK growth rates, the fleet development will be presented.

Within the formal validation process of the RPK output, an error rate (≤ 5 per cent) was applied (see Equation 2 below) as suggested by Barlas [35] and conducted in various other SD-related studies, such as [36] and [16]. $\bar{S}$ refers to simulated model results (Simulation) and $\bar{A}$ refers to actual data (Actual) used for the formal validation procedure.

$$(2) \qquad Error\ Rate = \frac{\bar{S}-\bar{A}}{\bar{A}} \leq |0.05|$$

The simulated average yearly RPK growth rate (2017 - 2036) is 3.22 per cent and detailed yearly growth rates for those years are depicted in Figure 7 below. Similar average growth rates p.a. for this period is provided in the Airbus Global Market Forecast for 2017 – 2036 (3.3 per cent). Applying Barlas' error rate, the model output of RPK growth can be verified, as seen in Table 2 below.

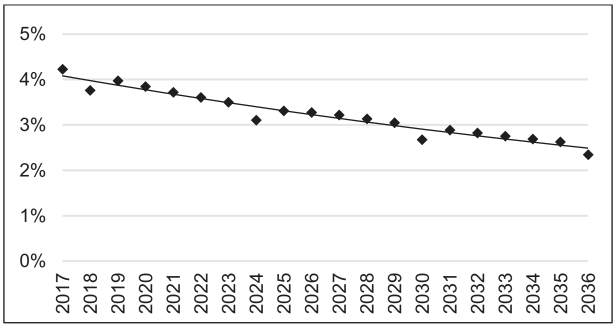

Figure 7. Simulation results: yearly RPK growth rates (2017 - 2036)

	$\bar{A}$ (RPK growth [%])	$\bar{S}$ (RPK growth [%])	Error rate
RPK growth [4]	3.3	3.22	-0.02

Table 2. RPK growth output validation

The MATS model generates demand for air travel based on a cumulative value for population for 43 selected European countries considered, including EU-28, EFTA, and additional countries. Due to that, the MATS model only comprises passengers with a nationality from one of these countries. Transfer passengers from other nations or countries are not considered in the current model version. Thus, the absolute RPK values resulting from the MATS simulation are expected to be below annual RPK values for Europe, reported in forecasts from the two aircraft manufacturers Airbus and Boeing. An analysis of the annual RPK values points out that the simulation results are 18 to 34 per cent below the values from the forecasts, as seen in Table 3 overleaf.

	$\bar{A}$ (RPK [billion])	$\bar{S}$ (RPK [billion])	Error rate
2000	440.10	350.22	-0.204
2001	449.30	360.67	-0.197
2002	453.80	370.71	-0.183
2003	474.70	381.31	-0.197
2004	523.12	392.48	-0.250
2005	560.00	403.99	-0.279
2006	590.00	415.22	-0.296
2007	630.00	427.07	-0.322
2008	660.00	437.91	-0.337
2009	624.90	448.38	-0.282
2010	644.10	464.64	-0.279
2011	659.50	485.45	-0.264
2012	710.00	506.38	-0.287
2013	714.00	533.17	-0.253
2014	760.00	560.28	-0.263
2015	796.80	585.41	-0.265
2016	859.40	610.58	-0.290

Table 3. RPK output validation

In order to underpin the line of argument that this delta represents transfer passengers, average annual figures from airports in Europe with a representative share of transfer passengers have been collected and compared with the simulation results. Data on transfer passengers is required for the validation of the RPK output. However, not all European airports publish this information. A recent working paper on how to assess the percentage of airport transfer passengers provides some data on this for European as well as for other airports [37]. Results reveal that the percentage of transfer passenger shares at selected European airports from 2004 until 2014 varies between 5 and 40 per cent. Thus, the error rate in Table 3 is situated between the literature values. However, further analyses with additional transfer passenger data needs to be performed for verification.

A second aspect, which has been validated in the current version of the model, is the fleet development and the airline aircraft order behaviour.

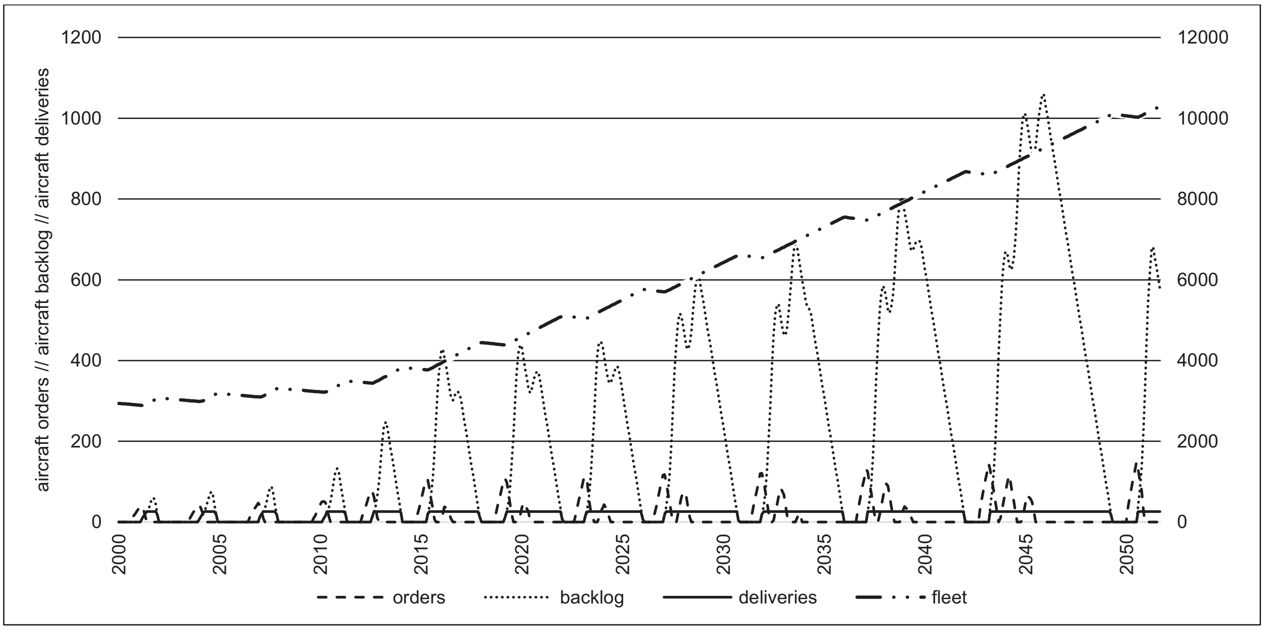

Figure 8. Simulation results: fleet development and airline aircraft order and delivery behaviour

Figure 8 presents the results with the aircraft order and delivery cycles on the left vertical axis as well as the fleet development on the right vertical axis.

Each of the aircraft production cycles begins with the order, represented in Figure 8 with the dashed black line. After that, the backlog, the black dotted line, is generated with the number of aircraft ordered as input. Subsequently, the aircraft production, the solid black line, with a capacity of 26 aircraft per month begins. This monthly production rate results from an analysis of the total production capacities worldwide and a subsequent calculation of the European share of these capacities based on the European share of the global available seat kilometres (ASK) [29], [38]. 12 complete aircraft production cycles are required between 2000 and 2050 in order to address number of aircraft required for fulfilling the increasing demand for air travel. Thus, the number of aircraft ordered and produced in each cycle increases. The aircraft building duration is set to an average value of six months per aircraft.

	$\bar{A}$ (no. of a/c)	$\bar{S}$ (no. of a/c)	Error rate
(1) no. of a/c [39]	2942	2940	0.00
(2) no. of a/c [5]	7721	7552	-0.02

Table 4. Fleet output validation

The fleet has been validated with figures from two Airbus Global Market forecasts [5], [39]. In 2000, the European aircraft fleet is expected to account for 2942 aircraft whereas this number increases to 7721 aircraft in 2017[1]. For the year 2050, the MATS model expects the European fleet to increase to 10059 aircraft.

The validation of RPK growth rates, RPK absolute values, and the fleet development reveal that the MATS model provides acceptable results in comparison with figures from the literature. However, weak points of the model in its current version emerge. The fact that the current air passenger demand logic implemented in the model is premised on the cumulated population of the selected countries in Europe, as mentioned before, lacks the model capability to consider transfer passengers within Europe. As soon as the system boundary of the model will be changed, e.g. to a global level, there is a need to not only define but also generate transfer passengers. This will be solved with a segmentation of air passengers. Thus, an air passenger originating from a different global region, e.g. Asia, can be identified as transfer passenger in a different global region, e.g. Europe.

With regard to the fleet development, production capacities are currently estimated from the global cumulative production capacities of all aircraft manufacturers and the European share of ASK. More detailed data, e.g. on aircraft purchases per aircraft manufacturer and airline or on aircraft production capacities per aircraft manufacturer, specifically for Europe, would increase the level of accuracy on the fleet development. Nevertheless, the MATS model provides insights in the aircraft order and production as well as fleet development in Europe for the case of one representative airline and one representative aircraft manufacturer. In case of several airlines with a demand for aircraft and more than one aircraft manufacturer producing and selling one or more aircraft types, competitive aspects need to be included in the system. This will be one of the subsequent development steps, which will be highlighted in the last section.

5. CONCLUSION AND OUTLOOK

The objective of this paper was to present a comprehensive SD model of the European air transport system. The MATS model represents the European air transport system, including all intra-European flights as well as flights to or from Europe. Based on a literature review of previous SD publications in the field of air transport, four major stakeholders, air passengers, airlines, airports, and aircraft manufacturers, were identified and their general functionalities as well as interrelations between two or more of these stakeholders were integrated in the MATS model. The interrelations were implemented as major feedback loops in the system. These feedback loops were described in the paper. Furthermore, the MATS model simulation results for air transport demand, represented as RPK, and fleet development were presented and compared with historical data as well as forecast values from the literature.

Further validation, e.g. of the impact on the number of air travellers from changes in the airport terminal capacity respectively the seat capacity provided by the airline, appears to be a reasonable supplement to the work in this paper. One shortcoming of the current MATS model version structure is the fact that both factors, the total seat capacity and the total passenger capacity, are provided by only one representative airline respectively airport. In order to consider different types or groups of stakeholders, several clusters will be introduced into the MATS model. An integration of airline and airport clusters will be realised through the implementation of different agents, one agent representing one cluster. This approach requires the combination of two methodologies, agent-based and SD modelling. The overall capacity provided from airports and airlines, then, needs to be allocated to the different clusters. Furthermore, competitive aspects mainly between different airlines need to be incorporated in the MATS model structure. The airport clusters exhibit differences in their expansion behaviour. These specifications can be represented with the implementation of the airport clusters.

The integration of airline clusters and the resulting competition between airlines induces the distribution of different customer segments. Thus, it is crucial to implement different types of passengers. These passenger groups show specific demand characteristics, e.g. different price sensitivities or a different perception of service.

Next steps of the MATS model development, besides the fragmentation of different stakeholders, will be the extension to a global scale with all its implications, e.g. the structure of traffic volumes between different global regions, differences in growth rates for air passenger demand, or fleet development in different global regions. Especially for the traffic volumes, a feasible allocation to the global regions as well as the introduction of air traffic volumes between global regions need to be integrated in the MATS model.

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[1] The figures from the forecast reports do only cover aircraft types with 100 or more seats. However, they provide a satisfactory basis for the validation of the fleet produced in the MATS model simulation.

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