M. Urban, K. O. Ploetner, M. Hornung, "Integrated Modeling of Dynamic Airline Behavior in the Air Transport System", 18th AIAA Aviation Technology, Integration, and Operations Conference, Atlanta, GA, 2018.

Integrated Modeling of Dynamic Airline Behavior in the Air Transport System

Urban, Marcia*; Ploetner, Kay Olaf†; Hornung, Mirko‡
Bauhaus Luftfahrt e.V., Willy-Messerschmitt-Straße 1, Taufkirchen, 82024, Germany

The air transport system has been studied in a multitude of previous research. However, many studies have analyzed specific aspects such as feedback loops within in the system or competition between different air transport stakeholders. This paper presents a combination of different methodologies, the System Dynamics (SD) and the Agent-based (AB) modeling methodology; and provides a hybrid model of the air transport system to investigate the European airline market considering competitive behavior between different airline types. Different stakeholders such as passengers, airlines, and airports will be integrated in the hybrid model as different agent types. Connections between the SD and the AB part of the hybrid model in both directions enable the exchange of data relevant for the agents' decision-making process as well as for the impact of an agents' decision on a specific variable of the SD model part, e.g. runway capacity. The paper will conclude with an outlook of calibration activities and the description of an application case to analyze the European airline market.

Nomenclature

AB	=	Agent-based	LR	=	long-range aircraft type
FIFO	=	first-in-first-out	REG	=	regional aircraft type
FSNC	=	full-service network carrier	SD	=	System Dynamics
GDP	=	gross domestic product	SLF	=	seat load factor
LCC	=	low-cost carrier	SMR	=	short- to medium range aircraft type

I. Introduction

The air transport system can be described with the interplay of demand for air transport services and supply of these services to accommodate this demand. Many stakeholders are involved in this process where their interrelated decisions spread out a large network[1]. The network that describes the air transport system can be considered as highly complex and volatile. A multitude of influences result from the interactions between different stakeholders in the air transport value chain as well as from external factors, e.g. the fuel price development, passenger demand or exogenous shocks.

When focusing on the stakeholder "airlines" in particular, not only interactions with other air transport stakeholders but also competitive behavior between different airline types have to be taken into account. These affect airline decisions, especially related to the network structure, aircraft, and market choice. Use cases which can be investigated with the hybrid model, presented in this paper, apply to interactions between different types of airlines such as full-service network carriers (FSNC) and low-cost carriers (LCC). One example is the entry of Norwegian Air International into the transatlantic air transport market[2]. Norwegian Air International can be characterized as a low-cost carrier which provides inexpensive alternatives for long-haul travel compared with the

* Research Assistant Economics & Transportation, marcia.urban@bauhaus-luftfahrt.net
† Head Economics & Transportation, kay.ploetner@bauhaus-luftfahrt.net
‡ Director Research and Technology, mirko.hornung@bauhaus-luftfahrt.net

established FSNC on routes between Europe and North America. The hybrid model, presented in this paper, can provide insights into the development of market shares in the market of routes outbound Europe. Furthermore, it can be investigated how FSNC reply to the market entry of a competing LCC since the hybrid model provides changes of available seats and average frequency applied by both FSNC and LCC on the market outbound Europe. For the example of Norwegian Air International, an increase of FSNC seat density and frequency can be expected in order to converge operating cost towards LCC levels for the corresponding passenger segment to maintain a competitive position.

For this as well as other specific examples of interactions between different airline types, there are specific underlying market conditions. However, the hybrid model only provides an aggregated level of the air transport market with two representative airline types. Thus, the model boundaries are reached in simulating individual competitive situations with several specific airlines involved such as described above. But parameters such as market shares of FSNC and LCC as well as capacity adjustments of both airline types, expressed in available seats and frequency, are implemented in the hybrid model. These parameters allow implications on the development of the market. The objective of the model simulation is to anticipate future developments of the air transport market in order to gain a deeper understanding of the effects of these developments on the two generic airline business model types, FSNC and LCC.

Several methodologies need to be combined in order to model all the different abovementioned aspects of the airline behavior in the air transport system. The authors have selected the System Dynamics (SD) and the Agent-based (AB) modeling methodology to develop a model that allows for the analysis of the airline behavior within the air transport system. Competition aspects between different airline types will be considered through integration of specific decision parameters within the AB modeling of each airline agent. The hybrid model provides capabilities to describe generic cases in which two different airline types, i.e. FSNC and LCC, interact with each other and react to the competitors' behavior. These capabilities will allow to derive implications for airlines' behavior in a specific competitive situation.

II. Literature Review

Previous research on air transport system modeling comprises several SD and AB based models as well as hybrid models combining the two methodologies, all focusing on one or two major stakeholders interacting with the air transport system or with each other. Two of these studies focus on airlines and their interactions with other stakeholders within the air transport system[3,4] Liehr et al.[3] present a SD model of the airline market for fleet planning and long-term capacity strategy development. Pierson and Sterman unite aspects of endogenous capacity expansion and yield management within a SD model on behavioral dynamics in the airline industry[4]. A comprehensive SD model on airline profit cycles has been published including aspects such as aircraft purchasing and retirement decisions, productivity of aircraft assets and aircraft utilization, and the impact of yield management on the profit cycle of an airline[5]. Furthermore, an initial study was published on the development of a SD model that considers four different air transport stakeholders, i.e. passengers, airlines, airports, and aircraft manufacturers, at a similar level of detail and represents all relevant interactions between the stakeholders through causal relations[6]. The integration of an AB model for analyzing airline evolution, competition, and airport congestion can be a feasible approach to gain a better understanding of modeling competing airlines as agents[7].

Besides these findings, a literature review on hybrid models combining AB and SD methodology mostly related to the transport sector has been performed in order to identify the previous research relevant for the development of a hybrid model for the air transport sector in Europe. Major findings are summarized in table 1 and will be explained in the following in more detail.

One application of the AB and SD methodology is presented in a model developed by Shafiei et al.[8] for the simulation of the transition to sustainable mobility. In their model, the energy supply and according infrastructure is modeled with the SD methodology. The major stakeholders in the alternative fuel vehicle market are modeled as agents such as car manufacturers, car importers or dealers, consumers, charging stations, the government, and the energy supply system. Simulation results point out the market share development of alternative fuel vehicles in Iceland between 2013 and 2050, the change of utilities for consumers and a forecasted fuel demand. The authors conclude that the combination of AB and SD methodology allows for a comprehensive analysis since a hybrid model can be more accurate compared with a SD based model[8].

This work has been evolved and further developed in Shafiei et al.[9] when applying the hybrid model to investigate different paths towards an alternative fuel market for road vehicles in Iceland between 2015 and 2050.

The hybrid model provides an insight into how energy supplier and infrastructure owner decisions have an impact on the behavior of the consumers and on the demand for alternative fuels[9].

Köhler et al. present an AB model with two types of agents: a large number of simple agents representing consumers and a small number of complex agents with an integrated SD structure in each of these agents[10]. The model was developed to investigate transition paths of sustainable fuel alternatives in road transport. The model is applied to UK transport data. Major results from the research with this model imply a long-term transition towards hydrogen fuel cell vehicles after 2030. Biofuels and internal combustion engine electric hybrids remain the major alternatives to conventional gasoline[10].

Table 1: Overview of previous research combining SD and AB methodology in one simulation model

Author(s)	Application case	Model
Shafiei, E. et al., (2015)	Analysis of transition paths towards alternative fuel market for road vehicles in Iceland between 2015 and 2050	Integrated model a renewable-based energy system with interactions between SD and AB components
Shafiei, E. et al., (2013)	Evaluation of the diffusion process of alternative fuel vehicles (cars) in the mobility sector	Integrated model of sustainable mobility with interactions between SD and AB components
Köhler et al., (2009)	Assessment of transitions to sustainable mobility	AB model integrating a SD model within a small number of complex agents
Kieckhäfer, K. et al., (2009)	Model development for the analysis of product strategies in the automotive sector	SD model integrating agents for strategic decisions on the automotive industry
Kieckhäfer, K. et al., (2012)	Analysis of product strategies in the automotive sector with special regard to alternative fuels and powertrain technologies	Further development stage of SD model integrating agents for strategic decisions on the automotive industry
Schieritz, N., Größler, A., (2003)	Analysis of a four-level supply chain with ten agents	AB model of customer – supplier relationship integrating a SD model within each agent

Another hybrid model for strategic decisions in the automotive industry is provided by Kieckhäfer et al.[11] and Kieckhäfer et al.[12]. More specifically, the model supports the decision of a car manufacturer on which powertrain to introduce at which date to the market at which vehicle class. Three major stakeholders are represented as agents: car manufacturers, customers, and legislature. The SD part of the hybrid model represents the market with modules of infrastructure, demand, and production. The two different parts of the model are interconnected through exchange of information in both directions. Thus, interactions within the SD modeled market have an impact on the decisions of the different agents and agents' decisions, in turn, affect the market environment. The customers' choice to buy a car with a specific powertrain depends on two different parameters: the price and the range of the car. Two different customer groups are considered in the model: poor and rich. A Multinomial Logit model is used to model the probability that a consumer decides for a specific option. Such a probability can be applied to a population of agents in order to define a proportion of customers who decide to purchase a specific type of car-powertrain configuration[11, 12].

Schieritz and Größler present a hybrid model integrating AB and SD modeling to analyze emergent structures of supply chains[13]. In contrast to the pervious examples of hybrid models, their model is based on a macro-level network of agents representing supply chain participants. On a micro-level, each one of the agents is provided with an internal SD structure which describes the consumer's individual decision-making behavior. Two parameter variation studies are presented. In a first case, the order fulfillment strategy is varied between a FIFO and a relationship-based order fulfillment strategy. Results provide that the latter strategy results in a more stable supply chain structure after a simulation of 50 periods. In a second case, the attractiveness decay time is changed for different simulation runs. The simulation results in this parameter variation study reveal that a high attractiveness decay time facilitates a more stable supply chain structure[13].

Within a SD model, the system behavior is generated through feedback loops representing the basic building blocks of the model. In turn, the interaction between agents within an AB model is responsible for the system behavior[14]. The hybrid model will consider both effects driving the behavior of a system, in this case the air transport system: feedback loops on the SD level and the interaction of different agents on the AB level. The literature review in this paper presents a comprehensive overview of all publications related to hybrid simulation models applied to the transport sector integrating AB and SD methodology to the best of the authors' knowledge at present. On this basis, the hybrid model, presented in this paper, will complement the existing research landscape with a hybrid model for simulating the European air transport market. All insights from previous models will be recognized during the development process of a hybrid model integrating the two methods of SD and AB modeling. The methodologies applied as well as the structure of a hybrid model presented in this paper, will be described in detail in the following chapters.

III. Methodology

The following chapter provides an overview of the methodologies implemented. To consider the interrelations within the air transport system, to take into account airline decisions with respect to their competitive behavior, and to gain a deeper understanding of the dynamics within this complex system, a combination of comprehensive methodologies needs to be applied.

One methodology that is well-established in the context of analyzing complex systems is SD[15]. The SD methodology allows for gaining insights into how complex systems operate and how they react to external impacts. SD models rely on causal loops between the different elements included. The model objective is to identify closed or circular causalities within the system since these loops ensure feedback between the elements included and, thus, enable dynamic behavior within a system[16]. Quantification measures are required to represent linkages between the elements within the system. All SD models are based on a generic structure of stocks and flows. Mathematically, these elements are linked by coupled, non-linear, first order differential equations[17].

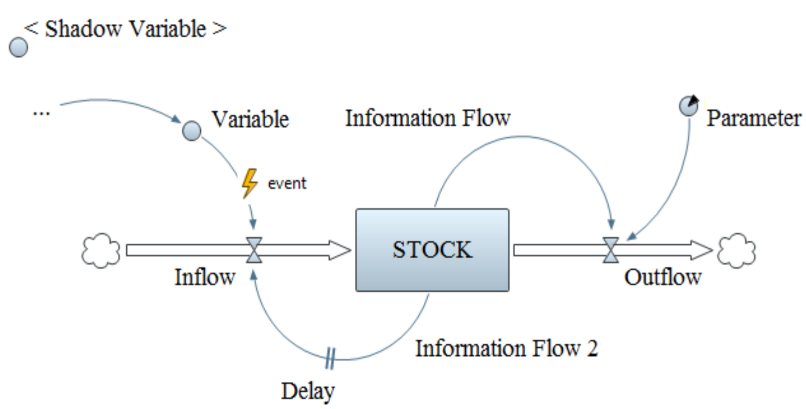

Figure 1: Schematic of basic constitutive elements in a System Dynamics model[6]

In figure 1, stocks are characterized by specific levels which can change over time due to an inflow, increasing the level, or an outflow, decreasing the level. Parameters and variables can impact the in- or outflows of a stock. This impact can be scheduled through integrating a time-related event.

The decisions of different actors can be implemented by using the AB methodology. The beginning of this methodology reaches back to the early 1970s[18, 19]. In an AB model, the individual behavior of different agents is implemented and drives the global behavior of the underlying system, which represents the environment in which the agents are embedded[20]. According to Davidson's definition, AB is a micro-simulation approach because it represents the behavior of an overall system, i.e. a population, by modeling the elements, i.e. individuals which interact with other agents within such a system as well as with the environment in which the agent is situated[21].

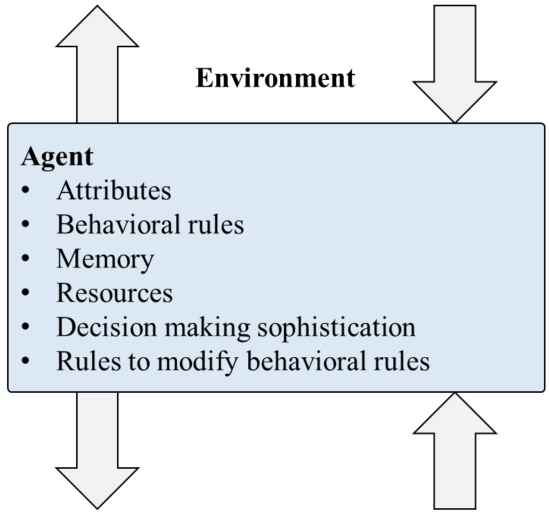

Figure 2: Schematic of basic agent characteristics[22]

As depicted in figure 2, an agent exhibits several characteristics such as attributes and rules governing its behavior and it is located within an environment in which it interacts with other agents as well as with the environment itself. An agent is capable of memorizing past interactions in order to learn and adapt its behavioral patterns based on these experiences[22].

In order to meet the requirements of modeling the air transport system as well as interactions between different agents representing the major air transport stakeholders, a combination of the two methodologies, SD and AB, is chosen. Previous research as summarized in the preceding literature review proves that the integration of the two methodologies is a feasible approach for this. The two methodologies differ in several characteristics as presented in table 2. SD applies a top-down approach to model complex and dynamic systems on a macro level including the major components and interactions of such a system. The major building blocks are feedback loops within the system and the system structure constitutes the unit of analysis. As mentioned previously, the different elements in a SD model are linked through differential equations. In turn, AB is a bottom-up approach where a system is analyzed by modeling actors as agents and their interactions with other agents and with the environment on a micro level to determine collective behavior patterns or rules. Time steps in AB simulation models are discrete whereas a SD model runs with continuous incremental time steps[14, 23].

Table 2: SD versus AB simulation (adapted from: Schieritz/Milling, 2003)[14]

	System Dynamics	Agent-based Simulation
Basic building block	Feedback loop	Agent
Unit of analysis	Structure	Rules
Level of modeling	Macro	Micro
Perspective	Top-down	Bottom-up
Handling of time	Continuous	Discrete
Mathematical formulation	Integral equations	Logic
Origin of dynamics	Levels	Events

For the investigation of interrelations between different actors within the air transport system and to answer the question how the actors' decision process affects the development of the system, it can be beneficial to combine SD and AB to benefit from the advantages of both methods[24]. Both methodologies have the same objective: to identify leverage points of a system. A hybrid model combining the two methodologies can be structured in two generic ways. One way is to define agents and to integrate them into an overall SD environment. The other way is to implement a SD logic within each agent to increase its complexity[25]. The hybrid model presented in this paper combines SD and AB by integrating agents for passengers, airports, and airlines into a SD environment representing the air transport system. In that way, the model is capable of representing both the air transport system on a macro-level as well as actors' interactions within an AB structure on a micro-level. In addition, impacts from the macro-level part of the model such as changes in demand for air transport or available airport capacity on airline behavior as well as vice versa can be simulated. At this stage of the model, two agent types are defined per stakeholder such that the population model is aggregated and within an agent type, individuals are not further distinguished[26].

IV. Model Structure

The following chapter provides a description of the hybrid model, including key elements and causalities. The hybrid model focusses on airline interactions with competitors as well as with the demand side, airports, and aircraft manufacturers. Furthermore, decisions of different airline types and different passenger preferences are included in the model.

One multi-paradigm modeling software that allows for combining up to three different methodologies, i.e. System Dynamics, agent-based, and discrete event modeling, is AnyLogic from XJ Technologies[27]. AnyLogic provides capabilities for an easy implementation with no interface required between the SD and the AB model part[28]. Figure 3 represents the multi-method architecture of combining SD and AB modeling methodology. The SD model image on the left-hand side represents the structure of the air transport system, including all major stakeholders involved, i.e. passengers, airlines, airports, and aircraft manufacturers. In turn, specific decision rules of different agents representing different airline types are implemented within an AB environment. This ensures that the behavior of different airline types considered within the air transport system can be modeled individually, including different strategies to react to actions of competitors in the market.

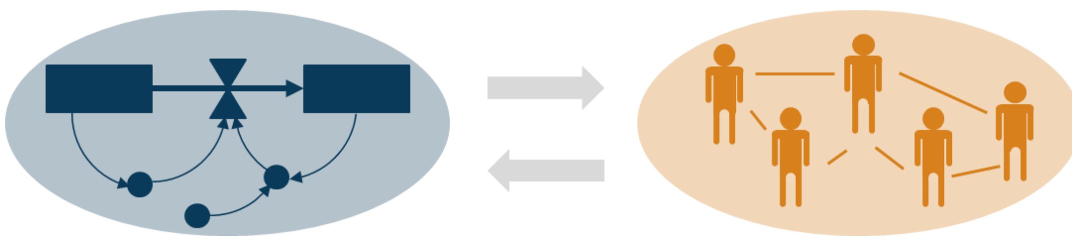

Figure 3: Multi-method architecture combining SD and AB methodologies[16]

Since the hybrid model is continuously further developed, each component within the SD as well as the AB part is structured modularly. The version of the hybrid model presented in this paper comprises the European air transport system and includes air traffic outbound Europe to other global regions. At a later stage of development, the consecutive integration of North America is envisaged in order to provide simulation capabilities to analyze transatlantic market.

The part of the hybrid model representing the structure of the air transport system consists of four SD subsystems representing four air transport stakeholders: passengers, airlines, airports, and aircraft manufacturers. For this, the structure of a previously developed model[6] (see figure 4) is transferred and further developed.

Demand is derived from the population development and GDP growth, within the passenger subsystem. Airlines traditionally consider two different customer groups: leisure and business passengers[29]. Thus, the hybrid model for air transport services distinguishes between these two passenger groups based on their individual preferences.[30] Leisure and business passengers will be represented by two agent types which will be included in the AB part of the hybrid model presented in this paper.

The aircraft manufacturer subsystem provides three different types of aircraft: regional, short- to medium-range, and long-range aircraft. A respective delay between order and delivery is implemented for each type due to different production times.

The airport subsystem provides capacities required by the airline subsystem to operate air transport services. These include the overall passenger capacity, the terminal capacity, and the runway capacity. The SD model part distinguishes between two different airport agents: hub airports and non-hub airports. The number of annual passengers as well as the annual average percentage of transfer passengers were used to categorize all European airports into these two agent types. Together, they provide the total airport capacity in Europe. The level of capacity has an influence on the airlines' market selection decision. For example, a LCC who decides to operate its flights from a hub airport enters a market where it is highly probable to enter a competitive market with established FSNC because these agent types conduct their flight operations within a hub-and-spoke network.

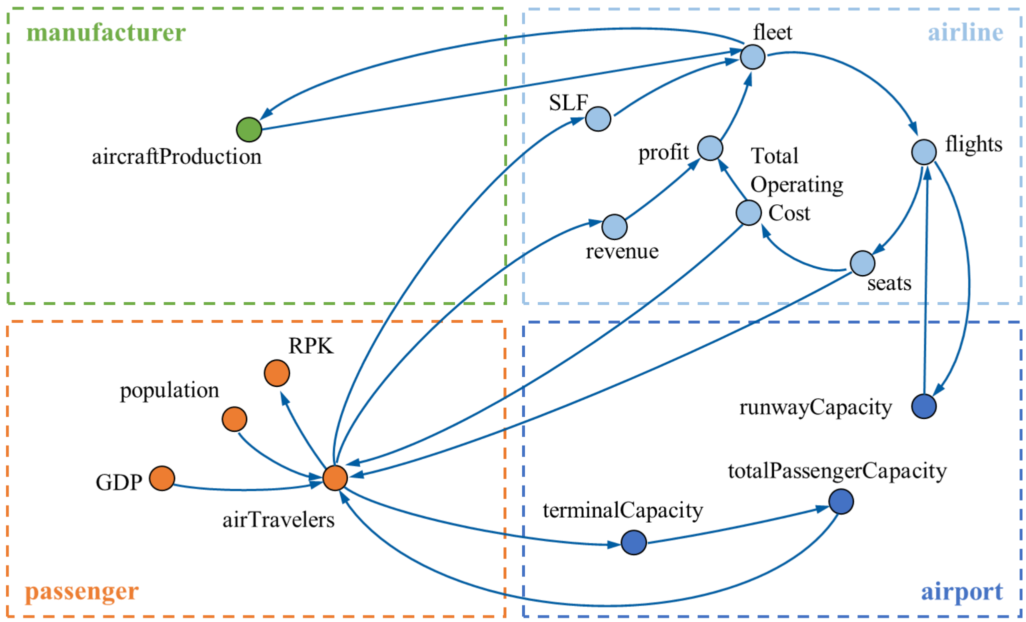

Figure 4: Conceptual graph of interactions within previously developed SD model, adapted from Urban et al. (2017)[6]

For the analysis of airline market structures, the two different airline types FSNC and LCC will be implemented in the model. The selection of these two airline types is based on results from research investigating the phenomenon that existing airline types tend to gravitate towards each other[31]. FSNC and LCC represent the two respective ends of the continuum on which existing airline types can be positioned, which is why these two airline types were selected. The two airline types will be implemented as agents with individual aircraft choice behavior, selection of airline markets in which they operate, and competitive behavior represented with different market strategies applying AB methodology. Porter has initially developed three generic competitive strategies: cost leadership, differentiation, and focus or niche strategy[32]. The FSNC will pursue a strategy of differentiation and will address the demand of quality sensitive customers. In turn, the LCC will focus on a cost leadership strategy. The decisions of both airline types will orient their decisions towards the respective primary strategy.

Figure 5 gives an overview of the agent types representing passengers, airlines, and airports implemented in the AB part of the hybrid model. Six active agent types are implemented which will be described in more detail in the following.

The demand side of the air transport system is divided into two passenger agent types as already described above: business and leisure passenger. These two agent types differ in their preferences regarding the price for a flight and a time related elasticity which will be expressed by the average frequency that an airline provides. Both passenger groups have the objective to maximize their utility from a flight. The implementation of this aspect will be explained later in more detail.

In contrast to the demand side, the supply side in the hybrid model is represented by the two airline types FSNC and LCC which both aspire to maximize their profit. The major attributes which affect the decision making process of an airline to increase the capacity are the seat load factor (SLF), the average frequency per region, and the aircraft fleet size. The different airline decision process steps to increase capacity will be explained later in more detail.

The capacity of airports is not limited in the current version of the hybrid model. Thus, airports will increase landside capacity, considered as terminals, and airside capacity, considered as runways, when the demand for air transport increases. The airport SD subsystem is connected with the passenger subsystem with regard to terminal capacity and with the airline subsystem with regard to runway capacity. In order to account for different capacity constraints, two airport types represented by the two agent types, hub and non-hub airport, are integrated in the AB part of the hybrid model. Hub airports have higher capacities compared with non-hub airports but also have to manage a higher demand which leads to a higher capacity constraint level compared with non-hub airports[33]. Furthermore, the airline types selected prefer different airport types to integrate in their network. The FSNC operates a hub-and-spoke network connecting larger airports. In turn, the LCC provides a variety of direct connections implemented within a point-to-point network[34].

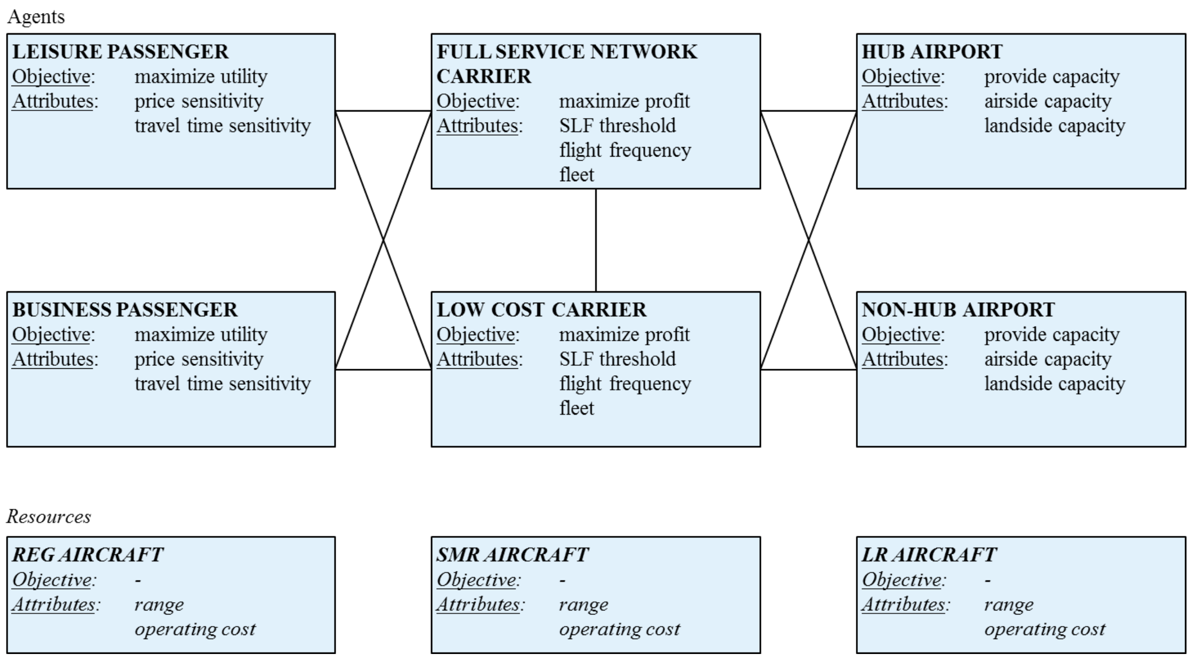

Figure 5: Model structure on agent-based level (adapted from: Shafiei et al. (2013), p. 50.)[8]

Besides the six active agent types described above, three different aircraft types are provided by the aircraft manufacturer. They are characterized by two attributes, the range and the operating cost. The two airline agent types FSNC and LCC select an aircraft type based on the two attributes for the operation within a region, i.e. Europe, or between regions, e.g. from Europe to North America, indicated as air traffic outbound Europe in the current state of the hybrid model.

All attributes of the six active agent types represent variables (e.g. frequency) or stocks (e.g. fleet) in the SD part of the model which are connected with the AB part and provide the input information required for the decision process of the agents. Changes in these variables or stocks after an agent decision time step are returned to the SD part as a feedback information. Thus, the agents' decisions have an impact on the development of the air transport system, implemented in the SD part on a macro-level, over time.

The following figure 6 gives an overview of the interfaces between the SD and the AB model part. Different agent behavior resulting from different behavioral rules of each agent group endogenously affects the overall air transport system on the macro-level. For example, decisions of the two different passenger agents, leisure and business passengers, have an impact on the variable representing the air travelers, implemented in the SD model part. The two different airline types, FSNC and LCC, affect the development of their respective aircraft fleet as well as their cost structure which changes the development of available seat capacity and overall number of available flights. On the airport side, different characteristics of the two different airport agent types, the hub and the non-hub airport, in the duration as well as the process of how to change landside or airside capacity influences the SD variable representing total passenger capacity.

Market entries of different airline types are expressed through changes in the market share of one specific airline type in one of the two markets, within Europe or from Europe to other global regions. One potential use case would be the market entry of a competitor LCC into the transatlantic air transport market. In this use case, a timely delayed decrease of FSNC market share within this market segment is expected.

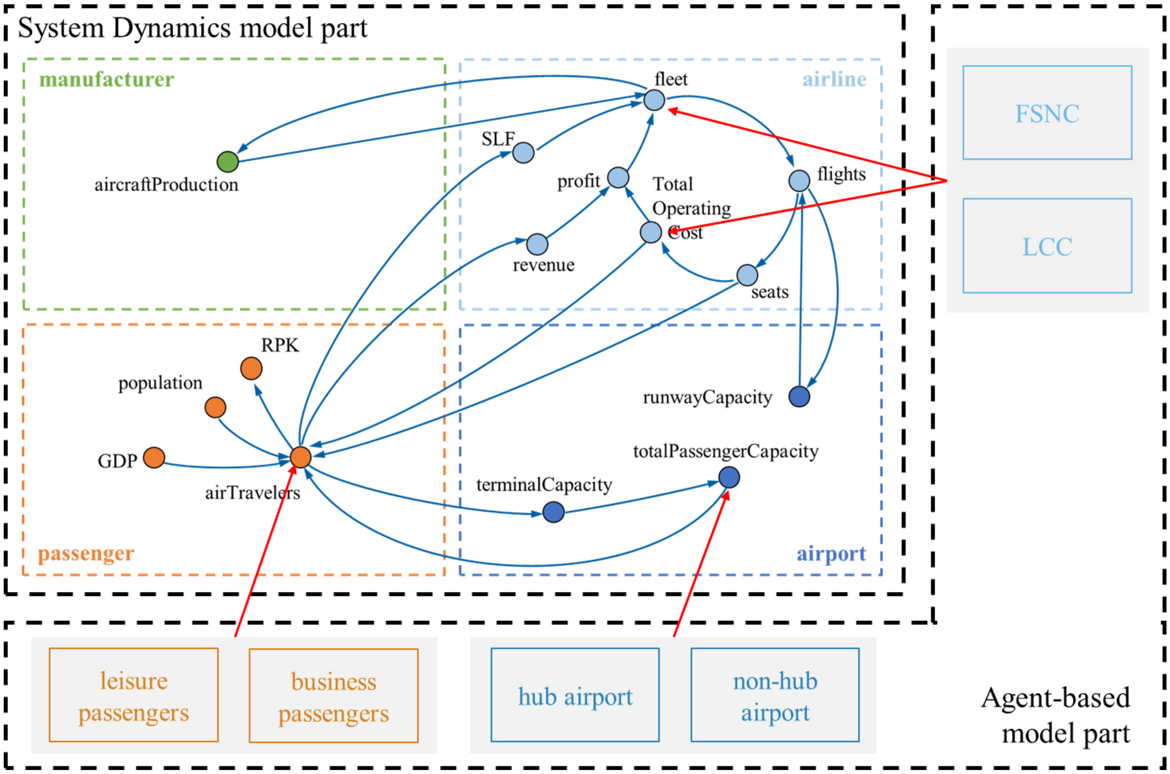

Figure 6: Model structure on agent-based level

The launch of long-haul low-cost operations of Norwegian Air International illustrates the characteristics of such a use case. With the hybrid model, the response of an established competitor in a specific market such as FSNC in the transatlantic market to the market entry of a LCC can be investigated. Representative variables for this analysis are average seat capacity, average frequency, ticket price, and SLF per respective airline agent type, and market segment, i.e. within Europe or from Europe to other global regions.

Two major competition variables for airlines are average fare ticket price and frequency[35]. These two parameters are integrated in the hybrid model within the passenger decision process. When passengers choose a ticket for a flight with a specific airline, they object to maximize their utility. Each of the two passenger agent types, business and leisure, has individual elasticities for ticket price and frequency, used as a time-related proxy for connectivity of an airlines' offered air transport services. For modeling the passenger decision process, utility functions in accordance with Discrete Choice Theory[36] for each passenger-airline type combination are introduced and a Multinomial Logit model[37] is implemented.

Utility functions represent the utility $U_{ij}(t)$ for a passenger i to select a flight from a specific airline j at time t. The utility of a passenger i depends on two characteristics k of the flight: ticket price and frequency. For each combination of passenger i and airline j, these are implemented based on the function[36]

$$U_{ij}(t) = \sum_{k} \beta_{ik} * x_{ijk}(t) + \varepsilon_{ij} \qquad \forall\, i, j, k \tag{1}$$

where the following notation is applied:

β_{ik}	Elasticity of passenger i and flight characteristic k
$x_{ijk}(t)$	Value of the flight characteristic k of airline j at time t
ε_{ij}	Intercept (bias), e.g. preference for local airlines, for passenger i and airline j

The probability P_{ij} that a passenger i decides to purchase a ticket for a flight with airline j can be implemented using the Multinomial Logit Model as follows[37]:

$$P_{ij} = \frac{e^{\sum_k \beta_{ik} * x_{ijk}(t) + \varepsilon_{ij}}}{\sum_i \sum_j e^{\sum_k \beta_{ik} * x_{ijk}(t) + \varepsilon_{ij}}} \qquad \forall i, j, k \qquad (2)$$

The sum of the probabilities of all potential airline and passenger combinations equals 1. With the probabilities, the purchase behavior of the two different passenger agent types, business and leisure passengers, and, thus, the demand can be allocated to the corresponding supply, i.e. flights within Europe and from Europe to other regions operated by one of the two airline types, FSNC or LCC.

The airline decision process to increase capacity is based on sequential steps. Figure 7 gives an overview of these steps. In the first step, the airline analyzes the development of demand for air transport. If a demand increase for air transport occurs in t within the SD part of the hybrid model, resulting from an increase of population within Europe or an increasing GDP, the airline proceeds with the second step and compares the actual SLF with a threshold defined individually for each of the two airline agent types. If the actual SLF value is higher than the according threshold, the airline conducts the third step where the capacity condition of airports is analyzed to gain information about whether flight frequency can be increased.

Airports in the hybrid model can adopt three different states: unconstrained, partly constrained, and constrained airports with respect to landside or airside capacity. An airport is partly constrained if its capacity is utilized to at least a level of 50%. Constrained airports obtain a capacity utilization level of above 70%[38].

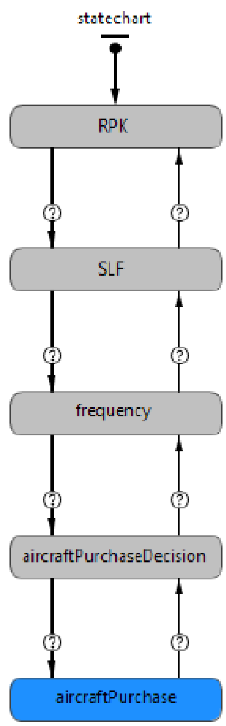

Figure 7: State chart – airline purchase decision process

The probability for an airline to obtain available slots in order to increase their flight frequency decreases with the increase of the level of congestion, expressed with the three states of an unconstrained, a partly constrained, and a constrained airport. In the hybrid model it is defined that an airline can only increase its flight frequency if a respective airport is unconstrained or partly constrained. If an airport is constrained, the airline moves to the fourth and last step of deciding which aircraft type to purchase for a defined sector of routes, either for routes within Europe or for routes from Europe to other global regions. Three different aircraft types were introduced beforehand in the section: regional (REG), small-range to medium-range (SMR), and long-range (LR) aircraft. All three aircraft types have two characteristics which affect the airline purchase decision: range and operating cost. The fleet planning process of an airline is highly complex[39]. In the hybrid model, a simplified airline purchase strategy is applied, i.e. to maximize profits which can be achieved through maximizing the operating profit for an aircraft type for the range of operation.

V. Application Case

The hybrid model presented in this paper will be applied to the European air transport market in a subsequent research activity considering not only flights within Europe but also flights to or from other global regions for the time period between 2000 and 2030+. With the expected simulation results, the airline market structure can be analyzed. Figure 8 provides an overview of the airline market share structure of FSNC and LCC between 2010 and 2016, measured in number of passengers and based on an analysis of the Sabre data and analytics market intelligence database[40].

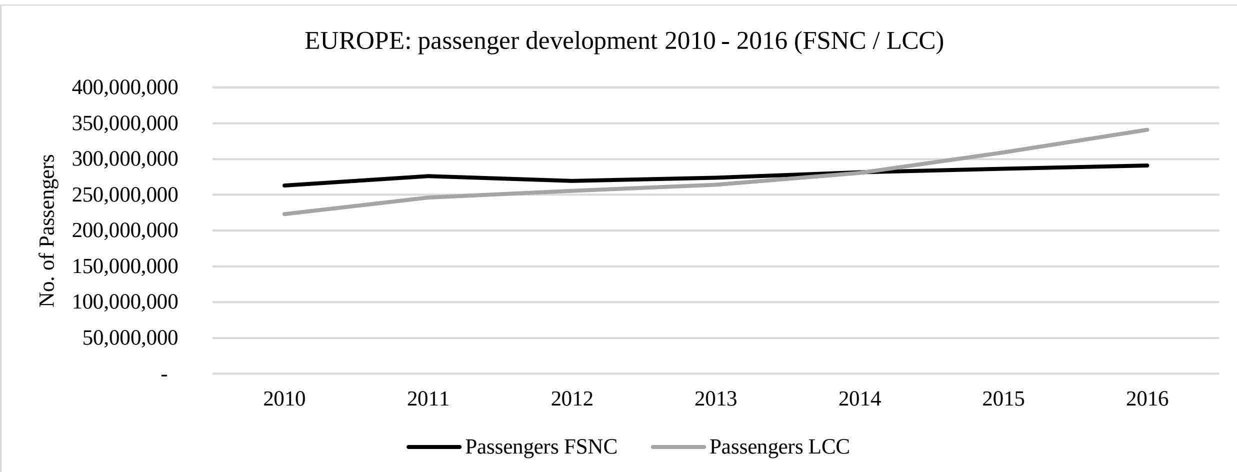

Figure 8: Market share of FSNC and LCC development 2010 – 2016 on the European market[40]

In 2014, a shift between the total number of passengers transported by FSNC and those who decided to travel with a LCC has occurred in favor of a higher market share of LCC in Europe compared with its competitors FSNC. Simulation results from the hybrid model are expected to present results for the future development of the airline market in Europe, not only with regard to market share but also to capacities such as seats provided and flight frequency and the development of the aircraft fleet in Europe, as well as for air transport markets outbound Europe in order to analyze case studies such as the market entry of Norwegian Air International.

A next step of the model development phase will include the complementation of the hybrid model with modules related to the transatlantic market, i.e. a passenger, airport, and airline subsystem for North America in the SD part of the model as well as corresponding agent types for North American passenger groups, airline types, and airport types. The resulting hybrid model will be capable of simulating air transport movements in the transatlantic market in order to analyze future market shares in this market. Subsequently, feasible approaches to calibrate and validate the hybrid model need to be identified and applied. As soon as the model calibration and validation is completed, simulation results will be presented and compared with historical data such as Sabre data at a later stage of this research.

VI. Conclusion and Next Steps

The paper has presented a hybrid model integrating AB and SD methodology for the analysis of future air transport markets. The approach of developing a hybrid simulation model using AB and SD methodology has been subject to previous research. However, only a few publications have been identified with an application case in the transport sector, i.e. studies on alternative fuel option transitions in the road transport sector. With regard to the air transport sector, there has been no research to the present day to the best knowledge of the authors. Thus, the hybrid model presented in this paper, provides an initial study on combining AB and SD modeling methods and applying it to the air transport market.

After finalizing the development of the hybrid model for the European market, the focus will be on selecting and applying feasible validation methodologies to ensure that the simulation results for the time period between 2000 and 2017 reproduce the past development of the European air transport system. These simulation results will, then, be presented at a later stage of this research.

The overall objective at a subsequent stage is to gradually expand the hybrid model with modules representing the North American air transport market and connecting these two markets in order to analyze the transatlantic air transport market and the development of different airline types within this market. This extension of the hybrid model will be utilized to simulate the future development in this market up to 2030+ with focus on the behavior of FSNC and LCC. An analysis of the future development of the two considered airline types with respect to the transatlantic air transport market, including the impacts from competitive behavior between FSNC and LCC can then be conducted. Results will contain the market shares of different airline types and the evolution of their respective fleet. Their share between primary hubs and secondary, non-hub airports will present interesting results. Furthermore, the development of capacities, i.e. available aircraft seats and flight frequencies, will be presented as an outcome of the simulation.

References

[1] Belobaba, P., Odoni, A., Barhart, C., *The Global Airline Industry*, John Wiley & Sons Ltd., West Sussex, United Kingdom, 2009.

[2] CAPA Centre for Aviation, *Norwegian Air International granted AOC by Irish Aviation Authority*, 2014. https://centreforaviation.com/news/norwegian-air-international-granted-aoc-by-irish-aviation-authority-307707 (accessed: 13.05.2018)

[3] Liehr, M., Größler, A., Klein, M., Milling, P. M., "Cycles in the sky: Understanding and managing business cycles in the airline market," *System Dynamics Review*, Vol. 17, No. 4, 2001, pp. 311-332.

[4] Pierson, K., Sterman, J., D., "Cyclical dynamics of airline industry earnings," *System Dynamics Review*, Vol. 29, No. 3, 2013, pp. 129-156.

[5] Cronrath, E. M., *The Airline Profit Cycle. A System Analysis of Airline Industry Dynamics*, Routeledge, London and New York, 2018.

[6] Urban, M., Kluge, U., Plötner, K. O., Barbeito, G., Pickl, S., Hornung, M., "Modelling the European air transport system: A system dynamics approach," *66th German Aerospace Convention*, Munich, Germany, 2017.

[7] Kim, J., "An agent-based model for airline evolution, competition and airport congestion," Ph. D. Dissertation, Virginia Polytech Institute and State University, Petersburg, VA, 2005.

[8] Shafiei, E., Stefansson, H., Asgeirsson, E. I., Davidsdottir, B., Raberto, M., "Integrated agent-based and system dynamics modelling for simulation of sustainable mobility," *Transport Reviews*, Vol. 33, No. 1, 2013, pp. 44-70.

[9] Shafiei, E., Davidsdottir, B., Leaver, J., Stefansson, H., Asgeirsson, E. I., "Simulation of alternative fuel markets using integrated system dynamics model of energy system," *Procedia Computer Science: ICCS 2015 International Conference On Computational Science*, Vol. 51, 2015, pp. 513-521.

[10] Köhler, J., Whitmarsh, L., Nykvist, B., Schilperoord, M., Bergman, N., Haxeltine, A., "A transitions model for sustainable mobility," *Ecological Economics*, Vol. 68, 2009, pp. 2985-2995.

[11] Kieckhäfer, K., Walther, G., Axmann, J., Spengler, T., "Integrating agent-based simulation and system dynamics to support product strategy decisions in the automotive sector," *Proceedings of the 2009 Winter Simulation Conference*, Austin, USA, 2009.

[12] Kieckhäfer, K., Wachter, K., Axmann, J., Spengler, T., "Model-based decision support for future OEM power-train portfolios: academic solutions for practical requirements," *Proceedings of the 30th International Conference of the System Dynamics Society*, St. Gallen, Switzerland, 2012.

[13] Schieritz, N., Größler, A., "Emergent structures in supply chains – A study integrating agent-based and system dynamics modeling," *Proceedings of the 36th Hawaii Conference on System Sciences*, Hawaii, USA, 2003.

[14] Schieritz, N., Milling, P. M., "Modeling the forest or modeling the trees – A comparison of system dynamics and agent-based simulation," *Proceedings of the 21st International Conference of the System Dynamics Society*, New York City, USA, 2003.

[15] Sterman, J. D., "Learning in and about complex systems," *System Dynamics Review*, Vol. 10, No. 2-3, Summer –Fall 1994, pp. 291-330.

[16] Borshchev, A., *The Big Book of Simulation Modeling – Multimethod Modeling with AnyLogic 6*, AnyLogic North America, 2013.

[17] G. Richardson, "System Dynamics," *Encyclopedia of Operations Research and Management, Boston*, MA: Springer US, 2013, pp. 1519–1522.

[18] Conway, J., "The Game of Life," *Scientific American*, Vol. 223, No. 4, 1970, p. 4.
[19] Schelling, T. C., "Dynamic Models of Segregation," *Journal of Mathematical Sociology*, Vol. 1, 1971, pp. 143-186.
[20] Borshchev, A., Filippov, A., "From system dynamics and discrete event to practical agent based modeling: reasons, techniques, tools," *22nd International Conference of the System Dynamics Society*, July 25-29, 2004, Oxford, England.
[21] Davidsson, P., *Beyond Social Simulation*, pp. 97-107, in: Paul, S., Davidson, P. (Eds.), Multi-Agent-Based Simulation, Berlin 2000.
[22] Macal, C. M., North, M. J., "Tutorial on agent-based modeling and simulation part 2: How to model with agents," *Proceedings of the 2006 Winter Simulation Conference*, Monterey, USA, 2006.
[23] Macal, C. M., "To agent-based simulation from system dynamics," *Proceedings of the 2010 Winter Simulation Conference,*, Baltimore, USA, 2010.
[24] Akkermans, H., "Emergent supply networks: System dynamics simulation of adaptive supply agents," *Proceedings of the 34th Hawaii Conference on System Science*, Hawaii, USA, 2003.
[25] Lättila, L., Hilletofth, P., Bishan, L., "Hybrid simulation models – When, Why, How?" *Expert Systems with Applications*, Vol. 37, 2010, pp. 7969-7975.
[26] Osgood, N., "Using traditional and agent based toolsets for system dynamics: Present tradeoffs and future evolution," *Proceedings of the 25th International Conference of the System Dynamics Society*, Boston, USA, 2007.
[27] AnyLogic: Multimethod Simulation Software providing System Dynamics, Discrete Event Modeling and Agent-based Modeling methods as well as their combination. www.anylogic.com (accessed 24.04.2018)
[28] Swinerd, C., McNaught, K. R., "Design classes for hybrid simulations involving agent-based and system dynamics models," *Simulation Modelling Practice and Theory*, Vol. 25, 2012, pp. 118-133.
[29] Doganis, R., *Flying off course: Airline economics and marketing*, Routeledge, London and New York, 2010.
[30] Gillen, D., Morrison, W. G., Stewart, C., *Air travel demand elasticities: Concepts, issues and measurement*, Department of Finance. Government of Canada, 2003.
[31] Daft, J., Albers, S., "An empirical analysis of airline business model convergence," *Journal of Air Transport Management*, Vol. 46, 2015, pp. 3–11.
[32] Porter, M. E., *Competitive strategy: Techniques for analyzing industries and competitors: with a new introduction*, The Free Press, New York, 1980.
[33] Tretheway, M., Kincaid, I., *Competition between Airports: Occurrence and Strategy*, in: Forsyth, P., Gillen, D., Müller, J., Niemeier, H.-M., Ed., Airport Competition – The European Experience, Ashgate Farnham, Burlington, 2010, pp. 119-136.
[34] Cook, G. N., Billig, B. G., *Airline Operations and Management – A Management Textbook*, Routeledge, Abingdon and New York, 2017.
[35] Banfe, C. F., *Airline Management*, Englewood Cliffs Prentice-Hall Inc., New York, 1992.
[36] Ben-Akiva, M., Bierlaire, M., *Discrete choice methods with applications to departure time and route choice*, in: Hall, W., Ed., Handbook of transportation science, 2nd Ed., 2003, pp. 7-37.
[37] McFadden, D., *Conditional logit analysis of qualitative choice behavior*, in: Zarembka, P., Ed., Frontiers in Econometrics, Academic Press, New York, Vol. 1, No. 2, pp. 105-142.
[38] Berster, P., Gelhausen, M., Wilken, D., "Is increasing seat capacity common practice of airlines at congested airports?" *Proceedings of the 17th Air Transport Research Society World Conference*, Bergamo, Italy, 2013.
[39] Clark, P., *Buying the big jets – Fleet planning for airlines*, 3rd Ed., Routeledge, Abingdon, New York, 2017.
[40] Sabre Data and Analytics Market Intelligence 5.14.1 database, 2018.