Agent-based Modelling and Simulation of Air Transport Technology and Passenger Demand

Dominik Grether, Sören Fürbas and Kai Nagel

Transport Systems Planning and Transport Telematics
Technical University Berlin
D-10587 Berlin
+49-30-314 23308
+49-30-314 26269

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Abstract

This paper aims at analysis and forecasting of mid-distance transport using a multi-agent simulation approach. A simulation model for air transport technology is proposed, that represents details of air traffic microscopically and is fast enough to enable an iterative-simulation based passenger-trip assignment. Aircraft are modelled in detail in respect to departure time and seat availability. Modelling of airports and routes of aircraft focuses on the available capacity of runways. Several simulation runs illustrate how the model can be calibrated using available parameters. Passengers are modelled as agents that may have individual attributes. In this paper, passengers differ by choice of departure time. Results for a passenger-trip assignment for flights within Germany are presented, that are based on real world data. Overall, the approach seems to be suited to analyze and forecast mid-distance transport.

1. Introduction

In Italy, recently a private company started providing 2.5 h non-stop train rides between Milano and Rome.[1] From Paris, nearly all major French cities can be reached by high-speed train in 2–4 h trips.[2] For the journey Berlin–Frankfurt in Germany, a 4h non-stop rail connection is provided.[3] Many airlines provide flights between all these destinations that take between 1 and 2 h. When comparing travel times, the additional access time to the airport or railway railway station needs to be included. Overall travel times are often not that different between middle range rail on the one side, and air transportation on the other.

Following recent forecasts, in 2030 13 major EU airports will operate at full capacity at least eight hours a day [Commission, 2011]. Legal opening hour constraints limit operations to a certain time frame. Yet even increasing opening hours for airports may not resolve capacity bottlenecks since it may not possible to move enough demand away from the peak hours.

In contrast, railway stations are normally not as much exposed to restrictions of opening hours due to noise protection as airports are. Also, in comparison with airports, railway stations mostly feature a more central geospatial location in urban areas. Slightly longer travel times can be compensated for by shorter access times and a longer opening hours. Passenger demand and technology supply for middle distance railway or air transportation may interact and are time dependent over a day or even a longer period.

In order to provide more capacity, railway or air transport networks may be target of planned extensions. New infrastructure is often accompanied by new emissions of noise and pollutants and is thus subject to lenghty planning, negotiation, and high private and public costs [Bubalo and Daduna, 2012]. However, improvements on infrastructure may improve quality of journeys or offer even new possibilities of transportation. Identification and appraisal of these disadvantages and benefits is one of the key subjects in infrastructure planning.

Mutual reactions on several scales may arise if one or several transport measures cause disbenefits and advantages for certain user groups or individuals. For each transport system user, changes in price, travel times, schedule, or available transport modes have different impacts, which depend on planned activities, available budget and geospatial location. In order to analyze, forecast, and assess changes in air transport infrastructure and service, this paper employs a simulation and forecasting approach for individual passenger reactions, using concepts of multi-agent simulation for urban transport forecasting. The technology of air transport networks, i.e. airports and aircraft, are microscopically modelled the same way as buses or street cars. Passengers are represented microscopically as multi-agent demand for air transportation. It is shown that

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[1] http://www.italotreno.it last access 19.12.2012
[2] www.tgv-europe.com/en/, last access 11.09.2012
[3] www.bahn.com, last access 11.09.2012

the simulation, originally built and successfully used for ground transportation [e.g. Neumann and Balmer, 2011, Balmer et al., 2009] can be used to model air transport microscopically, in a time-dependent way, and with capacity restrictions. While the modelling approach is kept simple, the paper discusses several possibilities how it could be refined in order to provide answers to more specific questions.

The paper is organized as follows. Related work concerning transport simulation tools and models is reviewed in the next section. Sec. 3 presents an overview of the methodology and the simulation framework. Modelling and simulation of air transport technology is described in the proceeding section. Then, sec. 5 explains how passengers are included in the model. The paper ends with a discussion and conclusion.

2. Related Work

Many commercial simulation tools for air traffic are available, e.g. SIMMOD[4], CAST[5], AirTOp[6], RAMSrams plus[7] or Total Airspace and Airport Modeler (TAAM)[8]. All of them provide high level of detail modelling of airports and airspace; some of them use multi-agent architectures for different actors of the scene, e.g. for airport controllers, air traffic manangement, etc. Also in research, simulation toolkits of a high level of detail are available, [e.g. see Bilimoria et al., 2000, Sweet et al., 2002, Alam et al., 2008]. All of them aim at detailed simulations of air traffic in order to improve air traffic management concepts. Neither commercial nor scientific simulation frameworks support agent-based modelling of individual passengers on all stages of a flight.

Queueing theory and queueing models are widely used to model the technology of air transportation systems. For example, Pyrgiotis et al. [2011] use queueing theory to model the propagation of delay through the network. Effects of new airspace management technologies are studied by Nikoleris and Hansen [2012]. The models for traffic flow on roads are usually more complex, e.g. "cell transmission models" [Daganzo, 1994, 1995], which model traffic based on discretized partial differential equations, "car following models" [Wiedemann, 1974, Gipps, 1981], which model traffic by following each car individually, typically using discretized time but continuous space, "cellular automata models" [Nagel and Schreckenberg, 1992], which are similar to car following models but also discretize space. Yet, all these models are computationally rather expensive. For that reason, also queue models are in use, which are computationally much faster [Gawron, 1998, Cetin et al., 2003, Cetin, 2005, Cremer and Landenfeld, 1998]. This paper uses a queue model. The model provides several parameters for an explicitly modelled segment of transport systems: The maximum flow that can pass a segment, the maximum amount of vehicles on the segment and

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[4]`www.airporttools.com`, last access 22.10.2012
[5]`www.airport-consultants.com`, last access 22.10.2012
[6]`www.airtopsoft.com`, last access 22.10.2012
[7]`www.ramsplus.com`, last access 22.10.2012
[8]`www.jeppesen.com/taam`, last access 22.10.2012

a maximum velocity per segment or vehicle. Several segments can be connected via nodes, building a transport network, on which individual vehicles can be simulated. Segments are modelled as FIFO (first-in first-out) queues, nodes can be interpreted as servers. Thus, the modelling of the road network is quite similar to queueing theory approaches in air transport [e.g. Pyrgiotis et al., 2011]. However, the proposed model is not solved analytically but by simulation. While analytical solveable models may conserve computational resources, a computational fast simulation model enables an agent-based modelling of every individual throughout the complete simulation lifecycle in complex scenarios.

3. Multi-Agent Transport Simulation

The simulation approach used in this paper is based on the software tool MATSim[9]. The next paragraphs provide an overview of the simulation approach and highlight the most important details used in this work. For more detailed information on technical aspects, please see Raney and Nagel [2006] or Balmer et al. [2005]. For a detailed discussion of methodology, see, e.g., Nagel and Flötteröd [2012]. Regarding economic concepts used in the simulation approach, see, e.g. Nagel et al. [2008], Kickhöfer et al. [2011].

3.1. Simulation overview

In MATSim, each traveler of the real system is modeled as an individual virtual person. The approach consists of an iterative loop that has the following important steps:

1. **Plans generation**: All virtual persons independently generate daily *plans* that encode, among other things, their desired activities during a typical day as well as the transportation mode. Virtual persons typically have more than one plan ("plan database").

2. **Traffic flow simulation**: All selected plans are simultaneously executed in a simulation of the physical system (often called "network loading").

3. **Scoring**: All executed plans are scored by an *utility function* which can be personalized for every individual.

4. **Learning**: At the beginning of every iteration, some virtual persons obtain new plans by modifying copies of existing plans. This is done by several *modules* that correspond to the choice dimensions available, e.g. time choice, route choice, and mode choice. In this paper, time and route choice will be used. Virtual persons choose between their plans according to a Random Utility Model (RUM).

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[9]Multi-Agent Transport Simulation, see `www.matsim.org`.

The repetition of the iteration cycle coupled with the plan database enables the virtual persons to improve (learn) their plans over many iterations. This is why it is also called **learning mechanism** which is described in more detail by Balmer et al. [2005]. The iteration cycle continues until the system has reached a relaxed state. At this point, there is no quantitative measure of when the system is "relaxed"; we just allow the cycle to continue until the outcome is stable.

3.2. Microsimulation

The microsimulation consists of a model of the physical environment, several agent-representations and a model for traffic flow. The physical environment comprises at least a model of the transportation network. Agent-representations exist for virtual persons, public transit vehicle drivers, traffic lights, etc. The traffic flow model is a queue model, that moves vehicles through the transportation network. Queue models for traffic flow disregard most of the details of vehicle movements on a road. Traffic networks are modelled as graphs. Each vertex models a crossing. Vertexes are connected by *links*, a directed edge that describes a road segment. Each link of a road network is described by the following attributes: maximum flow (capacity) c_{flow}, length l, and the amount of vehicles that fit on the link $c_{storage}$ if cars stand bumper to bumper.

Vehicles entering a link have to stay on that link at least as long as they would travel at their desired velocity or as fast as the speed limit on the link permits. During this time no computation needs to be done, the vehicles are stored in a priority queue. Afterwards the vehicle is placed into another FIFO-queue. In each simulated timestep $floor(c_{flow})$ vehicles may leave the FIFO-queue plus one additional vehicle when the accumulation over the last timesteps of fractional part of c_{flow} is equal or greater than 1. If there is space available on the downstream link, i.e. the number of vehicles is less than $c_{storage}$, a vehicle is moved to the downstream link. This makes the model capable to model spill-back.

3.3. Modelling of Public Transit

The public transit module of MATSim aims at modelling microscopic public transit simulation with a focus on several types of ground transportation, e.g. buses, streetcars or para transit [Rieser, 2010]. In a *TransitSchedule* transit stop facilities, lines and routes are specified. Passengers can access and leave vehicles at transit stop facilities. Each transit line contains one or more transit routes. Transit routes specify the order in which stops are lined up to a route and the departure time of a vehicle at the beginning of the route. Furthermore each route specifies which links in the network are used to connect stop facilites. Traffic flow is modelled by the queue model.

Characteristics of transit vehicles are specified using the default configuration of the MATSim framework[10]. Several *vehicle type*s can be defined that contain information as length, width, passenger capacity, maximum velocity and energy consumption. How fast passengers can access and leave a vehicle is also specified via the vehicle type. In addition to the different vehicle types a set of particular vehicles can be defined. Each vehicle has exactly one type assigned and inherits all its attributes.

3.4. Scoring

In order to measure the quality of a plan after execution and to compare plans, it is necessary to assign a quantitative score to the performance of each plan. For this purpose the utility function of the virtual persons is used. The total utility of a plan is computed as the sum of individual contributions:

$$U_{total} = \sum_{i=1}^{n} U_{perf,i} + \sum_{i=1}^{n} U_{late,i} + \sum_{i=1}^{n} U_{tr,i} \; , \tag{1}$$

where U_{total} is the total utility for a given plan; n is the number of activities, which equals the number of trips (the first and the last activity are counted as one); $U_{perf,i}$ is the (positive) utility earned for performing activity i; and $U_{tr,i}$ is the (usually negative) utility earned for travelling during trip i.

Further details on the default MATSim utility function can be found in Charypar and Nagel [2005] while one of the most recent discussions of this utility based approach is in Kickhöfer et al. [2011].

4. Modelling and Simulation of Air Transport Technology

This section focusses on the technology side of air transport networks. First, available and used data sources are rewieved. Then, it is shown how airports and aircraft can be modelled microscopically using a queue model based network representation and a simulation approach for urban transport systems. At the end of the section results of simulation runs are presented that show how the model works and how it can be enriched.

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[10]http://matsim.org/files/dtd/vehicleDefinitions_v1.0.xsd

4.1. Data Sources

The air traffic technology model takes advantage of data provided by OAG Aviation[11]. An OAG snapshot of worldwide direct flights in September 2009 is available for schedule generation. All flights with IATA airport codes, flight times, flight numbers and designators, aircraft types, available seats and distance between airport are gathered from the database and processed. Codeshares, multi-stop flights, buses and trains with flight numbers and cargo flights are filtered out of the schedule during the generation process.

Relevent data for schedule and network generation is excerpted from the OAG data using all flights departing on a Tuesday, taking each specific flight number into account only once. This may not always result in complete flight cycles, e.g. when the outbound and inbound flight operate on different days of the week. Compared to using all flights of an entire week, the network may be incomplete, as certain destinations are only served on specific days.

Since the OAG data does not include any airport coordinates, two alternative sources are consulted. OpenNav[12] is an online database of aeronautical navigation information featuring airport coordinates that may be retrieved with a web query based on the IATA airport code. Coordinates for those airports not available on openNav are prompted in the same manner from the Great Circle Mapper[13], which also includes a searchable database of airports. Worldwide, a total of 2683 airports with IATA code is retrieved from these data sources. The scenario used in this paper contains all Europe to worldwide, non-stop flights. For this scenario 73 airports are missing in our database[14] while for the majority of 808 airports coordinates are available. Airports for which no coordinates were available were removed for the present study.

Airport capacity data is available from many sources. However, no machine-readable source was found. Thus, the 50 busiest European airports in terms of total passengers per year were taken from wikipedia[15], and data for those airports was researched manually. A list of airport capacity information is given in Appendix A, together with the source for each information item. The list provides separate capacities for departures and arrivals. All remaining airports are modelled with arrival and departure capacities of 60 planes per hour each. This is considerably more than what these airports have.

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[11]`www.oagaviation.com`, last access 08.08.2012

[12]`www.opennav.com`, last access 09.08.2012

[13]`www.gcmap.com`, last access 09.08.2012

[14]bus and train stations with IATA code are counted as missing airports when no coordinates are found

[15]`en.wikipedia.org/wiki/List_of_the_busiest_airports_in_Europe`, last access 05.08.2012

4.2. Modelling

Based on the presented data an air network, a flight schedule and aircraft are generated as a precondition to run an air traffic simulation.

4.2.1. Network and Airports

The air network consists of airports, each showing an identical layout, and point-to-point connections in between. Every runway is solely used either for inbound or outbound flights with taxiways connecting the runways to the apron. The latter accommodates a transit stop where flight movements originate and terminate (see Fig. 1a).

The two runways of each airport possess a restriction of flow capacity restriction (c_{flow}) that is varied in the subsequent simulation runs. Furthermore not more than one aircraft can be simultaneously on a runway. This is modelled by setting the $c_{storage}$ parameter of the model accordingly. If the flow capacity restriction should have any influence on the model the storage capacity restriction should be at least as equal to $length/v_{fs} \cdot c_{flow}$, i.e. the time needed to traverse the runway in free flow conditions times the maximal permitted flow on the runway. If the storage capacity restriction is smaller, flow constraints would have any effect. As both values flow and storage capacity shall be set, freespeed velocity is varied according to the choosen value for flow capacity. E.g. an outbound runway of an airport with an outbound flow capacity of 60 veh/h on a 1500 m runway with a storage capacity constraint of 1 vehicle the speed restriction is set to $\frac{1500\text{m} \cdot 60 \text{veh/h}}{1\text{veh}} = \ldots = 90\text{km/h}$.

Each airport pair is directly connected by airway links, one for each flight and direction of travel (see Fig. 1b). The maximum speed on any of these links is calculated based on the distance and flight duration provided by OAG. Times for taxi, take-off and landing are also taken into account, i.e. the flight duration is reduced by the time needed from push-back to airborne before the maximum speed for an airway link is calculated.

ATS (Air Traffic Services) routes are not implemented, in order to simplify matters and because of data not being available in a desirable format. Note however, that each flight has an individual link that could be interpreted as route, each possessing individual characteristics. Fig. 2 shows the network used for European air traffic.

4.2.2. Flight Schedule

The flight schedule is taken from the OAG data and translated to a MATSim *TransitSchedule* containing information about each line, route and departure. For each airline that offers a connection between two airports a transit line is generated. A transit route, which represents the route on the air traffic network, is created for each flight offered by this airline. The route contains the links belonging to the airport representation plus the specific link for this flight connecting the airports' out- and
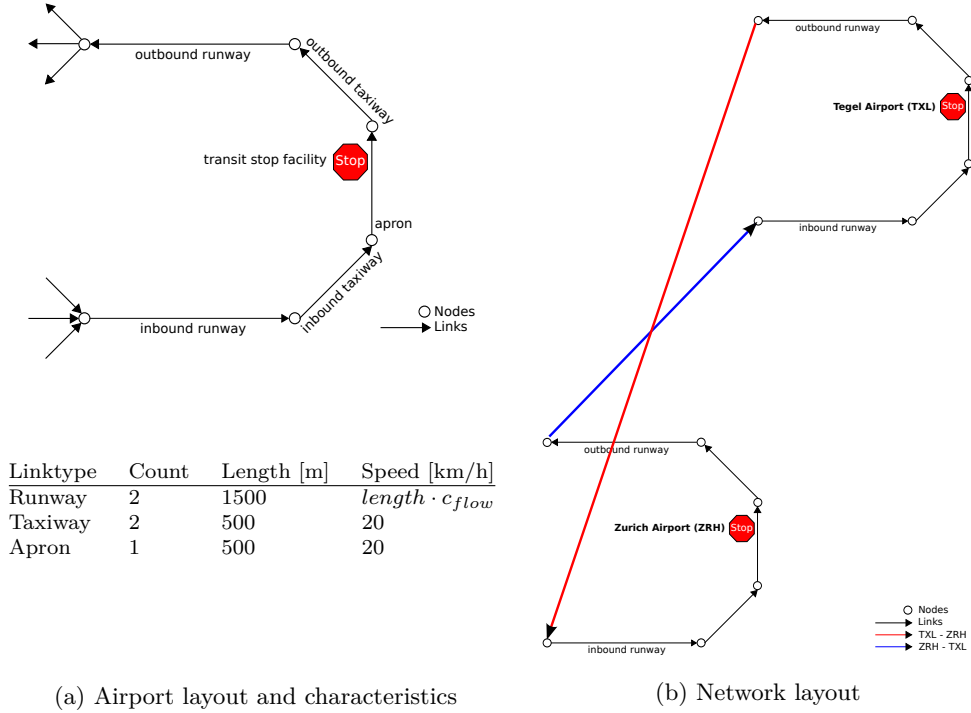
Linktype	Count	Length [m]	Speed [km/h]
Runway	2	1500	$length \cdot c_{flow}$
Taxiway	2	500	20
Apron	1	500	20

(a) Airport layout and characteristics (b) Network layout

Figure 1: Air Network

inbound runway. Mutual interferences of aircrafts en-route are not included in the model. Tab. 1 lists the number of (not included) airports, direct O-D connections and flight movements for three different area pairs.

For matters of consistency all local times are converted into Universal Time Coordinated (UTC). This ensures aircraft taking off and landing at the scheduled times throughout all time zones and also enables the model to reflect incoming and outgoing waves at hub airports worldwide at the appropriate times.

4.2.3. Aircraft

Vehicles are created on the basis of OAG data to represent individual aircraft in the simulation. IATA aircraft codes, operating airlines and seating capacities are reflected in the respective aircraft representation for every flight. Information about boarding times, i.e. passenger flow per door over time, is not available but could be set for each aircraft type. One aircraft per flight is generated, thus delays resulting from a delayed incoming aircraft are not modelled. Accordingly, no aircraft rotations and vehicle trip chains are implemented for the time being. The maximum velocity is set to twofold sonic speed, since speed limitations are set for each airway link of the network.
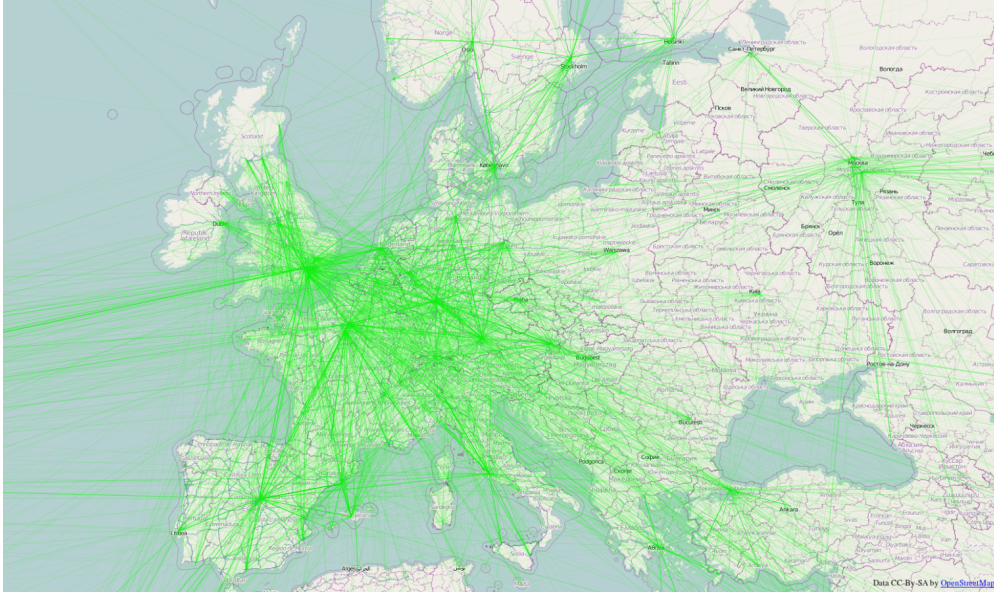
Figure 2: European air network with EU country boarders in the background (country boarders © `openstreetmap.org`)

Area pair	Airports	Airports missing	O-D Pairs	Flights	Flights missing
Worldwide	2333	81	27496	56376	2644
Europe to worldwide	808	16	14156	21425	577
Germany to worldwide	269	3	2814	4394	189

Table 1: Some numbers for different geospatial extends of the model.

4.3. Simulation Results

Results of a simulation for flights to, from, and within Europe are presented in the following. Several versions of the model have been simulated allowing a comparison of a model without capacity constraints, a model with runway capacity constraints, and a model including some delay. The simulation is run for one iteration, which starts at midnight and continues until after 40 h the last flight has arrived at its destination.

Delay resulting from changes of runway capacity is studied in three simulation runs. Scheduled flight times from the OAG data are compared to the simulated time each flight needs from its departure transit stop facility to its arrival transit stop facility. The resulting arrival delay distributions are shown in Fig. 4.

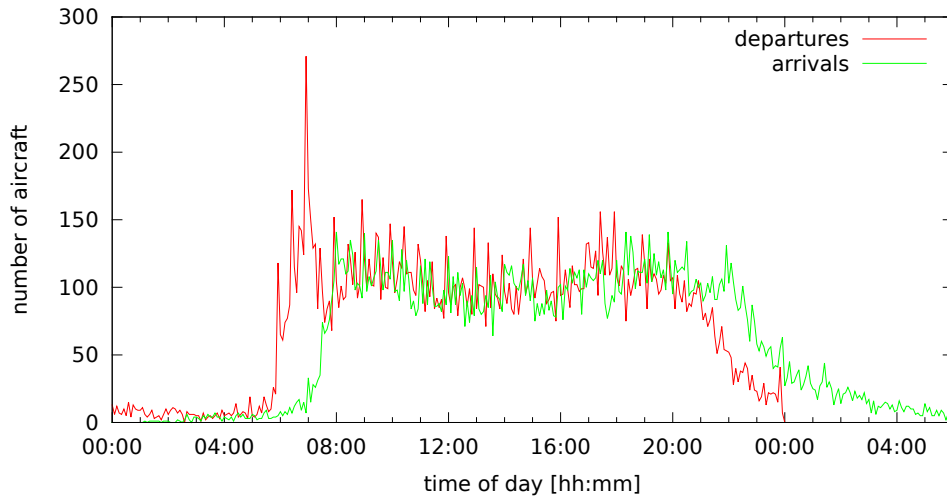First, the simulation is run with unrealistically high runway capacities. As expected,

Figure 3: Arrivals and departures over time of day. Model with high runway capacities.

resulted in all flights being on time. Fig. 3 shows the simulated number of departures and arrivals over time of day. Clearly, one can observe the morning departure peak between 05:00 am and 07:00 am UTC. The resulting delay distribution is depicted in Fig. 4a.

Second, in order to test sensitivity, all runway capacities are set to 60 vehicles per hour (vph), i.e. on each runway one take-off or landing per minute is possible. This is effectively *larger* than in reality for most airports, except for CDG and AMS, where it is less. The impact on the system is more profound than one might expect: The delay distribution shown in Fig. 4b. 10589 flights, i.e. 49,2 % of the simulated 21425 flights, arrive at their scheduled time; 99,6 % of the flights possess less than 16 min delay. The most delayed flight arrives 28 minutes after scheduled arrival.

In the third simulation run regarding delays, airport specific data is used for capacity of runways (see Sec. 4.1). Each modelled airport's arrival runway is set to the arrival capacity from the table, and each departure runway is set to the departure capacity from the table. As explained earlier, if no data is available, then each runway's capacity is set to 60 vph as in the previous experiment; since these are fairly large capacities, this implies that the model will generate few if any delays at those airports. Fig. 4c shows that the resulting overall delay distribution is similar to the run which was based on homogeneous runway capacities (Fig. 4b). 45,5 % of all flights arrive at the scheduled minute, while 99,2 % have a delay less than 16 min. The latest arrival is 32 min beyond schedule.

(a) High runway capacity

(b) Uniform runway capacity of 60 vph

(c) Airport specific runway capacities

(d) Normal distribution, high capacity

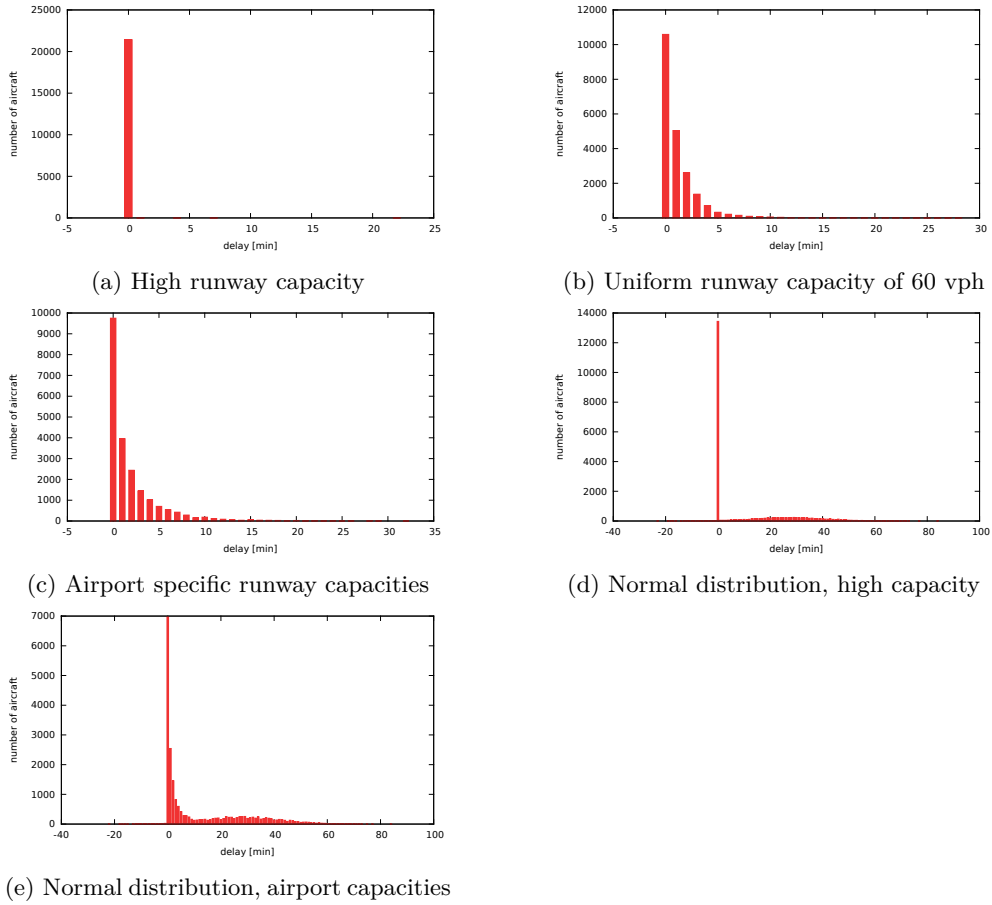(e) Normal distribution, airport capacities

Figure 4: Results for distinct delay models. Number of delayed aircraft over minutes of delay.

The delay runs show that limited runway capacities are a source of delay [Bubalo and Daduna, 2012]. By themselves, however, they can only explain a small part of delays. For 2011, the Central Office for Delay Analysis (CODA) reports that 37.1 % of all flights were delayed on departure [Central Office for Delay Analysis, 2012], with an average delay of 27.6 min. Those CODA values for 2011 are used for a rough approximation of randomly occuring delay in the simulation, as follows. In a preprocessing, a 37.1 % sample of all simulated flights is drawn, using a uniform distribution. The length of delay is then drawn from a normal distribution with a mean of 27.6 min and a standard derivation of 13.8 min, and added to the scheduled departure time. In order to get a clear picture of the effects of this method, the simulation is first run without capacity constraints. The resulting overall delays are shown in Fig. 4d; delayed flights show the expected shape of a normal distribution around 27.6 min. For

the next and last simulation run, the model with more realistic runway flow capacities is used. About 39 % of all flights are now delayed more than five minutes, average delay is 27,90 min. The resulting overall delay distribution (Fig. 4e) still posesses the shape of the normal distribution, but effects of flow capacity restrictions are observable as well.

4.4. Interpretation & Discussion

The results show that the the proposed approach can be used to model some important charactaristics of air traffic technology. In particular, runway capacity restrictions can be added to the model.

The current model uses two separate links for the runways of an airport, one for arrival and another for departure. In reality, it might happen that both runways are used for the same purpose for periods of time. The model thus could possibly be improved by modelling both runways as one link. When doing this, however, more elements of air traffic control would need to be included, such as priorization between incoming and outgoing aircraft.

Also, the model of the air network is not capturing delays resulting from en-route capacity constraints that may occur in the real ATS route network. Due to differences in air traffic flow and capacity management strategies, the present model may be more appropriate to model US airspace than EU airspace [Lulli and Odoni, 2007]. This could be addressed by employing the time-variant network feature of the simulation [Lämmel et al., 2010] that can vary a link's flow capacity, or set speed limits for certain time periods. Finally, the ATS route network itself could be included in the modelling process if exact data and routes are provided.

Reactive delays due to delayed incoming aircraft are not reproduced as aircraft rotations are currently not included in the model. The multi-agent approach is, in general, particularly suitable to to model reactive delays. For this, one would either need detailed trip-planning and scheduling data from private companies, or appropriate approximation algorithms for these elements.

5. Modelling and Simulation of Passenger Demand for Air Transport

With the results of the last section an air transport technology model is available. This section shows how a passenger demand for air transport can be modelled with the multi-agent approach.

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5.1. Data sources

There are many different ways in which passenger demand for transport systems can be generated [e.g. Balmer, 2007]. One option is to start with origin-destination (O-D) flows between geographical regions. In a European context, possible data-sources include OAG Aviation[16] and eurostat[17]. They provide data about passengers; O-D flows, however, are not provided. Data-sources geographically limited to Germany as "Der Flughafenverband"[18] or ITP/BVU [2005] do not come with O-D data, neither. The latter may have O-D relationships available in an upcoming version. The German Institute of Air Transport and Airport Research (DLR) provides monthly statistics containing O-D flows,[19] but the pdf format provided is not suited for machine reading, and data is only available up to 09/2010. DESTATIS[20] provides O-D data by airport for German air traffic in a machine readable format. Data is available for whole years or a specific month. DESTATIS data is thus used in the following to create an agent based air transport demand for Germany.

5.2. Passenger Demand

The passenger demand is based on the DESTATIS data for 2011. In order to be consistent with Sec. 4, September is choosen as month. DESTATIS provides data in two different representations. For all pairs of airports, the number of direct trips between the airports is given in the data (2.2.1). Furthermore, a second table (2.2.2) contains O-D pairs that do not include the first transfer, but provide the second, and possibly final destination. E.g. one person flying from HAMburg via FRAnkfurt to Munich (MUC) is contained in the data as one O-D pair: HAM → MUC. If a flight starts at CDG (Paris) going via FRA via MUC to HAM it is not clearly stated how the flight is represented in the data. It might be counted as CDG → HAM or FRA → HAM O-D relation. It is, however, unlikely that passengers will have two *transfer* stops inside Germany. Thus an origin or destination abroad may not be the original or final destination, but that at least all passenger movements that touch Germany along their itinerary are probably included in an unequivocal way.

The second table (2.2.2) is used to create the virtual persons for the passenger demand. For each O-D pair and trip a virtual person is created that performs its sole activity at the origin and destination airports. A "typical duration" (MATSim parameter) of 24 h is set for this activity. In between the two activities a flight leg is scheduled, connecting origin and destination. As is common, the demand does not specify if a direct flight from O to D is chosen or the virtual person is on a route containing one or more transfers. The departure time at the origin airport is drawn randomly from

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[16]`www.oagaviation.com`, last access 08.08.2012
[17]`ec.europa.eu/eurostat`, last access 10.09.2012
[18]`www.adv.aero`, last access 10.09.2012
[19]`http://www.dlr.de/fw/en/desktopdefault.aspx/tabid-2961/9753_read-19683/`, last access 10.09.2012
[20]`destatis.de`, Fachserie 8 Reihe 6, last access 10.09.2012

a uniform distribution in 04:00 to 18:00, UTC. This reflects estimated typical opening hours of airports in Europe. The resulting synthetic population contains 64006 virtual persons.

5.3. Simulation Setup

The synthetic population is used as input for the simulation. As scenario the European flight model with no delays and no effective runway capacity restrictions from Sec. 4 is used. The assignment of concrete flights to the desired O-D connection, i.e. the passenger routing, is done by the default public transit routing module of MATSim [Rieser, 2010]. The routing basically looks for a least cost path in terms of travel time. The network used for routing is constructed from the information contained in the transit schedule. In order to penalize transfers, the routing assumes an additional cost of $c_{lineswitch}$ for each transfer. The same parameter is also considered by the scoring function, i.e. a (dis-)utility of $-c_{lineswitch}$ is added to the score of the agent for each transfer. The simulation is run several times using different values of the $c_{lineswitch}$ parameter, i.e. $c_{lineswitch} \in \{0, -6, -12, -18, -24, -30\}$.

The simulation is run for 600 iterations. In each iteration, 10 % of the virtual persons may shift their departure time randomly within a 2 h interval. The amount of shift is drawn from a uniform distribution. Another 10 % may seek a different route, i.e. a different connection between origin and destination. Each passenger chooses out of a set of 5 plans using a multinomial logit model, see Nagel et al. [2008] for details. After 500 iterations, departure time choice and routing are switched off. For another 100 iterations only the logit model is used by the passengers to select a plan.

All other parameters used for simulation are the "default" values of the MATSim framework. For a detailed discussion, see, e.g., Nagel et al. [2008], Nagel and Flötteröd [2012].

5.4. Results

First, in order to show the effects of routing, the result after the zeroth simulated iteration is presented. Each virtual person gets a connection assigned based on a generalized cost routing for the connection and the preset departure time. Fig 5a shows the number of travellers en-route, i.e. waiting for a flight or travelling by plane, as a function of the time-of-day. Some passengers are still waiting for a flight at midnight. As only one day of operation is simulated, these passengers are stuck and will not reach their destination. The number of stuck passengers is decreasing with the increasing disutility of line switch.

The output after 600 iterations is depicted in Fig. 5b. The shape of all curves is different from the shape of the 0th iteration. One can identify two morning and two evening peaks. Some passengers still get stuck at the end of the day, but fewer than

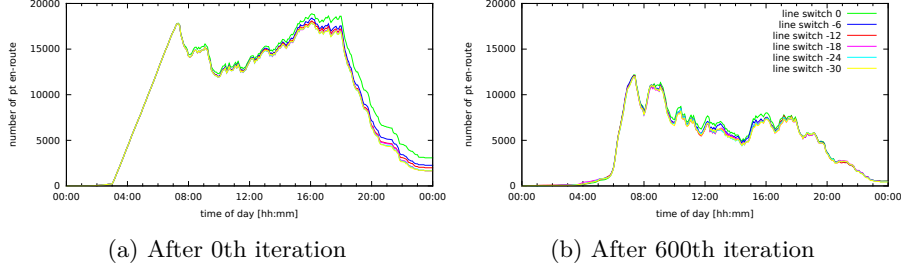(a) After 0th iteration

(b) After 600th iteration

Figure 5: Travelers en-route, i.e. waiting for a flight or travelling by plane, as a function of the time-of-day

in the 0th iteration. In addition, the differences between the curves for the $c_{lineswitch}$ parameter are diminishing.

In order to study the influence of the $c_{lineswitch}$ parameter, the simulation results are compared with the leg data. Recall that the synthetic population is generated based on O-D pairs that may contain transfers ($od_{transfers}$), while other data directly counts the number of passengers on actual direct flights (od_{direct}). The latter is used to evaluate the accuracy of the model. For comparison, the number of passengers on direct flights is thus calculated for each O-D pair (sim_{direct}) from the simulation results.

Based on these datasets, the mean square error σ^2 is computed as

$$\sigma^2 = \frac{\sum_{i \in OD}(sim_{direct}(i) - od_{direct}(i))^2}{|OD|} .$$

The (unsigned) mean relative error for each O-D relation is calculated as

$$\text{mean rel error} = \frac{\sum_{i \in OD} |(sim_{direct}(i) - od_{direct}(i))|/od_{direct}(i)}{|OD|}.$$

Tab. 2 shows the results for these calculations. The first line contains the comparison of the two input data sets from DESTATIS, i.e. in the above formulas sim_{direct} is replaced by $od_{transfers}$. This serves as reference as it would assume that *all* demand is served by direct flights. All simulation runs explain the data better than that refrence. The values for all simulation runs are then quite similar.

The last column of tab. 2 shows the number of passengers stuck at the end of day. Values for all parameter settings are around 980 passengers, i.e. around 1,5 % of the 64'006 simulated passengers.

5.5. Discussion

Overall, the results show that a microscopic, agent-based simulation of passenger demand for air transport is feasible. Most passengers are able to learn the constraints of

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$c_{lineswitch}$	σ^2	σ	mean rel error	stuck
$od_{transfer} - od_{direct}$	6714	81	1.56	-
-0	5329	73	0.29	982
-6	5663	75	0.27	976
-12	5801	76	0.28	967
-18	5838	76	0.24	985
-24	5889	76	0.25	968
-30	5935	77	0.25	971

Table 2: Simulation results for different values of $c_{lineswitch}$

air transport technology and arrive at their desired destination.

Some passengers fail to reach their destination; they become "stuck". As only trips within Germany are modelled, which are usually completed within a few hours without any requirement for an overnight stay at an airport, this is considered unrealistic. Fig. 6 shows that this is not a consequence of a general lack of seats: at any time-of-day, there are more seats than demand. There are many reasons why stuck passengers can arise in such a situation. Further analysis of the simulation results leads to the following insights

- 459 passengers are stuck because there is no seat, *and* there is no other flight by the same airline later during the day to which they would be shifted otherwise.

- 523 passengers are stuck at an airport because there is no connection after their departure time between that airport and their destination airport.

These results are for the run with $c_{lineswitch} = 0$; the other runs are similar. It may, for example, be possible that passengers depart from an origin that only has one –early– connection to a hub per day, and the passengers' departure times are too late to reach that connection, and the random departure time mutation may not be able to find that connection for all passengers. Alternatively, it may be the case that passengers have a connection that works in theory, but they are "crowded out" by other passengers who arrive earlier for the second leg. They would make it if either of them would take a different route. The current approach would not find such a solution, since passengers do not take into account the costs they impose on others [see Lämmel and Flötteröd, 2009, for an approach to take that into account]. The real-world solution presumably would be to raise prices on contested seats until one or the other passenger re-routes. The present model does not (yet) include such a process.

An alternative approach to remove some of these shortcomings might be to use a router that generates a larger diversity of routes even for the same departure time. Such a router would be able to point a passenger to a route where seats are available without by itself knowing about seat availability. That approach would, however, not address
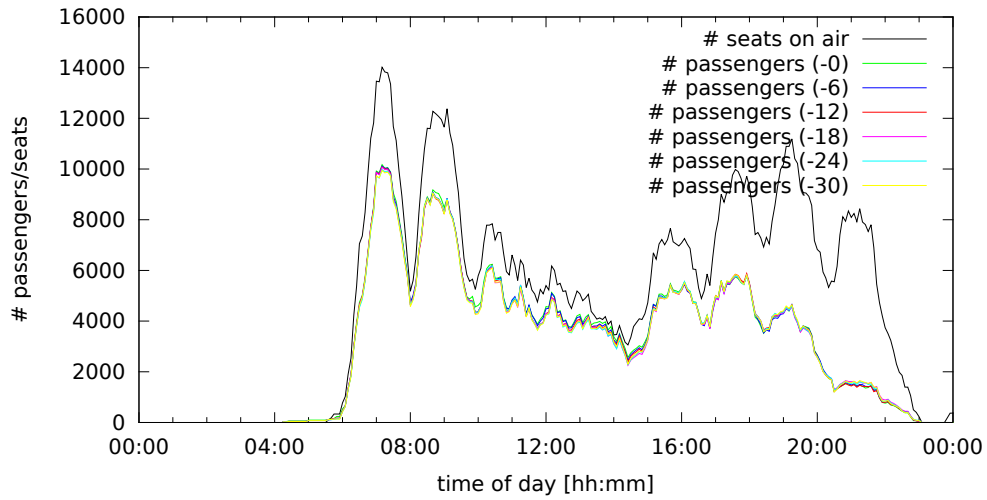
Figure 6: Passengers and available seats over time within Germany

the issue that some passengers might need to switch their path in order to allow *others* to obtain a feasible path.

6. Conclusion & Outlook

In the first part of this paper, a microscopic modelling approach for air transport technology is proposed. A multi-agent simulation approach from urban transport planning is used. Aircraft are represented microscopically featuring attributes as speed, available seats and boarding constraints. The air traffic network as well as flight performance is modelled at a low level of detail as the model is not intended for air traffic management. Despite the lack of detail, some relevant aspects of congestion and delays can be captured by the use of a queuing model for traffic flow. The queuing model is computationally relatively cheap so large scenarios can be simulated. As proof of example results for an Europe to world air transport supply are presented.

The computationally affordable simulation technique enables an agent-based modelling of passenger demand and its iterative assignment to flights, which is described in the second part of the paper. Results are presented for a simulation of German national air transport demand.

Models for other modes as rail or car transportation are the subject of current work, following the same approach as the one presented here. The same software and solution procedure is used. In consequence, these models can be integrated into the approach

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presented in this paper. This might help to get a more detailed picture of middle distance traffic modelling.

Acknowledgements

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A. Airport Capacity

For selected Airports `http://en.wikipedia.org/wiki/List_of_the_busiest_airports_in_Europe`, 05.08.2012:

Num	Code	Dep	Arr	Total	Source
01	LHR	46.0	44.0	90.0	`http://www.eurocontrol.int/sites/default/files/content/documents/nm/reports/network-operations-annual-report-2011-annex-02.pdf`
02	CDG	63.0	54.0	109.0	`http://www.cohor.org/`
03	FRA	50.0	43.0	93.0	`http://www.eurocontrol.int/sites/default/files/content/documents/nm/reports/network-operations-annual-report-2011-annex-02.pdf`
04	AMS	74.0	68.0	112.0	`http://www.eurocontrol.int/sites/default/files/content/documents/nm/reports/network-operations-annual-report-2011-annex-02.pdf`
05	MAD	50.0	48.0	n/a	`http://www.eurocontrol.int/sites/default/files/content/documents/nm/reports/network-operations-annual-report-2011-annex-02.pdf`
06	MUC	58.0	58.0	90.0	`http://www.eurocontrol.int/sites/default/files/content/documents/nm/reports/network-operations-annual-report-2011-annex-02.pdf`
08	IST	28.0	28.0	50.0	`http://www.eurocontrol.int/sites/default/files/content/documents/nm/reports/network-operations-annual-report-2011-annex-02.pdf`
09	BCN	36.0	36.0	64.0	`http://www.eurocontrol.int/sites/default/files/content/documents/nm/reports/network-operations-annual-report-2011-annex-02.pdf`
10	LGW	28.0	27.0	52.0	`http://www.acl-uk.org/UserFiles/File/Gatwick%20Summer%202012%20Capacity%20Declaration.pdf`
11	ORY	24.0	27.0	n/a	`http://www.cohor.org/`
13	AYT	25.0	25.0	45.0	`http://www.eurocontrol.int/sites/default/files/content/documents/nm/reports/network-operations-annual-report-2011-annex-02.pdf`
14	ZRH	41.0	36.0	66.0	`http://www.slotcoordination.ch/capacity.htm`

Num	Code	Dep	Arr	Total	Source
15	PMI	33.0	33.0	62.0	http://www.eurocontrol.int/sites/ default/files/content/documents/nm/ reports/network-operations-annual- report-2011-annex-02.pdf
18	VIE	50.0	48.0	68.0	http://www.eurocontrol.int/sites/ default/files/content/documents/nm/ reports/network-operations-annual- report-2011-annex-02.pdf
20	DUS	36.0	33.0	47.0	https://sws.fhkd.org/EWPS/ pAirportParameters.output?i_season= S12&i_button=RETRIEVE
22	ARN	42.0	42.0	84.0	http://www.arnslot.se/?name=declared
23	MAN	35.0	33.0	61.0	http://www.acl-uk.org/UserFiles/File/ MAN%20Capacity%20declaration%20S12. pdf
24	BRU	40.0	35.0	45.0	http://www.brucoord.org/Page02.html
26	STN	28.0	28.0	50.0	http://www.acl-uk.org/UserFiles/File/ STN_%2025-04-2012%20%20Declaration% 20for%20Winter%202012.pdf
27	TXL	30.0	30.0	52.0	https://sws.fhkd.org/EWPS/ pAirportParameters.output?i_season= S12&i_button=RETRIEVE
28	HEL	40.0	36.0	76.0	http://www.finavia.fi/ vuosikertomukset/2004/en/hkivan_ runway_capacity_inc.html
29	LIS	26.0	26.0	38.0	http://slotsportugal.ana.pt/en-US/ main/airports/lisboa/capacity/Pages/ default.aspx
31	HAM	27.0	27.0	53.0	https://sws.fhkd.org/EWPS/ pAirportParameters.output?i_season= S12&i_button=RETRIEVE
32	GVA	36.0	22.0	36.0	http://www.slotcoordination.ch/ capacity.htm
34	SAW	8.0	8.0	20.0	http://www.eurocontrol.int/sites/ default/files/content/documents/nm/ reports/network-operations-annual- report-2011-annex-02.pdf
35	PRG	33.0	33.0	46.0	http://www.slot-czech.cz/en/site/ capacity_parameters/summer-season- s12.htm
37	NCE	30.0	26.0	50.0	http://www.cohor.org/
39	CGN	40.0	40.0	52.0	https://sws.fhkd.org/EWPS/ pAirportParameters.output?i_season= S12&i_button=RETRIEVE

Num	Code	Dep	Arr	Total	Source

41	STR	32.0	32.0	42.0	`https://sws.fhkd.org/EWPS/`
					`pAirportParameters.output?i_season=`
					`S12&i_button=RETRIEVE`

44	WAW	28.0	26.0	38.0	`http://www.acl-uk.org/userFiles/File/`
					`WAW%20CAPACITY%20DECLARATION%20W12.`
					`pdf`

46	BUD	30.0	26.0	n/a	`http://www.hungarocontrol.hu/en/` `coordination-parameters`