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ASSESSMENT OF THREE COMMUTER AIRCRAFT CONCEPTS FROM A TRANSPORT SYSTEM PERSPECTIVE

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Abstract

Over the last few years the environmental impact of transport in general and aviation specifically has increasingly gained attention. In this context recent developments focus on new technologies for more sustainable aviation. This paper focuses on the assessment of three novel electric commuter aircraft concepts by comparing them not only with existing aircraft with similar top-level requirements, but also with other modes of transport. By choosing a solution-neutral statement of the problem (here regional travel) and taking into account aspects such as inter-modal door-to-door travel, environmental impact, and noise emissions, a holistic assessment of the proposed aircraft concepts is intended.

The evaluation of the aircraft concepts is conducted by considering the proposed aircraft designs as part of a more comprehensive transport system. This transport system includes other modes of transport that may be used for the range in which the proposed aircraft can be operated (e.g. car, train). It also considers the door-to-door travel time by taking into account the available infrastructure. Different modules are used to evaluate the vehicles when used on individual connections (traveling from origin A to destination B) in terms of time, cost, and overall passenger's choice preference. The model used to describe the choice behavior of the passengers does not only include door-to-door time and travel costs, but also soft factors like e.g. environmental awareness. Taking the example of Germany's transport system as a use-case scenario, an assessment of the aircraft concepts on a transport system level is attempted.

The developed methodology is applied to compare partial aspects of the proposed concepts such as environmental impact, as well as to estimate overall metrics, such as the potential market share of the concepts in the transport sector. Furthermore the impact of possible future scenarios, e.g. the availability of a larger number of airports or the introduction of a tax on emissions, on the overall performance of the proposed concepts is investigated from a transport system point of view.

Keywords: transport system, commuter aircraft, hybrid-electric aircraft

1. Introduction

The introduction of new technologies, especially with respect to propulsion systems, sets new requirements on the infrastructure around the air transportation system (e.g. battery charging, refueling of hydrogen, etc.). At the same time other external factors affecting the aviation sector keep changing, such as stricter regulations regarding greenhouse gas emissions and noise, a growing environmental consciousness in the population, etc.

This paper's goal is to trigger the discussion towards a more holistic assessment of innovative aircraft concepts. Applied on the use case of a commuter plane, the developed assessment framework visualizes some interesting factors when considering the introduction of a new aircraft concept into the market.

First the methodology adopted within the framework is presented by starting with the overall structure of the framework and later focusing on some of its most important modules (journey models), as well as the passengers' preference model for the market share estimation of the considered transportation modes. After this introduction of the implemented methods, a short overview of the commuter aircraft designs that are investigated in this study is given and the underlying assumptions for the analysis along with some results for different scenarios modeled within the framework are presented. Finally the benefits of such a comprehensive analysis on transport system level are discussed and some of the shortcoming of the current study as well as suggestions for further improvement are pointed out.

2. Methodology

In order to be able to describe different aircraft concepts as part of a more comprehensive transportation system and to analyze different aspects of this system from various perspectives, a framework named *overall System Analysis of Aircraft Designs (oSAAD)* has been developed at the Institute of System Architectures in Aeronautics of the German Aerospace Center (DLR). The goal of this Python-based framework is to allow rough but comprehensive evaluations of different aircraft concepts. It focuses not only on parameters that are usually considered in aircraft design, such as the resulting direct operating costs of the aircraft, but also on other factors such as the comparison to other modes of transport, which is important from a passenger's perspective and influences the competitiveness of the aircraft on the transport market. Another important feature of the framework is the possibility to evaluate the system under different prospective assumptions regarding possible future developments in the field of transportation and to propagate their impact throughout the modeled system.

2.1 The framework structure

The overall structure of the analysis framework is depicted in Figure 1 in form of an eXtended Design Structure Matrix (XDSM) diagram [1]. The green rectangles represent analysis blocks, while the white and gray parallelograms on the vertical axes show the inputs of the analysis block and the parallelograms on the horizontal axes are the outputs. The numbers indicate the execution sequence of the analysis. As seen in the diagram a design of experiments (DOE) can be executed over a network of cities that is given to the framework as an input. This way an iteration over all the combinations of origin and destination (OD) cities can be performed to calculate the attributes of the journeys with different modes of transport (e.g. journey cost, time, energy, emissions) and subsequently estimate their respective market shares. The inputs include data and assumptions with respect to the underlying economics (e.g. labor costs, fuel prices, etc.) and mobility characteristics (e.g. vehicle load factors, road detour factors, connection frequencies, etc.) as well as models of different vehicles. In order to take into account the entire door-to-door journeys, modules describing the access and egress trips to and from the "main" vehicle of the journeys are included in the framework. Further details regarding the analysis modules are given in the following sections.

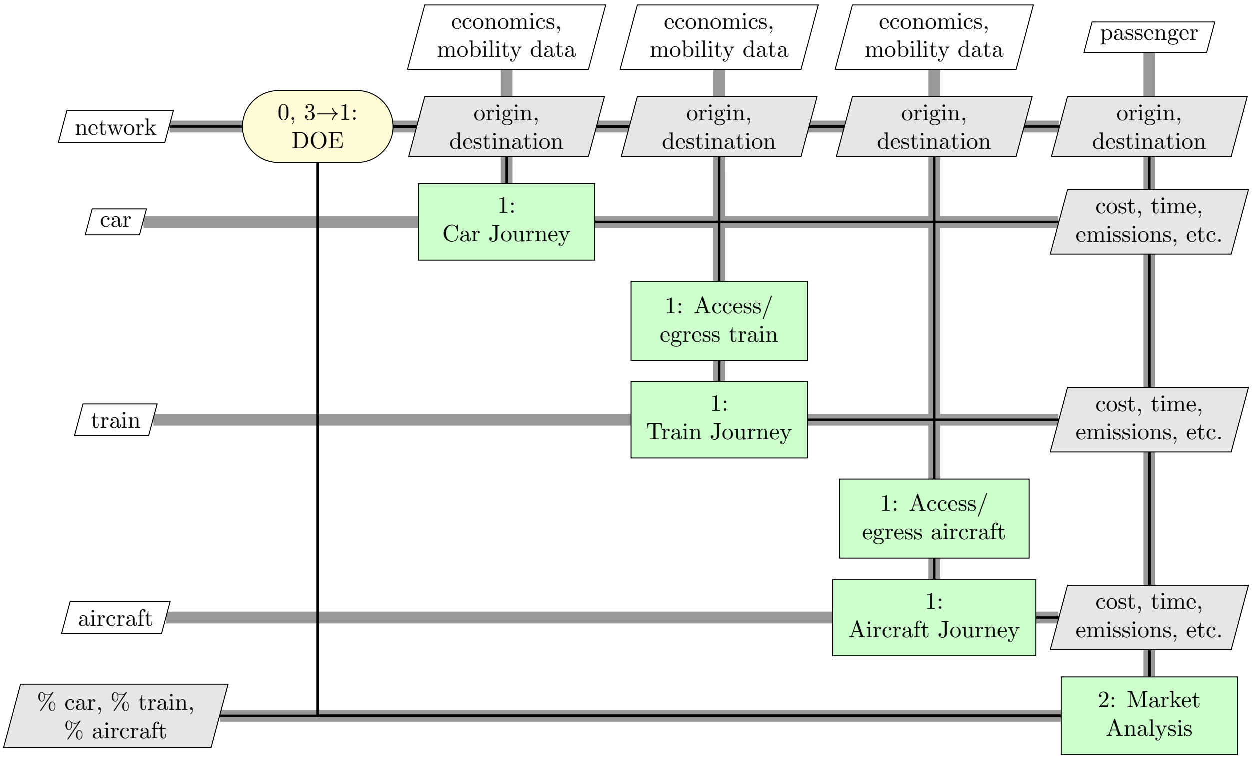

Figure 1 – Structure of the framework oSAAD.

2.2 Journey modeling

As already mentioned above, the simulation framework assumes different modes of transport for the door-to-door trips. In this analysis a comparison is being made for three different types of vehicles: a car, a train, and the commuter aircraft. The comparison of the modes is based on the following attributes: the travel time, the travel cost, the amount of fuel and/or electric energy consumed during the journey, and the amount of greenhouse gases emitted measured in CO_2 equivalents. The cities are modeled as circular discs with a radius determined from the known area of each city. For the analysis presented here, the case of Germany and its transportation system is taken as a basis for simulation. The flexibility and modularity of the framework allows however for a substitution of the used models and their parameters with different ones.

2.2.1 Car journey

The car journey is divided into two parts: the distance covered within the cities of origin and destination, and the distance covered on the highway in between. The highway part is assumed to start at the edge of each city. In order to consider the randomness of the points of origin and destination within the corresponding cities, the first moment of the geometric probability function describing the distance between a random point inside the disk's area and a point on the disks edge is calculated [2]. The distance covered on a highway is calculated by subtracting the radii of the cities of origin and destination from the great-circle distance between the coordinates of the city centers. Both the highway as well as the inner city distances are calculated by a detour factor in order to get the actual road distances. The detour factor is determined by averaging data collected using Google Maps for various connections within Germany.

The average speed within cities and on highways for car travel is determined similarly. The total travel time is calculated by additionally considering the recommended 15 minute break every 3 hours of driving as well as a few minutes of walking to and from the parked car. The amount of fuel/electricity consumed during the journey is derived from the average fuel/energy efficiency of the car in the city and on the highway and the respective distances. A database of average fuel/energy efficiencies of different car categories is included in the framework. Based on this data and taking into account the current prices for fuel/electricity, the cost of the car journey can be calculated. This cost does not only consider the required fuel/electric energy, but also the cost of ownership, maintenance, insurance etc., which is valid for privately owned cars as well as for rentals. Given the average load factor of cars (around 0.2, which corresponds to one passenger) the cost per person is derived. From the amount and type of fuel/electricity consumed during the journey and the corresponding emission indexes [3] the well-to-wheel emissions of the journey in CO_2 equivalents are calculated.

2.2.2 Train journey

The description of a door-to-door journey via train is divided in two parts: an access/egress trip to/from the train stations of the cities of origin and destination, and a part using the "main" vehicle of this trip, i.e. the train. The access/egress part of the journey is described in more detail in section 2.2.4. For the main part of the journey, it is assumed that a train station is located at the center of each city. This is a valid assumption for most German cities. The distance between the train stations of origin and destination is estimated by multiplying the great-circle distance of the two cities by a detour factor.

In order to estimate the duration and the cost of the main part of the trip, a small database of different train connections with their duration and ticket price was created using the website of the biggest German railway company, the Deutsche Bahn AG (www.bahn.com). The time and cost of a connection is determined through a regression analysis as a function of distance using the created database. The Deutsche Bahn also offers its own public API with the timetables of all the available train connections. However, for the sake of simplicity and in order to avoid a long response time of the software, especially for a large number of connections (because of the response time of the API), this data was not used here. For the ticket cost it is assumed that the traveler owns a BahnCard25, which offers a 25% discount on the full fare, in order to depict a compromise between the full fare and special offers or other types of fare discount.

Since most of the trains in Germany run on electricity (and the ones with an internal combustion engine are planned to be gradually replaced with other technologies [4]) the module assumes an electric train fleet. The energy efficiency of the train journey is derived from the data given in [5] and the number of operating ICE and IC type trains is found on the Deutsche Bahn website. For the sake of simplicity an averaged train is assumed independent of the actual OD pair. To determine the energy consumed for the journey per passenger, the typical load factors also given in [5] are assumed. The actual electric energy needed to power the trains is calculated by additionally considering the losses of the transmission network to the train's pantograph [6]. The resulting well-to-wheel emissions in CO_2 equivalents are calculated from the emission index that corresponds to the assumed electricity mix. The data on the current mix of electricity sources in Germany is taken from the website of the German Environment Agency (Umweltbundesamt).

2.2.3 Aircraft journey

Similarly to the train journey, the description of a door-to-door journey via aircraft is divided in two parts: an access/egress trip to/from the airports near the cities of origin and destination, and a part using the "main" vehicle of this trip, i.e. the aircraft. As mentioned above, the access/egress part of the journey is described in more detail in section 2.2.4. The closest airport/airfield to the location of origin and destination respectively is selected for the modeling of the aircraft journey. Only the airfields that have a sufficient runway length are selected as candidates for the hypothetical journey. For the sake of simplicity, a distribution of the travelers to multiple possible airports in the vicinity (as it would actually take place) is not considered. The airports and airfields database has been composed from publicly available data especially regarding the coordinates and the runway lengths found on the web.

The aircraft considered here are three versions of a hybrid electric commuter plane, which are introduced in more detail in section 3.1. The three aircraft concepts have a fully-(battery)-electric flight capability, supported by a range extender for longer flight distances. Two of the concepts are designed for low noise levels during takeoff and landing. The flight time as well as the amount of energy (electricity and/or fuel) are derived as functions of distance and payload from the aircraft design as described in [7, 8]. For battery-powered aircraft there are two main scenarios for "renewing" the electric energy on the aircraft: charging the batteries between landing and takeoff or swapping them for ones that have been pre-charged. Each concept has pros and cons, however in this study a recharging of the batteries is assumed. The turnaround time of the aircraft is thus including the charging time of the batteries. This is taken into account during the journey modeling.

Cost assessment A comparison between the different modes of transport requires the estimation of the journey cost using the aircraft, i.e. the plane ticket cost. For the derivation of the ticket cost it is assumed that all the revenues of the airline that operates the commuter aircraft result from the tickets sold. Other possible sources of revenue are not considered. Similarly it is assumed that the airlines' expenses consist entirely of the operating expenses (direct and indirect). Non operating expenses are omitted from the model. The profit of the airline is thus derived by the difference between revenue and expenses. A profit margin of 7% is assumed [9].

The operational expenses are divided into direct operational costs (DOC) and indirect operational costs (IOC). The IOC include promotion and sales, general and administrative costs, passenger service costs, ground property and equipment costs etc. Assuming that there is almost no passenger service provided in a commuter plane, the IOC are estimated to amount to 44% of the total operating costs. This assumption is in line with the figures from [10] excluding passenger service costs.

DOC are assessed using the TU Berlin method [11], as it is widely used by the aircraft design community. Since this method is based on data from airline operations of EASA CS-23 aircraft, e.g. Airbus A320, applying the same method to the operation of significantly smaller commuter planes must be viewed with caution. The yearly DOC per aircraft includes costs for energy, crew, maintenance, fees for air traffic control (ATC) and capital costs. In order to take into account some changes in the cost calculation for the operation of a hybrid-electric aircraft, such as the commuters investigated here, the model for capital costs is modified to include the costs for the electric motors additionally to the gas turbines. For the electric motors including the power electronics a cost of 150 €/kW is assumed, while the cost for the turboprop engines is modeled according to Gudmundsson [12]. Furthermore, the battery costs are added to the capital costs. The battery costs are calculated by multiplying the energy capacity with the price per kWh (here 100 €/kWh are assumed with an exchange rate of 0.82 € per USD) and the annuity factor for batteries. The latter is derived using a residual value factor of 40%, assuming a second life for the batteries, and a depreciation rate DP:

$$DP = \frac{\text{Number of battery cycles}}{\text{Number of flight cycles per year}}. \tag{1}$$

It is assumed that the batteries have a lifetime of 1500 cycles before being replaced. The number of flight cycles per year is calculated from the yearly operation time (potential yearly operation time minus the yearly forced downtime) divided by the average block time of a flight. The maintenance costs for the hybrid-electric aircraft are not modified in this study since it is not yet clear what impact a hybrid architecture will have on the maintenance. The crew costs for the operation of the commuter aircraft only include the costs for the cockpit crew (pilots) since it is assumed that no flight attendants will be required. The fees for ATC are mainly based on the Maximum Takeoff Mass of the aircraft. However, with the introduction of more (hybrid-)electric aircraft in the future and the rising requirements regarding the climate and noise impact of aviation, this fee structure is expected to change.

All the components of the capital costs except for the energy costs are calculated on a per-year basis. The cost per flight is derived from the yearly utilization (flight cycles). The energy costs per flight are calculated from the actual energy consumed for a flight and the respective prices for fuel and electricity. Finally, the ticket price per flight can be derived from the assumed IOC, profit margin, and considering a load factor of 74% (i.e. 14 passengers on a 19-seater).

Environmental impact The emissions related to the electricity required to charge the batteries and the emissions from the combustion of fuel need to be considered for the calculation of the environmental impact of the aircraft journey. The first part considers the well-to-tank (WTT) emissions from the production of electricity depending on the mix of electricity sources. It also takes into account the losses during transmission of the electricity and charging of the batteries. The second part considers the WTT emissions from the production and distribution of the used fuel [13] and the tank-to-wake (TTW) emissions from the combustion of the fuel during flight.

The main combustion products of jet fuel with air are carbon dioxide (CO_2) and water vapor (H_2O). These emissions are proportional to fuel burn. Other emissions due to the non-ideal combustion include nitric oxide (NO) and nitrogen dioxide (NO_2) (together termed NO_x), sulfur oxides (SO_x), and soot. The NO_x emissions contribute to the formation of other greenhouse gases such as atmospheric ozone (O_3) and methane (CH_4) [14]. Other emissions, e.g. soot particles and water, can influence the formation of contrails and cirrus clouds, which have a warming impact. Since some of these emissions are more short-lived than others, their impact is bound to have a spatial and temporal variability.

In order to assess the environmental impact of aviation, an analysis normally considers an entire aircraft fleet over longer periods of time and utilizes more aggregative metrics, such as the Average Temperature Response [15]. Since the scope of this study is limited to a journey level, the environmental impact of each flight is estimated in terms of CO_2 equivalents. These can be calculated by multiplying the mass of the emitted gas by the gas' global warming potential (GWP). The masses of emitted gas for CO_2, SO_x, soot are calculated by multiplying the mass of the fuel burnt during a flight by the emission index of the respective gas. The emission indexes are taken from [14] and the GWP values for Europe for a 100-year time horizon from [16].

Unlike CO_2, the emission of NO_x depends on the load condition and characteristics of the engine, and on the ambient atmospheric conditions. In order to estimate the NO_x emission the DLR fuel-flow method [17] is used. This method calculates NO_x emissions based on an engine's reference emission indexes for sea level static conditions. The fuel flow for the given ambient atmospheric conditions in each flight phase can be calculated from the flight profile of the aircraft. Furthermore the corresponding emission index can be derived from the emission characteristics of the engine. The total amount of emitted NO_x is calculated using the NO_x emission index and the fuel burnt in each flight phase. By multiplying this amount with the GWP of NO_x, the impact in terms of CO_2 equivalents can be obtained.

2.2.4 Access and egress modeling

Since the framework scope includes the entire door-to-door journey, traveling with the previously mentioned three "main" modes of transport involves an access trip to and an egress trip from this "main" vehicle. For this purpose the journey modules encompass another module describing these access and egress trips, as seen in Figure 1. For the journey by car an average walking distance to and from the parking spot of the car is assumed. The access and egress trips for the train and aircraft journeys are schematically depicted in Figure 2.

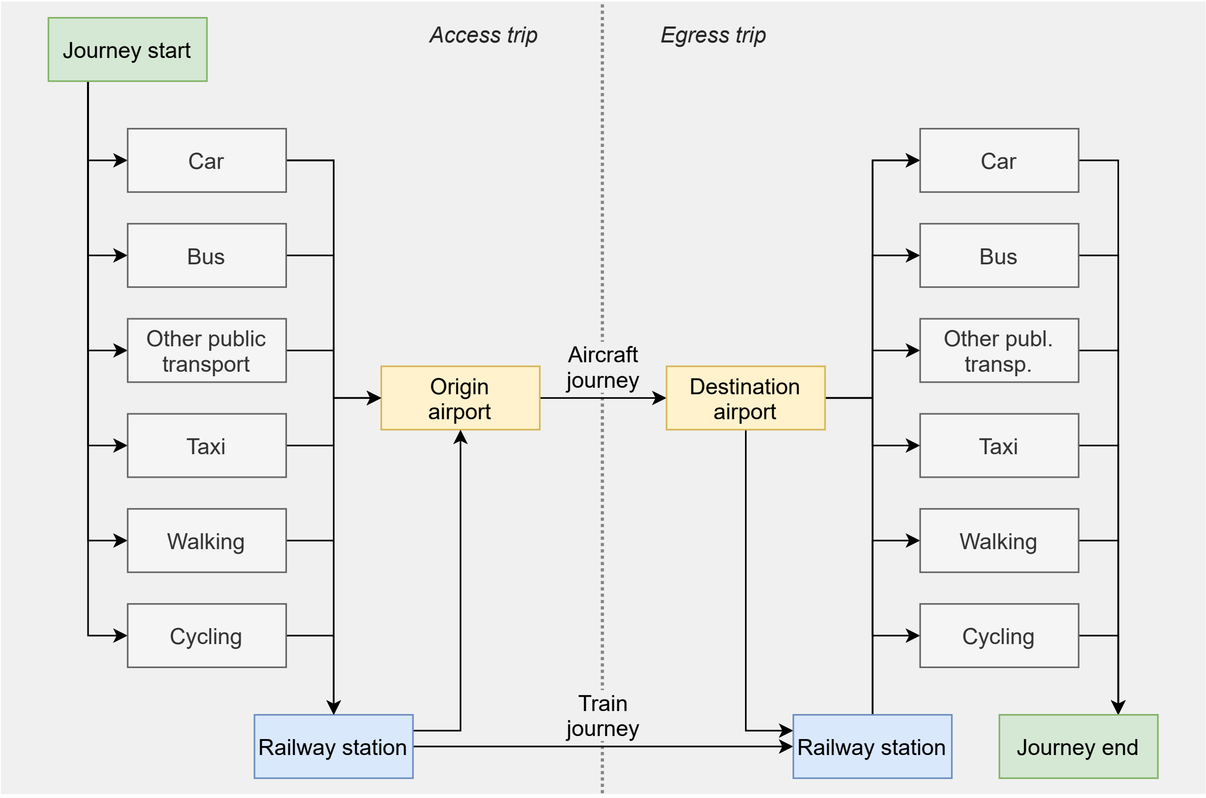

Figure 2 – Diagram of access/egress model for train and aircraft journeys.

For the train journey the different access/egress modes include car, taxi, bus, rail-based public transport, bicycle, and walking. For each of these modes a series of distance-independent time factors is assumed, e.g. door-to-vehicle time, parking time, waiting time, etc. The values for these time factors are determined empirically. Additionally, a distance-dependent time factor is included, which takes into account the average speed of each mode to estimate the time between the location of origin/destination and the train station. Finally, a certain waiting time at the train station is taken into account. In order to estimate the average access and egress times, a statistical distribution of the choice of access/egress mode to the train station is adapted from [18].

A similar concept of access and egress trips is assumed for the aircraft journey. Here the possible modes include car, taxi, bus and rail-based public transport. For airports that are located farther from the city of origin/destination (here a distance > 30 km is assumed) an additional possible mode of taking a train to reach the airport is included in the model. In that case the access/egress trips include a part to/from the railway station and riding the train to the airport. Again, the various distance-independent time factors corresponding to the different modes are considered. Also the time on the vehicle(s) chosen for the access/egress trip is considered through the traveled distance and average speed. For the access trip to the airport an additional waiting time is taken into account based on the recommended time buffer between arrival at the airport and flight departure. The average access and egress times are estimated using an adapted statistical distribution of the choice of access/egress mode to the airports from [19].

The differences in the access/egress distribution of smaller airports compared to large commercial airports, which are more likely to have a good accessibility with public transport, as well as other regional characteristics are not considered for the sake of simplicity. Regional specifics are also not considered for the train stations or regarding the availability of certain access and egress modes. Since most analyses are intended to be conducted for multiple OD pairs, those local differences are expected to be averaged out statistically.

Regarding the evaluation of the entire door-to-door journey, only the time of the access and egress trip is taken into account. Since the costs and emissions of the access/egress trip are expected to be significantly less than those of the main part of the journey, they are not considered in the final cost and emission calculations of the journeys.

2.3 Market analysis

All cities in Germany with a population above 75,000 (data from statistical offices in Germany, date: 31 Dec. 2017 [20]) are included for the generation of origin-destination (OD) pairs. The OD pairs are subdivided by distance in four different intervals starting at a distance of 200 km and using an increment of 200 km. The distance used for this categorization is chosen as the great-circle (GC) distance between the locations of origin and destination. This means that the actual door-to-door distances slightly differ due to the added access and egress trips to the airports and the deviation factors by which the connection via car or train would be multiplied. OD pairs with distances below 200 km are not considered, since it is assumed that the time benefit of the aircraft in this category would be negligible due to the access/egress trip as well as the time spent at the airport. OD pairs with distances above 800 km are not considered due to the fact that more than 95% of the cumulative share of scheduled passenger flights with 19-seater aircraft in the years between 2000 and 2018 were for distances below 800 km [21].

The preferences of the passengers are described using a mode-choice model that is based on the assumption that the decision maker opts to maximize his utility. The utility U of each option is described as a linear function

$$U = \sum_i \theta_i \cdot x_i \tag{2}$$

where x_i is the i-th variable influencing the utility and θ_i is the corresponding weight for this variable. The variables influencing the utility of each mode of transport in this model are: the travel time (in minutes), the travel cost (in Euro), the accumulated access and egress time (in minutes), the frequency of the connection (in minutes), the reliability (score from 0 to 10), the comfort (score from 0 to 10), and the boarding time (in minutes) for aircraft journeys. Additionally, in order to factor in an increasing awareness of the environmental impact of traveling that may influence the mode choice [22], a further variable describing the environmental awareness of the passenger (score from 0 to 10) is included in the model and calibrated using data from [23, 24].

The probability P_m of choice m using the multinomial logit model [25] can be calculated as

$$P_m = \frac{e^{U_m}}{\sum_{k=1}^{N} e^{U_k}} \tag{3}$$

with U representing the utility and N the number of available mode options. Each variable of the utility function, e.g. the travel cost, is normalized taking into account the mean value of all the different options as well as the so called anchoring effect. According to the principle of anchoring in decision making, an individual decides by comparing the available options to pre-existing information [26]. For example, when choosing a mode of transport, an individual has an expectation of the cost and duration of a certain journey and will base their decision not only on comparing the available options to each other, but also by comparing them to their expectation. The weights θ of the variables are determined using the choice data from various corridors found in literature [27, 28, 29].

Some passenger characteristics such as their income, and trip characteristics, e.g. business vs leisure, also influence the mode choice. For the sake of simplicity, an average passenger is modeled in this study and the trip is assumed to have a mean intended duration of stay of 6 hours at the location of destination. The implementation of this methodology within the assessment framework allows an estimation of the choice probabilities of different modes of transport on a given OD pair.

3. Commuter aircraft concepts as a use case

After having introduced the methodology implemented within the analysis framework, the relevant data regarding the investigated commuter aircraft as well as the underlying assumptions for the analysis will be presented in the following sections. Finally some analysis results for different scenarios will be presented.

3.1 Commuter aircraft concepts

In order to demonstrate the potential of the presented analysis framework, three novel hybrid-electric commuter aircraft are modeled as modes of transport within the framework. All three hybrid-electric aircraft have an all-electric flight capability and the gas turbine serves a range extender function. The E19a represents an optimized solution for passenger transport from conventional airports. The E19b and E19c, on the other hand, offer passenger and cargo transport and are designed for low-noise operation on short airfields in densely populated areas. The electrical propulsion and battery technology for the E19a is assumed to be state-of-the-art. The E19b and E19c, however, are designed with a technology level of 2030+ in mind. Additionally, an existing turboprop commuter aircraft, the Dornier Do228, named Ref19 here, which serves as a reference for the design of the other aircraft, is also introduced in the analysis framework. The most important technical data of the four commuter aircraft is listed in Table 1. A more extensive description of the hybrid-electric concept E19a can be found in [7] and for the silent hybrid-electric concepts E19b (parallel hybrid-electric propulsion) and E19c (serial hybrid-electric propulsion) in [8].

Table 1 – Technical data of commuter aircraft.

	Ref19	E19a	E19b	E19c
Operating empty mass [kg]	3900	6621	6418	6411
Installed engine mass [kg]	590	763	838	884
Battery mass [kg]	-	2018	1848	1838
Battery specific energy [Wh/kg]	-	230	400	400
Cruise speed [kts]	230	160	140	140
Range at max. payload [km]	230	190	266	283

3.2 Use-case assumptions

Most of the data and assumptions used in the analysis were mentioned in the previous sections. The car used for the comparison is modeled as a midsize diesel car and the fuel price for diesel is assumed to be 1.3 €/l. The jet-fuel price is assumed at 0.4 €/l (commercial kerosene consumption has been tax-exempt in the European Union) and the electricity price for non-household consumers at 0.086 €/kWh. For the calculation of the market shares using the presented mode-choice model, connection frequencies of 60 minutes for the train and 160 minutes for the aircraft journey are assumed. The additional parameters of comfort and reliability of the different modes are set to a fixed value of 5 (on a score from 0 to 10) for all the modes, since these parameters are subjective and may depend on the specific connection.

An overview of the cities and airports/airfields used in this study is depicted on a map in Figure 3. The different scenarios evaluated in this study include the following:

- An increased number of available airports for the commuter plane by also using the existing airfields with a sufficient runway length in addition to the commercial airports (see Figure 3).

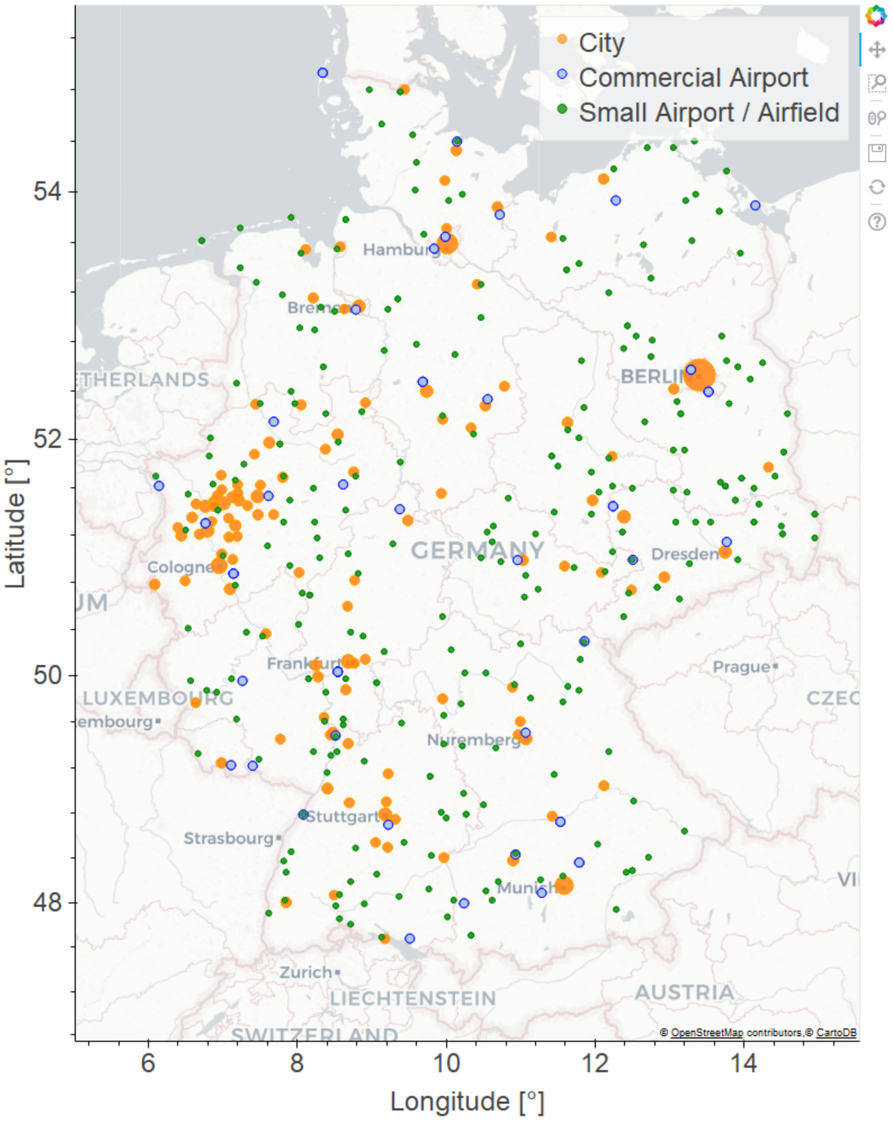

Figure 3 – Map of German cities with a population above 75,000 and all airfields in Germany. The size of the orange dots is proportional to the population of the cities.

- An increased emission tax for all transport modes (tax per amount of emitted $CO_{2,\,eq}$) and a more renewable electricity mix.

Changes in overall travel demand due to e.g. cost differences are ignored for this analysis. Also the possible impact of an increased electricity demand on the electricity price due to more electricity-powered vehicles is not taken in to consideration. The available ATC capacities are not considered for the analysis of the aircraft journeys, which might in reality lead to increased turnaround times or ATC fees. All these effects would require a dynamic modeling with system feedbacks that are outside the scope of the current analysis.

Regarding the environmental impact assessment, it needs to be mentioned that the greenhouse gas emissions consider only the operational part of the journeys, i.e. the environmental impact of the manufacturing and end-of-life phase of the vehicles is not taken into account for this assessment. Even though the operational phase is considered to play the most significant role in the life cycle assessment of the vehicles, a complete life cycle analysis would be required in order to have a clear view of the respective environmental impact of the studied modes. Finally, it needs to be mentioned that the GWPs of some of the emitted gases is potentially estimated too high, as the commuter aircraft flies at lower altitudes compared to bigger aircraft that are considered in the literature on the GWP factors.

3.3 Analysis results

In order to visualize some of the calculations done within the analysis framework, the results of a sample door-to-door journey using different modes of transport are depicted in Figure 4. More specifically the time, cost, energy and GHG emissions for an exemplary door-to-door journey and the six different modes of transport (diesel car, train, four different commuter aircraft) are shown. In the case of the journey time, it can be seen that due to the high access/egress time to and from the airport the aircraft journeys are only slightly faster compared to the car and train journeys. It can also be observed that the silent aircraft concepts, i.e. E19b and E19c, have a slightly higher journey time compared to the other two aircraft, due to the lower average speed. Regarding the journey cost per person the hybrid-electric aircraft (E19a, E19b, E19c) perform the worst, mostly due to the higher capital costs for the aircraft. In terms of energy per person, the hybrid-electric aircraft perform better than the reference aircraft (and than the diesel car), as a big proportion of the journey energy is provided by the electric powertrain, which is more efficient than its thermal engine counterpart. Finally, with respect to the GHG emissions per person, the reference aircraft performs the worst compared to all other modes. Even though the energy consumed per person for the reference aircraft journey is comparable to the one needed for the car journey, the climate impact of the former is significantly higher due to the emission at higher altitudes.

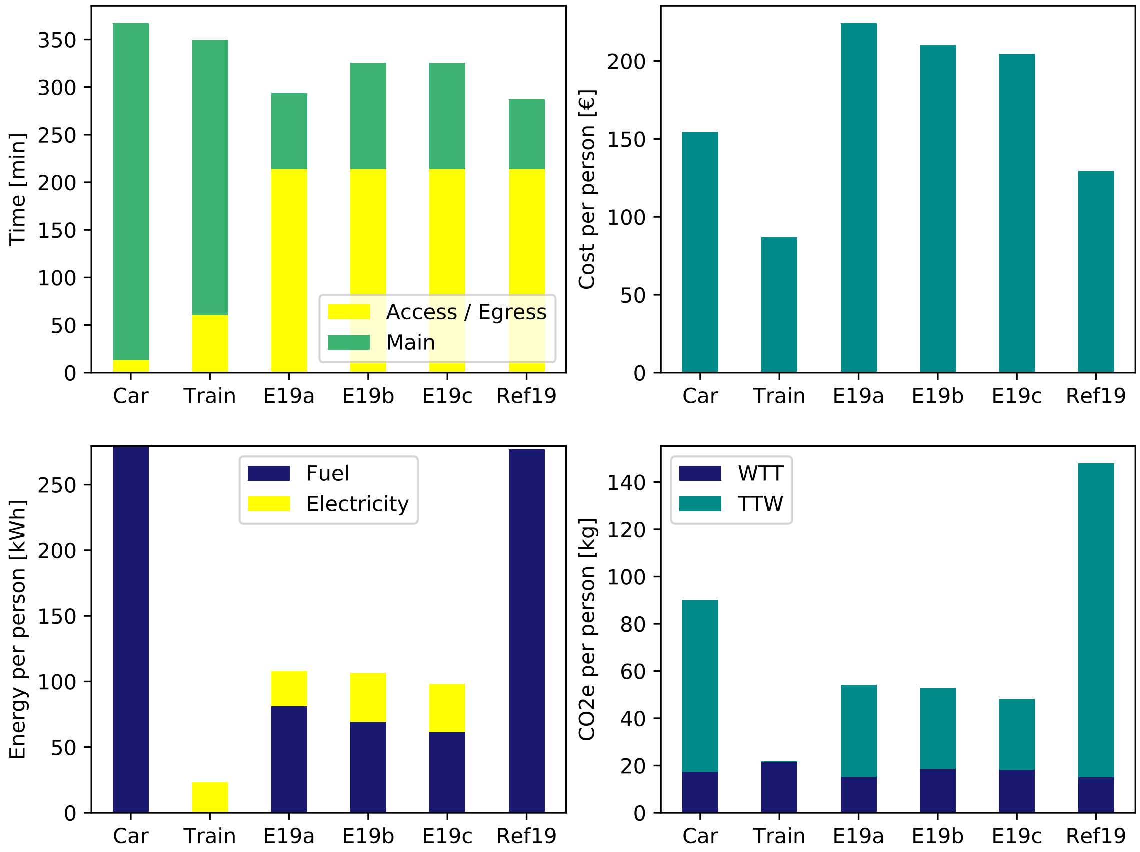

Figure 4 – Analysis results for different journeys (ICE car, train, four commuter aircraft) regarding time (access/egress, main), cost, energy consumed at the vehicle (electricity, fuel), emissions (WTT, TTW) for one exemplary connection between Hamburg and Dresden (GC distance: 378.4 km).

By conducting these calculations for all the possible OD pairs modeled within the assessment framework and using the presented mode-choice model, the market shares of the different modes can be derived. The results of such an analysis are shown in Figure 5 in the form of box plots and divided into different distance categories. The lower and upper borders of the box represent the first and third quartile of the dataset distribution and the orange line inside the box shows the median of the dataset. The whiskers outside the box depict the datasets at a distance smaller that 1.5 times the boxes height (interquartile range) and the circles beyond the whiskers are the dataset outliers that do not fall within this range. It can be seen that with increasing journey distance the market shares of the two commuter aircraft chosen for comparison, namely the E19a and E19c, also increase, while the market share of the car journey decreases. The train is still the most competitive for all three distance categories due to the lower journey cost and the fact that the door-to-door time for the aircraft journeys is quite long (because of the access/egress time).

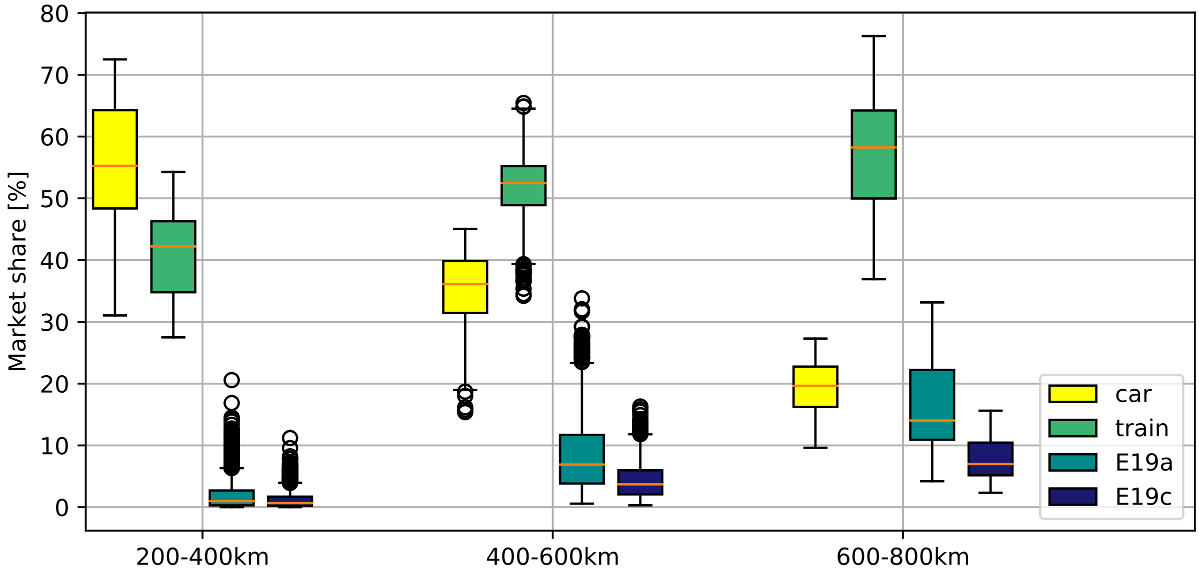

Figure 5 – Box plot of average market share per distance category per vehicle with only existing commercial airports.

Assuming that the commuter aircraft can also be operated using the existing airfields that offer a sufficient runway length, the analysis can be repeated. In Figure 6 an increased aircraft market share can be seen, especially for longer distances. This is due to the fact that on average the access/egress time to the airport decreases through the availability of more airports. For the E19a aircraft the market share in the distance segment 600 to 800 km almost doubles, while for the E19c, which has a significantly lower take-off field length requirement, the market share nearly triples.

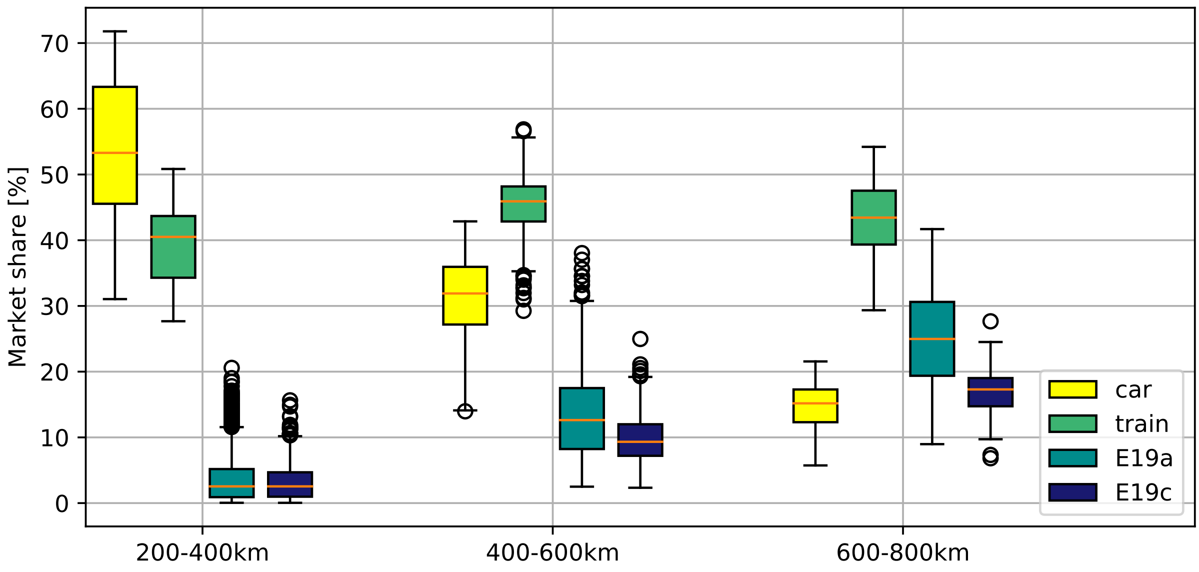

Figure 6 – Box plot of average market share per distance category per vehicle with all airfields.

Different strategies to reduce greenhouse gas emissions from the transportation sector are currently being discussed in politics and the public. An analysis framework that allows the investigation of different scenarios, such as the one presented here, can help visualize the effect of different strategies on the transportation system. Figure 7 represents a reference case with the E19a and the Ref19 as air transportation modes and an underlying assumption of 10 € per ton of $CO_{2,\ eq}$ emitted and the German electricity mix of 2019 (0.338 kg $CO_{2,\ eq}$/kWh [30]). Figure 8 depicts an example of a different policy by introducing an emission tax of 150 Euro per ton of $CO_{2,\ eq}$ emitted and assuming the electricity mix of Sweden for 2019 (0.008 kg $CO_{2,\ eq}$/kWh [30]). For this simulation the WTW emissions are taken into account. It can be observed that preference for "greener" modes of transport, especially the train, increases slightly, while the market share for the turboprop commuter plane Ref19 slightly decreases.

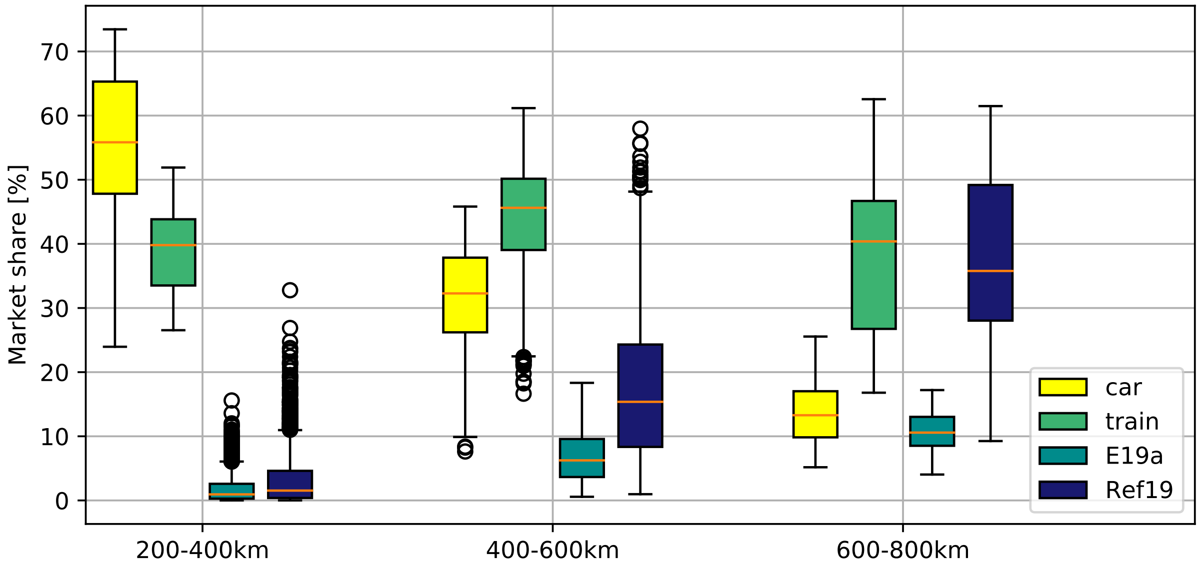

Figure 7 – Box plot of average market share per distance category per vehicle with commercial airports assuming an emissions tax of 10 Euro per kg $CO_{2,\ eq}$ and the electricity mix of Germany.

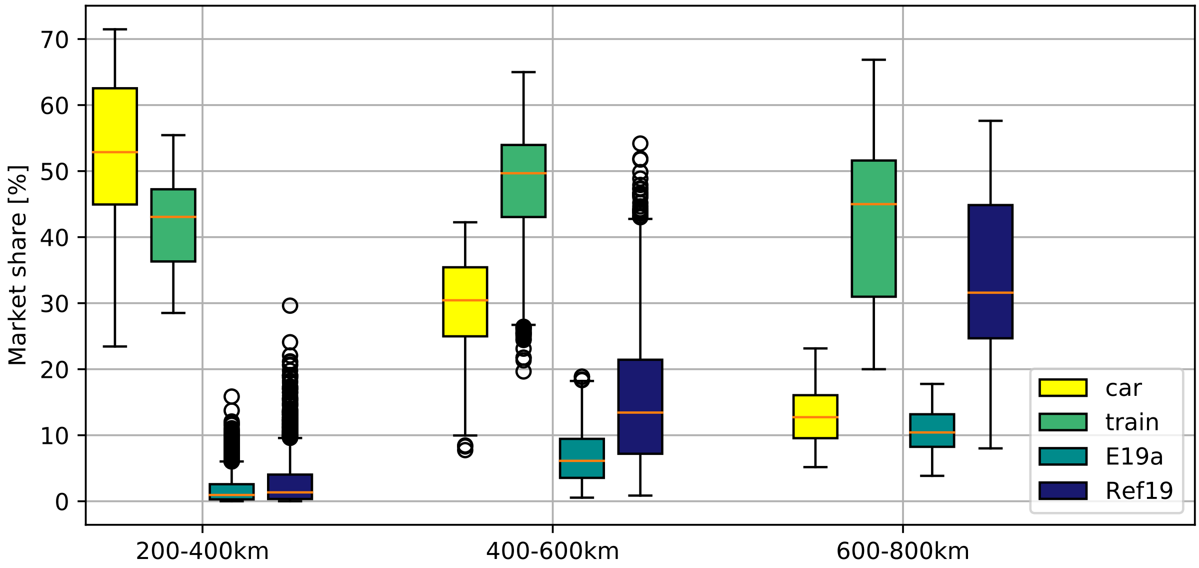

Figure 8 – Box plot of average market share per distance category per vehicle with commercial airports assuming an emissions tax of 150 Euro per kg $CO_{2,\ eq}$ and the electricity mix of Sweden.

All in all, it is demonstrated that using the introduced analysis framework the impacts of changes in the aircraft design, as well as changes in the surrounding transportation environment on the behavior of the transportation system can be visualized.

4. Summary and Discussion

This paper presented a framework for the analysis of aircraft as part of a wider transportation system including other modes of transport and considering the door-to-door traveling for passengers. Based on the use case of different commuter aircraft and assuming different future operation scenarios some of the capabilities of the developed framework were demonstrated.

As seen from the analysis results, it was possible to visualize the effect that changes in certain parameters regarding the aircraft, e.g. required runway length, or the overall transportation system, e.g. a tax on GHG emissions, may have on the performance of the commuter aircraft as part of a transportation system. The ability to explore the effect of such parameters or the influence of different operational environments/scenarios on the performance of an aircraft can open up new possibilities to aircraft designers as well as to stakeholders involved in the transport sector.

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6. Copyright Statement

References

[1] Lambe A B and Martins J R R A, Extensions to the Design Structure Matrix for the Description of Multidisciplinary Analysis, Design, and Optimization Processes. *Structural and Multidisciplinary Optimization*, Vol. 46, pp 273-284, 2012.

[2] Solomon H, *Geometric Probability*. Society for Industrial and Applied Mathematics, 1978.

[3] Department for Business Energy & Industrial Strategy (BEIS), 2019 Government greenhouse gas conversion factors for company reporting: Methodology Paper for Emission Factors. *Final Report*, 2019.

[4] NOW GmbH, Deutsches Zentrum für Luft- und Raumfahrt e. V., Institut für Fahrzeugkonzepte, *Marktanalyse alternativer Antriebe im deutschen Schienenpersonennahverkehr*, 2020. Available: `https://www.now-gmbh.de/en/news/pressreleases/high-market-potential-for-alternative-drives-in-rail-transport`

[5] DB Regio AG & Deutsche Bahn AG, Grundlagenbericht zum UmweltMobilCheck, *Report*, 2019.

[6] ifeu, EcoPassenger: Environmental Methodology and Data. *Report*, 2016.

[7] Atanasov G, van Wensveen J, Peter and Zill T, Electric commuter transport concept enabled by combustion engine range extender. *Deutscher Luft- und Raumfahrtkongress (DLRK)*, Darmstadt, Germany, 2019.

[8] Wassink P, Atanasov G, Hesse C and Fröhler B, Conceptual Design of Silent Electric Commuter Aircraft. *32nd Congress of the International Council of the Aeronautical Sciences, ICAS 2021*, Pudong Shangri-La, Shanghai, China, September 6-10, 2021.

[9] Taneja N K, *Airline Survival Kit*. 1st Edition, Routledge, London, 2017.

[10] Douglas Aircraft Co. Inc., Study of short-haul aircraft operating economics, Volume 1. *Technical Report prepared for Aeronautical Systems Office, NASA*, Report Number NASA-CR-137685, 1975.

[11] Thorbeck J and Scholz D, DOC-Assessment Method—TU Berlin—DOC Method. *3rd Symposium on Collaboration in Aircraft Design*. Linkoeping, Sweden, 2013.

[12] Gudmundsson S, *General aviation aircraft design. Applied methods and procedures*, 1st edition, Butterworth-Heinemann, Oxford, 2014.

[13] COWI Consortium, Study on actual GHG data for diesel, petrol, kerosene and natural gas. *Final Report, prepared for European Commission DG ENER*, 2015.

[14] Intergovernmental Panel on Climate Change, *Aviation and the Global Atmosphere*. Cambridge Univ. Press, Cambridge, England, U.K., 1999.

[15] Schwartz Dallara E, Kroo I and Waitz I, Metric for Comparing Lifetime average Climate Impact of Aircraft. *AIAA Journal*, Vol. 49, No. 8, pp 1600-1613, 2011.

[16] Lund M T, Aamaas B, Berntsen T, Bock L, Burkhardt U, Fuglestvedt J S and Shine K P, Emission metrics for quantifying regional climate impacts of aviation. *Earth Syst. Dynam.*, Vol. 8, No. 3, pp 547–563, 2017.

[17] Deidewig F, Döpelheuer A and Lecht M, Methods to Assess Aircraft Engine Emissions in Flight. *ICAS Proceedings 1996*, Vol. 1, ICAS-96-4.1.2, 1996.

[18] Crisalli U and Gangemi F, The access/egress mode choice to railway terminals. *WIT Transactions on The Built Environment*, Vol. 33, pp 43-52, 1997.

[19] Grimme W, Berster P and Gelhausen M, Analyses of the European air transport market, Airport Accessibility in Europe. *Report prepared for the European Commission DG TREN*, 2010.

[20] List of Municipalities Information System (GV-ISys), Available: `https://www.destatis.de/DE/Themen/Laender-Regionen/Regionales/Gemeindeverzeichnis/_inhalt.html`

[21] Paul A, Grimme W, Atanasov G, van Wensveen J and Peter F. Evaluation of the Market Potential and Technical Requirements for Thin-Haul Air Transport. *Deutscher Luft- und Raumfahrtkongress (DLRK)*, Darmstadt, Germany, 2019 .

[22] Gössling S, Humpe A and Bausch T, Does 'flight shame' affect social norms? Changing perspectives on the desirability of air travel in Germany. *Journal of Cleaner Production*, Vol. 266, 2020.

[23] Carlsson F, Private vs. Business and Rail vs. Air Passengers: willingness to pay for transport attributes. *Working Papers in Economics*, No. 14, 1999.

[24] Lu J L and Shon Z Y, Exploring airline passengers' willingness to pay for carbon offsets. *Transportation Research Part D: Transport and Environment*, Vol. 17, No. 2, pp 124-128, 2012.

[25] McFadden D, Conditional logit analysis of qualitative choice behavior, In *Frontiers in Econometrics*, Zarembka P, Ed., Academic Press, New York, Vol. 1, No. 2, pp 105-142, 1973.

[26] Tversky A and Kahneman D, Judgment under Uncertainty: Heuristics and Biases, *Science*, Vol. 185, No. 4157, pp 1124-1131, 1974.

[27] Steer Davies Gleave, Air and rail competition and complementarity. *Final Report, prepared for European Commission DG TREN*, pp 64-72, 2006.

[28] Romàn C, Espino R and Martín J C, Analyzing competition between the high speed train and alternative modes. The case of the Madrid-Zaragoza-Barcelona corridor. *Journal of Choice Modelling*, Vol. 3, No. 1, pp 84-108, 2010.

[29] Valeri E, Air and rail transport in the Rome-Milan corridor: competition policy implications based on a discrete choice analysis. *PhD Thesis*, Università degli studi di Trieste, 2013.

[30] European Environment Agency (EEA). `https://www.eea.europa.eu/data-and-maps/daviz/co2-emission-intensity-6`