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Derivation of Top-Level Aircraft Requirements for Small Aircraft Transport by Modelling Demand in Europe

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Abstract. Advancements in aircraft technologies and in the process of aircraft electrification allow for the design of new small aircraft transport (SAT) configurations with a significant impact on sustainability, travel time and operating cost. Additionally, the European Flightpath 2050 creates a European-wide political landscape to enable developments in that field to thrive. All this together provides an environment that promises to open new business opportunities in the form of new and revived mobility services. However, the described ecosystem raises the question of what demand exists for SAT and what top-level aircraft requirements (TLAR) need to be achieved to realize customer-centric SAT. Data of the existing traffic patterns in Europe is analyzed to create a demand model, derive the TLAR and ultimately lay the foundation for a successful European SAT transport system. Initially, traffic pattern data is collected with a resolution on county and city level, thereby ensuring a high accuracy of larger and smaller travel distances. Subsequently, to the data collection, the income distribution in European countries is analyzed and in combination with a Willingness To Pay (WTP) function the actual existing SAT demand is determined. The demand optimized TLAR are then derived by varying the demand models input parameters to maximize the demand. The above-described approach allows to extract the potential annual demand in Europe for a certain set of requirements, it also details how a single parameter effects the demand. Hence, it provides sensitivities to illuminate design focal points. In consideration of all the described factors the paper defines the TLAR, thereby enabling the design of new SAT configurations.

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1. Introduction

Aviation, as every aspect of life, will need to undergo major revolutions to ensure it meets the highly ambitious environmental goals of the future. Currently, aviation annually contributes 3.9 % to the effect of global warming, while only a fraction of the world population uses air transport regularly [1]. This climate impact is likely to rise when considering that projections by the International Transport Forum are showing that the passenger kilometers are going to increase from 44 trillion to 122 trillion annually by the year 2050 [2].

At the same time, people desire more individual travel solutions, which also reduce travel time and cost. On the road, this tendency was shown in the last few years by the success stories of individual on-demand car services. For air transport, this progress has not yet reached the customer, but rather is shown by the high number of new start-ups aiming to provide short-distance transportation services. Most start-ups select one of two approaches to achieve this. First, flying short distances either within cities or within a few miles of the city relying on electric propulsion and vertical take-off and landing. This category is considered as urban air mobility (UAM). Regional air mobility (RAM), the second category, is one size bigger in capacity and range. On the technical side, it also takes advantage of an electrified propulsion system. However, contrary to UAM, RAM uses solely the existing airports infrastructure while taking-off and landing conventionally.

This tendency towards more individual transport strains Europe's transport infrastructure. Already, 1 % of the GDP of Europe is annually lost in traffic jams. With road traffic projected to increase by 30 % from 2010 to 2050, this strain on the infrastructure will increase even further [3]. A possible solution is to move the traffic from the ground to the air, since air transport only requires infrastructure at both ends of the journey.

Based on the environmental situation, the tendency towards more individual transport solutions, and the shift towards an electrified propulsion system, the paper aims to show that a significant number of people would take advantage of an additional mode of transport. To ensure that the selected TLAR will produce an aircraft meeting the demand within Europe, a demand model for Europe is created. It models the traffic patterns of trains, cars, conventional aircraft and SAT. The demand model is then used to derive the TLAR for a SAT vehicle.

The paper elaborates on the process of determining suitable TLAR for a SAT vehicle by creating and subsequently applying a European demand model. Since the demand model is the basis for the TLAR derivation, the method of developing such a model is first presented, followed by a description of the TLAR derivation process. After the methodical approach, the results are illustrated in two parts. First, the TLAR derived from the demand model and second, the TLAR derived from other sources. At the end, the discussion sets the context for the results followed by the final section, the conclusion.

2. Methods

Based on the goal stated above, the approach can be split into two parts. First, the development of a demand model by modelling the traffic patterns within Europe. Second, applying the demand model in addition to already existing information to derive the TLAR.

2.1. Demand Model

The development of the demand model can be split into data acquisition and filtering, creating a quantity structure to model the traffic patterns and adding additional detailed information to the demand model. With the European demand model established, the next step is to determine the number of people that would switch from the existing modes of transport to SAT.

The approach of data acquisition and filtering is executed in the following steps. As a first step, all SAT relevant airports and airfields in Europe are identified. For this purpose, three different airport categories are defined, which from a population and geographical perspective have a significant potential for SAT vehicle services. If an airport has at least 50,000 inhabitants within a radius of 10 km, it is classified as "urban". The second category is considered a "remote" airport, which has at least 10,000 inhabitants within a radius of 20 km and is more than 50 km a way from the nearest urban center. An urban center is defined by the European Commission as "high-density clusters of contiguous grid cells of 1 km^2 with a density of at least 1,500 inhabitants per km^2 and a minimum population of 50,000" [4]. The third category "island" represents an airport which is located on an island with at least 10,000 people living within a radius of 10 km of the airport. The analysis and filtering of the airports according to the process mentioned above is carried out using a geographic information software. In addition to the geographic coordinates of all European airports, a global grid (1x1 km^2) with detailed population data, a vector map with all islands in Europe and geographic coordinates of all European urban centers is used. By applying the buffer analysis method to the collected data, all airports in Europe are identified that apply to one of the three airport categories. The result is an overview of SAT nodes that are representing a significant potential for SAT traffic. Moreover, the individual SAT nodes are evaluated if they meet the infrastructural requirements for SAT vehicles.

For each of the transport modes air, rail and road a quantity structure is created. Airline data from Sabre [5] containing detailed information about worldwide flights is used to create the quantity structure of large aircraft traffic. For SAT, especially indirect flight connections, which from an origin-destination perspective can also be flown directly with a SAT vehicle, represent great potential. The assumption is that people would save a lot of time, if an affordable direct connection is offered. Therefore, the direct air distance (great circle distance) between the origin airport and the destination airport of all European flight connections (with at least one stopover) are analyzed. In the next step, all connections with direct air distance exceeding 2,222 km are filtered out to reduce complexity. Resulting in the identification of 25,396 indirect flight connections from 2019. Additionally, detailed information on passengers and ticket prices for the individual connections are exported from the Sabre data portal.

A different approach is used to create the quantity structure for road and rail traffic. Using the traffic origin/destination matrix from the EU-funded ETISplus project [6], containing detailed trip data at a resolution on the NUTS 3 level, a quantitative framework for the ground-based traffic between all European NUTS 3 regions is created. These regions represent the highest possible resolution of the European NUTS classification and are either counties or cities [7]. The data is structured as trips per year between every NUTS 3 region in Europe. A minimum number of 5,000 trips per year is set as a threshold, resulting only in the consideration of connections with a significant potential. In total, 51,326 European NUTS 3 road traffic relations and 4,126 European NUTS 3 rail traffic relations are incorporated into the model's quantity structure.

The subsequent step is to define plausible cost and time assumptions for the model's modes of transport. For conventional air traffic, the average ticket prices of the respective flight connections is used. To consider access and egress times to and from the airport, 3 hours are added to the flight time. For road traffic, a value of 0.30 € is assumed for the kilometer costs in Germany, which is adjusted accordingly for all other countries using the global Fuel Price Index [8]. The assumed kilometer costs for train traffic in the individual countries are taken from a European rail study [9]. In addition, country-specific assumptions about the average speed are used to determine the respective time for trips of the ground-based traffic.

Finally, an analysis of the income distribution in the individual European countries is carried out to determine the buying power for each European country. This is done by adding detailed income statistics for each country, using the World Inequality Database [10]. The usage of the database makes it is possible to analyze the income distribution of the population in 1 % percentile steps for all European countries.

Applying the WTP function [11] to the demand model allows to calculate the number of people that will switch from existing transport modes to a SAT vehicle. This WTP function (1) uses a variable input mask to allow for the optimization of the TLAR. Those parameters are the vehicle-specific and the infrastructure-specific parameters that are relevant for determining suitable TLARs (speed, costs, runway length etc.).

$$WTP = Cost_m + (T_m - T_{SAT}) \times VTTS \tag{1}$$

$WTP =$ Willingness to pay
$Cost_m =$ Cost for a trip with a personal vehicle, by train or by conventional flights
$T_m =$ Time for a trip with a personal vehicle, by train or by conventional flights
$T_{SAT} =$ Time for a trip with a SAT vehicle
$VTTS =$ Value of Travel Time Savings [Monetary value for a minute´s time savings]

2.2. TLAR Derivation

With the demand model established, the main figure of merit as well as the baseline input parameters need to be determined before the TLAR could be derived. The annual demand is selected as the figure of merit because it determines if the aircraft succeeds on the market.

The following baseline values are assumed for the demand model input parameters: Cost, for the base value the above described average cost of 0.30 € for driving a kilometer with a car in Germany is used. The lower bound of the range is set to 150 km because for any distance below that, the assumptions is made that other modes of transport are more desirable. However, for the upper bound the limit is reduced to 1500 km from the initial 2,222 km limit because early runs of the demand model showed a negligible small demand above 1500 km. A resulting advantage is the deceased complexity of the model. The number of passengers is set to nine because a nine passenger configuration allows for single pilot operations according to the FAA [12]. Although the evaluated market is the European one, setting the seat number to nine considers the possibility to also operate the aircraft with less crew cost in North America. Setting the cruise speed to 350 km/h ensures that the aircraft can be propeller-driven. Moreover, considering the ICAO Annex 14 Aerodrome categorizations [13], the decision is made to meet Category 3 runway requirements. Category 3 airports must have a runway length of 1200 m to 1800 m. Hence, the baseline value is set to 1200 m, ensuring all Category 3 airports can be serviced.

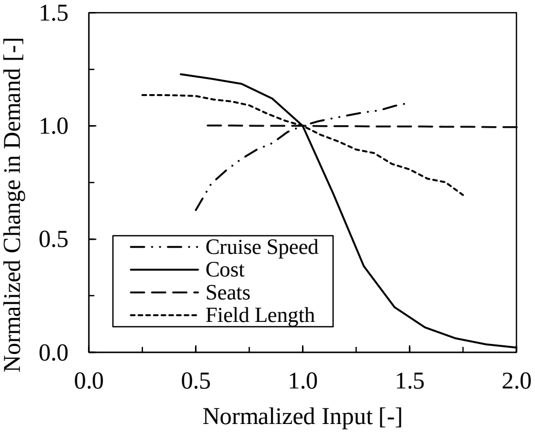

Figure 1. Sensitivity analysis show the normalized change in demand depended on the normalized input variables for the baseline iteration.

Setting a baseline value allows it to illustrate the improvement of each iteration, while simultaneously providing a starting point for the TLAR derivation process. The process's target is to determine the optimum input parameter value. Thus, making the optimization process part of the TLAR derivation. The following steps are executed for each iteration:

(1) Running the demand model with the determined input parameters. For the first iteration, the baseline values are assumed.

(2) Identifying the most promising demand model input parameter to improve the annual demand. This is done by using the sensitivity analysis with normalized input and output. An exemplary sensitivity analysis can be found in Figure 1.

(3) Plotting the identified parameter with absolute values and subsequently optimizing the demand with it. The arguments of the input parameter are made within the bounds of the technologies' feasibility, assuming an entry into service in 2030.
(4) Feeding the newly determined input parameter back into the demand model.

Steps one through four are repeated until each parameter has been adjusted once. For requirements that are not derived from the demand model litterateur and studies are used. The requirements and their reasoning can be found in the section Data and Results.

3. Data and Results

Following the methodical approach described above, the resulting TLAR will be presented below. The separation is made between the requirements derived from the demand model and the requirements that are based on literature and studies. Furthermore, all TLAR derived in this paper can be found in Table 1.

3.1. Demand Model Based TLAR

For a better understanding of the process to determine the demand models input parameters, the first iteration is examined as an example. Figure 1 illustrates the normalized sensitivities for the baseline analysis, thereby showing which variable is best suited for an adjustment within the first step. In the case of the exemplary first iteration, the seat-km-cost variable is selected because it offers an increase in demand by 18.6 % when lowering the seat-km-cost by 10 cent to 0.25 €. The increase of 18.6 % equals to 99.07 million more annual passengers, resulting in 633.19 million total annual passengers.

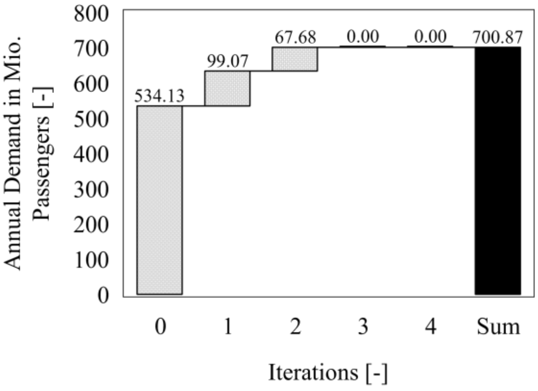

Figure 2. Annual demand gain per iteration when adjusting the demand models input parameters.

The gains per iteration are shown in Figure 2, with Iteration 0 representing the baseline assumptions and Iteration 1 the cost adjustment. For Iteration 2 the field length is adjusted to 800 m, resulting in an increase of 67.78 million annual passengers to 700.87 million. Adjusting the take-off distance to 800 m considers the ICAO airport categorization, thereby enabling the aircraft to land in all ICAO Category 2 airports, under Category 2 the runway length of the airport varies between 800 m and 1200 m. For iterations 3 and 4 no adjustments are made. This is due to the resulting sensitivity analysis for Iteration 3, which shows that only an improvement could be made by increasing the cruise speed. Due to the resulting drag penalty an increase in cruise speed would cause, the choice is made to remain with a speed of 350 km/h. For the reaming input parameter, the number of passengers, the demand model shows no effect on the annual demand. Hence, the number of passengers is kept at the baseline value of nine.

With the input parameters defined, the demand model output is evaluated in detail to derive further requirements. The demand distribution can be seen in Figure 3. The highest SAT demand exists on routes between 200 km and 300 km, with an annual demand of 247 million passengers. Also, on distances between 300 km and 400 km the SAT demand is significant with 124 million passengers per year. However, on greater distances the number of passengers continuously declines from 63 million passengers on distances between 400 km and 500 km to

5 million passengers between 800 km and 900 km. Thus, on such long distances, the number of people — and therefore the SAT shift potential — who travel with a personal vehicle or by train is minimal. Additionally, the provided time savings of a SAT vehicle compared to indirect flights with conventional aircraft decreases. Based on the illustrated trip distribution, the design mission distance as well as the required maximum range can be deduced. For the maximum range, the target is set to cover 95 % of the demand, which is achieved at 525 km. Contrary to the maximum range, the design mission range aims at optimizing the aircraft for a design point. As Figure 3 indicates, the maximum demand occurs between 200 km and 300 km. Thus, the design mission distance is set to 225 km.

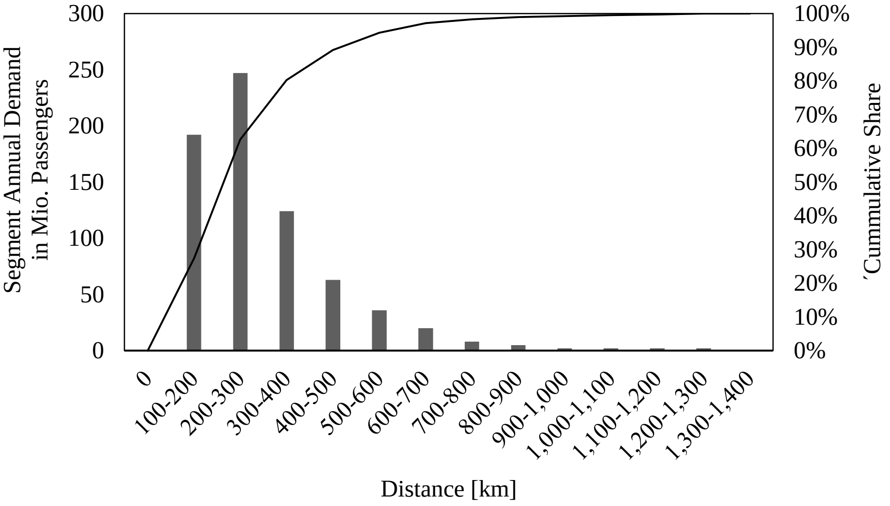

Figure 3. Demand distribution for each segment of the demand models analysis and cumulative share.

3.2. *Additional TLAR*

With the demand model defining most mission related requirements, the missing ones are the max cruise altitude and the max payload. Although the aircraft is to be certified under the CS-23 regulations, the assumption is made that if the cruise altitude exceeded 25,000 ft the EASA would require a second live support system as defined in the CS-25 category [14]. Hence, the maximum cruise altitude is set to 25,000 ft. Using the above defined seat number, the payload is determined. This is done by multiplying the total sum of average passenger weight and average luggage weight which equals to 106 kg/PAX [15] with the sum of the passenger number and two pilots. Regardless of the targeted one-pilot operation of the aircraft, the cockpit needs to seat two people for training purposes.

Since the requirements aim at meeting a marked that provides schedule operations, further requirements can be derived. The turnaround time should not exceed 45 min. Furthermore, the aircraft is required to be designed for one-pilot-operation, to decrease crew cost and thereby lower the operating cost.

As explained in the introduction, the environmental impact of aviation is substantial. Hence, the next generation of SAT aircraft need to ensure that they have as little impact on the environment as possible. This is achieved by using the environmental goals of the European's Flightpath 2050 and apply them as requirements for this aircraft. Since the aircraft is targeting an entry into service for the year 2030, the goals are 20 years ahead of Europe's timeline. Thus, the requirements are a 75 % reduction in CO_2, a 90 % reduction in NO_X and a 60 % reduction in noise compared to the levels of 2000 [16]. Additionally, the aircraft should taxi on the ground without producing emissions of any kind.

Table 1. TLAR overview of the different requirements and their corresponding values.

Requirement	Value
DOC per PAX	0.25 € / km (0.67 US$/nm)
Field length	<800 m (2600 ft)
Cruise Speed	>350 km/h (190 kt)
Capacity (fix value)	9 + 2
Max Range	>525 km (285 nm)
Design Range	>225 km (120 nm)
Max Altitude	<25,000 ft
Max. Payload	1166 kg (2570 lb)
Weather Conditions	All conditions
Turnaround time	<45 min
One Pilot Capable	Yes
CO2	>75% Reduction*
NOx	>90% Reduction*
Noise	>60 % Reduction*
Taxing	Zero emission taxiing

* Compared to levels from 2000 [16]

4. Discussion

The previously derived TLAR clearly show that an aircraft meeting those requirements would result in a substantial amount of demand. Evaluating the results of the demand model of Paparoth [17] further underlines this statement. Although the demand estimation of Paparoth focuses solely on the country of Germany, a comparison of the two models can partially validate the results. Both models estimate that with a range of above 400 km over 85 % of the demand for SAT vehicles is covered. Furthermore, the TLAR presented in the previous section are of the same magnitude as the ones resulting from Paparoth's model. An additional comparison to the mobility analysis of Moore and Goodrich [18] presents the same picture for the trip distribution on the North American continent, underlining the decision to also consider FAA regulations.

When putting the demand model based TLAR into an engineering context, the significance of the TLAR results become evident. The reason for this is that the TLAR are right on the edge of what is assumed by Bill at el. [19] to be feasible for battery electric flight. Hence, it could be argued that there is a business case to develop a SAT vehicle for the European market.

However, the European demand model is based on ideal world assumptions, which distorts the real demand. Those assumptions can be split into two categories. In the first category, assumptions that overestimate the demand can be found. The model, for example, does not consider that airports could be restricted due to other air traffic. Moreover, for the calculations of the demand, the influence of the weather on the operability is neglected. This leads to an overestimation of the demand because most small airport do not have the technical capability to allow low visibility operations. Also, a 100 % reliability is assumed, further overestimating the demand. On the contrary, in the second category, assumptions can be found that underestimate the demand. The following assumptions fit into the second category. The initial filtering of the airports will eliminate airports that could offer profitable connections. Additionally, only people are considered that would travel in any case. This underestimates the demand because it neglects people that could not make the trip with the existing transport modes.

Considering the ideal world assumption, it can be argued that instead of focusing on the low budget high-volume segment, chances of success would increase when focusing on the higher price segment first. This allows to learn more about the aircraft and the future technologies that are required to enable climate friendly aviation. Furthermore, the high price segment will then lay the basis to create an aircraft meeting the described TLAR.

5. Conclusion

The developed demand model uses data from existing traffic patterns of road, rail and air between NUTS 3 regions in Europe as a basis. By applying a modular choice based on a WTP function that considers time gained when using the SAT vehicle, the model estimates the number of people that would use a SAT vehicle instead of other transport modes. Using the described European demand model, the TLAR are derived by an iterative adjustment of the demand model's input parameters. Additionally, to the iterative adjustment regulatory aspects are considered such as ICAO airport categories. The resulting demand in Europe for a SAT vehicle with a capacity of nine passengers and a range that exceeds 400 km is above 700 million annual passengers. Those derived TLAR show the potential of a SAT vehicle in Europe and at the same time provide specifies requirements for future aircraft development.

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