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Summary of contributions / Ph.D.theses

Non-Linear Prediction Model for the European Small Aircraft Accessibility for 2020

by

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1. Introduction (actuality, general approaches, goal)

Mobility studies showed that between 1966 and 2006, each percent of Gross Domestic Product (GDP) growth resulted from one to two percent of motorized passenger traffic increase [1, 2]. Among other transportation systems in 2006, the further GDP development is projected to double the air traffic volume by 2020 [3, 4]. Even so, the air transportation is already reaching its limits of capacity (in numerous domains such as safety, security, environmental and airport considerations), thus it might not be able to cope with the predicted growth. Potential solutions to this problem include the demand capacity balancing that could ensure the expansion and improvement of the air transportation system by introducing new air vehicles or Small Aircraft (SA) [R6, R10] that use underutilized infrastructures such as small or regional airports. This is also reasonable, knowing that (i) the alternative transportation modes for example the high speed trains operate only along established high population corridors [5, R4], and (ii) the new EU member states lack of transportation infrastructures [R4, 6]. From our definition this class of small aircraft carries up to 6 or 8 passengers and applies all single or multi- piston, turboprop and jet propulsion systems, since the available related works in 2007 cannot clarify which of them is more appropriate for the European market. In 2007, there are approximately 300 000 [7, R7, R11] private pilots in Europe that use more then 60 000 SA [7, R11, R9]. On the other hand – similarly to the philosophy of the Small Aircraft Transportation System (SATS) [8], the Personal Air Transportation System (PATS) [2, 6], the UK JETPOD [9] and other relevant concepts – the emerging technologies might even allow such air transportation system to become personal-based [R10] that could maximize the satisfaction of market requirements with on-demand, point-to-point and more flexible operation [R10]. Using simplified cockpit environment [R6, 10, 11] with highway-in-the-sky [12, 13, 14], synthetic vision technologies [10], automatic take-off / landing vehicle control [2, 5, 6] and other instruments [R6, 15, 16] small aircraft could also be designed to be accessible to common / ordinary people that enable even a pilot with limited experience to fly, similarly to the difficulty of driving an automobile [R10, 2, 5, 6]. In short, as the affordability or the accessibility of that class of aircraft might change, the European SA activity has to be analyzed, for example to identify what the impact of small aircraft on the Air Traffic Management / Air Traffic Control (ATM / ATC) is. Seeing that the investigations in this domain are limited and therefore the available data is inadequate to accomplish such analyze, the goal of this thesis is to provide a European small aircraft prediction model that could establish the background for further investigations related to SA.

In 2006, several small aircraft forecasts are available from different representatives of the aerospace industry, such as Embraer [17], FAA [18], Forecast International [19], Honeywell [20], NASA [21], Rolls-Royce [22], and the Teal Group [23]. Since SA is a novel air transportation that offers limited historical data, these investigations use different assumptions and methodologies to define the possible operations that covers owner-pilot, fractional ownership and air taxi services. However, their drawback is that the methodologies are not publicly available. Additionally, all focus on the American market and on the Very Light Jets, which might be powerless in considering the European socioeconomic characteristics and regarding the fact that other propulsion systems might be applied. Therefore, this investigation also discovered those prediction / demand models which are applied generally in air transportation. With respect to the demand models, their functional form might be classified into the followings [24, R5]: the linear and log-linear demand modes, logit model and translog demand system. The first, the linear has been extensively used for demand and sales forecasting, since – compared to others – it is relatively easy to estimate and advantageous in interpreting the empirical results. However, the assumed linear effect of the model parameters on the dependent variable might not realistic in the context of the non-linear small aircraft development.

The log-linear (or double-logarithmic or Cobb-Douglas [25]) model specifies the logarithm of the traffic volume as a linear function of the logarithms of the potential independent variables. Due to its advantage in estimating the respective elasticities, this is found to be the most popular functional form. Nevertheless, the main drawback of this model is that each elasticity is invariant across all data points, which is powerless in considering novel transportation means (such as small aircraft), where the responsiveness of the quantity demanded to a change in one independent variable, might be non-linear.

Other functional form for modeling the demand considers the market shares of alternative transport modes. This, called logit model [26, 27], extends the log-linear form to allow a mixture of categorical and common independent variables and to estimate one or more categorical dependent variables. The major advantage of the logit model is that the two alternative case yield the logistic curve, which being an S-curve is intuitively attractive and realistically describe the mode switching behavior of decision makers.

The translog demand model [24, R5] is derived from a flexible utility or production function that provides a quadratic approximation to the unknown true function. While this method is widely applied to the cost functions of transport industries [24, 28, 29], its primary disadvantages for the small aircraft application include (i) the complexity in evaluating the coefficients, and (ii) the statistical concerns with over parametrization due to the presence of numerous interaction terms involving the explanatory cost factors.

As for the prediction methods, first the regression and trend analysis is discovered [R5, 30]. These use past data to establish the historical trends, and project future values of the dependent variables. While these are frequently used methods that cover both linear and non-linear functional forms, their major constraint with respect to the European SA is the need of using historical data. Additionally, according to NASA [5], these predictions are only of value as general trends, since performing extrapolations when new factors (e.g. simplified cockpit environment) might dramatically change the market might not provide reasonable results.

The exponential smoothing is based on time series analysis of observations in which the most weight is given to the latest observation, while decreasing importance is attributed to earlier observations [R5, 30]. Since this might better capture the most recent characteristics of small aircraft, the exponential smoothing might provide more appropriate results than regression, although the projections still require past records.

Another prediction method is the comparison, within the analyst contrasts the objective of the research with other relevant activities having similar characteristics [30]. One particular use of this technique is in projecting the SA development after the growth of early general aviation activity or even early jet age business jets / VLJ. However comparison might be applicable to the requirements of this investigation, it would be more than difficult – if not impossible – to bring into play the specific values of SA (e.g. pilot requirements).

On the other hand, the survey techniques [R5] might directly deal with the potential aircraft users, and therefore reflect the characteristics of the passengers (e.g. the importance of the total operating cost, the role of the cockpit requirements, average annual flight hours). Moreover several surveys could be done for different geographical areas across Europe, which could take into account the differences between socioeconomic characteristics and country specific attributes such as the presence of alternative transportation systems.

Finally, an alternative to the simple point predictions – within the demand is projected with a single number best estimate – is an interval or range forecast. Unlike others, this technique addresses the uncertainty behind the evolution of the dependent variable by defining numerous alternative scenarios on the future development of the independent variables. While this technique is advantageous in considering extraordinary events (e.g. oil crisis) its application to support further risk analysis and decision making is limited.

As a result, the application of the above introduced generally applied demand / prediction methods to the context of SA is not reasonable, as (i) they require adequate statistical data on the European SA activity (which is limited and cannot consider the parameters without past records), or (ii) provides a linear structure with constant elasticities that is powerless in reflecting the non-linear attribute of the small aircraft growth.

2. Small aircraft traffic analysis

Due to the lack of the European SA records, this investigation carried out a small aircraft air traffic analysis to support the development of the prediction model with arguments on the European characteristics. The analysis is based on the EUROCONTROL's CFMU [31] database in nearly a one year period over 2004. According to the results, the average number of flights is 1429. The distribution of these is relatively high, or at least when compared to commercial flights. Otherwise with 59 %, piston small aircraft are in majority, and most of the flights take place at for short flights (150 km) and at low altitudes (FL100). With respect to the rest of the airspace users, this traffic might pose problems at low altitude airspaces with high aircraft density, such as the airport surroundings. From a small aircraft point of view, airport surrounding means the areas with commercial flights lower than the FL 190, which is found to be an optimal limit between the small aircraft and commercial flight where both influence the other in a minimal way. Depending on aircraft performance and airports (Standard Instrumental Departures (SIDs) and Standard Terminal Arrival Routes (STARS), this means a radius of 130 km around the airports. As the representation of these areas on a European scales cover a relatively large geographical area, this suggested to capture the potential relationship of small aircraft and commercial flights.

3. Initial prediction model

As discussed, the simple application or adaptation of the generally used models to the European small aircraft context is not promising, due to numerous limitations and drawbacks. Therefore, to obtain a valuable model, which replies to the specific requirements of the European SA, the results of the air traffic analysis are employed. Using its arguments on the most preferred propulsion technology, number of flights, cruising altitude and other characteristics, it clarified several attributes and variables [R3, R7, R9, R11] that could be considered for the prediction model. The proposed initial prediction model consists of four pars [R3, R7]. First of all, the market attributes, containing the factors that define the demand of air transportation [R3, R9]. As preliminary data analysis shows [R4, 32, 33] these factors could be the GDP, SA cost, population density and other socioeconomic data [R4]. Even so, to obtain a valuable model that meets the specific tasks of small aircraft prediction, the input data – that is called here market attributes – is considered to consist of the GDP (as the main factor to determinate the mobility) and other variables that are indispensable in the special context of small aircraft. To reflect these elements, the technological development and the regulation level is taken into account. The technological development , because it might shift the SA accessibility; firstly in terms of costs via the total operating costs decrease with more reliable materials (e.g. MEMS [34], nanotechnologies [35]), and secondly in terms of aircraft maneuverability with advanced cockpit instrumentations (e.g. easy-to-follow 4 D guidance

[12], synthetic vision technologies [10]). As for the regulation, it was brought into play to capture the positive or negative influence of the SA development on the environment (e.g. noise restrictions). Following the economical theories [32, 33] in the initial prediction model, the market attributes drive the small aircraft and the traditional traffic group. To characterize these parts of the model, this investigation considered two major elements; the number of aircraft and the cost, since from a small aircraft point of view both might influence the future characteristics of the European traffic. Otherwise, a supplementary element, called flexibility of market requirements is also a part of the SA group [R3, R11], which – due to the lack of relevant data – aims to capture the uncertainty in the flexibility of the market to the small aircraft cost variance, regardless to any GDP growth or technological development. The final group of the model is called interaction on ATM [R3, R11]. The objective of the presence of that part is to enable the analysis of the impact of small aircraft on ATM. Additionally, it also permits to consider, whether the characteristics of the ATM (for example the costs of automation) is in relationship with the SA demand. Therefore, this group is made up of some of the domains and potential problems in the Air Traffic Management areas from a SA point of view, such as the airspace management (ASM), the level of cockpit instrumentation (avionics), the separation responsibility and the level of automation. The choice of these elements is based on the outcome of the small aircraft air traffic [R4, R7] and future perspectives in ATM analysis [R4]. For example, as initial investigations in air traffic analysis showed, the difficulty of small aircraft flights at airport surroundings might require an adapted ASM, which therefore is a part of the model. Following this logic, avionics defines the cockpit instruments and navigation tools (such as TCAS, GPS or ADS-B [15, 16]). Separation responsibility represents its importance, without taking into consideration whether pilots or controllers should deal with it. Similarly, the domain of automation means more a significance, without underlining that it might range from automation of controllers' routine tasks to autonomous operation with advanced airborne system application (such as Airborne Separation Assurance Systems) and even free flight [R4, R7].

Mathematically, the initial prediction model could be based on the following non-linear differential equation such as follows:

$$\dot{\mathbf{x}} = \mathbf{f}_x(\mathbf{x}, \mathbf{u}, t) \tag{1}$$

where the vector **x** represents the dependent variables, **u** the input vector, and *t* the time:

$$\mathbf{x} = [SAneed\ \ SAmark\_req\ \ SA\cos t\ \ Tneed\ \ T\cos t\ \ avionics\ \ ASM\ \ sep\_resp\ \ \text{automation}\ ]^T,$$
$$\mathbf{u} = [GDP\ \ regulation\ \ techn\_developmen\ ]^T.$$

Since the equation (1) is a non-linear differential equation, with its linearization, and discretization using *T* discretization time where $t=k*T$ and $k \in N$, the prediction model takes the following form:

$$\mathbf{x}[k+1] = \mathbf{A}\mathbf{x}[k] + \mathbf{B}\mathbf{u}[k] \tag{2}$$

where the matrix **A** defines the internal dynamics of the system, **B** stands for the outer (control) influence, and k is the simulation time.

Using several scenarios (for the independent variables) and numerous potential matrix coefficients, the evidence for the model applicability was found [R3, R5, R7, R11]. It reacted to the evolution of the independent variables, and responded to the shift of regulation level. The major advantage of this model lies in the potentialities of using independent variables with a predefined role and weight in their influence on the small aircraft development. Using the matrix A, the model could assist to analyze the internal dynamics of the underlying mechanism, such as the effect of regulation or technological achievements on the small aircraft development. This enables further investigations, even with different aircraft characteristics, and the capability to find the right balance between initial conditions and potential solutions. However, to provide a reasonable prediction, numerous drawbacks were discovered [R3, R5, R9]. First of all, due to the limited data on the European small aircraft activity, the determination of the matrix coefficients was inadequate. Additionally, the assumed relationship between the independent variables might not always hold in the reality, therefore the approach was rejected.

4. Research approach

Due to the limitations of the generally used demand models applied in air transportations, in this paper, an analogical approach has been used: the prediction of accessibility of personal cars. To carry this investigation out, one potential technique instead of a linear or log-linear approach, is some sort of an S-curve [36], which provides detailed information on the adoption of a new technology [36], due to the division of the market into several segments. Investigations showed that it could also be applied to determinate car ownerships, since on the long-run, good could also mean transportation systems. Additionally, its advantage is that provides non-linear elasticities, since it is a non-linear approach. Other advanced technique is the idea of the Traveling Money Budgets (TMB), first observed by Zahavi [37], as a fix proportion of income devoted for traveling. It has been clarified [37] that it rises with the GDP or income growth, therefore knowing the unit total operating cost of traveling by personal cars and using GDP, we can estimate the budgetary constraints of the population, associated to traveling. However, for SA purposes a more advanced approach lies in the idea of having instead of one TMB for the whole population, several curves, associated to different social classes. This is also more realistic, since the population ratio with higher income is less sensitive to GDP increase or to small aircraft cost decrease, however they only represent a small proportion of the population. Since generally the population is also price sensitive, finally form our analogical approach, the SA accessibility is determined by the budgetary constraints (or the TMB) and the small aircraft unit total operating cost evolution, that is also in line with basic economic theories of the demand.

5. The proposed prediction model

In the proposed prediction model an analogical approach is proposed, therefore it is assumed that SA becomes accessible, once its TOC meets the travelling budget, estimated from the TOC of personal cars, from different market segments.

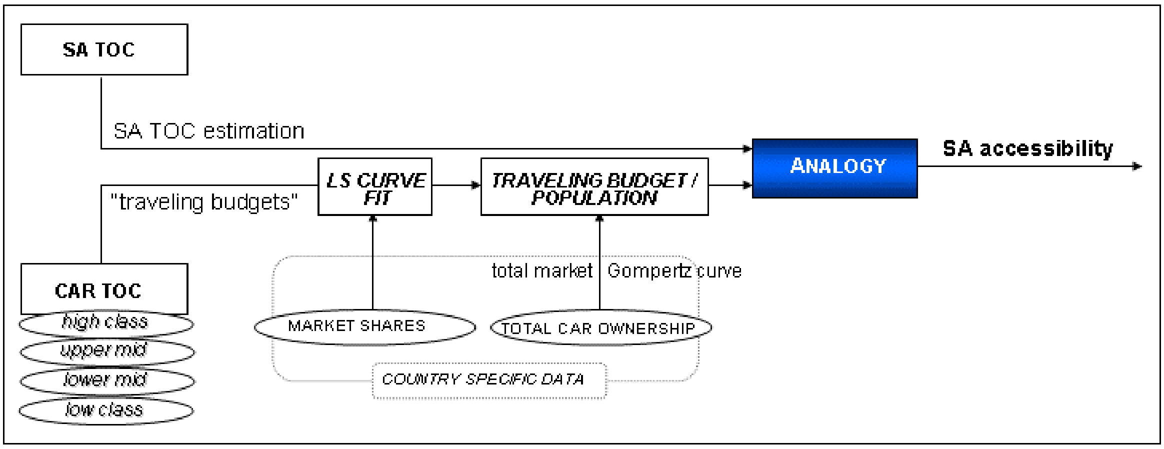

Fig. 1. The scheme of the proposed non-linear prediction model.

As the Figure 1. indicates, the model first estimates the TOC of both SA and cars. Following the economic theories [38] and the investigations in transportation domains [39], the total operating cost is the sum of all direct and indirect costs. In case of small aircraft this results in:

$$TOC_t^{SA} = u_{1_t} + u_{2_t} + u_{3_t} + \ldots + u_{n_t} \tag{3}$$

where TOC_{it}^{SA} is the total operating cost, and u_{nr} are the independent variables at the simulation time t.

On the other hand, due to several market segments, the total operating cost of cars is rather characterized such as:

$$TOC_{i_t}^{car} = v_{1_t}^i + v_{2_t}^i + v_{3_t}^i + \ldots + v_{m_t}^i \tag{4}$$

where $TOC_{st}^{\;car}$ is the total operating cost, and $v_{mr}^{\;i}$ are the independent variables for the market segment i, and the simulation time t.

Following to the practice in automobile industry [40, 41], the car market segments are classified into the following groups: low class, lower-mid class, upper-mid class and high class. Due to these four segments, while considering representative cars for each class and knowing their market shares [40], this technique allows representing the unit total operating costs in function of the market shares. According to our investigations, a curve that can fit on these points (TOC-market shares) should have the following (non-linear) power growth form:

$$M_{i_t} = a_t * TOC_{i_t} \,\hat{}\, b_t \tag{5}$$

where at the simulation time t, M_{it} represents the market share, TOC_{it} stands for the total operating cost (or the travelling budget constraint) for the market segment i, and a_t , b_t are the unknown coefficients of the equation. To estimate them the least squares method is applied [42] due to its advantage in analyzing the precision of the adjusted data.

Using the equations (3) and (4) and knowing the car market shares [40], the model estimates the parameters (a_t, b_t) of the power growth function to express the budget constraints in function of the market shares. To convert this curve to a function that associates the budget constraints to the population, rather then the overall car market, the model estimates the total car ownership per population ratio. After experimenting with a number of different models for this task, an S-curve is used based on the model proposed by Dargay [43]. The primary justification of using this work lies in the benefit of country specific prediction, which enables to take into consideration the specific characteristics of the European context. For that reason, the total car ownership is given by:

$$V_t = \gamma * \exp[\alpha * \exp(\beta * GDP_t)] \tag{6}$$

where V_t represents the vehicle ownership per population ratio, GDP_t stands for the GDP per capita, and α, β, γ are the Gompertz curve coefficients.

Finally, using the analogical approach, the small aircraft accessibility – or affordability in terms of costs – is determined as:

$$SA_t = [a_t * TOC_t^{SA} \wedge b_t] * [\gamma * \exp(\alpha * \exp(\beta * GDP_t))] \tag{7}$$

which at each t represents the small aircraft accessibility (SA_t) in function of the parameters of the power growth function (a_t, b_t), the coefficients of the Gompertz curve (α, β, γ), the total operating cost of SA (TOC_i^{SA}), and finally the GDP per capita (GDP_t).

6. Monte Carlo Simulation

To estimate the base TOC (or the TOC at the beginning of the simulation horizon) of both SA and cars of different market segments, the mean value of several relevant SA and cars have been used, as in 2006. However to carry out future estimations, uncertainty was faced due to the unclear evolution of the cost elements. Therefore, a Monte Carlo Simulation (MCS) is used, as it is a probabilistic approach that can quantitatively address uncertainties present in the system, unlike predictions based on scenarios or point estimates.

To deal with uncertainties in this investigation, several distributions are applied for the MCS. First of all a uniform is used, where the probabilities of all potential values of the particular variables are equal. Generally, these are the ones associated to SA since in Europe, no reliable data is available to estimate other probability distribution. Otherwise, the upper and lower limits of these distributions are obtained following the operational possibilities. For example small aircraft might be a professionally or a personally operated easy to fly small aircraft [2, 6], which might not require advanced pilot skills, or to have a PPL (private pilot license). This operational possibility comes from the related works; firstly from the PATS project [2, 6] that aims to reach this objective via aircraft automation and control theory, and secondly from the Small Aircraft Transportation System [8] that facilitates the pilot tasks with enhanced cockpit environment and advanced operational concepts such as the High Volume Operation [44] at small airports. In the same time, these flights could happen in controlled airspaces, or in FIRs (Flight Information Regions) under VFR (Visual Flight Rules), which according to EUROCONTROL [45] could make the en-route costs irrelevant. As for the airport charges, SA would have the choice to use major airports (to take the benefits of better connectivity) or utilize small airports to bring into play lower costs. Additionally, SA could be defined to follow the past evolution of maintenance and ownership costs, or to be closer to the level of luxury cars. This last assumption is reasonable, since both the SATS [8] and SkyCar [46] projects, showed the evidence for the cost decrease possibilities with the use of more reliable materials and the newest technological achievements (e.g. MEMS [34], nanotechnology [35]) in numerous domains, for example in aerodynamic or propulsion system design. With respect to the SA fuel consumption, car ownership, car fuel consumption, car maintenance and car other costs point estimates are available in the literature [41]. Therefore, to scatter the potential values in proximity of the available data, a normal distribution is used, with confidence intervals computed by adding and subtracting the past standard error units around the line of the point estimate. Finally, to deal with the fuel price, and the GDP per capita evolution, a triangular distribution is applied following the practice [47] when all minimal, maximal and a most likely future evolution values are known.

7. Sensitivity analysis

Seeing as the uncertainty of the input parameters might imposes a limit to the confidence related to the output (especially for further decision making and risk analysis), this paper also demonstrates the relevance of the model via a sensitivity analysis. There are several possible procedures to perform sensitivity analysis [48]. Among others (e.g. analytical, computer algebra based), this investigation selected the most common, the Monte Carlo sampling-based method due to its ability to incorporate the probability density functions of the independent variables [48]. To visualize the *N* values of the inputs Z_i against the output *Y*, scatterplots are used, because of their advantage when the parameter relationships are supposed to be non-linear. Once plotted on a common scale for *Y*, these enable to visualize the sensitiveness of the parameters. For example, if the variables are related, then the data points should form a straight line or a curve. On the other hand, figures representing rather a uniform cloud of points over the range of the input parameter, is the evidence that the factor is less – or not – influential [R8].

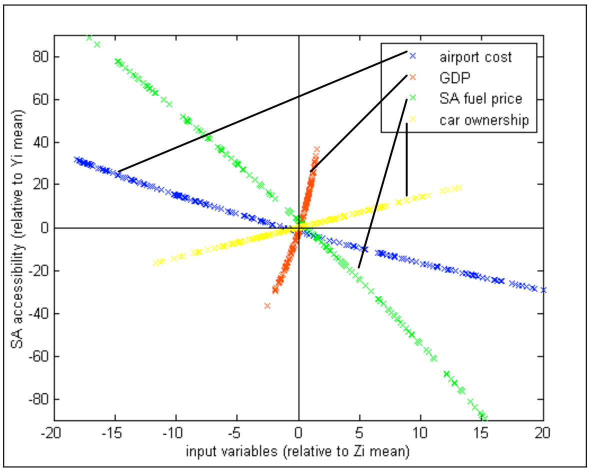

Fig. 2. The sensitivity analysis of the small aircraft accessibility (note: Z_i are the input variables and *Y* stands for the accessibility).

In this investigation, as the extensive treatment of the sensitivity analysis for all parameters is considered complex, only a limited example of the whole investigation is given. Using the input variables Z_i as the airport cost, GDP, fuel price and car ownership cost (to represent the traveling budget constraint) the model response to the sensitivity analysis is given in the Figure 2. This shows that on average the relationships between the *Y* and Z_i are straight lines or non-linear curves, which represents the evidence of the non-linear relationship between certain *Y* and *Z* (e.g. the GDP). Otherwise, the signs of the connections are also reasonable, since as expected, the SA accessibility rises with GDP and car ownership growth, while it falls off by the increasing cost of the airport charges and fuel price. As the slope of the lines indicates, it is clear that *Y* is more sensitive to the GDP, and less responsive to the car ownership. Additionally, since none of the input variables form a uniform cloud of points, we found the evidence that all variables should retained in the model, and none of them can be safely ignored in the analysis. Due to these characteristics, the sensitivity analysis finally shows the evidence for the relevance of the model.

8. Major results

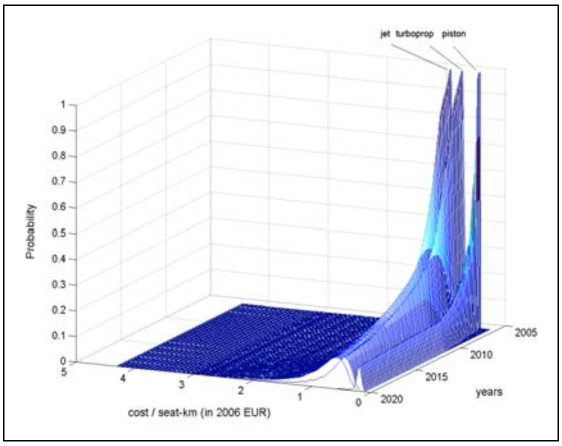

Fig. 3. The probabilistic evolution of the unit total operating cost of small aircraft.

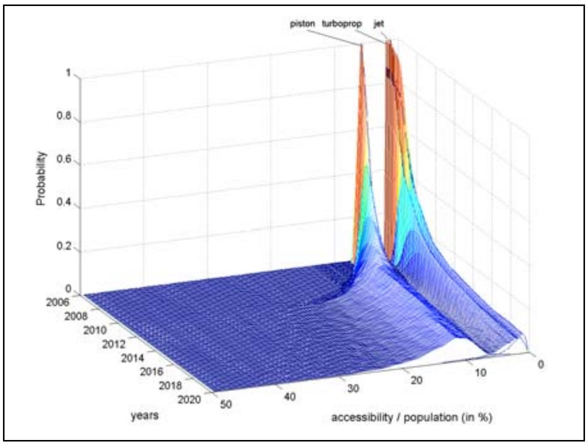

Fig 3. The probabilistic evolution of small aircraft accessibility.

Due to the Monte Carlo Simulation, the results of the proposed prediction model are given with probability distributions [R1, R2, R12]. The Figure 3. represents the major outcomes; the unit total operating cost and the accessibility evolutions. With respect to the first, I calculated that in 2020 the most probable results belong to 0.2, 0.45 and 0.59 EUR / seat-km respectively for the piston, turboprops and the jets. Compared to the 2006 values the figure indicates the all unit total operating costs are decreased over the simulation horizon. While the distribution of the outcomes in the vicinity of the above listed values is in balance for the pistons, turboprops and jets show a probability of 0.65 and 0.63 respectively, to receive higher unit total operating costs. Additionally, these two aircraft indicate 43 % and 42 % of chance that the TOC in 2020 remains the same or even gets higher than it is in 2006. As for the accessibilities, the simulation gives the most probable values of 11.7, 2.35 and 1.8 % respectively for the pistons, turboprops and jets. This means for example that in 2020 for 11.7 % of the population piston small aircraft become accessible or affordable in terms of costs, which represents 94.5 % of relative growth to its 2006 value. Otherwise, while higher accessibilities are also possible (for example more the 25 % of the population) this happens with relatively low probabilities (0.029) and only with respect to the pistons.

9. Summary of contributions / theses

1. I discovered that the European small aircraft activity is driven by the country specific (socioeconomic and transportation) characteristics (e.g. the GDP, the budget spent on travelling) and the factors influencing the total operating cost of SA, like the technological developments in aircraft industry (e.g. the advanced aerodynamic design, novel / alternative propulsion systems, simplified cockpit environment, autonomous aircraft operation) [R2, R6].

    1.1 The investigation demonstrates [R6, R9, R10] that unlike between 1950 and 1995 when the technological developments in the small aircraft industry were limited and therefore considered as irrelevant factors to estimate the demand, in 2006 such developments are leading to a relatively inexpensive small aircraft – similarly to the Small Aircraft Transportation System, the UK Jetpod, or the SkyCar – and become a driving factor of the European SA activity.

1.2 I found the evidences [R6, R10] for the fact that using the technological achievements in automation [6], cockpit developments (e.g. weather information, synthetic vision systems) and the first operation concepts (e.g. High Volume Operations), small aircraft pilots could meet an operational environment that is closer to the level of personal automobiles, and therefore it require less skills.

1.3 The analysis showed that the small aircraft activity is also a factor of the budget constraint, as a fix proportion of income devoted for traveling [R1, R2, R8, R12].

1.4 This investigation revealed [R4] that the driving factors of the European small aircraft activity are different from those in the United States, since Europe (i) has a higher population density, (ii) a high speed train network, (iii) consist of numerous countries with different transportation characteristics / socioeconomic data, and (iv) at the same level of GDP its population travels about three times less than the North-Americans.

2. I found that the enlargement of European small aircraft traffic could cause conflict situations with the conventional air traffic at the vicinities of the major European airports [R3, R7, R9, R11] .

2.1 Using the FAA weight category for small aircraft and the real flight data from CFMU, I estimated the characteristics – such as the number of flights a day, the flight distance, the flight altitude, the propulsion technology distribution – and the most frequently used geographical areas of the European small aircraft traffic [R3, R7, R9, R11].

2.2 As a criteria for the safety of air navigation, I defined the Flight Level, where both small aircraft and conventional air traffic has a minimal impact on the other [R3].

2.3 Applying the safety criteria within both small aircraft and conventional flights had a minimal influence on each other, I assessed the potential region of conflicts due to airspace use, which found to be the range of 130 km at the airport surroundings [R3, R9].

3. I discovered that the conventional demand / prediction models are powerless to be employed for projecting the European small aircraft development [R5].

3.1 I found that [R3] the available US small aircraft demand models are irrelevant with respect to the European context, since Europe – unlike the US – (i) covers numerous countries with different socioeconomic characteristics and transportation habits, (ii) offers a high speed train network that might become an alternative to SA, and (iii) has specific geographical conditions with smaller distances between the major cities that might result in the application of different propulsion systems

3.2 I demonstrated [R5] that it is not resonable to apply the conventional demand / prediction models of the air transportation (e.g. log-linear) to the European small aircraft, since these methods require the past data on the activity to predict, which in case of the European SA is limited – if not non-existent – while the available information is insufficient to capture the relevant small aircraft driving factors (e.g. the required pilot skills, the value of simplified cockpit environment, or the shift in the total operating cost).

3.3 I revealed [R5] that the potential application of the linear methods (or those that provide linear elasticities) are limited in the context of the European small aircraft, as these could not reflect the non-linear market adoption phases and the dissimilarities in the price and income sensitiveness of the different social classes.

4. Following the analysis of the small aircraft stochastic adoption process, I introduced a Markov diffusion model, which – after statistical linearization – resulted in an initial prediction model [R3, R5, R7, R11].
   - 4.1 Following the progress of the small aircraft activity, I determinate the independent variables of the initial SA prediction model [R3, R5].
   - 4.2 I demonstrated that the initial prediction model might be based on two linear matrixes, within A could define the internal dynamics of the system, and B represent the outer (control) influence [R3, R5].
   - 4.3 Using several scenarios (for the independent variables) and numerous potential matrix coefficients, the evidence for the initial prediction model applicability was found [R7, R11].
   - 4.4 I found [R3, R5] that the major advantage of the initial linear approach lies in the potentialities of using independent variables with a predefined role / weight, and that the model could assist to analyze the internal dynamics of the underlying mechanism (such as the effect of regulation or technological achievements on the small aircraft development).
   - 4.5 I revealed that due to the limited available data on the European small aircraft activity, the major drawback of the initial prediction model is the determination of the matrix coefficients [R5].
5. Using an S-curve form the innovation diffusion theory to project the personal car ownership development as an analogical approach, I established a general non-linear small aircraft prediction model for the European context [R1, R2, R8, R12].
   - 5.1 For the applicability of the developed non-linear SA prediction model, I established a method to estimate the total operating cost of small aircraft [R2, R8].
   - 5.2 The parameters of the non-linear small aircraft prediction model have been examined with a sensitivity analysis in order to prove that all elements are sensitive and reasonable to use [R12].
   - 5.3 The results of the small aircraft prediction model were validated via a historical data validation technique that gave an error rate of about 6 % in a five year period.
   - 5.4 I demonstrated [R1, R2] the applicability of the developed SA prediction model with a Monte Carlo Simulation, since this is capable to represent the unclear parameters with probability distributions and therefore quantitatively address the uncertainties in the system.

10. List of authors publications

Refereed journal in foreign language (published in Hungary):

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