Potential European Small Aircraft Prediction and Demand Models

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Abstract: The further globalization and mobility freedom indicate rapid increase in needs of personal used air transport systems (see NASA SATS program). This paper develops the potential small aircraft prediction and demand model techniques. It also deals with the possible model structures, model classes and finally gives a relatively simple model based on Markov chain that has been chosen for testing it in simulation. The simulation results show, that the developed model could be used in preliminary prediction of the European small aircraft activity and in the definition of required changes in regulation, management and service providers to ensure the further development of SA.

Index terms: general aviation, prediction methods, small aircraft, traffic characteristics

I. INTRODUCTION

Today there are approximately [1],[2] 300 000 private and small aircraft pilots in Europe that fly more then 60 000 small aircraft. As the technology is already available to establish a safe, economical and environment friendly new air transportation system based on personal air transportation purposes, small aircraft users’ traveling habits might change. Maximum satisfaction of their requirements could take over the lead, such as traveling on demand, point-to-point and in a more flexible way [3]. Additionally as such a small aircraft could be designed to be affordable to ordinary people, even a pilot with limited experience might be able to fly without any special or extra knowledge, similarly to the difficulty of driving a personal car (see also the philosophy of NASA SATS [3],[4], UK JETPOD [5], PATS [2], [6] and SkyCar [7]). As this future state could enhance people’s quality of life and ensures their freedom, such an aircraft could be used very widely [4],[5],[6],[7].

In the face of this increase, the current system is already reaching its limits, thus most probably it will not be able to meet that future need of tomorrow’s capacity (in several domains such as environmental consideration, security, safety, etc. [4]). Moreover, the saturated fact of today’s big airports could oblige personal aircraft flights to use regional airports, or other underutilized landing possibilities, which in most of the cases are not equipped with modern radio-location systems for controlling the air traffic. Thus, in the aim of decreasing such and other negative effects - caused by the increased number of small aircraft - current ATC/ATM, airport and airline operators might call for a change. Therefore we have to develop radically new concepts to be able to accomplish future tasks (such as pilot workload monitoring, simplified control [2], automatic control system, etc.), and to minimize the interaction between SA and the conventional air traffic. Hopefully, such change in air transportation of the future has a perfect timing [8], because
we still have a little time to prepare ourselves for the work ahead of us, before air transportation and especially small aircraft might reach record levels.

For a better understanding of the work to be accomplished in the domain of SA activity, initially the following related works have been discovered. First of all, the NASA’s Small Aircraft Transportation System (SATS) [4], [3] that desire to expand the use of small airports and small aircraft for public transportation, through cockpit development and some advanced operational concepts in non-radar airspace at non-towered airports. Or the Personal Air Transportation System (PATS) [2], [6] project that is very similar to SATS, however here, investigations are done in the domain of aircraft maneuverability simplification via automation, without focusing on cockpit development. Another thought provoking idea is the SkyCar [7], a vehicle capable of vertical take-off and landing that looks like a cross between a sports car and a tiny jet aircraft. And finally the UK JETPOD [5], which is a European pre-designed study for advanced personal air transportation.

Generally, the purpose of these programs is to make small aircraft as easy and safe to operate as cars, with a cost the same as a mid-range car. However these have been very useful to name the currently available small aircraft, cockpit development benefits and requirements vis-à-vis pilot experiments, their limitation (expect the UK JETPOD) is the focus on the American market. As Europe consists of several countries, with different social and economical characteristics, the importance of our study is to adopt their results and predictions on the European market attributes. Additionally, expect the last few years of development in this field, small aircraft development has not been in focus for over 40 years, since the World War II. The companies producing these aircraft have partly changed their activity, or jointed to a bigger civil and military aircraft development. Due to this past, we do not have enough statistical data and experience for describing the future growth of small aircraft activity, especially for the European market.

In order to deal with this past and to ensure future needs described above, the impact of small aircraft on the European air transportation system has to be analyzed.

As the analysis of small aircraft activity is a pioneer task in Europe, our objective is a European small aircraft prediction model in which could forecast any SA traffic load on current and future ATC/ATM parameters.

Once these objectives have been accomplished, further investigations might focus on tasks, to minimize the impact of small aircraft on the air transportation system. This could be imagined by giving proposals, solutions for a particular domain, and shifting the ATM attributes towards a system that could give solutions for future requirements of small aircraft purposes.

II. FORECAST AND PREDICTION METHODS IN GENERAL

In order to prepare a small aircraft forecast model, we had to discover the generally used methods [9]. However the followings is not a complete list, it might provide a base for further selection or combination of several applicable techniques.

First of all it we could mention the regression and trend analysis [9] that use past data to obtain future values of the dependent variables via regression or projections of historical trends. However it is a frequently used method, its applicability for our purposes is limited due to the non availability of relevant European small aircraft past activity.
Same problem has to be faced for the share analysis [9], which calculates historical shares for projecting future values, and the exponential smoothing [9] that is based on time series of analysis of observations.

The first technique that might be valuable for the small aircraft purposes is the comparison [9]. This method aims to compare to objective of the research with similar and relevant activities. One possible use of this technique lays in the idea of compare the development of small aircraft with the growth of early general aviation activity or even early jet age business jets. However this technique could be relevant, it might be more than difficult – if not impossible – to bring into play the added values of small aircraft such as low cost, flexibility and others.

On the other hand analysis based on surveys [9] could apply these small aircraft characteristics. 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 any “competitive” transportation, like the high speed trains. A typical example of such survey technique is a questionnaire given to general aviation users, business and other passengers that might afford a personal aircraft.

Another technique is the cohort analysis [9]. Here the element to forecast is divided into its components (cohorts) in order to study them separately. In our case, as small aircraft is a complex entity, it might be better understood once it is disaggregated into its elements, such as small aircraft for business, leisure or a fully personal use such as a family car.

The next technique is the choice and distribution models [9] that could explain how the allocation of demand across the alternatives might change with the introduction of a new alternative. Concerning the applicability of this technique, numerous questions might be posed: first of all: if small aircraft is the new alternative transportation, what would be the other transportation means? Is it the general aviation, cars, high speed trains, or the low cost carriers? And finally is its main assumption correct - namely that the overall size of the market is fixed – for our objectives (which would not certainly be true if small aircraft would open a new public for air transportation)?

A possible solution to deal with all of these questions is the use of interval or range projections [9]. With specified scenarios it take into account even extraordinary events such as oil crisis, or a strict noise regulation of small aircraft due to increased traffic at city surroundings.

These techniques could also be combined in order to apply them for specific purposes, for instance a combination of survey and comparison technique could be a questionnaire given to current high and upper-middle class owners to obtain the future amount of passengers that might allow a small aircraft.

III. GENERALLY USED DEMAND MODELS IN AIR TRANSPORTATION

To estimate the demand of air transportation, the available models could also be classified into the followings [10],[11]. The linear demand model, which assumes a linear relation between the dependent and independent variable. The log-linear demand model that specifies the logarithm of the dependent variable as a linear function of the logarithms of the independent variables. The logit or linear logit model to model market
shares of alternative modes of transports. And finally the translog demand system, where a translog function is applied to the study of the cost functions of transport industries.

Between these, the most popular model is the log-linear [10],[11],[12] because the coefficients themselves are the respective elasticities, as it is visible in equation (1),

\[
\ln(D) = \alpha + \beta_1 \ln(Z_1) + \beta_2 \ln(Z_2) + \ldots + \beta_n \ln(Z_n) + \varepsilon
\]

where \( D \) is the demand, \( \varepsilon \) is the error and \( \beta \) is the elasticity that measures the responsiveness of the dependent variable to a change in an independent variable while all others are held constant [10],[13].

Using this method, numerous publications are available, which gives a large scale of elasticity values depending on country specific socioeconomic characteristics, or geographical conditions. The possibility to use or adapt these values could be seen as logical, conversely for our task it should be considered as irrelevant due to their biggest drawback namely the constant elasticities. However the application of constant elasticities is logical for commercial aviation since it is currently in a constant long-term development phase, for a new air transportation (such as small aircraft) elasticity values should vary over the time, otherwise there would not be any "boom" in the beginning of the development phase.

Finally due to the above mentioned problems, other solutions should be considered, which is described more in detail in the following chapters.

IV. FACTORS INFLUENCING SMALL AIRCRAFT TRAVEL DEMAND

The initial investigations described above clarified, that the problem with SA prediction or demand modeling is, that the generally used solutions can not give a suitable result, since small aircraft transportation does not exist today in Europe, hence the relevant information which might be used is more than limited. This lack of input data, and the aim to have an advanced model that could reply to our specific requirements, forced us to come up with a new method based on the combination of two or several techniques.

The first approach lays in the idea of modeling the demand of small aircraft as a balance between the market attributes, small aircraft -, commercial traffic and ATM parameters as it is presented on the figure 4.1. Such a technique might allow the elimination of unforeseen complexities and side effects due to the relationship of these four elements. For instance investigations in future perspectives in ATM clarified, that several ATM parameters might act as a driving factor on small aircraft development since - for example - an increased air traffic due to a relatively cheap small aircraft could call for an enhanced on-board instrumentations, which would finally shift the initial cost of small aircraft to higher values.
The first group of the model called market attributes is made up of the factors influencing the air traffic demand. As it comes from the literature [14],[15],[16], the key elements are the airline price, personal income, population density and other country specific socioeconomic characteristics. Nevertheless several other driving factors could be named, such as follows:

- passenger type (business or leisure) [17]: to take into account the difference between price and income elasticity,
- flight distance (long haul, short haul) [12]: to bring into play the difference between their price elasticity,
- airport size (hub or non-hub) [12]: since large hub can positively influence airline and connecting flights choice, however can negatively impact traveling time,
- alternative transportation modes [12]: to take into consideration the presence of alternative or ”competitive” transportation modes such as high speed trains, low-cost carriers, that could influence the traveling price,
- seasonality [12],[13]: since convective weather might seriously influence the air traffic.

From a small aircraft point of view, the most important element of these is the seasonality, since it might cause scheduling complexities or could even postpone the flight. However due to lack of relevant data their introduction to the model was not possible. Finally, our approach to the market attributes elements is, that the GDP might totally describe the mobility of passengers, hence our input data – that we call here market attributes – consists of the GDP and other small aircraft relevant elements such as technological development and regulation. These last two elements have been appended since we do believe that the demand mainly depends on the availability of SA, which might be driven by the technological development. The effect of regulation might also be relevant it might seriously influence the SA activity, in any future scenario (such as noise restriction at airport vicinities as it has been already mentioned).

Then, as the figure 4.1. shows, that market attributes defines the characteristics of small aircraft (SA) and traditional air traffic as it comes from economical theories [15],[16].

The final element of the model – interaction on ATM - is made up of some of the air traffic management domains from a SA point of view. These elements are mainly the outcome of the SA traffic and future perspectives in ATM analysis [14]. Avionics – for example – means cockpit instruments and navigation tolls (such as TCAS, GPS, ADS-B, and others). Separation responsibility is defined by its importance, without taking into consideration whether pilots or controllers should deal with it. Similarly, the domain of ”automation” means more its 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.

V. APPLICABLE SMALL AIRCRAFT PREDICTION MODEL STRUCTURES

Generally, the transportation systems are the dynamic systems. The future of the dynamics systems can be defined with the following general models written in continuous/discrete form such as follows:
\[ x(t_0) = x_0, \]  
\[ x(t) = f(x(t), u(t), p(\zeta)) + F(p(\zeta))n(t), \]  
\[ y(t_i) = g(x(t_i), u(t_i), p(\zeta)) + G(p(\zeta))\eta_i. \]

where \( x, u, p, n, y, \eta \) are the state, control (input or regulatory) and parameter (system structural and operational characteristics), state noise, observation (output), and measurement noise vectors, \( f \) and \( g \) are system state and observation functions, \( F \) and \( G \) are system matrices, \( t \) is time and \( \zeta \) is a random value.

However in general – and with accordance to control theory - \( u \) is a known vector, in our case it is defined by regulatory aspects, like changes in requirements generated by safety reasons, or changes in taxation systems, application of radically new technologies, etc. The system characteristics, \( p \) are depend on the development of SA, economical characteristics, and on the competitor aspects (such as growth of the high speed trains, road traffic problems, etc.). Hence, \( p \) is an unknown vector, which can be changed randomly and non-continuously that is described by a random value, \( \zeta \) depicting real position of the parameter vector, \( p \) in its possible space, \( \Omega_p \). As usually, the state noise vector is assumed to be zero-mean; and the measurement noise vector is assumed to be a sequence of independent Gaussian random variables with zero mean and identity covariance.

Finally, the model (2) can be given in linearised form (as is the case of stability and control derivatives of an aircraft):

\[ x(t_0) = x_0, \]  
\[ x(t) = Ax(t) + Bu(t) + Fn(t), \]  
\[ y(t_i) = Cx(t_i) + Du(t_i) + G\eta_i. \]

On the other hand, the model (2) represents the following stochastic (random) differential equations in system of equations (1a):

\[ x = f(x, t) + \sigma(x, t)\xi(t), \]

which is called as diffusion process. The first, deterministic part at the right side of the equation describes the direction of the changes of the stochastic process passing through the \( x(t) = X \) at the moment \( t \), while the second part shows the scattering the random process, where, \( \xi(t) \) is the white noise.

In prediction and forecast technology several models based on the use of diffusion models were developed [18]. From one hand the innovation diffusion theory has applied the S models for getting information about the introducing of a new product/service into the market that aims to describe the market share changes [18].

On the other hand the model classes defined by (4) can apply to the description of the system dynamics rewriting the model (1b) into the following form of controlled diffusion process:
\begin{equation}
\dot{x} = \Phi(x,t) + b(t) + \sigma(x,t)\xi(t),
\end{equation}

where \(\Phi\) is the deterministic vector function describing the rate of changes in state vector, as the products of the functions of the state and the time increment; \(b\) is the vector of control effects and finally \(\sigma\) is the transfer matrix giving the effects of the noise disturbance on the state vector.

Replacing the state (or phase) vector \(x\) by \(x = m_x + \Delta x\) the equations (5) can be statistically linearised in the area closed to \(x = m_x\):

\begin{equation}
\dot{x} = \frac{d}{dt}(m_x + \Delta x) = F(m_x,t) + U(m_x,t)\Delta x + b(t) + \sigma(x,t)\xi(t)
\end{equation}

where \(U(m_x,t)\) is the sensitivity matrix, i.e. matrix of partial derivatives of vector function \(F(x,t)\) respectively to state vector \(x\) determined at \(x = m_x\).

In case of stationer white noise the equation (6) represents the well known linearised model of aircraft motion:

\begin{equation}
m_x = F(m_x,t) + b(t).
\end{equation}

However, this class of models could be applied for the prediction of the small aircraft activity, the relevant preliminary information – in Europe - that might be required for model estimation, is more than limited. Moreover, according to our analysis, the prediction model can not be given in a generalized form, since the system should include the major effects influencing on SA growth, which defines a large and very complex system with internal coupling and discrete (step) changes - depending on the regulational aspects or the application of the new technological achievements.

Thus, the prediction model - in a general form - is the result of the superpositions of the general growth (exponential), periodical changes (in requirements) and the discrete changes (in characteristics of general growth). Hence, the model (2b) should be rewritten in the form of stochastic equations, such as follows:

\begin{equation}
\dot{x} = f_x(x,u,t)
\end{equation}

We assume that the equation (8) holds the form, and where \(x\) is the vector of the dependent variables like:

\(x^T = [S\text{need} S\text{mark\_req} S\text{cost} T\text{need} T\text{cost} \text{avionics ASM sep\_resp automation}]\)

\(u\) is the input vector,

\(u^T = [\text{GDP regulation techn\_development}]\)

and \(t\) is the time.

The equation (8) is now a non-linear differential equation. With its linearization we receive (9) such as follows:

\begin{equation}
\dot{x}(t) = A^x \cdot x(t) + B^x \cdot u(t)
\end{equation}

where
The equation (9) could also be discretized. If $T$ is the discretization time, we could define $t = k * T$, where $k \in \mathbb{N}$ is the time in years. Therefore after the rearrangement, the prediction of the vector $x$ could be done with the following equation:

$$x[k + 1] = Ax[k] + Bu[k]$$

(10)

where, the matrix $A$ describes the relationships between the elements of the vector $x$,

$$A = \begin{bmatrix}
S\text{need} & a_{12} & \ldots & a_{17} & a_{18} & a_{19} \\
\vdots & \vdots & \ddots & \vdots & \vdots & \vdots \\
a_{21} & a_{22} & \ldots & a_{27} & a_{28} & a_{29} \\
\vdots & \vdots & \ddots & \vdots & \vdots & \vdots \\
a_{n1} & a_{n2} & \ldots & a_{n7} & a_{n8} & a_{n9} \\
\end{bmatrix}$$

therefore $a_{ij}$ (where $i \neq j$) are coefficients, that express the connection between $a_{ii}$ and $a_{jj}$ (such as the connection between automation and SA need). $B$ similarly to $A$ describes the relationships between the input elements (vector $u$).

The advantage of such an approach is that it could be used for any interaction modeling even with different small aircraft characteristics. However, the challenge is to find the coefficients for both $A$ and $B$ matrixes. For our small aircraft purposes, they are partially based on statistics, and on estimations.

Finally, the outcome of the equation (10) could give us an initial prediction of each element of the vector $x$, that might help us to understand their role, and to foresee, what could be a relevant domain to focused on.

VI. ADVANCED MODELS

This relatively new approach in air transportation is based on the idea of describing the air travel demand – instead of a linear or log-linear form – a more suitable model, some sort of an S-curve [19].

Such inspiration is also known in the literature in other transportation domains, such as car ownership determination [20],[21]. This might better represent the relationship between small aircraft affordability and time [20], since small aircraft – as new technology - when first introduced is unproved, relatively expensive and difficult to operate. Just a very small amount of the population might experiment the technology at this stage, however once it becomes clear and price falls, the main market starts and the adoption curve heads upward. Finally, with the saturation of this technology, that S curve becomes complete [19],[22]. Thus the acceptability of the market could be divided into the early adopters, early majority, late majority and finally the laggards [22]. Using such an advanced and new approach to small aircraft prediction modeling, several advantages could be brought into play such as a saturation level [20],[21], partial adjustment mechanism and its relatively easy model structure that does not require detailed socioeconomic and transportation characteristic data.
VII. EXAMPLE OF SIMULATION

In this example of simulation only the equation (8) have been used. To have the prediction of the key elements (vector $x$), in this paper, input data is defined with five scenarios, that ranges from optimal (4: large number of SA) to catastrophic (5: limited number of SA) and some between such as follows: scenario 1 is defined by a moderate GDP, technological development growth with a non-flexible market, which is more sensitive to SA price and the fulfill of market requirements. Scenario 2 is the opposite of the previous, thus here, the market is flexible. Additionally, for both scenario 1 and 2, a regulation has been added, since it might be interesting to define, and to analyze its impact on the key elements. Note that in this model, the effect of regulation is considered as a decreasing factor on the “flexibility of market requirements”, and an increasing cause on “SA costs”. Finally, scenarios 3, 4 and 5 are the ones with a flexible market, and without regulation, where the difference between them lies in the definition of a low (4), moderate (3), and rapid (5) GDP, technological development growth. As a final point, note, that all the input data are based on assumptions.

By running a simulation with these scenarios, the model gives the outcome of each key elements (vector $x$), however, this paper only presents the SA need element as it is shown in the figure 7.1.

It predicts nearly six times (see figure 7.1.) more small aircraft (that is today) for the most optimal scenario (4). This number becomes a bit smaller with scenario 3 and 5, which is caused by the decreased GDP and technological development growth. Finally, scenario 1 and 2 are the situations, where the outcome is impacted by a regulation. Its effect is clearly visible on both curves, causing a wave part that lasts for several years. Logically, for scenario 1 it is easier to track, due to the non-flexible market situation, which is more sensitive to any “cost” or “flexibility of market requirements” change.

VIII. CONCLUSION

The increasing economy and air traffic volume might allow the future of small aircraft transportation. In that future, traveling habits will change. Maximum satisfaction of market requirements will take over the lead, which could enhance people’s quality of life and ensures their freedom.

Such a shift in air traffic attributes might increase the air traffic volume in terms of small aircraft, thus it has to be analyzed.

As the analyze of the potential models clarified, the problem with SA prediction or demand modeling was, that the generally used techniques could not give a suitable result, since small aircraft transportation does not exist today in Europe, hence the relevant information which might be used is more than limited. This lack of input data, and the
aim to have an advanced model that could reply to our specific requirements, forced us to come up with a new method based on the combination of two or several techniques.

The first approach was to model the demand of SA as a balance between the initial objectives (such as easy to fly and cheap SA) and potential solutions in SA development. This allowed us to obtain a flexible model that could be used for further applications, however it might be difficult to define all factors in the matrixes, that is presented in the equation (9).

Finally this paper gives an example for an advanced model, where small aircraft is understood as a new technology, and its adoption is represented with an s-curve. This relatively new approach in air transportation is more than advantageous, since it is easy to apply, and could take into consideration the specific requirements of our needs, even with a limited available data.

IX. FUTURE WORKS

Once the mathematical background of the initial small aircraft prediction model (equation 9) is given, further investigations should focus on the definition of the matrix coefficients in (9). Naturally, due to the lack of preliminary information and dependence on the applied scenarios, the model must be tested and enhanced in accuracy for further use.

Moreover, we should build another model using – most probably - the idea of s-curves. This might allow us to compare the models and to name and understand the differences, if any.

Finally, once the model is already available, we could provide some recommendations and proposals for further investigations in the analysis of the impact of small aircraft on Air Traffic Management, and other relevant research areas.

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