Comparative analysis of light transport aircraft usefulness from the point of view of direct operating cost and fuel consumption

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ABSTRACT
The need to increase speed, range and operational load in air transport is currently more topical than ever and is related to the efficiency of fuel use. Minimisation of costs and fuel consumption is connected with the necessity to analyse the influence of profile and procedures of flights depending on the type of aircraft functioning in the transport system. The main objective of the paper was to develop a method of determining costs and fuel consumption depending on the aircraft type and the profile of transport tasks fulfilled, and then to carry out comparative calculations for various types of aircraft designed for local transport. Based on the comparative analysis of results, conclusions have been formulated concerning the optimum ranges of using aircraft with various types of propulsion and optimum flight profiles.

KEYWORDS: transport, airplane design, optimization

1. Introduction

There are 1,270 airports and approximately 1,300 landing fields in Europe. This means that ca. 80 % of population live within the distance of a 30-minute drive to the nearest airport. At present, the main part of passenger air traffic is concentrated on 43 major international airports and 450 national airports. The remaining airports are not used to a great extent. What follows from analyses carried out within the EPATS project (European Personal Air Transportation System) is that it is possible to create a competitive network of European air connections operated with light communication aircraft, using the less burdened and equipped airports, and properly adjusted landing fields. Such connections might take over a number of people travelling by passenger cars previously.

The chances of such a system becoming successful largely depend on its competitive advantage towards alternative means of transport. Airplanes meant for passenger transport should feature competitive operational costs compared to other means of transport along routes longer than 500 km, high cruise speed, flight range in the order of 1,500 km, high security indicators, high flight comfort, satisfaction of ecological norms, ease of service, etc.

With this end in view, special software has been developed that enables evaluating the properties of airplanes and
simulating flights according to appropriate aviation procedures. This software allows obtaining all interesting characteristics of a plane depending on the number of passenger seats (or commercial weight), speed, cruise height, range, and profile of a flight. The characteristics of fuel consumption, direct operational costs and other significant features of an airplane are specified according to a uniform, reliable and comparable methodology, which in turn allows correct conclusion and comparison of results for various types of airplanes and conditions of carrying out flights.

2. Current situation

Analysis of literature [1, 2, 3, 15, 16, 19, 20, 21, 23] allows distinguishing several types of evaluation criteria for airplanes with various scope of usability and complexity. Simple technical criteria describe the performance and weight characteristics of an airplane (these are usually treated as restrictions). The following values may constitute the criteria: maximum velocity $V_{\text{max}}$, maximum ascent velocity $w_{\text{max}}$, practical ceiling $H_{\text{pc}}$, range $L_{\text{Zmax}}$, take-off distance $L_{\text{TO}}$, landing distance $L_{\text{land}}$, payload weight $m_{\text{p}}$, take-off weight $m_{\text{TO}}$. These are absolute criteria with no reference to the dimensions, weight or class of an airplane; they only state “isolated” facts.

Compound technical criteria [18, 20, 21] combine a number of simple characteristics of an airplane, yielding a slightly more “succinct” quality evaluation, albeit restricted to a selected class of aircraft with not too remote technical properties. Such criteria are comparative by nature and their suitability is also limited. Operation criteria should also be counted as technical criteria. The more important ones are [15]: airplane recovery time and service time per hour of flight. The former specifies the time necessary to prepare an airplane for the next flight (taking into account over-haul, necessary maintenance work, loading, filling up fuel, exchange of crew). The latter specifies work consumption of land personnel necessary to keep an airplane in good working order and preparing it for flight with reference to flight duration. Operational criteria are based on the airplane features, which to a small extent might be specified based on its external features. The principal method of determining them is through surveys of airplanes existing and operated in specified conditions. During the design stage, requirements in this area are intentional and when choosing an airplane, it is a value declared by the manufacturer.

Economic criteria were originally created for needs of airlines (freight companies) [1, 2, 16] using them to rationalise their aircraft fleet, to establish competitive transport fares, etc. Despite the complexity and necessity to take into account a large number of components based on statistical data or assumptions, these criteria constitute nowadays the basic form of evaluation of airplanes used commercially.

The most complex and general economic criterion is the airplane’s total $LCC$ (Life Cycle Cost) [15], comprising costs of design, research, manufacturing, sale, usage and

![Mathematical model of aircraft](image-url)
disposal of the general stock of specified type of aircraft. The life cycle cost of an airplane is a sum of four components:

\[ \text{LCC} = C_{\text{RDTE}} + C_{\text{ACQ}} + C_{\text{OPS}} + C_{\text{DISP}} \]  

(1)

where: 
- \( C_{\text{RDTE}} \) - costs of design, development, research and test phase, 
- \( C_{\text{ACQ}} \) - sales costs, 
- \( C_{\text{OPS}} \) - operational costs, 
- \( C_{\text{DISP}} \) - costs of aircraft disposal after operation period.

The criterion (1) is particularly useful when evaluating the functioning of large aviation companies or military aviation, allowing specification of total costs of development and use of an airplane, as well as annual expenditure on airplane fleet.

A less general and derivative criterion in relation to (1) is the DOC (Direct Operating Cost), expressing the cost of a time unit of using an airplane of a specified type [1, 2, 15]. It consists of costs incurred for the flight (fuel, crew's remuneration, depreciation, repairs, airport and navigation fees, etc) of each airplane and unit of account (an hour of flight in most cases). The DOC enables determining the prime costs of the ton-kilometre or prime costs of the passenger-kilometre:

\[ \bar{c}_{\text{tkm}} = \frac{\text{DOC}}{m_h} \quad \text{or} \quad \bar{c}_{\text{pkm}} = \frac{\text{DOC}}{n_{\text{pas}}} \]  

(2)

where: 
- \( m_h \) - average commercial (payload) weight, 
- \( n_{\text{pas}} \) - average number of passengers.

Economic criteria, compared with technical criteria that evaluate separate features of an airplane, have “integral” characteristics, taking into account flight characteristics, structural and manufacturing technology properties, power unit properties, as well as operational environmental and market factors. They are a considerably better measurement of an aircraft’s general properties.

**Special forms of criteria** may be justified when evaluating unusual market situations, in periods of insufficient supply or sudden fuel price rises, pressure on emission reduction, etc. A useful, though fragmentary, measurement of an airplane’s quality is the fuel consumption efficiency seen as the weight of fuel necessary to carry out a specified task, referred to the product of service mass and flight distance:

\[ F_c = \frac{m_{\text{pal}}}{m_h L_{\text{blok}}} \quad \text{or} \quad F_c = \frac{b_{\text{fu}} m_{\text{pal}}}{m_h L_{\text{blok}}} \]  

(3)

where: 
- \( b_{\text{fu}} \) - calorific value of fuel used.

Airplanes featuring minimum values of this indicator when carrying out identical tasks show higher energy efficiency.

Fig. 2. Cruise profile (task model)
Table 1. The data of example airplanes

<table>
<thead>
<tr>
<th>Airplane type</th>
<th>Cirrus SR-2</th>
<th>Piper Saratoga</th>
<th>Piper Seneca V</th>
<th>Pilatus PC-12</th>
<th>King Air350</th>
<th>BAE 31 Jetstream</th>
<th>Eclipse 500</th>
<th>Cessna Encore</th>
<th>Cessna Mustang</th>
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<td>Engine type</td>
<td>piston</td>
<td>piston</td>
<td>piston</td>
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<td>turboprop</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>B [m]</td>
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<td>11.85</td>
<td>16.23</td>
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<td>15.85</td>
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<td>16.48</td>
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<td>0.478</td>
<td>0.286</td>
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<td>0.231</td>
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<td>7.24</td>
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<td>0.000</td>
<td>0.000</td>
<td>0.061</td>
<td>0.017</td>
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<td>0.087</td>
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<td>4.82</td>
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<td>0.000</td>
<td>0.000</td>
<td>0.087</td>
<td>0.314</td>
<td>0.122</td>
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<td>0.197</td>
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<td>1.48</td>
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<td>1.26</td>
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<td>1.52</td>
<td>1.05</td>
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<tr>
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<td>0.365</td>
<td>0.393</td>
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<td>1.87</td>
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<td>2.68</td>
<td>-</td>
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<td>316</td>
<td>380</td>
<td>1200</td>
<td>1122</td>
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<td>4</td>
<td>4</td>
<td>9</td>
<td>15</td>
<td>18</td>
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<td>4</td>
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<td>Mw [kg]</td>
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<td>380</td>
<td>380</td>
<td>855</td>
<td>1425</td>
<td>1710</td>
<td>380</td>
<td>855</td>
<td>380</td>
</tr>
</tbody>
</table>

3. A computational example

Due to the current fuel and ecological problems, we present results of calculations obtained for criteria (2) and (3). The calculations have been made for nine one- and two-engine airplanes with various power units: piston engines (Cirrus SR-22, Piper Saratoga II TC, Piper Seneca V), turboprop engines (Pilatus PS-12, Beechcraft King Air 350, BAE Jetstream 31), and jet engines (Eclipse 500, Cessna Citation Encore, Cessna Citation Mustang). The data on airplanes is illustrated by Table 1. Selected results of calculations concerning fuel consumption are shown in Fig. 3.

Fig.3 shows the range to cruise speed relation for various fuel weights for three sample airplanes powered with different types of engines. The nature of the relation for remaining airplanes is similar. The graph analysis allows evaluating approximate trajectory parameters depending on the flight distance and engine type.

Fig.4 shows the relation of the fuel consumption efficiency of nine sample airplanes shown against the histogram of possible and existing air connections in Europe. It is easy to notice that an airplane’s suitability for tasks differing in flight range is a function of the power unit type. It can also be seen that from the perspective of the criterion of fuel consumption effectiveness, jet planes have no reason for existence.

Fig.5 illustrates the direct passenger-kilometre costs for the same set of airplanes, when carrying out tasks identical to those shown in fig.3.

4. Conclusions

The analyses and calculations carried out allow drawing a series of general and specific conclusions. The principal conclusion, concerning the suitability of criteria, amounts to a statement that technical criteria can only play auxiliary functions while comparing a narrow set of airplanes (in terms of dimensions, weight, speed and purpose). Economic criteria feature a synthetic grasp of functioning of an aircraft, enabling evaluation and comparison of airplanes with various parameters. The power criterion (fuel consumption...
efficiency) is a fragmentary measure of an airplane’s characteristics and is useful when evaluating an airplane in a broad sense, using a number of criteria.

The analysis of results of calculations using the fuel efficiency criterion \( \text{Fe} \) and the direct costs criterion \( (\text{tkmC}) \) for a selected group of airplanes allows stating that:

- the highest fuel consumption efficiency is displayed by turboprop airplanes within the entire range of distances under consideration;
- for distances shorter than 250 km, airplanes with piston engines show fuel consumption efficiency comparable to that of turboprop airplanes, while jet planes are definitely worse for the entire range of the distances under consideration;
- the improvement of fuel consumption efficiency when using a diversified airplane fleet requires optimisation of the area of using the airplanes (task division), in accordance with its properties;

Fig. 3. Range-cruise altitude dependence for constant fuel weights
a - Cirrus SR-22 (piston), b - Pilatus PC-12 (turboprop), c - Eclipse 500 (jet)

Fig. 4. Fuel weight per pax per km comparison for all nine planes (with all European air connections lengths histogram)

Fig. 5. DOC per pax per km comparison for all nine planes (with all European air connections lengths histogram)
• the lowest passenger-kilometre costs are incurred by turboprop airplanes within the entire range of distances under consideration;
• piston engine airplanes - the cheapest and the smallest in the group under consideration – display costs comparable to those of jet airplanes for short distances;
• calculation results may be used for rough estimate of suitability of airplanes with characteristics similar to those used in this paper;
• reduction of direct costs and improvement of fuel consumption efficiency when using a diversified airplane fleet requires optimisation of the airplane usage area (task division), in accordance with its properties.

The paper has been executed within the ASA6-CT-2006-044549 European Grant, European Personal Air Transportation System STUDY (EPATS).

Bibliography


Received 2008-08-27, accepted in revised form 2008-10-10