APPLICATION OF FLEET CREATION PROBLEMS IN AIRCRAFT PRE-DESIGN

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Abstract

Nowadays the competition on the passenger air transportation market becomes stiffer with each year. The market share that the Russian civil aviation industry currently occupies on the global passenger airplane market is not very big. However, the government of Russian Federation plans to take measures for increasing this share up to 10-15%.

A number of new aircraft is planned for development and manufacturing to implement this idea. One of such new projects is the family of MS-21 (MC-21) medium-and-short-range trunk-route airplanes. "Irkut" company plans to create a family of these airplanes with three versions.

It is necessary to mention that the experience of Russian aviation industry in the creation of trunk-route passenger families is relatively small compared to that of the Western aircraft-producing companies. The research concerning the problems of the evaluation of the effectiveness of trunk-route passenger airplane family creation was carried out both in Russia and abroad. However, such research did not take into the account the problems of operation of these families within the composition of multi-type airplane fleets. The paper adduces the fundamental principles of the Methodology, which was developed by its author with the purpose of taking the abovementioned factors of trunk-route passenger airplane operation into the account. The usage of the Methodology is illustrated on the example of evaluation of various variants of the short-and-medium range trunk-route passenger airplane fleet.

1 Problems and challenges

One of the most important tasks of modern aviation designers consists in minimizing the manufacturing costs while catering to the market needs. One of the ways of the solution of this problem consists in creation of the aircraft families. Aircraft family consists of a number of versions, which are created as a result of the modification of the basic family version. All of the family members (versions) are characterized by a high degree of commonality while having different performance. Statistics shows that the costs of creation of a new version lie within 20-40% of the cost of the creation of the basic version for modification (new airplane).

Due to the constantly increasing costs and efforts, which are required for the development of new airplanes, it is important to evaluate their future success at all design stages (especially the early ones). Such task can be accomplished by the solution of the fleet creation problems [1, 2].

The current plans of "Irkut" company consist in manufacturing a family of MS-21 aircraft, which should consist of 3 versions with the following maximum values of onboard passenger quantities: 162, 196 and 210 (for MS-21-200, MS-21-300 and MS-21-400 accordingly). However, according to the official information [3], MS-21-400 (with maximum passenger capacity of 210) should be developed with a new composite wing. The development of a new wing increases the cost of the project by approximately 50% and therefore such an airplane cannot be considered as a version of the family and should be regarded as a new type of airplane [4]. Therefore it is only possible to consider MS-21-200 and MS-21-300 as members of the MS-21 family during the fleet comparison.

Also it is quite well-known that one of the key factors, which determine the success of the new civil airplane on the international market, is the positive experience of its successful operation at the domestic market (market of the country, which manufactures the aircraft).

Thus it is reasonable to evaluate the expedience of creation of the MS-21 airplane family from the point of view of carrying out the passenger transportation within the civil aviation system of Russian Federation.

2 Problem statement and calculation methods

2.1 Objective function for the problem of airplane family design

The airline company income mainly depends on the ticket prices. However, since it is extremely hard to obtain the data concerning the profit margin of the company, the evaluations of airplane operation are normally carried out via the **criteria of costs of carrying out the given volume of passenger transportation** [5].

The evaluation of the future aircraft projects according to the criteria of costs of carrying out the given volume of passenger transportation with the created fleet is done according to the following formula [1]:

$$W_S^* = \min_m \sum_{i=1}^{m} FD_i(\bar{a}_i^*, \{x\}_i) = \min_m \sum_{i=1}^{m} \min_{\bar{a}_i} \min_{\{D_i\}} \sum_{x_j \in D_i} f(\bar{a}_i, x_j) \quad (1)$$

where:

W_S is the objective function (the total expenses on transporting the given amount of passengers over a given period of time);

W^*_S is optimal value of the selected objective function;

$\bar{a}_i$ is the vector of performance and parameters of the evaluated airplane of type i (geometrical parameters, aerodynamic characteristics, performance etc.);

$\bar{a}_i^*$ is the optimal vector of performance and parameters of the evaluated airplane of type i (the vector, in which all of the values of the performance and parameters are optimal);

S is the mission (e.g. passenger air transportation program), which should be fulfilled; it is described by the characteristics from the $\{x\}$ multitude;

FD_i are the total expenses on carrying out the transportation on the multitude of routes, which are served by the type i of airplane;

m is the total quantity of airplane types in the fleet;

$\{x\}_i$ parameters, which describe all missions (routes, on which the passengers are transported), which are served by type i of airplane;

$f(\bar{a}_i, x_j)$ are the costs of carrying out one flight on route j by type i of airplane;

D_i is the multitude of routes, on which the airplanes of type i are assigned for carrying out air passenger transportation.

To take into account the absence or presence of a family in the fleet it is necessary to keep in mind that the increase of amount of the airplanes of the same type influences positively the costs of maintenance, repairing and overhaul (MRO), spare parts, pilot and maintenance crew training and so on.

2.2 Transportation costs calculation methods

It was necessary to take the costs of fuel [6, 7], airport [8, 9] and air navigation charges, flight crew salaries, on-board food pricing [10] and other expenses from the available modern statistics to calculate the transportation costs $f(\bar{a}_i, x_j)$.

The method for calculation of the costs of carrying out one flight $f(\bar{a}_i, x_j)$ was derived from [11].

The costs were divided into two groups:

- direct operational costs, which are proportional to the volume of passenger transportation and
- indirect operational costs, which are proportional to the number of flights that should be carried out to fulfill the given demand.

The MRO costs are changed and a discount on the airplane price is given to take into account the change (reduction) of operational costs with the increase of the quantity of airplanes of the given type i or family. The reduction of flight crew expenses is not considered due to the absence of the appropriate statistics and methods.

To evaluate the expedience of creation of the MS-21 family (MS-21-200 and MS-21-300) it is necessary to compare it to the airplane fleet, which includes the same number of separate airplane types m (airplane types, which do not belong to the same family). In this case it would also be possible to determine how the availability of a family influences the operation of an aircraft fleet.

2.3 Selection of fleets (combinations of airplane types) for comparison

"Irkut" Company, which is developing the MS-21 family, has made numerous announcements that the main competitors of MS-21 are the Boeing 737 Next Generation (B737NG) and Airbus 320 (A320) families. Therefore it is reasonable to look at these families for comparison.

It is necessary to put all of the compared objects under similar conditions to obtain proper results. Therefore each airplane would be considered as having a single-class passenger cabin with maximum possible number of seats. The airport requirements of the airplanes are also assumed to be similar.

B737NG family consists of 6 versions: B737-600, B737-700, B737-700ER, B737-800, B737-900, B737-900ER. However, B737-600 is much smaller than MS-21-200 and MS-21-300, which does not allow considering them as competitors. B737-700ER is the business version of B737-700. Thus it also cannot be considered as a competitor for MS-21-200 and MS-21-300.

A320 family consists of 4 versions: A318, A319, A320 and A321. All of those airplanes meet the requirements of the stated problem.

However, it is obvious that A318 cannot compete with the MS-21 family neither in terms of maximum passenger capacity nor in terms of flight range. The maximum passenger capacity of A321 is too big and its flight range is too small. Thus it also cannot be compared with MS-21-200 and MS-21-300.

Thus the research was carried out for: MS-21-200, MS-21-300, B737-700, B737-800, B737-900, B737-900ER, A319, A320.

The following rules were taken as the main ones during the selection of the competitor pairs (competing fleets):

1) All competitor pairs should differ from the evaluated [(MS-21-200)+(MS-21-300)] pair according to the described below criteria by no more than 10% (**Graphical Method**).

The **Graphical Criteria** is calculated as follows:

$$K = \frac{2S_{12}}{S_1 + S_2} \qquad (2)$$

where:

- S_{12} is the area of the geometric figure, which is formed by the aggregation of the flight envelopes of the evaluated and competing airplane pairs;
- S_1 is the aggregated area of the flight envelopes of the evaluated [(MS-21-200)+(MS-21-300)] pair,
- S_2 is the aggregated area of the flight envelopes of the competing pair.

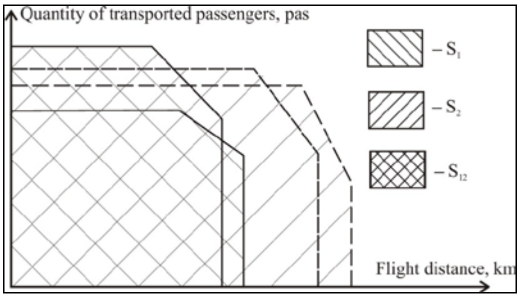

Fig.1. Illustration of the areas of two competing fleets.

2) It is necessary to compare the evaluated pair with several pairs, which include airplanes with maximum flight range and/or maximum passenger capacity bigger and smaller than those of the evaluated pair. Otherwise it is impossible to put the compared pairs into equal conditions.
3) It is impossible to determine the comparability of the MS-21-200/MS-21-300 with other airplanes based only on the **Graphical Method** described above.

Therefore an **Analytical Method** was used as well. It consisted in evaluating the sum of the percentage differences between the maximum passenger capacities and flight ranges for each airplane. If this sum does not exceed 30% it is possible to compare the analyzed airplane pair with MS-21-200/MS-21-300. Otherwise, this pair is excluded from consideration.

The difference between maximum passenger capacities (**Analytical Criteria of Passenger Capacities**) is calculated as follows:

$$\Delta N = (\frac{N_S}{N_{MS-21}} - 1) \cdot 100\% \qquad (3)$$

where:

N_S is the maximum passenger capacity of the competitor airplane;

N_{MS-21} is the maximum passenger capacity of MS-21-200/MS-21-300 airplane.

The difference between maximum flight ranges (**Analytical Criteria of Flight Ranges**) is calculated as follows:

$$\Delta L = (\frac{L_S}{L_{MS-21}} - 1) \cdot 100\% \qquad (4)$$

where:

L_S is the maximum flight range of the competitor airplane;

L_{MS-21} is the maximum flight range of MS-21-200/MS-21-300.

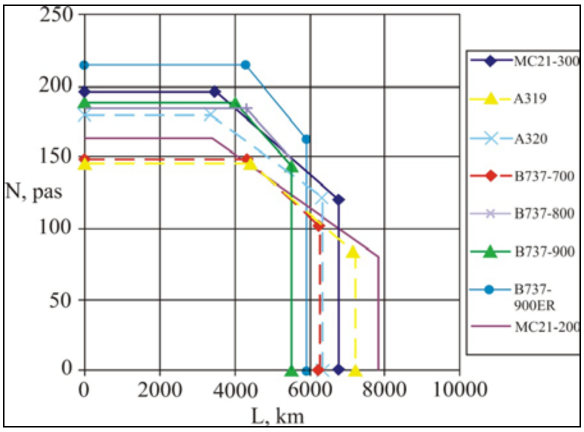

Fig. 2. Flight envelopes of the MS-21-200/MS-21-300 airplanes and their potential competitors.

Fig. 2 shows that the area of each transportation diagram can be found as a sum of areas of a rectangle and a rectangular trapezium. The following airplanes were determined as competitors (according to the Analytical Criteria):

- for MS-21-200: A319, A320, B737-700;
- for MS-21-300: A320, B737-800, B737-900, B737-900ER.

Thus the following potential competing pairs for [(MS-21-200)+(MS-21-300)] pair can be constructed:

- [(A319)+(B737-800)];
- [(A319)+(B737-900)];
- [(A319)+(B737-900ER)];
- [(A320)+(B737-700)];
- [(A320)+(B737-800)];
- [(A320)+(B737-900)];
- [(A320)+(B737-900ER)].

The analysis according to the Graphical Criteria shows that the following competitor pairs can be selected for [(MS-21-200)+(MS-21-300)] fleet:

- [(A319)+(B737-900)],
- [(A319)+(B737-900ER)].

The first pair has smaller passenger capacities and flight ranges than those of MS-21 family and the second one has bigger capacity and range values. This helps to balance the comparison out better.

Since the family is compared to fleets with two separate airplane types, it is important to properly capture the differences between them (and in particular, reflect the changes in fleet operation costs W_S^* depending on the number of operated airplanes of the same type $\boldsymbol{i}$ and/or family).

2.4 Dependence of the selling price on the quantity of the produced/purchased airplanes

The airplane price is reflected in the depreciation expenses. Thus price decrease also results in the decrease of transportation costs $f(\bar{a}_i, x_j)$.

The maximum discount, which can be given to an airline company according to the available statistics, is 30%. Such discount can usually be obtained for the purchases of 200 airplanes and more. Minimum discount applies to purchases of at least 2 airplanes and is equal to 1-3%. Such discount can attain 20% for average purchase of 40-50 airplanes. However, there are also exclusions. For example "Aeroflot" ordered 50 MS-21 airplanes with an approximate discount of 22% [12].

Therefore based on the abovementioned data it is possible to build an approximate dependency of the airplane price discount on the amount of units sold. The graphical representation of this dependency is shown in Fig. 3 below.

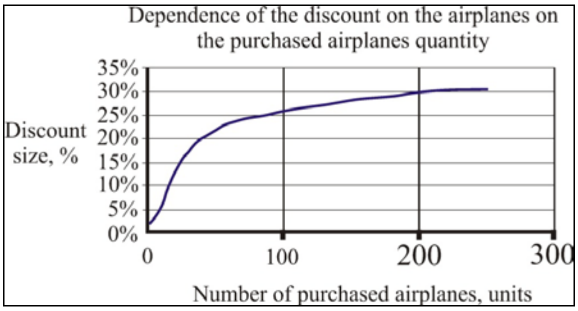

Fig. 3. Dependency of the discount on the quantity of purchased airplanes.

This dependency can be approximated by the following formula:

$$C_N = \frac{C_1}{N^{0,06}} \tag{5}$$

where:

- $\boldsymbol{C_N}$ is the price of one airplane when $\boldsymbol{N}$ airplanes of one type are purchased;
- $\boldsymbol{C_1}$ is the catalogue price of one airplane;
- $\boldsymbol{N}$ is the quantity of purchased airplanes.

Thus it is possible to determine the discount (%) on the price of one airplane when $\boldsymbol{N}$ airplanes of one type are purchased by the following formula:

$$Disc = (1 - \frac{C_N}{C_1}) \times 100\% \tag{6}$$

It is important to point out that ***such discount Disc will be obtained for all airplane versions within one family. The total amount of the discount would depend on the total quantity of the purchased airplanes N, which belong to one family***. This is explained by the fact that the manufacturer uses effectively the same facilities to produce various versions of the same family.

2.5 Adjustment factors based on the experience of the SSJ-100 airplane creation

The first flight of the first MS-21 family version is planned for 2020. Right now the project is still under development and only preliminary data is available for evaluation [3]. It would be extremely desirable to try and take the existing experience of the recent airplane creation in Russia into account to increase the precision of such preliminary estimations.

This can be done, in particular, based on the data about SSJ-100 – the new Russian short-range trunk route airplane. Since both airplanes were created at approximately the same time and under approximately similar conditions it is possible to assume that the experience of SSJ-100 creation can be used during the evaluation of the possible MS-21 future performance.

According to the available data [13], it is known that SSJ-100 came out 10% heavier and 20% more expensive than was initially planned. Its fuel consumption is also 11% higher than planned (announced during the design). At that the flight range and passenger capacity of SSJ-100 remained unchanged.

Thus it is possible to introduce the following adjustment factors into the calculation of the total expenses of MS-21-200/MS-21-300 fleet on passenger transportation W_S^*:

- $\boldsymbol{m_{ssj}}$ is the adjustment factor for the take-off weight of the MS-21-200 and MS-21-300 airplanes. $\boldsymbol{m_{ssj}}$ = 1.1;
- $\boldsymbol{C_{ssj}}$ is the adjustment factor for the calculation of the price of the MS-21-200 and MS-21-300 airplanes. $\boldsymbol{C_{ssj}}$ = 1.2;
- $\boldsymbol{F_{ssj}}$ is the adjustment factor for the calculation of the fuel consumption of the MS-21-200 and MS-21-300 airplanes. $\boldsymbol{F_{ssj}}$ = 1.11.

The introduction of these factors into the vector allowed us to carry out an additional parametrical study. In particular, if the values of these factors are taken as equal to 1, it is possible to estimate how much the fulfillment of the announced requirements influences the competitiveness of the created airplanes.

2.6 Method of assignment of airplanes onto routes

It is necessary to assign one of the types of the airplanes within the fleet onto each route (line) of the transportation network ***{x}***, on which the fleet is carrying out passenger transportation.

First of all, it is necessary to allocate the multitudes of lines, which should be served by the evaluated fleets. **It makes sense to only take amounts of passengers per flight that would either be equal to or exceed 50% of the maximum airplane capacity.** Since all airplanes should be in same conditions, it is necessary to take 50% of the minimal maximum passenger capacity among all compared airplanes (in our case it would be for A319 with 145 passengers).

All of the considered airplanes fly over the distances of more than 875 km in Russia. And none of them can fly onto the distances of more than 6750 km except for MS-21-200. Since all airplanes should be in equal conditions these will be the limits of the considered flight ranges (above 875 and below 6750).

The allocation algorithm is the following:

1) Flight envelops are built for both airplane types in the fleet.
2) The starting required quantities of airplanes ***N*** are calculated. Those are equal to the quantities of airplanes, which are required to carry out transportation within the parts of their transportation diagrams, where the appropriate airplane types are the only ones capable of transporting passengers.
3) In those parts of transportation diagrams where both types can carry out transportation, the required airplane quantities are split between both types as 50%-50% (passenger-flow wise).
4) The discount ***Disc*** on the price of the airplanes of each type is calculated.
5) The costs of transportation $f(\overline{a}_i, x_j)$ are calculated for each aircraft type ***i*** on each route ***j*** based on the calculated discounts and prices.
6) The calculated transportation costs $f(\overline{a}_i, x_j)$ are compared and the airplanes with smaller transportation costs are assigned to the appropriate routes (***D_i*** are formed). On routes, where the costs of transportation by smaller airplane are lower than those of the bigger one by no more than 10%, the bigger airplane type is selected.
   The “tolerance zone” of 10% from the total costs is due to the fact that it is not always possible to assign the “optimal” type on each route in real operation. Thus, if the difference is sufficiently small (<10%), there is an opportunity to assign a non-optimal (e.g. bigger) airplane onto the appropriate route.
7) The new required airplane quantities ***N*** are calculated and the process is repeated. When the new calculated required quantities differ from the quantities at the previous step by less than 10% the algorithm stops and the quantities stay fixed for further calculations. Otherwise the process is repeated starting from step 4.

2.7 The results of comparison of the MS-21 family airplane fleet with the competing airplane fleets according to the proposed Methodology

The following results were obtained during the research (Table). All of the fleet operation costs W_S^* are shown in %, where 100% are the total fleet operation costs of the A319/B737-900 pair.

3 Conclusions

The following was accomplished and obtained during the research:

- The research was focused on the development of the Methodology for evaluation of improvement of the trunk-route passenger airplane fleet effectiveness due to the usage of airplanes, which belong to one family, during its creation. The developed Methodology is versatile and can be used both at the stages of new airplane design as well as during the strategic planning of airline company activity.

- The developed Methodology includes several original Methods:
  - Method of selection of potential competing airplanes;
  - Method of assignment of various types of airplanes for carrying out passenger transportation onto the routes;
  - Method of taking the quantity of produced and purchased airplanes into the account;
  - Method of taking the influence of the factors of the presence of a family among the operated airplane types into account;
  - Method of the correction of evaluation results, which is based on the practical experience of aircraft design.
- The developed Methodology was tested during the evaluation of the effectiveness of the MS-21 airplane family usage in an advanced airplane fleet, which transports passengers within the Russian air transportation system:
  - the competing airplanes were identified (A319, B737-900, B737-900ER) and the comparison with the usage of the developed Methods was carried out;
  - the Total Fleet Costs W_S^*, which are required to carry out passenger transportation on the forecasted transportation network of Russian Federation over a given period of time, were selected and substantiated as the Criteria for the Evaluation of the Competitiveness of the Airplane Fleets;
  - a parametric study of the relative influence of various factors, which are connected with the design of new aircraft, on their competitiveness was carried out;
  - it was demonstrated that MS-21 family can compete successfully with its declared competitors on the market, if the company that designs it would be able to successfully attain the announced airplane performance;
  - the research has proved that the usage of the short-and-medium range airplanes of the MS-21 family in the future fleet (instead of individual airplane types) would result in a beneficial effect during the creation of the fleet of advanced short-and-medium range airplanes.

Table. Relative change of the total fleet operation costs depending on various conditions.

Compared Fleet Alternatives	A319/B737-900	For MS-21-200/MS-21-300 in the area where they compete with A319/B737-900	A319/B737-900ER	For MS-21-200/MS-21-300 in the area where they compete with A319/B737-900ER
Without taking the quantity of airplanes into the account	100%	95,3%	102,2%	96,8%
With taking the quantity of airplanes into the account	89,6%	85,2%	91,5%	86,6%
With taking the quantity of airplanes and previous development experience (SSJ-100) into the account	89,6%	92,7%	91,5%	94,2%

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