The Ministry of Education and Science of the Russian Federation
Samara State Aerospace University
(National Research University)

CONCEPTUAL AIRCRAFT DESIGN

Electronic Textbook

SAMARA

2011

УДК 629. 7. 001 (075)
ББК 68.53

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CONCEPTUAL AIRCRAFT DESIGN = Концептуальное проектирование самолетов [Electronic resource]: Electronic Textbook /V.A. Komarov and others; The Ministry of Education and Science of the Russian Federation, Samara State Aerospace University. - Electronic text and graphic data (1,1 Mb). - Samara, 2011. - 1 CD-ROM.

The aim of this manual is to briefly acquaint readers with the theoretical basis of methods and models that are used in the conceptual airplane design, to develop and consolidate the understanding of relations between main parameters and characteristics of the airplane and also to prepare students for performing their graduation works.

The manual summarizes experience of teaching aircraft designing disciplines in SSAU.

The second edition comprises the significant corrections for the purpose of increasing the accuracy of project estimations and taking into account current achievements of the world aircraft industry. A new section is devoted to applying methods of scientific and technical forecasts while processing statistics.

The manual is dedicated to support class and laboratory lessons and a sketch part of the graduation work for the specialties 160201 Airplane and helicopter construction and 160901 Technical maintenance of aircrafts and engines, and also for executing the term projects and for the Masters programme «Designing, construction and CALS-technologies in Aeronautical Engineering » for education direction 160100.68 «Aeronautical Engineering».

Prepared by the Department of Aeronautical Engineering SSAU.

CONTENTS

SYMBOLS

$A_{го}$, $A_{во}$ – volume coefficients of horizontal and vertical tail.

a – speed of sound;

α – wing angle of attack;

B, $\bar{B}$ – landing gear track, relative landing gear track;

b – wing or tail chord;

$b_А$ – mean aerodynamic chord of wing or tail;

$b_о$ – root chord of wing or tail;

$b_к$ – tip chords of wing or tail;

$\bar{c}$ – thickness-to-chord ratio of wing or tail;

$C_р$ – specific fuel consumption of turbojet engine;

$C_е$ – specific fuel consumption of turboprop/turbofan engine;

C_{xa}, C_{ya} – drag and lift coefficients in the velocity-related coordinate system;

C_{xa0} – zero-lift drag coefficient (C_{ya}=0);

$D_о$ – induced drag ratio;

$D_ф$ – fuselage diameter;

δ – deflection angle of control surfaces and wing high-lift devices;

f – safety factor, the friction coefficient;

g – acceleration due to gravity;

γ – landing gear offset angle;

$\gamma_{дв}$ – engine specific weight;

H – flight altitude;

χ – sweep angle of wing or tail;

K – lift-to-drag ratio;

κ – coefficient;

L – flight range;

l – wing span, tail span;

$l_{разб}$ – the takeoff run;

λ – aspect ratios of wing or tail;

M – Mach number;

m – weight of an aircraft or its part, engine bypass ratio;

N – engine power;

$\bar{N}$ – aircraft power-to-weight ratio;

$n_р$, $n_э$ – ultimate and limit load factors;

$n_{пас}$ – number of passengers;

P – engine thrust;

$\bar{P}_0$ – aircraft start thrust-to-weight ratio;

p_0 – wing loading;

q – dynamic pressure;

ρ – air density;

Δ – air relative density;

S – wing area, tail area;

$\bar{S}$ – the relative tail area;

η – wing taper ratio, tail taper ratio;

V – flight velocity;

$V_у$ – rate of climb;

$X_м$ – center of gravity coordinate;

X_F – aerodynamic center coordinate;

φ – aircraft overturning angle;

$\varphi_н$ – coefficient to account for thrust change with flight altitude;

$\varphi_{др}$ – engine throttling coefficient;

ψ – aircraft ground angle;

ξ – coefficient to account for thrust change with flight velocity.

ABBREVIATIONS

daN=10N – decanewton;

MAC – mean aerodynamic chord;

TJEA – turbojet engine with the afterburner duct;

BTJE – the bypass TJE;

RE – the reciprocating engine;

TPE – the turbo-propeller engine;

TPFE – the turbo-propeller and fan engine;;

SUBSCRIPTS

в – wave;

взл – takeoff;

во/го – vertical/horizontal empennage;

дв – engine;

зп – landing approach;

к, кон – frame, airframe;

ком – commercial;

крейс – cruise, cruising;

кр – critical, limit;

0 – initial, start value;

об упр – equipment and control system;

отр – airplane takeoff;

наб – climb;

нз – air navigation margin;

пас – passengers;

пос – landing;

пн – payload;

полн – total load;

п, (пот) – altitude limit;

пуст – empty;

р – calculated;

разб – takeoff run;

рейс – flight;

рв/рн – elevator/rudder;

сн – equipment;

су – power plant;

ф – fuselage;

цн – payload;

ш – landing gear;

эк – crew.

PREFACE

Design of new technical systems is one of the most challenging kind of engineering activities.

The aim of this manual is to briefly state theoretical bases of methods and models used in conceptual airplane design, to develop and consolidate understanding of the relations between the main airplane parameters and characteristics, and to prepare students to perform their graduation projects.

The main feature of the conceptual design is the necessity of making decisions without sufficient data or, contrary, with redundant data. It has big difference from "school" tasks, which have the number of inputs that is exactly enough to obtain one certain result.

Besides, a designer should try to make his work in the way that guarantees the best results. For example, when designing a wing it is necessary for this wing to have the maximum lift-to-drag ratio, the minimum weight, the sufficient lifespan and enough internal volume to contain the large amount of fuel, to be easy to manufacture and etc. I.e. the design tasks are usually multi-criteria. In this example almost all criteria are inconsistent, so a designer should be able to make trade-offs. All of this makes the solution of design problems very complicated.

In practice the special technology of solving these tasks was developed, and it consists of problem decomposition, criteria hierarchy and other methods. Drawing on the previous experience in the form of prototype statistics plays an important role in conceptual design.

In this manual the task of choosing airplane general shape and defining its main parameters and characteristics is divided into several relatively independent sub-tasks, in which some decisions have to be made. Solutions to the previous sub-tasks are the starting data for the following sub-tasks.

It is important to notice, that a project of a new airplane should be obtained in the result of this work, and simple redesign of existed airplanes should be excluded. The statistics should used only as auxiliary information for solving problems that arise on the corresponding design stages.

The manual includes the minimum set of simple relations that are necessary for draft design. It was intended to lighten the difficult work that should be done during one semester. These relations were sorted out to make students better understand (without overstressing them) an influence of separate project parameters (airplane aerodynamic layout, wing specific load, thrust-to-weight ratio and etc.) on the main airplane characteristics (take-off weight, fuel consumption efficiency and etc.). Thus it is necessary to provide computer-aided support of executing students' work in the way that the relations will be noticeable for students. So it is useful to vary some parameters in calculating formulas and make plots of the calculated results.

It should be mentioned that relatively simple models, based on fundamental laws of physics and mechanics, underlie the base of the analytical formulas. For example, a weight estimation for a bending cantilever underlies is used for a wing weight formula. Estimation of wing unloading by engines, fuel, account for sweep angles, taper ratio, technological factors are usually made with the help of coefficients that are taken from analysis of existed airplane statistics. Students should notice that these coefficients are dimensional, and their units depend on the units used for project parameters. So the product of mass square root and aspect ratio in the power of 3/2 divided by wing specific load gives a result in kilograms due to dimensional coefficient. Thus students should pay attention to the units of the parameters which are used in formulas; particularly, it concerns foreign sources that contain formulas which assume parameters with non-SI units as inches, pounds and etc.

This tutorial contains only necessary information for obtaining the first experience in the conceptual airplane design. Also it is supposed that students refer to textbooks and other scientific Russian and foreign sources, which seems difficult at first. In this case this tutorial should be used as a guide-book for additional information sources.

The main information source, on which this tutorial is based, is the textbook published in 1983, edited by S.M. Eger and republished in 2005. Both the textbook and this manual offer the design methodology intended mostly for educational purposes: it shows the sequence and algorithms of executing main stages of draft design, helps to understand relations between chosen project parameters (starting values) and airplane characteristics (airplane performance) and helps to find a way of increasing an airplane efficiency.

In practice high-accuracy mathematical simulations of all airplane life-cycle stages (from the beginning of design till utilization) are used in airplane design. Software complexes enable to execute separate project stages with using state-of-the-art optimization methods optimization in order to provide high efficiency of the airplane during its whole life-cycle. Besides, solutions of real project tasks requires the use of the standard documentation. The difficulty and lack of clearness (black box effect) of this design approach do not allow to use it in educational purposes. At the same time, executing the simplified project allow a future specialist to adapt more easily to real current conditions of airplane computer-aided design.

The manual contains models that should be complemented by more accurate and adequate simulation models in the graduation design project. Their complexities should be chosen according to available resources (information, computer, time and etc.).

1 DEVELOPING THE AIRPLANE DESIGN CONCEPT

Designing a new airplane starts from development of a concept - a general idea for airplane. The concept defines ways, means and parameters that should provide high efficiency and competitiveness of a future airplane, its superiority in comparison with airplanes that are already exploited or designed.

The concept of a future airplane is determined by requirements for corresponding airplane functional and performance characteristics defined by a customer. Then a concept of a future airplane – its scheme and set of values for main parameters – is chosen. All main parameters that will be chosen and determined at these stages should be based on statistics and take into account the aviation development dynamics by forecasting changes of the most important airplane features and characteristics with time. It requires knowledge of the latest achievements in the field of aviation science and technology - aerodynamics, engine, equipment, weapon and airframe engineering, constructional materials, airplane operation and etc.

Development of the airplane design concept while executing laboratory works, term and graduation design projects, requires working up a list of new technical achievements in the field of aviation with estimation of its approximate positive influence on the main airplane parameters and characteristics: possible decrease of airframe mass, fuel and power plant; expected improvement of airplane performance. This list should contain specific technical innovations that should provide the improvement of efficiency ratios for the designed airplane. For example, in aerodynamics it can be using new supercritical airfoils, utilizing tip vortex scatterers, wing boundary layer laminarization systems. Constructional perfection can be provided by decreasing the number of structural divisions, applying honeycomb structures, employing new materials such as aluminum-lithium and titanium alloys. While making a detailed list you may approximately estimate the influence of each innovation on corresponding airplane parameters and characteristics. This information can usually be found in dedicated literature, and it is recommended to use it while executing this stage of your project.

An example of such estimation of positive influence of state-of-the-art solutions on advanced airplane performance is the fifteen - year scientific and technical forecast made by one of the foreign airplane production companies. According to it passenger planes designed and built with 2010th technologies have to weight on 23-35% less then airplanes of the year 1995. This significant take-off mass decrease is achieved by using following technological advances: wing boundary layer laminarization (4-6%), advanced aerodynamic schemes (6%), applying new materials (8–10%), advanced power plants (3%), equipment and systems (1%). These numbers are just an example, and now it can be a little out of date. Fresh forecasts can be found in new publications, especially periodic, combining it with gathering statistics. For example, TzAGI Technical Information bulletins are very useful.

Development of the future airplane design bases on foreseeing changes of airplane main parameters and characteristics with time. Methodology of making such forecasts are considered in the special scientific discipline [4]; its general aspects are given further (in the section 1.3).

1.1 Working out statistics

Before developing a new airplane project it is necessary to scrutinize statistics of airplanes of the same type as your design. These data should be in the form of tables which contents and structure should satisfy goals and tasks of the early design stages. The statistic tables comprise main parameters and characteristics of prototype airplanes that are similar to the design airplane in type and values of payload weight and flight range.

The tables should include data on at least 5-6 airplanes (up to 10 airplanes for diploma project): country and company of production, year, type, number of engines and its main characteristics; airplane mass, geometric and performance characteristics. Geometric characteristics are given in absolute and relative forms. Additionally, there should be brief descriptions of each airplane with its design features, the most interesting ideas and new technological solutions. Also a number of airplanes built or demand for such airplanes can be mentioned.

The description of each prototype should include scaled three-projection drawings, which can be used for definition of missing geometric parameters.

An example of such table is given in the Appendix A.1 (see APPENDIX A). This table in general can be applied for different airplanes, but it should be modified according to critical airplane parameters. Parameters unimportant for the certain airplane type can be taken away from this table.

Only the latest generation airplanes must be included in a statistics table because it guarantees getting up-to-date information that shows current aviation development tendencies. Old airplanes can give some irrelevant information and influence on accuracy of design parameter forecasts.

Also while choosing airplanes for statistics you should remember that performance characteristics and some relative parameters do not noticeably depend on absolute airplane dimensions and masses. It allows to include prototypes, whose the payload weight and the flight range can substantially (30-40%) differ from design airplane parameters.

While choosing prototype airplanes you should prefer mass-production airplanes whose accurate parameters can be figured out from books rather than experimental airplanes, whose parameters and performance characteristics are often preliminary and conditional. Besides, the performance of experimental airplane can be changed significantly during the development.

If there were several modifications of the chosen airplane, each can be separately accounted for on statistics. Or sometimes it is enough to choose just one modification that has the most in common with the design airplane.

Sources for obtaining statistics are domestic and foreign reference books, aviation encyclopedias, reports of different scientific and research institutions, specialized magazines and other periodical editions. Also you can use aviation databases from the Internet [29].

You should pay attention to data reliability while collecting statistics. Different sources often give conflicting data.

Sometimes there are no remarks that given characteristics are maximum, but not simultaneously achievable, for example, the maximum range and maximum payload can't be achieved at the same time. Thus it is necessary to make corresponding remarks in your table about conditions under which the specified performance value can be achieved (see lines 37, 38 in the table of the Appendix A.1).

While analyzing and forecasting changes of the most important design parameters, another kind of statistical survey should be done.

It should include more airplanes (at least 8-10) which can be of different generations. All these airplanes are entered in the statistics table that contains only the analyzing parameters. The values of these parameters are used for regression analysis. A list of parameters, that should be forecasted using the method from section 1.3, is discussed with your project supervisor.

1.2 Analyzing the design situation

A design situation analysis is carried out on basis of statistics research and airplane development study. During this analysis the following problems should be solved:

1) Future demand for airplanes should be assessed with the required number of airplanes in the certain time, for example, 5-10 years. This information can be found in publication from periodical editions, describing the airplanes of a given type, and in review magazines dedicated to international air shows.
2) History of the development should be investigated, and achieved perfection degree of a given type of airplanes should be mentioned.

The average statistical and maximum values of the most important performance parameters, geometric and weight parameters, the mileage rating and cost efficiency of these airplanes should be given. Also maintenance and operating features - airplane cost, traffic handling cost, an airplane life, reliability indexes, comfort ratios and etc. should be included.

3) Development prospects should be studied, and changes in main performance and relative airplane parameters should be forecasted for the near future. Thus, dynamic and static diagrams for the most important prototype parameters should be plotted using data from statistic tables; then their trend functions with an approximation errors should be figured out and forecasted (extrapolated) parameter values should be found [4]. New engineering solutions that are expected to improve the value of each parameter should be mentioned.

The approximate average values are used for the parameters that have a small number of statistical points.

Each airplane is a part of a complex system comprises a number of subsystems that supports all stages of an airplane life-cycle: from production till utilization. All subsystems are interrelated, and improvement of one's performance will increase efficiency of others and of the whole system. Each new airplane influences on operation and efficiency of adjacent serving systems, so it is possible to estimate the change of global system efficiency at early design stages: how can new airplane change production and operation, environment and other related fields.

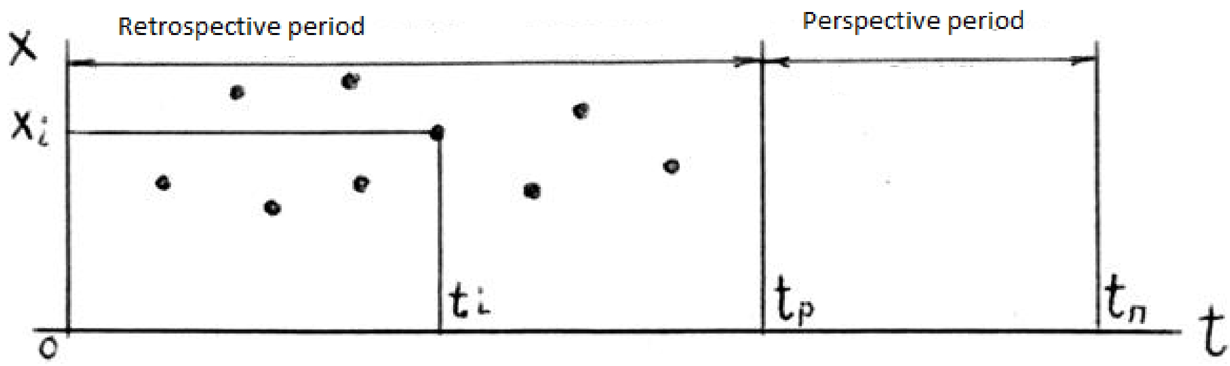
1.3 Scientific and technical forecast basics

An airplane, as a technical object, is a complex system comprising a large number of subsystems (assemblies and equipment systems), which in turn consist of smaller subsystems and elements (units and parts). Each of these components has the certain number of parameters that define its performance: geometry, weight, aerodynamics, operation and etc. The sum of these parameters gives what is called an “airplane shape”. Instead of this generalized meaning it can be used in more simple specific variants that combine only some group of parameters: geometric, weight and etc.

All parameters can be conventionally divided into two groups:

- constant parameters that do not change in the airplane design process; they are usually defined by requirements;
- variable parameters that are chosen and varied in the design process; their combination defines the main features and properties of a design object that are called “characteristics”.

The statistics of already produced prototype airplanes allows for deriving dependences between their parameters and characteristics of interest. If we take the current time t as the factor, diagrams can show the tendency of changing parameters according to year of production, and we obtain dynamic parametrical series of the retrospective period t_p for each parameter x (Figure_1_1).

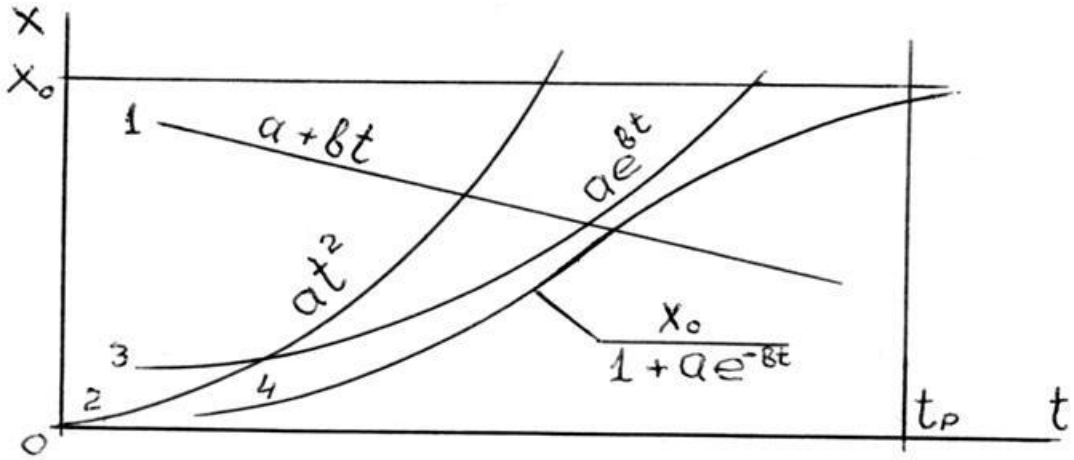


The Figure 1.1 – The dynamic parametrical series

It is important to know the values of the main airplane parameters and characteristics for the certain period of time $t_п$, when you are designing an airplane. This task of forward-looking analysis is carried out by methods of scientific and technologic forecasting.

The forecasting is usually based on a preposition that the same kind of relation between parameters and characteristics as was observed in the past, will hold in the future. Thus it is enough to find this relation - the general tendency of changing a parameter during some period of time t_p, by retrospective series interpolation, and extrapolate it to the future moment $t_п$. The time $t_п$ must correspond to the length of development cycle of a new airplane (at present it can be 5 years or more).

To discover a tendency (a trend) of changing a parameter it is necessary to select a mathematical model (a function) that approximates time-parameter relation. Approximating functions are usually simple: linear (1), quadratic (2), exponential (3), logistic (4), etc. (Figure 1.2). Logistic approximations or S-shaped curves are used for processes that, on the one hand, have the initial stage of quick change and, on the other hand, have significant physical constraints and limits. For example, the coefficient of efficiency cannot be more than 1; the maximum range of passenger airplanes quickly increased at the second half of the 20th century, but the range that is more 16-17000 km is unnecessary because of geographical considerations. In practice other approximating functions can be used.



The Figure 1.2 – The standard trend functions

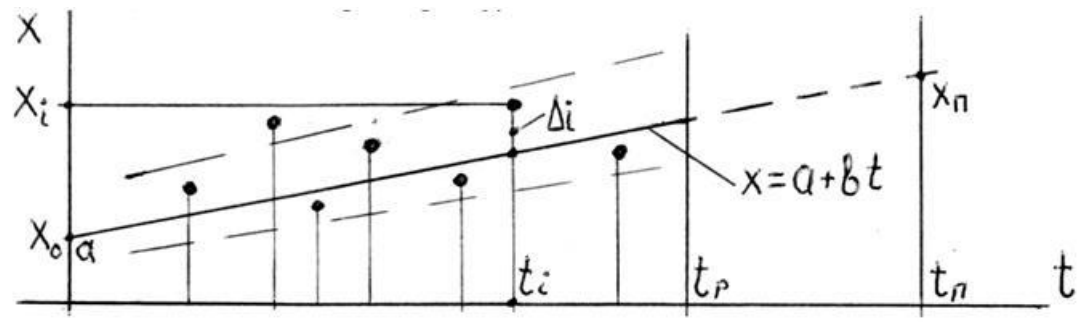
The approximation accuracy of the chosen trend function is defined by least-squares method.

The behavior of an approximating function can be chosen from overall picture of retro series statistical point location, or by using additional relations between investigated parameter and some factor chosen from simple physical considerations. If there are no such factors, trends of 2-3 standard functions can be tried for the retro series and then you can choose a trend that gives the least approximation error.

The method of defining trends for some simple standard functions is discussed further.

1.3.1 The linear trend function

Let retro series statistical points locate in some narrow “corridor” that is constrained by straight lines (The Figure 1.3). Each point corresponds to value of the parameter x_i at the time t_i. The number of points is n.



The Figure 1.3 – The approximation of the linear function retro series

For this case the linear relation between the parameter and time can be considered as the trend function.

$$x(t) = a + bt.$$

This straight line should pass through the given “corridor” and show the averaged dependence of a parameter from time. The exact location of this line is defined by parameters a and b.

Each statistical point $x_i(t_i)$ has the divergence (the error) relative to the trend line in the point t_i, $x_i(t_i)$

$$\Delta_i = x_i(t_i) - x(t_i).$$

The “best” values of the parameters a and b, that provide the least approximation error, are found by the least-squares method. According to this method the most accurate location of the trend function is correspond to the minimum sum of squares of statistical points deviation from the approximating line

$$S_{min} = \sum_1^n [x_i(t_i) - x(t_i)]^2.$$

The minimum of this sum provides the minimum value of the root mean square (RMS) error that defines the accuracy of the statistical retro series approximation.

$$\sigma = \sqrt{\frac{S}{n-1}}.$$

The minimum conditions for S define that partial derivatives are equal to 0

$$\frac{\partial S}{\partial a} = 2\sum_1^n [x_i - (a + bt_i)]\,(-1) = 0;$$

$$\frac{\partial S}{\partial b} = 2\sum_1^n [x_i - (a + bt_i)]\,(-t_i) = 0.$$

After transformations we obtain two equations for *a* and *b*

$$na + Ab = B;$$

$$Aa + Cb = D,$$

where determinants are defined by parameters

$$A = \sum_1^n (t_i); \qquad C = \sum_1^n (t_i)^2;$$

$$B = \sum_1^n (x_i); \qquad D = \sum_1^n (x_i t_i)$$

and equation solution (sought trend parameters) is equal to

$$a = \frac{BC - AD}{nC - A^2};$$

$$b = \frac{nD - AB}{nC - A^2};$$

$$x_0 = a.$$

The predicted parameter values

$$x_n = a + bt_n.$$

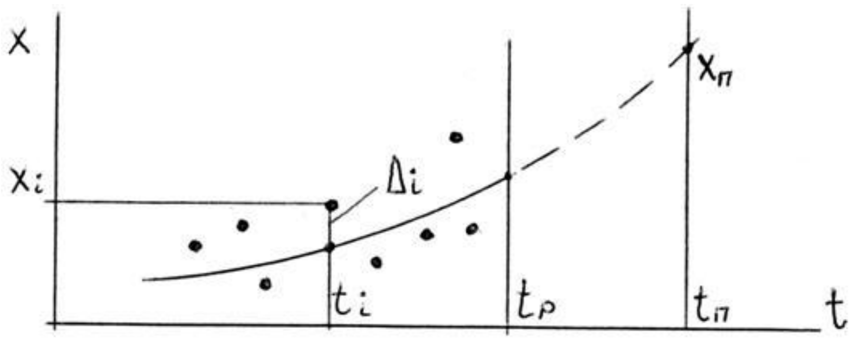
The parameters x_0 and $x_п$ are defined by the approximating line location at the diagram $x(_t)$.

Calculating the approximate values for points t_i we can find deviations Δ_i, the sum of deviation squares S and the root mean square error σ.

These calculations can be made by hand in a table. Or you can use the procedure to create a computer program for defining the trend function parameters, or employ built-in approximation tools from software package Mathlab.

1.3.2 The exponential trend function

Consider a case when statistical values from retro series rapidly increase with time (Figure 1.4)



The Figure 1.4 – The exponential function approximation

It is convenient to use an exponent as the approximating trend function in this case

$$x = x_0 e^{bt} e^{bt}.$$

To find x_0 and b we can take the logarithm of the exponent to obtain

$$y = a + bt,$$

where

$y = \ln x$y;

$a = \ln x_0.$

The coefficients *a* and *b* are defined by formulas that are similar to ones for the linear trend

$$a = \frac{BC - AD}{nC - A^2};$$

$$b = \frac{nD - AB}{nC - A^2};$$

where

$$A = \sum_1^n t_i; \qquad C = \sum_1^n t_i^2;$$

$$B = \sum_1^n \ln x_i; \qquad D = \sum_1^n (t_i \ln x_i).$$

When *a* and *b* are found, we can find x_0

$$x_0 = ea$$

and the trend function

$$X = e^a e^{bt} = e^{a+bt}.$$

Then the deviations Δ_i, their sum S and the RMS error σ can be calculated.

1.3.3 The logistic trend function

You should use S-shaped functions if, on the one hand, a parameter of the statistical array has the rapid changing zone and, on the other hand, it has the maximum and/or minimum constraints related to the physical of other reasons. The most simple of the S-shaped functions is the logistic function, whose shape and mathematical expression are shown at the Figure 1.2.

The example of such relation is a history of change for airplane flight velocity $V_{рейс}$. Flight velocity is equal to the average velocity of travel from a point of departure to a point of arrival, including the time spent on taking off and landing an airplane: from the moment of starting the engine till the moment of the engine cutoff. The flight consists of three stages:

— Airplane takes off and reaches the cruise flight altitude;

— Airplanes flies with the cruise speed at the cruise flight altitude;

— Airplane descends and lands.

The average velocity at the first and the last stages is much less than the cruise velocity at the main flight stage (the second stage). Thus the averaged flight velocity is always less than cruise velocity. But if we suppose that the distances of the first and third stages are almost independent from the total flight distance, the time span of the second stage increases with increasing the total flight distance; it leads to increasing flight velocity which asymptotically approaches the cruise velocity at large flight distances.

The logistic trend function:

$$X = \frac{x_k}{1+a e^{-bt}},$$

where $x_к$ – the limiting value of the parameter X,

$$a = \frac{x_k}{x_0} - 1;$$

x_0 – the initial value of the parameter X.

You should use the standard computer programs as Mathlab mentioned above for calculating logistic function parameters.

The statistical dependences of parameters that are irrelative are also used for airplane design. These dependences are called static dependences. So using statistics you can figure out the relation between parameters and airplane characteristics, and also the relation between different parameters.

These relations are usually defined by different scientific disciplines and areas of knowledge that assist the aviation development. Results of this scientific knowledge are realized in formulas that express relations and contain a number of parameters. At the beginning of the design process most of the parameters are unknown. In this case you can use statistics in the form of dynamic and static diagrams for choosing the values of main parameters as a first approximation. The simplest static diagrams show the connection between two parameters. They define the practical use area of the considered parameters for the period of time. As the aviation develops the limits of this area can be extended, and forecasting these limits can be made by extrapolation of existing relations to the future. Finding the static tendencies and relations and obtaining their trend functions can be done in the same way as for dynamic parameters. The static diagrams for two parameter straight lines or curves in the parametric space defined by these parameters. If we plot such curves for several discrete values of the third parameter, we obtain a curve grid that shows the relation between three parameters. Extrapolating this grid, we can get the view of extended area for these parameters.

In practice parameter values chosen as the first approximation basing on statistics are updated by optimization methods and computer programs.

2 DEVELOPING THE AIRPLANE PERFORMANCE REQUIREMENTS

The performance requirements (PR) to an airplane define the main goals and tasks of its creation, conditions of practical operation, required values of the main airplane parameters and characteristics, conditions of production. The initial data for developing the performance requirements are the content of the design requirements specification and the results of analyzing a design situation.

All airplane requirements are divided into several groups. The content of these groups and recommendations of their development are offered below.

2.1 The functional requirements

These requirements give the general idea for creation of a new airplane. They define the airplane type and class, the airplane functions and main parameters and characteristics. This group includes the following airplane design properties:

1. Airplane type.
2. The main tasks fulfilled by an airplane.
3. The variants of operation for an airplane and its possible modifications.
4. The content of payload
5. Airplane crew.
6. Degree of automation of the main flight stages.
7. Conditions of stationing, airfield class, runway types.
8. The equipment necessary for handling freights/payload.
9. The opportunity for personnel and material airdrops.
10. The opportunity of autonomous maintenance at unprepared airfield.
11. Armament.
12. Mission tactics and combined arms requirements, time to prepare for the next sortie.

13. ECM and other defense.

2.2 The technical requirements

This group of requirements defines the main flight characteristics of a future airplane, its reliability and safety.

First, a list should be made of the most important qualitative requirements for the airplane without specifying their numerical values.

Second, numerical values and/or limits for the main performance parameters and characteristics are specified.

The list of qualitative requirements contains the most important airplane properties requiring the closest attention. The list of these requirements can help designers to make right and well-founded decisions about key problems that arise in the design process.

The content of these requirements is defined by airplane functions and goals. Each type of an airplane has its specific requirements.

Generally, the requirements in this list are contradictory. The improvement of some airplane properties can lead to deterioration of others. This situation is described by the Pareto set in the optimal design theory.

Resolution of conflicts between requirements can be made by first weighting their importance. You can rank all requirements and sort them according to their relative rang. It allows designers to focus on top priority requirements.

The procedure of ranking the requirements is subjective, and its results depend on the knowledge and experience levels of the designer, and also on the general concept for a new airplane.

The ranking objectivity can be increased by using expert estimations, involving highly qualified specialists, which can be difficult for educational projects. So it is easier to apply one of the scoring methods - the paired comparison method.

The method contains the following stages. All important requirements are listed in random order. Each pair of listed requirements is considered one after another. Within the pair requirements are compared. According to this comparison each requirement is given a number of points. The scale of points can vary. For example, the most important requirement can obtain 2 points, the requirement of less importance - 0. The requirements of equal importance obtain 1 point each. If there is the significant difference of importance the score can be 2:0; if the difference of importance is not so big the score can be 1:0. You can make your own scale for comparing requirements. The results of the paired comparison are listed in the special table, the last column of which contains the rank of each requirement that is defined by summing points. The rank defines the place of each requirement in the general list.

The example of using the paired comparison method for ranking requirements for the military transport airplane is given below. The approximate list of the main requirements for this airplane (in random order):

1. High cruise speed.
2. Time necessary for loading and unloading freights.
3. The possibility for transportation and air-dropping of light- and mid-weight infantry equipment.
4. Good taking-off and landing performance and the opportunity to operate from unpaved runways.
5. High fuel efficiency.
6. The opportunity for autonomous maintenance at unprepared airfields.
7. The convenience of maintenance and repair.

Considering each pair of requirements one after another, you should give the comparative evaluation of importance using the mentioned above three-point scale.

a) Requirement "1" - Requirement "2".

Decreasing the time of loading and unloading is more important than decreasing the time of the cruise flight (achieved by high cruise speed). Thus the requirement "2" gets 2 points, the requirement "1" gets 0.

b) Requirement "1" - Requirement "3".

The necessity of transportation and air-dropping personnel and equipment is more important than the increased flight velocity. Thus, the requirement "3" gets 2 points; the requirement "1" gets 0.

c) Requirement "1" - Requirement "7".

These two requirements are approximately equal in importance, that's why they get 1 point each.

The results are entered in the Table 2.1 after comparing all requirements.

The Table 2.1 – The results of ranking requirements

№	1	2	3	4	5	6	7	score	rank
1	☼	0	0	0	0	1	1	2	7
2	2	☼	1	1	2	2	2	10	1
3	2	1	☼	1	1	1	1	7	3
4	2	1	1	☼	2	2	1	9	2
5	2	0	1	0	☼	0	0	3	6
6	1	0	1	0	2	☼	2	6	4
7	1	0	1	2	2	0	☼	6	5

If two requirements got the equal number of points, their ranks are defined by comparing them one more time (requirements 6 and 7).

The ranked results enable to make the list of requirements in the decreasing order of their importance.

1. Time necessary for loading and unloading freights.
2. Good taking-off and landing performance and the opportunity to operate from unpaved runways.
3. The possibility for transportation and air-dropping of light- and mid-weight infantry equipment.

4. The opportunity for autonomous maintenance at unprepared airfields.
5. The convenience of maintenance and repair.
6. High fuel efficiency.
7. High cruise speed.

Now a designer should pay attention to the top priority requirements before making some decisions while designing an airplane.

It should be mentioned that the estimations of the requirements entered in the table are approximate, they only to show the idea of the paired comparison method. Each designer can change the list of requirements and give them other ranks according to the airplane features, operation conditions, his understanding of the design situation and the general concept of an airplane design.

2.3 The performance requirements

These requirements set up numerical values for the main performance characteristics of the designed airplane. These are usually flight velocity and altitude, design range, rate of climb, take-off and landing characteristics, design and operating g-loads and etc.

The numerical values of performance characteristics should be based on statistics and take into account the forecasted development for such airplane type. It can be aided by making diagrams that show the relations between parameters: velocity - range, flight altitude - range and etc., and also diagrams that show the change of performance characteristics for prototype airplanes according to their time of production. The forecasting of parameter values should be executed by finding the trend functions and their extrapolation for the next few years.

For PR the numerical values of each performance parameter should be set up within the range "from-to", or below the upper limit "no more than", or above the lower limit "no less than". It’s not recommended to set up the certain value for a parameter. Such strongly defined parameters are given only in the design task.

The list of performance parameters and characteristics that are set up while developing PR defines the airplane type.

Thus for passenger and military transport aircraft you should give the general parameters of the cruise flight - cruise velocity and flight altitude, together with take-off and landing characteristics - take-off run and landing speed. Expected range and payload are usually listed in requirements specification.

For maneuverable and military aircraft beside take-off and landing characteristic you should add maximum velocity, maximum altitude, rate of climb, turn radius, allowable g-loading and etc.

2.4 The manufacturing requirements

These requirements define the scale of production, the general constructional materials, also including the necessary kinds of new semi-manufactured and raw materials and their limiting dimensions, the general manufacturing methods and new processes required, the degrees of standardization and unification, and other qualitative and quantitative characteristics of an airplane manufacturability.

2.5 The operational requirements

There are requirements related to main and emergency exits and entrances, devices for emergency escape, convenience for the crew, control automation, cockpit visibility, passengers comfort, mechanization of loading and unloading, maintainability and ease of repair, ease of detachment and replacement of parts and equipment, possibility for autonomous maintenance, airplane life-span (in flight hours), required airfield class.

2.6 The technical and economic requirements

These are efficiency parameters of airplane manufacturing and operation: the airplane anticipated cost, traffic handling cost, fuel efficiency ratio, the cost of a flight hour and etc.

2.7 The other requirements

These are airplane class according to durability standards, the anticipated airplane market, environmental requirements.

3 CHOOSING THE AIRPLANE SCHEME

The airplane scheme defines a number, shape and relative position of its main units - the wing, the empennage, the fuselage, the take-off and landing equipment, and also the number and placement of engines and their air intakes. The airplane scheme has an influence on airplane properties and characteristics, and, finally, it defines the total efficiency of an airplane. The scheme of each airplane is stipulated by its type, operation conditions and the main requirements for airplane design. The key problem that should be solved while choosing an airplane scheme is to satisfy PR in the best way and provide the minimum airframe and takeoff weight, the highest lift-to-drag ratio and the maximum airplane efficiency.

The aerodynamic scheme depends on airplane layout. Thus questions of placing the crew, payload, fuel and engines should be considered at the time of airplane scheme develop.

According to a number of units there are following airplane schemes available: monoplane or biplane, with one or two fuselages, with one or more surfaces of horizontal and vertical empennage, with two-, three- or multi-support landing gear, with different number of engines.

The airplane scheme main features are defined by a number and relative position of lifting surfaces, that are divided into main surfaces that create the most part of lift (wings), and additional surfaces (empennage) that provide the balancing, the control and the stability of an airplane. There are the following airplane balancing schemes according to relative positional of the empennage and the wing:

- "normal" - the horizontal empennage (tail) is behind a wing;
- "tailless" - there is no horizontal empennage;
- "canard" - the horizontal empennage is in front of the wing;

— "combined" - the "normal" scheme plus the additional horizontal empennage that is in front of the wing; this scheme has some layout advantages due to the wing displaced backwards; additional front empennage also improves stability and control of maneuverable airplanes.

If take-off weight and dimensions of an airplane are undefined, its scheme can be described by non-dimensional geometric parameters that determine the shape. As a result, the development of the scheme adds up to choosing numerical values of relative parameters that define the shape and the relative position of the main airplane units.

Decisions made while forming an airplane shape are significant, because it is difficult to correct errors that are made at this stage. Thus the choice of airplane scheme and its parameters should be well-considered and well-founded; particularly, it concerns the most important parameters that have the strongest effect on airplane performance.

3.1 Choosing the scheme parameters

The sequence for choosing the airplane scheme is the following:

1. Estimate the layout of crew, payload and fuel.
2. Choose the lifting system configuration for cruise, take-off and landing stages.
3. Choose the balancing scheme.
4. Choose the parameters for wing, empennage, fuselage, control units and lift augmentation devices.
5. Choose the scheme and parameters for the landing gear.
6. Choose the type of engines, their number and placement on the airplane.
7. Estimate the approximate values of aerodynamic performance, power-plant performance and specific wing load.

8. Draw a three-projection and/or axonometric design drawing of the airplane general view.

The parameters of the main airplane units to be chosen are the following.

Wing scheme parameters

Wing aspect ratio λ, wing taper ratio η and sweep angle χ.

Type of an airfoil and its relative thicknesses at root and tip chords $\bar{C}_0$, $\bar{C}_к$, wing dihedral angle. Type of lift augmentation devices, their relative areas and relative chords, flap deflection angles, slat deflection angles, interceptor deflection angles, spoiler deflection angles.

The influence of the main wing parameters on the airplane performance is considered in [1], [2], [3], [5],[6],[7], [17].

Choice of the wing aspect ratio and sweep angle should be biased on trend functions for static series, showing the relation between these parameters and flight velocity and range.

Fuselage parameters

Fuselage cross-section shape: round, oval, rectangular, vertical or horizontal "8"-shaped, etc. Using statistics you can assume preliminary values for fuselage aspect ratio $\lambda_ф$, forward fuselage part aspect ratio $\lambda_{нч}$ and rear fuselage part aspect ratio $\lambda_{хч}$. Shape and parameters of a cockpit canopy can be chosen according to [1], [3], [5], [6]. The values of fuselage parameters will be adjusted at later design stages.

Empennage parameters

Relative areas:

$$\overline{S_{го}} = \frac{S_{го}}{S};$$

$$\overline{S_{во}} = \frac{S_{во}}{S};$$

Aspect ratios $\lambda_{го}$, $\lambda_{во}$, taper ratios $\eta_{го}$, $\eta_{во}$, and sweep angles of horizontal and vertical empennage $\chi_{го}$, $\chi_{во,}$ their relative thicknesses $C_{0во}$, $\bar{C}_{го}$.

Control unit parameters

Main and additional units for longitudinal, transversal and lateral control and their location on the airplane. According to the statistics and balancing scheme, the relative areas of all control surfaces and their relative chords and deflection angles are set up.

Relative position of airplane units

Wing-fuselage

You should choose one of the three schemes for the wing vertical location with respect to the fuselage - low wing, mid wing or high-wing. The background for this choice is described in [1], [2], [3], [5], [6]. Wing position along the fuselage axis is defined by the relative distance from the fuselage nose to the wing apex (the point of intersection between extended wing leading edge and airplane symmetry line), and is usually chosen from statistics:

$$\bar{\ell}_{ц} = \frac{\ell_{ц}}{\ell_{ф}}.$$

Another way of binding the wing to the fuselage is considered in [3], p.475, where you can find the statistics diagram for the relative length of forward fuselage part defined as the distance from the fuselage nose to the quarter mean aerodynamic chord (MAC) of the wing. This parameter, $\bar{\ell}_{нч}$, generally depends on the engine location and can be taken equal to:

- 0,45 – 0,50 – for airplanes that have turbo-jet engines located under the wing;
- 0,52 – 0,53 – for airplanes that have two engines under the wing and the third engine in the rear fuselage;
- 0,52 – 0,57 – for airplanes that have all two, three or four engines at the rear fuselage.

Wing incidence angle is usually taken about $\alpha_{зак}$= (2-3)°.

Wing - empennage

The airplane balancing scheme parameters should be checked more thoroughly [1]. The arms of the horizontal and vertical empennage are chosen according to statistics

$$\overline{L_{го}} = \frac{L_{го}}{bA}$$

$$\overline{L_{во}} = \frac{L_{во}}{\ell};$$

also their static moment coefficients are defined

$$A_{го} = \overline{S_{го}} \cdot \overline{L_{го}}$$

$$A_{во} = \overline{S_{во}} \cdot \overline{L_{во}}.$$

These parameters will be revised while making the airplane general drawing.

Landing gear parameters

Landing gear type and location can be chosen according to [1], [2], [3], [5], [6]. The main relative parameters are chosen according to statistics:

— wheelbase $\overline{\mathrm{b}} = \frac{\mathrm{b}}{\ell_{\phi}};$

— tread $\overline{B} = \frac{B}{\ell};$

— offset $\overline{e} = \frac{e}{b}.$

Wing landing angle of attack $\alpha_{пос}$ is chosen with using the typical polar graphs ([1], p. 582-584), static ground angle $\psi_{ст}$ is chosen according to ([1],p. 525), then the angle of airplane tipping can be found as

$$\varphi = \alpha_{пос} - \psi_{ст} - \alpha_{зак}$$

and main wheel offset angle is defined

$$\gamma = \varphi + (1-2)^0.$$

All parameters of the landing gear will be revised later while working out the layout and calculating the airplane balance.

Power plant parameters

Engine type is chosen on the basis of velocity range and flight altitudes specified in PR [1], [2], [6], [14], [15]. Bypass ratio m, compression ratio $\pi_к$, gas temperature before turbine $T_к$* are chosen for high-bypass-ratio turbo-jet engines basing upon forecasts of their future development. The value of engine specific weight is chosen according to statistics:

$$\gamma = \frac{m_{\partial в} g}{10 P_0},$$

where $m_{дв}$ – engine mass, kg;

P_0 – engine thrust, daN;

g – acceleration due to gravity, m/s^2.

The values of engine mass and engine thrust are chosen according to statistics, again with the account for prospects of engine industry development. Starting fuel consumption rate C_{p0} is defined according to statistics ([1], p.589–591; manuals [14], [15]); fuel consumption rate at cruise $C_{p\ кр}$ is calculated according to [1], p. 422.

The usage of afterburner increases the thrust by 30– 70% and fuel consumption by 200 – 250%.

For turboprop and piston engines specific weight can be found, according to statistics, as

$$\gamma_{\partial в} = \frac{m_{\partial в} g}{10 N_{в0}} \text{(dN/kWt)}$$

Fuel consumption rate C_e (kg/kW h) is defined according to statistics.

Performance data and parameters of modern engines can be found in the handbooks referenced above.

The number of engines is chosen according to the flight safety requirements and the efficiency of aircraft operation. You need to account for the general tendency of decreasing the number of engines for modern airplane.

Then engine locations (and their air intake locations, if necessary) are defined and justified.

The detailed information on this topic can be found in [1], [2], [3], [6]. It should be noted that once popular scheme of the engine location at the rear fuselage is almost abandoned now because of yielding significant increase of mass for main airframe units (fuselage, wing and tails), which in turn reduces airplane efficiency.

3.2 Justifying the choice of scheme parameters

The choice of scheme parameters is based on statistics. Statistics allows to define the approximate range for each parameter by considering of prototype airplanes. The lower and upper limits of this range are usually constrained by unacceptable values of some other airplane properties or characteristics; for example, possible deterioration of airplane aerodynamics, manufacturing complications, rise of the airframe mass and etc. At the same time, breaking the limits of statistical range can improve some positive airplane properties and characteristics. Thus when choosing the main airplane parameters a designer aims to go beyond the statistical range limits for improving the airplane performance and providing higher efficiency. But this requires usage of the special methods for decreasing the possible negative influence of such going beyond the limits. It can be achieved by state-of-the-art aeronautical and engineering. This way of aviation development, aimed at extension of the limits, is confirmed by statistics of change of the main airplane parameters with time.

In your project you should make the list of new engineering solutions supposed to be used.

The influence of new solutions included in the project on airplane parameters can be taken into account by using the scientific and technological forecast for the choice of the most important design parameters. It is easy to figure out the perspective parameter values in the near future utilizing their trend functions. The perspective time period should be equal to five years and more.

The choice of less important parameters of can be biased in the following way:

- Listing the airplane properties and characteristics that are influenced by the chosen parameter;
- Picking out two-three characteristics from the list that correspond to PR and have the highest rank in the ranked list of requirements (see section 2);
- According to statistics, the parameter value is chosen that satisfies these requirements in the best way.

Consider the example of applying this method for choosing wing aspect ratio λ.

1. Choosing the airplane characteristics and properties that depend on wing aspect ratio:

- flight range $L_{\text{р}}$;
- airplane lift-to-drag ratio $K_{\max}$;
- take-off and landing characteristics $C_{ya\ \max\ \text{пос}}$, $V_{\text{пос}}$;
- maximum velocity $V_{\max}$ and cruise velocity $V_{\text{кр}}$;
- wing mass;
- wing stiffness.

2. Figuring out the main characteristics, depending on the airplane type:

- for passenger, transport and other long-range airplanes they are range (provides the lower limit for λ), wing mass and stiffness (provide the upper limit for λ);
- for short range airplanes of the same type the lower limit is defined by the take-off and landing characteristics and the upper limit is defined by wing mass;
- for fighters the lower limit is defined by take-off and landing or maneuvering characteristics and the upper limit is defined by maximum velocity.

3. Choice of the numerical value for wing aspect ratio λ can be made with the help of statistical diagrams $\lambda(L_{р})$, $\lambda(V_{кр})$, etc.

In practical design the choice of the airplane scheme parameters is made by their optimization using mathematical simulation and CAD programs ([1], [31]). At early design stages simplified optimization methods are usually employed, which allow to find partial optimums for specific parameters. In this case the values of one or two parameters are varied, while others are considered constant. Values of the airplane take-off weight, airframe weight or traffic handling cost for transport and passenger airplanes can be used as target functions. The results of partial optimization of the most important parameters for the wing, the fuselage and the power plant and the recommendations for their choice are given in [24], p.70–78.

3.3 Defining the initial airplane parameters

After the choice of relative scheme parameters the values of the parameters which are necessary for further development of a design can be defined, with the account for PR airplane performance characteristics.

3.3.1 Defining specific wing load

The value of specific wing load p_0 daN/m^2 is defined according to airplane type and its expected performance. The estimations for the influence of this parameter on the main airplane properties are given in [1], [2], [3], [6]. For the given lift augmentation devices, the approximate value of $C_{ya\ max\ пос}$ for landing configuration is chosen according to [1], p.88, [2], p.282.

The necessary value of specific wing load p_0 is defined for main flight configurations that depend on this parameter.

A. Non-maneuverable airplanes

1. Landing configuration

The necessary value of p_0 (daN/m^2) is calculated by one of the formulas^{2}耀given the values of landing velocity $V_{пос}$ or approach velocity $V_{з\ п}$ (m/s):

$$p_0 = \frac{C_{ya\,max\,пос} V_{з\,п}^2}{30{,}2(1-\overline{m}_m)};$$

or

$$p_0 = \frac{C_{ya max пос} V_{пос}^2}{24{,}5(1-\overline{m}_m)};$$

where $\overline{m}_т$ – relative fuel mass; see [1], table 6.1.

<u>Only one of the above formula should be used for calculating p_0!</u>

For military airplanes during the landing stage you can account for the decrease of airplane landing weight by the values $\overline{m}_т$ and $\overline{m}_{расх}$ (expendable combat load - it is taken from the statistics): 1- $\overline{m}_т$- $\overline{m}_{расх}$.

2. Cruise stage

Cruise velocity $V_{кр}$ at altitude $H_{кр}$ should be given in PR. The necessary specific wing load is

$$p_0 = \frac{\Delta_н V_{кр}^2 \sqrt{\lambda_э C_{xa0}}}{13(1-0{,}6\overline{m}_m)},$$

where $\Delta_{н\ кр}$ – relative air density at altitude $H_{кр}$(it is taken from ISA [8]);

$$C_{xa0} = 0{,}8(09 + 0{,}15\mathrm{M}_{кр})\left[0{,}0083(1 + 3\overline{C}_0 + \left(0{,}0083\lambda_ф + \frac{0{,}5}{\lambda_ф^2}\right) + 0{,}004\right],$$

here the Mach number $M_{кр}$ corresponds to cruise flight velocity, when calculating for the case of maximum velocity V_{max} you should take M_{max};

effective wing aspect ratio is equal to

$$\lambda_э = \frac{\lambda}{1+0{,}025\lambda}.$$

B. Maneuver airplanes

Maximum altitude case (see. [1], p.84) and maximum g-load case ([1], p.88) are considered for this type of airplanes besides landing stage.

The final value of specific wing load is the minimum of the three calculated values.

3.3.2 Aerodynamic parameters

Induced drag ratio D_0 ($Cx_{ai}=D_0Cy_a^2$) for subsonic regime

$$D_o = \frac{k}{\pi\lambda_э},$$

where k=1,02 – for tapered wings with λ>3;

k=1,6 - for delta wing with $\lambda\simeq$2.

For supersonic regime

$$D_o = \frac{B_0\sqrt{M^2-1}}{4}$$

where $B_0 = \frac{1}{1-\frac{1}{2\lambda\sqrt{M^2-1}}}$ for straight tapered wings,

B_0=1 – for delta wings with supersonic leading edge.

The maximum lift-to-drag ratio

$$K_{max} = \frac{1}{2\sqrt{D_0 C_{xao}}}.$$

3.3.3 Preliminary airplane sketch

At the final stage airplane scheme choice a three-view projections and/or axonometric sketch of the airplane is made with a summary of its initial parameters:

— For the wing – λ; χ; $\bar{C}_0$;

— For the fuselage – $\lambda_ф$;

— For the horizontal and vertical empennage – $\bar{S}_{г\,о}$, $\bar{S}_{в\,о}$, $A_{г\,о}$, $A_{в\,о}$;

— For the landing gear – $\bar{b}$, $\bar{e}$, φ;

— For the power plant – m; γ; C_{p0}; $C_{р\,кр}$; π_k;

— For the airplane in general – C_{xa0} ; K_{max}; $C_{ya\,max\,пос}$, p_0.

4 REQUIRED START THRUST-TO-WEIGHT RATIO

Start thrust-to-weight ratio is the ratio between net static engine thrust P_0 and airplane take-off weight

$$\overline{P}_0 = \frac{10}{g} \cdot \frac{P_0}{m_0}.$$

These two forces are measured in daN, thus the thrust-to-weight ratio is a dimensionless quantity.

Thrust-to-weight ratio defines the main airplane performance parameters that depend on the power plant. These parameters are flight velocity at given altitude, maximum altitude, rate of climb, take-off characteristics, maneuverability and etc. According to the values of performance characteristic given in PR the required thrust-to-weight ratio can be defined. It is done in the following sequence. First, you make a list of the main airplane performance parameters which should achieved according to PR. Then the required thrust-to-weight ratio is calculated basing upon each parameter. The maximum required thrust-to-weight ratio value is taken for further calculations, as it should allow to achieve all performance parameters given in PR.

The example of parameters which should be taken into account when calculating thrust-to-weight ratio for the most common airplane types is given below.

For non-maneuver airplanes (passenger, transport and other similar types) they are:

- cruise flight velocity $V_{кр}$ at altitude $H_{кр}$;
- required take-off run $\ell_{разб}$;
- possibility for the take-off in case of engine failure;
- if an airplane operates from unpaved airfields, one more conditions is added: moving out from the parking place on wet ground.

For maneuver airplanes (fighters, aerobatic and training airplanes) the parameters are the following:

— maximum velocity V_{max}(or maximum Mach number M_{max});

— rate of climb at sea level V_{y0};

— maximum altitude $H_{п}$;

— maximum g-load $n_{доп}$.

For strategic missile carriers one can also add V_{max} at sea level (for low-altitude flight).

The formulas for calculation of the required thrust-to-weight ratio of an airplane with turbo-jet engines for different flight cases are given below.

1. **Cruise flight with velocity $V_{кр}$ at altitude $H_{кр}$:**

$$\overline{\mathrm{P}}_0 = \frac{1 - 0{,}6\overline{\mathrm{m}}_m}{\xi\varphi_{\mathrm{н}}\varphi_{\mathrm{др}}\mathrm{K}_{\mathrm{кр}}};$$

where $\xi(M_{крейс})$ takes into account the change of thrust with velocity (see [1], p.83);

$$\xi = 1 - 0{,}32M + 0{,}4M^2 - 0{,}01M^3,$$

for $M_{крейс}$=0,8–0,9 it can be taken $\xi \simeq 1$;

$\varphi_{н}$ – correction for flight altitude,

if $H < 11$km $\varphi_{н} = \Delta^{0,85}$,

if $H > 11$km $\varphi_{н} = 1{,}2\Delta$,

Δ – relative air density at altitude $H_{кр}$ (ISA, [2], p.613; [8]);

$\varphi_{др}$ =(0,8 – 0,9) – correction for throttling at cruise flight;

$K_{кр} \simeq (0{,}85 - 0{,}9)K_{max}$ – airplane cruise lift-to-drag ratio.

2. **Required take-off run $\ell_{разб}$:**

$$\overline{\mathrm{P}_0} = 1{,}05\left[\frac{1{,}2\mathrm{p}_0}{\mathrm{C}_{ya\,max\,взл}\ell_{\mathrm{разб}}} + \frac{1}{2}\left(f + \frac{1}{\mathrm{K}_{\mathrm{разб}}}\right)\right],$$

where p_0 – specific wing load;

f – landing gear wheels friction coefficient (see [1], p.76);

$K_{разб}$ – airplane lift-to-drag ratio at take-off (see [1], p.76);

$C_{ya\ max\ взл}$ – wing lift coefficient at take-off (see [1], p.90).

3. Take-off in case of one engine failure

$$\overline{P}_0 = \frac{1{,}5n_{дв}}{n_{дв}-1}\left(\frac{1}{K_{наб}} + tg\theta_{min}\right),$$

where $n_{дв}$ – number of engines;

$K_{наб}$ – lift-to-drag ratio at climb,

$K_{наб} \simeq 1{,}2K_{разб}$;

$tg\Theta_{min}$=0,024 if $n_{дв}$=2,

$tg\Theta_{min}$=0,027 if $n_{дв}$=3m

$tg\Theta_{min}$=0,030 if $n_{дв}$=4;

4. Moving out on wet ground at unpaved airfield

$$\overline{P}_0 = 1{,}4f_{кач},$$

where $f_{кач}$ = 0,1 – 0,12 – rolling friction coefficient for wet ground.

5. Providing maximum velocity V_{max} (M_{max}) at the prescribed altitude

$$\overline{P}_0 = \frac{c_{xao}\Delta_н V_{max}^2}{16.3p_0\xi(M_{max})\varphi_н\varphi_{др}};$$

or

$$\overline{P}_0 = \frac{c_{xao}q_{M=1}M_{max}^2}{p_0\xi(M_{max})\varphi_н\varphi_{др}};$$

where $q_{M=1}$ – dynamic pressure for M=1 at altitude $H_{M\ max}$ (ISA, [8]).

6. Maximum altitude $H_п$:

Subsonic airplanes

$$\overline{P}_0 = 1.67\frac{\sqrt{D_0 c_{xao}}}{\Delta_{пот}};$$

supersonic airplanes

$$\overline{P}_0 = 0{,}83\sqrt{\frac{c_{xao}\sqrt{M^2-1}}{\xi\Delta_{пот}}}.$$

7. Sustained g-load $n_{y\ э}=n_{доп}$ at given V and H:

$$\overline{P}_0 = \frac{1+n_{доп}^2}{2n_{доп}K_{max}\xi\varphi_н\varphi_{др}}$$

For cases 5, 6 and 7 $\varphi_{др}$ is equal to 1 if there is no afterburner, and $\varphi_{др}$ = 1,3 if there is an afterburner.

8. Rate of climb V_{y0}:

$\overline{P}_0 = (\frac{V_{y0}}{V} + \frac{1}{K_{max}}) \frac{1}{\xi \varphi_{др}}$;

if $H = 0$: $\varphi_{др} = 1$, velocity is equal to optimal $V = V_{нвг}$,

$\varphi_{др} = 1$ for nominal thrust; $\varphi_{др}$ = 1,3–1,6 for thrust with afterburner.

Airplanes with turbo-prop and piston engines

For these airplanes the key parameter is start power-to-weight ratio, which is defined as

$$\overline{N}_0 = \frac{10N_0}{m_0 g} (\text{кВт / даН}),$$

where $\overline{N}_0$ – net start engine power, kW, (effective power N_{e0} for turbo-prop engines).

1. Cruise flight

K_N^{VH} takes into account change of power with flight altitude and velocity, it is chosen according to relative engine altitude-velocity performance curves (manuals).

2. Required take-off run

$$\overline{N_0} = 0{,}75(\frac{1{,}2p_0}{C_{ya max взл} f_{разб}} + 1{,}1 f_{разб} + 0{,}033),$$

$C_{ya\ max\ взл}$ (see [1], p.90).

3. Take-off in case of engine failure

$$\overline{N_0} = 0{,}93 \frac{1{,}5 n_{дв}}{(n_{дв}-1) K_{наб}} (\frac{0{,}62}{C_{ya взл}} + \frac{C_{ya взл}}{\pi\lambda} + tg\theta_{min},$$

where $C_{ya\ взл}$= 0,756 $C_{ya\ max\ взл}$,

$tg\theta_{min}$ is chosen the same as for turbo-jet engine.

4. Moving out on wet ground

$$\overline{N_0} \geq 1{,}4 f_{кач}.$$

See [1], p.76 for $f_{кач}$.

The maximum value $\bar{N}_0$ is taken for further calculations.

$\bar{N}_0$ for light and ultra-light aircraft can be found in [9].

5 AIRPLANE TAKE-OFF MASS

One of the most important design tasks is to define the airplane take-off mass $m_{0.}$ The basic idea is to provide all necessary airplane performance and at same time to minimize the value of m_0, because the inappropriate overweight of the airplane decreases its efficiency and competitiveness. The complexity of solving this problem lies in the fact that some take-off mass components depend on the take-off mass value, thus the problem arises: the takeoff mass can not be found without defining some component masses and vice versa. This contradiction is usually resolved by iterative methods: some initial guess is made at the first stage, then more accurate methods and formulas are utilized for calculation of the airplane mass. Statistics of prototypes helps a lot.

5.1 The order of operations

The equation of airplane existence is used for defining the airplane take-off mass [10]. According to this equation, the take-off mass can be defined if some of its components are defined as absolute values (m_i), and others are defined as relative values (m_j=m_j/m_0). In this case the take-off mass can be found from the formula

$$m_0 = \frac{\sum m_i}{1 - \sum \overline{m_j}}.$$

The payload mass $m_ц$ (commercial or expendable combat) is usually given by the absolute value in the requirements specification. The number of airplane crew members is defined while developing PR, so the total crew mass $m_{эк}$ and mass of the service equipment can be defined. Other components of the tak-eoff mass can be defined in the relative form by using the approximate statistical formulas and dependences for the main groups that are included in the airplane take-off mass formula. These formulas usually take into account the most important parameters and contain some number of the statistical coefficients that are obtained by processing statistics on the certain airplane types and classes. Thus, you should pay attention to the airplane type before using these statistical formulas.

The take-off mass itself is included in some of these. So you should take some initial guess value of the take-off mass $m_{0исх}$ before using these formulas. The initial value of the take-off mass can be calculated from the formula given above: the nominator is equal to the sum of absolute masse that are already known or easily calculated; the denominator is equal to the sum of relative masses of airframe $\bar{m}_{к}$, power plant $m_{с\ у}$, fuel system $\bar{m}_{т\ с}$, avionics and control system $\bar{m}_{об\ упр}$, equipment $\bar{m}_{сн}$ that are approximated from statistics. For these purposes you can use the data from the textbook [1], p.130, table 6.1. As a result, you can calculate the initial take-off mass value

$$m_{0исх} = \frac{m_{ц} + m_{эк}}{1 - \overline{m_{k}} - \overline{m_{су}} - \overline{m}_{Тс} - \overline{m}_{обупр} - \overline{m}_{сн}}.$$

When you have $m_{0исх}$, you can find the relative masses more accurately using the approximation formulas and define the take-off mass of the first approximation

$$m^{I}_{исх} = \frac{m_{ц} + m_{эк}}{1 - \overline{m}_{к}(m_{0исх}) - \overline{m_{су}} - \overline{m}_{Тс} - \overline{m}_{обупр}(m_{0исх}) - \overline{m}_{сн}}.$$

It should be mentioned that the mass of each group can be included in the nominator or the denominator of the formula for m_0 according to the form of its representation: absolute or relative. For example, if you know the content of some equipment and its absolute mass, you can put this mass to the numerator decreasing its relative weight in the denominator correspondingly. Sometimes the airplane design is carried out for the certain engine type and all engine parameters and its mass are well-known. In this case the power plant mass is accounted in the absolute form, so it is carried from the denominator to the nominator.

5.2 Payload mass

For passenger airplanes the payload contains passengers, luggage, paid cargo and mail. The payload mass is approximately defined by the number of passengers $n_{пас}$:

$$m_{ком} = 1{,}3(m_{пас} + q_{баг})n_{пас},$$

where $m_{пас}$=75 kg – average weigh of one passenger;

$q_{баг}$ – average weigh of luggage that belongs to one passenger;

$q_{баг}$ = 30 kg – for long distance airplane ;

$q_{баг}$ =15 kg – for local airline airplane;

1,3 – coefficient that accounts for the mass of additional paid cargo and mail.

For transport and military transport airplanes payload mass is equal to cargo mass from PR.

For military airplanes payload contains expendable combat load: shells, unguided and guided missiles, bombs, special containers and etc., i.e. everything which is dropped or fired during sortie. In educational projects design the payload mass for military airplane is usually given in the design task.

5.3 Service load and equipment weights

Service load include:

- crew (including cabin crew);
- parachutes, crew personal belongings and luggage;
- detachable equipment of kitchens, bars and wardrobes, water closets, carpets, curtains, magazines, food;
- technical liquids, oil for power plants, residual fuel;
- survival equipment - boats, rescue rafts, life belts and life vests, emergency ladders, emergency rations, removable equipment;
- service equipment: ladders, stairs, onboard equipment, covers, chocks;

— additional equipment: external tanks, special mountings, removable armor.

The mass of this group contains the mass of crew and equipment

$$m_{сл} = m_{эк} + m_{сн},$$

where $m_{эк}=m_{1эк}n_{эк}$;

$m_{1эк}$ = 75 кг – average weight of one crew member for civic airplanes;

$m_{1эк}$ = 90 кг – average weight of one crew member for military airplanes;

$n_{эк}$ – the number of crew members that can be found in the recommendations [1], p.215. It should be mentioned that the crew of modern airplanes consists of only 2 pilots and cabin crew.

The mass of equipment can be approximately taken in the relative form and then it can be put into the denominator of the formula for defining m_0

$\bar{m}_{сн}$ = 0,02 – 0,03 – for midweight and heavy airplanes;

$\bar{m}_{сн}$= 0 – for light airplanes.

5.4 Relative airframe mass

This mass is defined by approximate statistical formula [24]

$$\overline{m}_k = (\alpha\varphi n_A\sqrt{\frac{m_{0исх}\lambda}{1000p_0}+\frac{5,5}{p_0}})\left(1+\beta_1\lambda_ф m+\beta_2\right)+0,065,$$

where $\alpha = \frac{0,027}{\cos\chi}$ for subsonic airplanes with straight or swept wing,

$\alpha = 0,049\mu$ for supersonic airplanes with delta wing;

$\mu = 1+\varepsilon(\frac{\sigma_т}{\sigma_т^{\prime}}-1)$ – accounts for additional mass required because of kinetic heating,

ε – ratio of load-carrying elements mass to total airframe mass (for the first approximation $\varepsilon \approx 0,5$),

$\frac{\sigma_T}{\sigma'_T}$ – ratio of yield stress at normal temperature to yield stress at higher temperature (due to kinetic heating);

$\varphi = 1 - \frac{3(\eta+1)}{\eta+2}(\bar{z}_1\varepsilon_1\overline{m}_T + \bar{z}_2\varepsilon_2\overline{m}_{cy})$ – wing unloading coefficient,

η – wing taper ratio,

ε_1 – part of fuel located in the wing,

$\bar{z}_1$ – relative position of fuel COG (measured from the symmetry plane, related to half-span),

ε_2 – part of the power plant located at the wing,

$\bar{z}_2$– relative position of power plant COG (measured from the symmetry plane, related to half-span),

n_A – estimated g-load: approximately equal to 3-5 for passenger airplanes, less for heavier airplanes;

β_1 = 0,065 – 0,08 – for heavy subsonic airplanes;

β_1 = 0,08 - 0,115 – for transport airplanes;

β_1 = 0,07 – 0,09 – for supersonic airplanes;

m = 1,2 – 1,3 – for subsonic airplanes;

m = 1 – for supersonic airplanes;

β_2 = 0,15 – for subsonic airplanes;

β_2 = 0,27 – for supersonic airplanes;

λ, $\lambda_ф$ – aspect ratios of wing and fuselage;

p_0 – specific wing load daN /m^2;

$m_{0\ исх}$ – initial airplane mass, kg.

5.5 Relative mass of the fuel system

This mass is defined by the relative fuel mass $\bar{m}_T$ and mass of the fuel system units, which is accounted for by correction factor $k_{тс}$

$$\overline{m}_{TC} = k_{TC}\overline{m}_T,$$

where $k_{тс}$ = 1,02 – 1,08 – for heavy airplanes with long flight range;

$k_{тс}$ = 1,1 – 1,2 – for fighters, light and midweight airplanes.

The required fuel mass for airplanes with long cruise stage can be written as a sum [1], p.149:

$$\overline{m}_T = \overline{m}_{T\text{кр}} + \overline{m}_{T\text{нрп}} + \overline{m}_{T\text{нз}} + \overline{m}_{T\text{пр}},$$

where $\overline{m}_{т\ кр}$ – cruise flight fuel,

$m_{т\ н\ р\ п}$ – fuel necessary for take-off, climb, acceleration, descent and landing;

$m_{т\ н\ з}$ – navigation fuel margin;

$\overline{m}_{т\ пр}$ – other fuel consumptions (maneuvering of an airplane on the ground, engine start and run-up, residual fuel).

Cruise flight fuel can be found (without accounting for mass reduction due to fuel consumption) as

$$\overline{m}_T^0 = \left(\frac{L_p - L_{\text{н сн}}}{V_{\text{кр}} - W}\right)\frac{C_{p\ \text{кр}}}{K_{\text{кр}}},$$

where $L_р - L_{н\ сн} = L_{кр}$ – supposed length of the cruise stage;

$L_р$ –supposed flight range (km);

$L_{н\ сн} \approx 40H_{кр}$ (км) – horizontal flight distance during climb and descent (km);

$H_{кр}$ – average altitude of the cruise flight (km);

$V_{кр}$ – cruise velocity (km/h);

W – supposed headwind speed (km/h):

$H_{кр}$(km)	3-6 ;	7-9;	10-12;
W (km/h)	30;	50;	70;

$K_{крейс} = (0{,}85 – 0{,}9)K_{max}$;

fuel consumption rate in cruise flight:

$$C_{p\ \text{кр}} = C_{p0} + \frac{0{,}4\text{M}}{1+0{,}027\text{H}_{\text{кр}}},$$

where

$$C_{p0} = 0{,}052\frac{\sqrt{T_{\Gamma}^{*}}}{(\pi_{\text{к}}^{*})^{0{,}25}}(1 + 0{,}05m - \sqrt{0.14m});$$

values of $T_{\text{г}}$* and $\pi_{\text{к}}$* can taken according to [6], p.168–171.

If we take into account the influence of mass reduction due to fuel consumption on flight range ($\bar{m}_{\text{т}}^{0}$>0,2), then

$$\overline{m}_{\text{Т кр}} = \frac{\overline{m}_T^0}{1+0{,}625\overline{m}_T^0}.$$

For take-off and landing stages

$$\overline{m}_{\text{Т нрп}} = (1 - 0{,}03m)\frac{0{,}0035H_{kp}}{1-0{,}004H_{kp}},$$

where m is engine by-pass ratio.

Navigation fuel margin is

$$\overline{m}_{\text{Т нз}} = \frac{0{,}9C_{\text{р кр}}}{K_{max}}.$$

Other fuel consumptions are

$$\overline{m}_{\text{Т пр}} \approx 0{,}006.$$

The ways of finding $\bar{m}_{\text{т}}$ for supersonic, aerobatic, general aviation airplanes and etc. are given in [1], p.151.

5.6 Relative mass of the power plant

The initial parameters for defining this mass are specific engine mass that is defined while choosing the type of the power plant

for turbo-jet engines

$$\gamma_{\text{дв}} = \frac{m_{\text{дв}}g}{10P_0}$$

for turbo-prop, turbo-fan and piston engines

$$\gamma_{\text{дв}} = \frac{m_{\text{дв}}g}{10N_0}\ \text{[daN/kW]}.$$

These parameters are derived from statistics taken from engine handbooks.

If you know the required thrust-to-weight ratio P_0 (or power-to-weight ratio $\overline{N}_0$), you can find the relative mass of the power plant

for turbo-jet engines

$$\overline{m}_{\text{су}} = k_{cy}\gamma_{\text{дв}}\overline{\text{P}}_0$$

for turbo-prop, turbo-fan and piston engines

$$\overline{m}_{\text{су}} = k_{cy}\gamma_{\text{дв}}\overline{N}_0.$$

For turbo-fan engines you can actually use both of the above formulas according to which parameter - P_0 or N_0 - is available.

Coefficient $k_{\text{с у}}$ takes into account the difference between the mass of the whole power plant and engine mass. It can be calculated by approximate formula

$$k_{c\,y} = k_1 - k_2\gamma_{\text{дв}},$$

where the coefficients depend on the number of engines

the number of engines:	2	3	4
k_1	2,26	1,87	2,14
k_2	3,14	1,54	2,71.

Coefficient $k_{\text{с у}}$ can also be calculated by the formulas from the textbook [1], p.147.

For turbo-prop and turbo-fan engines $k_{\text{с у}}$ can be calculated as

$$k_{cy} = 1{,}1 + \frac{1{,}36}{\gamma_{\text{дв}}}\left(0{,}1 + \frac{0{,}9}{N_0^{1/3}}\right),$$

where N_0 (kW) is chosen according to statistics for prototypes.

5.7 Relative mass of equipment and control system

This mass is defined by following statistical relations [1].

For passenger airplane with $m_{\text{исх}} > 10000$ kg:

$$\overline{m}_{об\ упр} = \frac{250+30n_{пас}}{m_{0исх}} + 0{,}06,$$

where $\overline{m}_{0исх}$ is measured in kg,

$n_{пас}$ – number of passengers.

For cargo airplane or military transport airplane

$$\overline{m}_{об\ упр} = 0{,}2 - 0{,}00027\sqrt{m_{0исх}}.$$

For other airplane types the value $\overline{m}_{об\ упр}$ can be taken from table 6.1 in [1].

5.8 First approximation of take-off mass

The relative values $\overline{m}_{к}$, $\overline{m}_{с\ у}$, $\overline{m}_{т\ с}$, $\overline{m}_{об\ упр}$, $\overline{m}_{сн}$ calculated with the approximation formulas should be compared with the data table 1.1 that was obtained in the section 1 and with the average statistical values from table 6.1 from [1]. If your calculated masses differ significantly from statistics, you should correct the results or use other statistical formulas.

Besides, the calculated values should be corrected to account for new engineering solutions employed in the project. The list of such solutions with their estimated influence on airplane characteristics and corresponding masses should be made during statistical survey and project situation analysis. These new solutions can change some airplane parameters that appear in the formulas for relative masses. In this case the impact of new engineering solutions on the relative masses will be taken into account by usage of these formulas. If the parameters improved by new solutions do not appear in the formulas, the calculated values of relative masses should be corrected according to the expected influence of these solutions on the main airplane masses.

When the values of relative masses $\overline{m}_{i}$ are corrected, the first approximation of airplane take-off mass can be found

$$m_0^I = \frac{m_{ц}+m_{эк}}{1-\overline{m}_{к}-\overline{m}_{су}-\overline{m}_{ТС}-\overline{m}_{об\ упр}-\overline{m}_{сн}}.$$

This value should be compared with $m_{0исх}$.

The difference between these two values cannot exceed (5–7)%. Otherwise, the values of relative masses $\bar{m}_i$ that are located in the denominator should be defined more precisely. This especially concerns the values of $\bar{m}_к$ and $\bar{m}_{об\ упр}$ that itself depend upon the airplane take-off mass (see subsections 5.4, 5.7). Other terms in the denominator can be defined more precisely by using more detailed statistics. For further corrections the calculated value of the first approximation of take-off mass is then taken as $m_{0исх}$. After correcting the values of $\bar{m}_i$ the procedure for calculation of m_0^{I} and its comparison with $m_{0исх}$ should be repeated.

6 DEFINING THE MAIN AIRPLANE PARAMETERS

When the airplane take-off mass is found, its main geometric, mass and other parameters can be found in the absolute form. The initial data are the take-off mass, the relative geometric parameters of the scheme, the specific wing load, the thrust-to-weight ratio and the relative masses of the airplane units and subsystems.

Also the absolute values of engine thrust and mass should be defined, as this will allow to select the specific engine model. Then the required fuel tank volume, the type of the landing gear and its main dimensions are defined.

6.1 The order of operations

Defining the absolute values of airplane parameters values is usually executed in the following order.

6.1.1 Engine parameters and selection

According to the thrust-to-weight ratio $\bar{P}_0$ and the take-off mass value m_0^1 the net engine thrust is defined (daN)

$$\sum P_0 = \frac{m_0^1 g}{10} \overline{P}_0$$

Then the thrust of one engine is defined according to the number of engines $n_{дв}$

$$P_{01} = \frac{\sum P_0}{n_{дв}}.$$

Using engine catalogs and handbooks the specific engine model with appropriate values of static thrust P_0 and by-pass ratio m is selected. When selecting the engines the possible deviation of P_0 can be in the range -5%...+10%. If there are several engines available with similar values of P_0, the one with the smaller values of specific weight $\gamma_{дв}$ and fuel consumption rate C_{p0} should be chosen.

If there is no engine with the proper values of P_0 and m, you should take the hypothetical engine with the required values of thrust P_{01} and by-pass ratio m. The weight of this engine can be calculated as

$$m_{дв1} = \frac{10P_{01}}{g}\gamma_{дв} ;$$

For defining the size of this engine (its diameter and length) you can use the statistical formulas from the textbook [1], p.422–423, or the encyclopedia [6], p.172–173 and statistical data: [1], p.589–591, [14] [15].

For turbo-prop and piston engines the net engine power (kW) is defined according to the required values of N_{e0} and m_0^1

$$\sum N_{e0} = \frac{m_0^l g}{10}\overline{N}_{e0}$$

The power of one engine is then defined

$$N_{e01} = \frac{\sum N_{e0}}{n_{дв}}.$$

Using engine catalogs and handbooks the specific engine model with the appropriate value of N_{e01} is selected. Otherwise, the hypothetical engine with the power N_{e01} and the dimensions taken from the statistics [2, p. 207–210] is taken.

The engine selection for light and ultra-light airplanes is considered in [9].

6.1.2 Fuel mass and volume

The required fuel mass

$$m_T = \frac{\overline{m}_{TC}}{k_{TC}}m_0^l.$$

The fuel volume

$$\upsilon_T = \frac{m_T}{800}(м^3).$$

The volume of fuel tanks

$$\upsilon_{\text{тб}} = \upsilon_{\text{т}} + \Delta\upsilon_{\text{т}} \text{ (м}^3\text{)},$$

where $\Delta\upsilon_T$ –additional fuel margin while carrying the reduced payload for increased (the distance that are more than L_p); the take-off mass m_0^1 is considered to be constant. Taking up the value of payload mass reduction $\Delta m_{ком}$, the required volume of the additional fuel is found

$$\Delta\upsilon_T = \frac{\Delta m_{\text{ком}}}{800} \text{ (m}^3\text{)}.$$

Taking into the account fuel thermal expansion, the tank volume is increased by 5%.

6.1.3 Wing parameters

The wing area $S = \frac{m_0^1 g}{10 P_0}$;

the wing span $\ell = \sqrt{\lambda S}$;

the central chord b_0=$b_ц$: $b_ц = \frac{2\eta}{1+\eta} \cdot \frac{S}{\ell}$;

the tip chord $b_ц = \frac{2}{1+\eta} \cdot \frac{S}{\ell}$;

the mean aerodynamic chord

$b_A = \frac{2}{3} b_0 \left[1 + \frac{1}{\eta(\eta+1)}\right]$ - for the tapered wing,

$b_A = \frac{2}{3} b_0$ - for the delta wing.

Aileron span and chord, interceptor span and chord, spoiler span and chord, flap span and chord, slat span and chord can then be defined according to their relative parameters - see [1], p.394. Shapes, sizes and locations of winglets, chines and fairings are chosen according to the statistics - see [1] p. 379–381, 394–403.

6.1.4 Empennage parameters

Areas of horizontal and vertical empennage

$$S_{\text{г о}} = \bar{S}_{\text{г о}} S;$$

$$S_{\text{в о}} = \bar{S}_{\text{в о}} S.$$

and their arms

$$L_{\text{г о}} = \bar{L}_{\text{г о}} b_A;$$

$$L_{\text{в о}} = \bar{L}_{\text{в о}} \ell.$$

According to the relative parameters $\lambda_{\text{г о}}$, $\eta_{\text{г о}}$, $\lambda_{\text{в о}}$, $\eta_{\text{в о}}$ the spans and chords are defined. The chords of control surfaces are defined by their relative parameters $\bar{b}_{\text{р в(р н)}}$.

6.1.5 Fuselage dimensions

According to the design purposes, the shape of fuselage cross-section is adjusted, the cross-section area $S_{\text{мид}}$ is chosen and then the equivalent fuselage diameter is calculated

$$D_{\text{э}} = 2\sqrt{\frac{S_{\text{мид}}}{\pi}}.$$

The first approximation of the fuselage length is calculated

$$\ell_{\text{ф}} = \lambda_{\text{ф}} D_{\text{ф}}$$

and then the forward fuselage length

$$\ell_{\text{н ч}} = \lambda_{\text{н ч}} D_{\text{э}}$$

and the rear fuselage length

$$\ell_{\text{х ч}} = \lambda_{\text{х ч}} D_{\text{э}}.$$

Recommendations for choosing the fuselage dimensions are given in [1], p.237–243, p.403–419; [2], p.71–106, [6] p.256–264.

6.1.6 Landing gear parameters

The following dimensions are defined:

the wheelbase $b = \bar{b}\ell_{\Phi}$;

the landing gear tread $B = \bar{B}\ell$;

the main landing gear offset $e = \bar{e}b$.

The angle of airplane back-tipping φ, the angle of the main landing gear offset γ and the static ground angle ψ are specified.

The static ground loads at the main landing gear and the nose landing gear are calculated. Taking into account the statistics the number of wheels is chosen and the load per one wheel $P_{к1}$ is calculated. According to the take-off and landing velocities the dimensions and weight of wheels are chosen from catalogs. The catalogs of wheels are given in the appendix B.

For the chosen airfield class the landing gear passability is estimated basing on the equivalent one-wheel load [1], p.531.

6.2 The first approximation of the airplane general view

The preliminary drawing of the airplane three views is made using the calculated dimensions. The drawing size is (A2 – A1). The final dimensions and the general view drawing will be corrected during the further design process and after defining the center of gravity position.

7 AIRPLANE WEIGHT ESTIMATE

After defining the geometric dimensions the airplane take-off mass can be found by calculating the masses of the main airplane units and systems. The statistical weight formulas that allow estimating the masses for the airplane and its units are used for these purposes. The weight formulas usually take into account the airplane dimensions and its take-off mass, unit shapes, engine location, fuel location, payload location, properties of constructional materials, also they contain statistical coefficients that depend on the airplane type.

Weight formula estimation gives only the approximate expected value of mass, and if you use formulas from different sources, you may have the significant spread of values. V.M. Sheynin, who is one of the airplane weight estimation theorists, suggested the array estimation method for minimizing calculation errors. The idea of the method is to use a large number of weight formulas and then, after obtaining their results, to exclude extreme values and average all the other values. This method gives rather accurate and true results, its accuracy increases when increasing the number of used formulas.

Let's specify the terms "weight" and "mass".

The tradition of usage of the terms with the adjective "weight", such as "weight calculation", "weight design", "weight control", "weight efficiency", was established during the airplane design practice. In the International System of Units (SI) the weight is the gravity force that is equal to the product of the mass of a body and the acceleration due to gravity (*mg*) and it is measured in Newtons (N). The old sources employ kilogram-force as a force unit, which is equal to ~ 9,807N. As a result the numerical values of all parameters, which belong to weight and force, increased by about approximately one order of magnitude when using SI units. This makes difficult to use the large amount of data and knowledge which was collected in the past. Thus, in this manual and the main textbook [1] the decanewton (daN): 1daN = 10N is used as the force unit in order to reduce complexity. This unit numerically differs from kilogram-force by 2%: 1daN ~ 1,02kgf and it makes easy to use data from the old sources.

In modern engineering literature terms with the adjective "weight" are replaced by the terms with the adjective "mass", for example, "mass calculation", "mass parameters", "mass list" and etc. The usage of «weight» and «mass» terms at the same time is not contradictory, moreover, the terms ‘‘weight’’ (gravity force) and ‘‘mass’’ is both included in SI. Besides, the numerical value of mass measured in kg is equal to weight value measured in kgf. But it should be mentioned that mass and weight have different physical interpretations and are measured in different units.

The unit of each parameter is defined by its physical interpretation. It covers also "specific" parameters: specific weight (unit weight), specific wing load (unit load), dynamic pressure and etc.

7.1 Defining airframe and equipment masses

The masses of airplane units are calculated by weight formulas given in some domestic publications:

for wing – [1], p.131; [2], p.307; 313; [3], p.152; (formula 13.4);

for fuselage – [1], p.135; [2], p.315; [3], p.170; (formula 13.36);

for empennage – [1], p.139; [2], p.310; [3], p.193; (formula 13.52-53);

for landing gear – [1], p.142; [2], p.315; [3], p.203 (formula 13.63).

It should be mentioned that these formulas do not take into account new constructional materials, for example, composite materials that provide mass decrease of load-carrying elements by (15–20)%. Thus, the obtained results can be corrected by coefficients: (0,80 – 0,85) for airplane produced from new materials, (0.9 – 0.95) for airplane partially produced from new materials.

Weight formulas and statistics from [1], p.149, [2], p.319–330 together with statics given in the tables of this manual 7.2, 7.3, 7.4 can be used while defining power plant weight, fuel system weight, equipment weight and others. Taking into account the scientific and technological progress in electronics, automation systems and equipment some correction factors should be applied while calculating the masses. It leads to mass decrease by at least (5 – 10) %.

In the appendix B the weight formulas borrowed from foreign sources are given.

A new approach for estimating load-carrying elements masses using finite-element design that is appropriate for design of airplanes with unusual shapes and dimensions is considered in the textbook [7]. Additional data and statistics of weight estimations can be found in [6].

7.2 The airplane mass list

Using the results of weight estimation the list of the airplane masses is made that contains masses of all units included in the airplane take-off mass (table 7.1). These masses are grouped according to their functions. The total mass in the absolute form m_i (kg) and in the relative form $\bar{m}_i$ is defined for each group. Within the group the masses are listed approximately using the statistics from the tables 7.2, 7.3, 7.4. The detailed typical list of masses is given in the textbook [1], p.578–580.

Payload and fuel masses are not specified in this estimation. Their values are taken from the first approximation for take-off mass.

The total mass obtained from the list of masses is the updated value of the airplane take-off mass - the second approximation for take-off mass.

Table 7.1 – List of the airplane masses

№	Name	m_i kg	$\bar{m}_i$
I	AIRFRAME	xxx	xxx
	Wing	xxx	xxx
	Fuselage	xxx	xxx
	Empennage	xxx	xxx

	Landing gear	xxx	xxx
	Paint	xxx	
II	POWER PLANT	xxx	xxx
	Engines	xxx	
	Propellers	xxx	
	Engine mounting	xxx	
	Engine nacelles or air intakes	xxx	
	Exhaust system, thrust reversal	xxx	
	Engine systems	xxx	
	Fuel system units	xxx	
III	EQUIPMENT AND CONTROL SYSTEM	xxx	xxx
A	Airplane equipment		
	Hydraulics	xxx	
	Electrical equipment	xxx	
	Radio equipment	xxx	
	Radar equipment	xxx	
	Air navigation equipment	xxx	
	Anti-ice system	xxx	
	Control system	xxx	
B	Special equipment		
	Passenger equipment	xxx	
	Cargo handling equipment	xxx	
	Armament, armor	xxx	
IV	EMPTY AIRPLANE	xxx	xxx
V	MUNITIONS AND SERVICE LOAD	xxx	xxx
	Crew	xxx	
	Survival equipment	xxx	
	Munitions	xxx	
VI	EMPTY AIRPLANE EQUIPPED (IV+V)	xxx	xxx
VII	PAYLOAD	xxx	$К_{\text{во ком}}$
	Passengers	xxx	
	Luggage	xxx	
	Paid cargo, mail	xxx	
	Shells, missiles, bombs	xxx	
VIII	FUEL	xxx	xxx
	Consumable fuel	xxx	
	Air-navigation fuel margin	xxx	
	External tank fuel	xxx	
IX	TOTAL LOAD (VII+VIII)	xxx	$К_{\text{во ком}}$
X	TAKE-OFF MASS m_0^{II}	xxxx	

Coefficient of weight efficiency for the total load

$$K_{во\ пол} = \frac{m_{пол}}{m_0}$$

and for the payload

$$K_{во\ ком}\ ,$$

are defined in the end of weight estimation.

These coefficients define the transport efficiency of the airplane.

The simplified mass lists of different airplane types: passenger airplanes (tables 7.2 and 7.3) and military airplane (table 7.4) are given below. The tables contain the data submitted by manufacturing companies of these airplanes, so they comprise the important data about the content of different groups of masses.

Table 7.2 – Mass lists of Tu-154 and Tu-204 airplanes

Name of units and systems	Tu-154		Tu-204	
	m, kg	*m/*	*m, kg*	*m/*
I AIRFRAME	24885	0.2777	29099	0.2835
Wing	9200	0.10267	11090	0.1080
Fuselage	9490	0.1059	11689	0.1139
Tails	2370	0.0264	1995	0.0194
Landing gear	3715	0.04145	4325	0.0421
Paint	110	0.00123	-	-
II POWER PLANT	10921	0.1218	11520	0.1122
Engines	8230	0.09184		
Engine mounting	1289	0.01438		
Engine systems	913	0.01018		
Fuel system	489	0.00545		
III EQUIPMENT AND CONTROL SYSTEM	12644	0.14110	11250	0.1096

A Airplane equipment Hydraulics, pneumatics Electrical equipment Radio equipment Radar equipment Air navigation equipment Anti-ice system Control system B Special equipment Passenger equipment Cargo handling equipment				
IV EMPTY AIRPLANE	48450	0.5407	51869	0.5053
V MUNITIONS AND SERVICE LOAD Crew Survival equipment Munitions	2325 525 252 1548	0.02594 0.00586 0.00281 0.01728	5782 600 252 4930	0.0563 0.0058 0.0025 0.0480
VI EMPTY AIRPLANE EQUIPPED	50775	0.56665	57651	0.5616
VII PAYLOAD Passengers Luggage Mail	18000 11400 4560 2040	0.20088 0.12722 0.05089 0.02277	21000 14700 3920 2380	0.2046 0.1432 0.0382 0.0232
VIII FUEL Consumable fuel Air-navigation fuel margin Residual fuel	20831 18056 2375 400	0.23247 0.2015 0.0265 0.00446	24000	

IX TOTAL LOAD (VII+VIII)	38831	0.43335	45000	0.4384
X TAKE-OFF MASS	89606	1	102651	1
Weight efficiency for the total load for the payload	0.4593 0/200879		0.494705 0.204577	

Table 7.3 – Mass lists of Il-96-300 and Il-114 airplanes

Name of units and systems	Airplanes	
	IL-96-300	IL-114
	Mass, kg	
I. AIRFRAME	67159	6893
Wing	32718	2829
Fuselage	19865	2504
Tails	4984	640
Landing gear	9592	920
II. POWER PLANT	21933	2808
Engines:		
— engine (dry)	11800	1060
— engine accessories	2248	325
— thrust reverser	2280	-
Oil system	-	42
Propellers	-	430
Engine nacelles, mounting, exhaust system	1653	645
Engine pylons	2290	-
Control system of engines	86	64
Fuel system	855	109
Residual fuel	200	20
APU	521	113
III. EQUIPMENT	23065	5447

Electrical equipment	5084	1767
Radio equipment and cabin entertainment system	1006	225
Aircraft instrumentation, onboard automated control system and etc.	1614	631
Hydraulics	1654	216
Rudder and aileron control	1100	375
Lift augmentation control system	1574	138
Fire extinguishing system	391	67
Anti-ice system	145	59
Stationary oxygen system	85	21
High-altitude system (air-conditioning system and engine starter)	2078	374
Heat and noise insulation	1179	264
Water closets, water supply and sewerage systems	979	83
Kitchen appliances	338	27
Decoration, luggage compartments and partitions	2058	560
Seats for cockpit and cabin crew	250	67
Passenger seats	2757	439
Luggage equipment	547	124
Survival equipment mounting	226	10
Paint and coatings	325	55
Unaccounted parts	948	-
Total: Empty airplane	113431	15203
m_0	216000 kg	21000kg

Table 7.4 – Mass lists of military airplanes

Units and Systems	Mass, kg						
	AlfaJet	F-16A	Jaguar S	Mirage 2000	A-10A	F-15C	Tornado

AIRFRAME	2055	3549	3343	3550	5620	6269	7330
Wing	636	970	720	1310	1700	1250	2250
Fuselage	810	1575	1380	1300	1587	3300	2650
Horizontal tail	90	128	156	-	190	272	268
Vertical tail	60	132	134	184	135	232	272
Nose landing gear	50	92	100	100	100	165	192
Main landing gear	210	424	440	450	470	745	818
Survival equipment (ejection seat, canopy)	170	175	180	173	165	190	370
Drag parachute, arresting hook, thrust reversal system	24	25	25	25	30	100	310
Paint, armor	5	28	208	8	1243	15	200
POWER PLANT	759	1787	1873	1858	1735	3765	2675
Engine	620	1540	1550	1602	1370	3280	1974
Fuel system	90	170	214	178	230	292	384
Engine control system	10	10	19	10	15	23	20
Engine starting system	20.5	46	47	48	40	90	127
Fire extinguishing system	18.5	21	43	20	80	80	170
EQUIPMENT	700	1445	1523	1670	1545	2360	2695
Avionics	180	610	520	670	606	795	1050
Electrical eq.	160	230	260	320	320	420	450
Oxygen and air-conditioning	120	144	143	150	119	285	215
Control system						260	
Hydraulics	240	461	450	390	500	550	760
Additional equipment	-	-	150	140	-	50	220
Gun without ammo	282	260	272	272	1000	260	350
EMPTY	3796	7041	7011	7350	9900	12654	13050
AIRPLANE							
WITH GUN	2414	4509	4809	4865	6600	8485	8600
COMBAT	117	175	162	225	540	105	300
LOAD	260	160	190	160	200	250	400
Ammo							

Crew, oil, residual fuel Fuel in internal tanks Pylons, hardpoints, launchers Suspensions	1530 25 482	3162 105 907	3440 108 909	3360 120 1000	4850 105 905	6100 218 1812	6000 200 1700
Normal take-off mass	6210	11550	11820	12215	16500	21139	21650

8 AIRPLANE LAYOUT

The development of the airplane layout contains three main stages:

1. Developing the spatial-weight layout that defines location inside the airplane of all loads: equipment, fuel, crew, payload, power plant and etc. (i.e. all the components of mass list). For military airplanes part of fuel and expendable combat load can be placed on hardpoints.
2. Developing the structural and load-carrying layout which means designing structural and load-carrying scheme of the airplane in general and load-carrying schemes of all of its units in particular and defining exact locations of main load-carrying elements: spars, ribs, bulkheads, beams, joints.
3. Updating the aerodynamic scheme by correlating locations of loads inside the airplane and load-carrying elements. As a result the dimensions and relative positions of the airplane units which define its external shape are defined more exactly.

8.1 The airplane spatial-weight layout

Placement of the total load, the equipment and the airplane systems should satisfy the following requirements:

- providing the best crew operation environment;
- providing passenger comfort;
- providing the maximum operation efficiency of the equipment and the systems;
- providing the efficient usage of the internal fuselage volume $v_ф$ and the internal wing volume $v_{кр}$; it can be estimated by nominal density of empty equipped airplane

$$\rho_{п\ сн} = ;$$

— providing the required balance of all possible airplane load variations, which can be achieved by placing variable load and consumable load (payload and fuel) as close as possible to the airplane center of mass or symmetrically to the airplane center of mass;

— providing the minimal moments of inertia.

While arranging the spatial-weight layout the following parameters are defined and updated:

— cockpit dimensions – [1], p.215–219; [2], p.98–99;

— passenger cabin dimensions – [1], p.237; [2], p.80–84;

— shape and size of fuselage cross-section [1], p.238–240; [2], p.73–79;

— shape and size of passenger cabin windows and doors [1], p.245–246; [2], p.89;

— dimensions of kitchens, wardrobes, water closets [1], p.247–249; [2], p.84–92;

— placement of passenger seats [1], p.238; [2], p.84;

— locations of emergency exits [1], p.243; [2], p.86;

— locations of cabin crew work places [1], p.246; [2], p.90;

— dimensions of baggage and cargo bays [1], p.246–247, 257; [2], p.92–98; (baggage and cargo bays can be increased for transporting large cargo with the decreased number of passengers);

— location and size of cargo doors [1], p.255–257; [2], p.97–98;

— placement of standard freight containers [1], p.246; [2], p.96;

— location of engines, dimensions of engine nacelles and engine pylons [1], p.443–447; [2], p.226–230;

— location and size of air intakes [1], p.425, [6];

— location of exhaust system [1], p.439;

— location of the auxiliary power unit (APU) [1], p.384; [2], p.233–234;

— volume of fuel [1], p.454;

— dimensions and location of the fuel tanks [2], p.490;

— passenger cabin specific volume [1], p.242.

While defining these parameters all of the decisions must be documented and references to the source of information that was used for justifying them must be listed.

Then the locations of landing gear compartments or wheel nacelles are defined. Landing gear parameters chosen in section 3 are updated. The layout drawing should show the landing gear in both extended and retracted positions. Functional kinematic diagrams of the gear retraction and extension are developed. Landing gear compartments (or wheel nacelles) should house the landing gear in the retracted position and strong load-carrying elements should transfer loads from the landing gear to the wing (or the fuselage) at landing.

The fuel tank volume should be specified while dividing the fuel tanks into the groups of the fuel consumption. In order to minimize balance changes and to increase the fuel efficiency of passenger/transport airplanes, you should follow these simple rules:

— the fuel tank volume is calculated for the maximum range with the reduced payload;

— the fuel should be located as close as possible to the airplane center of mass;

— the fuel should be consumed separately from the front and rear tanks or the tank groups; thus consumption programming allow to keep the balance in the acceptable limits;

— the program of fuel consumption should be chosen in such a way that at the beginning of cruise flight the airplane center of mass shifts to the rear acceptable balance limit, to decrease the static stability margin and thus the balancing drag;

— for the same purpose fuel transfer from the front tanks or from the special balancing tanks to the additional tanks in the rear fuselage or in the fin should be considered for average- and long-range airplanes;

— fuel from the wing tip tanks should be consumed as later as possible, so it will provide unloading of the wing during the most part of flight and decrease bending stress at the most loaded wing root sections.

Indexes of rational usage of fuselage and the wing volumes are:

The fuselage:

1) coefficient of usage of the fuselage volume

$$K_{исп\,v} = (V_{пас\,сал} + V_{всп\,ом} + V_{баг\,пс};$$

2) specific volume of the useful space for one passenger

$$K_{v\,пол} = (V_{пас\,сал} + V_{всп.пом} + V_{баг\,пом});$$

3) fuselage specific volume for one passenger

$$K_{v\,пас} = V_{ф};$$

where $V_{пасс\,сал}$ – passenger cabin volume, m^3;

$V_{всп.\,пом}$ – volume of utility spaces (water closets, wardrobes and etc.), m^3;

$V_{баг\,пом}$ – luggage compartment volume, m^3;

$V_{ф}$ – fuselage volume, m^3, approximately

$$V_{ф} = 0{,}25K_{\eta};$$

where K_{η} - takes into account taper ratio of the forward fuselage and the aft fuselage portions; it is equal to 0,72 – 0,80 depending on the fuselage length.

Increasing $K_{исп\ v}$ and decreasing $K_{v\ пасс}$, $K_{v\ пол}$ increase fuselage layout density and airplane efficiency. Airplanes with the equal seat pitch can be compared by $K_{v\,пол}$ and $K_{v\,пасс}$

The index of using the wing volume is the ratio of wing useful volume $V_{полезн}$ to wing total volume $V_{кр}$

$$V_{кр} = 0{,}67K_{\eta}(,$$

where K_{η} depends on the wing taper ratio [3], p.445.

8.2 The airplane structural and load-carrying layout

This part of the project consists of the following stages:

— the load-carrying schemes of all airplane units are defined: wing, empennage, fuselage, landing gear attachments;

— constructional materials of the main load-carrying elements are chosen: skin, spars, stringers, reinforced panels; preference should be given to composite materials, titanium alloys, high-strength steels, aluminum-lithium alloys;

— progressive structural element types should be considered: honeycomb panels, monolithic large-size stamped elements (ribs, spars and etc.);

— locations of technological and operational cut-offs are defined; the principle of structural solidity should be enforced, which means decreasing the number of junctions and cuts by using long-sized raw materials: skin plates, long (up to 30-40 meters) extruded sections; operational cut-offs and joints should be located in the least loaded areas;

— problems of load correlation and load transfer between the units are solved and functional diagrams for all joints are developed.

The principles of minimizing masses of load-carrying elements should be used while developing the load-carrying schemes:

— load transfer should follow the shortest possible way;

— using the maximum structural height for the bending stressed element;

— using thin-wall closed circuits for rotational moment transfer;

— matching and integration of the load-carrying elements intended for transferring loads that applied at different times and under different loading cases;

— minimizing disruption of the load flow caused by different stress concentrators (cuts, holes, acute angles, abrupt changes of cross section area) that lead to increase of structural weight and decrease of airplane life span.

The criterion of general design rationality for separate units and for the whole airframe is the load-carrying factor that takes into accounts the internal stress value and the length of its action. It should be mentioned that all joints and cuts increase the airframe weight.

The airplane structural and load-carrying scheme should define ways of load-transfer and specify elements that take part in load-transfer and balancing of the loads that applied to the airplane: aerodynamic forces, mass forces, forces of engine thrust, land reaction forces.

The airplane structural and load-carrying scheme should provide the simplest and the most efficient methods of manufacturing airplane parts, junctions and units.

This scheme together with the spatial-weight layout should provide the best airframe operating performance owing to the convenient access to all units and systems for their maintenance and repair.

All decisions made when choosing the load-carrying scheme should be listed in the explanatory notes with the specification of the chosen load-carrying scheme for each unit, the main construction material, the type and the dimensions of raw materials, the type of the load-carrying elements that carry large concentrated loads, the principle of strengthening for big cut-offs in the fuselage and in the wing.

8.3 Specifying the aerodynamic scheme

Development of the spatial-weight and the structural and load-carrying layouts and solution to problems of correlating space required for placing payload with locations of the load-carrying elements yield changes of some parameters and dimensions of the airplane units and also their relative position.

Thus the final stage of the layout is to update and finalize the choice of all parameters and dimensions that define the aerodynamic scheme and the external shape of the airplane. These changes and specifications lead to the necessity of updating the drawing of the airplane that was made in section 6.

Nowadays all three stages of layout development are carried out in parallel-sequential way with the aid of three-dimensional mathematic models (3D models) and software that automate this process or some of its stages.

8.4 The airplane layout drawing

The result of airplane layouts development is the airplane layout drawing that should exactly define the airplane design.

The main drawing projection is the airplane longitudinal section along the symmetry plane or the planes that are parallel to the symmetry plane. It is supplemented by plan view (with reduced scaling) at which the starboard wing can be shown partially. Additionally, the drawing should contain several large-scale fuselage cross sections.

The locations of crew, passengers, luggage, cargo, engines, landing gear in extended and retracted and retracted positions, armament, expendable combat load, large pieces of equipment and systems, radar antennas, control levers and links should be shown at the drawing.

Power plant layout, layout of equipment and systems should provide the best conditions for their operation, maintenance and repair.

All airplane projections should show the main elements of the load-carrying scheme. At the fuselage longitudinal sections - sections of bulkheads (ordinary and reinforced), center wing section, center stabilizer sections with the adjustment mechanism, spar sections, torsion box structural panels, additional beams for engines and main landing gear mounting, elements of auxiliary power unit (APU) mounting. The fuselage cross sections should show stringer sections (excluding sections at reinforced bulkheads), longitudinal bars and beams sections and etc. The plan views show the locations of spars, girders, reinforced ribs for mounting rudders, ailerons and lift augmentation devices. The fuselage cross sections at reinforced bulkheads should show attachment fittings, taking into account load transfer from spars to bulkhead frames and applying the “smearing” method that implies transfer of large concentrated loads to booms and thin-walled load-carrying elements by fittings [18].

Also the longitudinal sections at the mounting points of main landing gear and the longitudinal sections of engine nacelles and pylons should be drawn.

The cross sections should be made in places where the loads are applied and load-carrying elements are located:

- cockpit with the instrument panel view;
- front landing gear compartment;
- reinforced bulkhead for mounting the center wing section;
- typical section of passenger cabin and luggage compartment;
- cross section or longitudinal section of the main landing gear compartment;
- reinforced bulkhead for mounting the fin;
- reinforced bulkhead for mounting the stabilizer (with the adjustment mechanism);
- reinforced bulkhead for mounting the engine pylon beams (in case of engines located at the aft fuselage);
- equipment compartment and armament compartment;
- longitudinal section of the engine nacelle.

Some of these sections can be combined at one drawing view.

9 THE AIRPLANE BALANCE

Developing the airplane layout is accompanied by balance check, i.e. by defining the airplane center of mass location relative to the wing mean aerodynamic chord:

$$\overline{\mathrm{X}}_{\mathrm{M}} =;$$

where $X_{\text{м}}$ – x-coordinate of the airplane center of mass;

X_{A} – coordinate of the mean aerodynamic chord leading edge.

The airplane balance ($\bar{X}_{\mathrm{M}}$) defines the characteristics of the airplane stability and controllability, and it should lie in the range of balance limits $\bar{\Delta}$

$$\overline{\Delta X}_{M\,\text{доп}} = \bar{X}_{M\,\text{пер}} \div ;$$

where $\bar{X}_{\text{м пер}}$ – forward balance limit that is governed by the longitudinal control efficiency at landing and take-off stages;

$\bar{X}_{\text{м зад}}$ – aft balance limit that is governed by the minimum level of the static longitudinal stability

$$\overline{\Delta X} = -m_z^{c_y} = \bar{X}_{M};$$

where $\bar{X}_{\text{ф}}$ – relative coordinate of the airplane aerodynamic center.

The adjustable or controllable stabilizer shifts the forward balance limit forward, thus it widens the airplane balance range.

Automatic equipment for the longitudinal control of modern airplanes (maneuverable and non-maneuverable) allows to decrease the longitudinal static stability margin (down to zero – the flight of the statically indifferent airplane), significantly decreasing the balancing drag and increasing the airplane fuel efficiency.

9.1 Choosing the acceptable balance range

The acceptable balance range depends on the airplane scheme, mainly on the wing planform and parameters of the longitudinal control elements. The acceptable range limits are defined by estimating the airplane stability and controllability. At the early stages of the airplane design there are no such estimations, so the acceptable balance range is chosen approximately according to the statistics.

Table 9.1 contains the forward limit (f e) and aft limit (r e) balance values for the large number of passenger and transport airplanes of different types and sizes. Choosing the prototype airplane that is similar to yours (in terms of scheme, wing planform, stabilizer type, number and location of engines) from this table, you can define the approximate acceptable balance range limits $(\overline{X}_{M\,\text{пер}} \div \overline{X}$.

The acceptable balance range can be:

(20–25)%b_A – for passenger and transport airplanes;

(10–15)% b_A – for military airplanes.

Start or initial balance of fully loaded airplane (m_0) should lie in the middle of the chosen acceptable range:

0,20 – 0,25 – for airplane with straight wing;

0,26 – 0,30 – for airplane with swept wing;

0,32 – 0,36 – for airplane with delta wing.

Table 9.1 – Airplane forward and aft balance limits

Airplane	Number and type of engines	$\bar{X}_{м\ п.п}$, %	$\bar{X}_{м\ п.з}$, %	Stabilizer type
Jet Commander 1121	2xturbo-jet	20,0	36,0	Fixed
Learjet 25	2xturbo-jet	9,0	30,0	Fixed
Hawker Siddeley HB-1251 A/1B	2xturbo-jet	18,0	37,5	Fixed
Dassault Mystere 20F	2xturbo-jet	14,0	28,5	Adjustable
HFB «Hansa 1121	2xturbo-jet	11,7	23,0	Fixed
Fokker VFW F28 Mк1000	2xturbo-jet	17,0	37,0	Adjustable
BAC 1-11 seria 400	2xturbo-jet	14,0	41,0	Adjustable
Sud-Aviation Caravelle 10R	2xturbo-jet	25,0	41,5	Fixed
McDonnell Douglas DC-9/10	2xturbo-jet	15,0	40,0	Adjustable
McDonnell Douglas DC-9/33F	2xturbo-jet	3,1	34,7	Adjustable
Boeing 737/100	2xturbo-jet	15,0	35,0	Adjustable
Airbus A-300B2	2xturbo-jet	11,0	31,0	Adjustable
Lockheed L-1011 “TriStar”	3xturbo-jet	12,0	32,0	Adjustable
Boeing 707/120	4xturbo-jet	16,0	34,0	Adjustable
Boeing 720/022	4xturbo-jet	15,0	31,0	Adjustable
Boeing 747/200B	4xturbo-jet	12,5	32,0	Adjustable
McDonnell Douglas DC-8/21	4xturbo-jet	16,5	32,0	Adjustable
Lockheed C-141A	4xturbo-jet	19,0	32,0	Adjustable
Lockheed C-5A	4xturbo-jet	19,0	41,0	Adjustable
Cessna 172, normal category	1xpiston	15,6	36,5	Fixed
Cessna 177, normal category	1xpiston	5,0	28,0	Adjustable
Cessna177, general usage	1xpiston	5,0	18,5	Adjustable

9.2 Calculating the airplane balance values

Balance position drawing and balance report should be made for calculating the balance values.

9.2.1 Balance position drawing

It contains the airplane side view together with plan view at which only starboard wing can be shown with the exact location of the wing mean aerodynamic chord relative to the fuselage nose. MAC b_A is transferred to the side view with the exact vertical location, taking into account the wing attitude $\alpha_{зак}$ and wing dihedral $V_{0\ крыла}$.

Side view shows the landing gears in extended and retracted positions, ground level at parking according to the fuselage attitude ψ and ground level at landing tangential to the fuselage aft portion. The airplane tipping angle φ should also be shown. The coordinate axes are shown: the X axis - along the airplane axis or along the ground level at parking, the Y axis - perpendicular to the X axis and tangential to the fuselage nose.

All airplane masses from mass list are divided by 20-30 mass points, each with its own mass m_i. All points are numbered and shown at the drawing side view with precise specification of their locations according to coordinate axes. The point location should approximately coincide with center of mass of the units assigned to this point. Mass points of the empty airplane and of varying load are calculated separately. Accuracy of balance calculation increases with increasing the number of points. Thus, large sized units should be additionally subdivided into a number of mass points.

Mass points for empty airplane:

- fuselage: 2-3 points (nose section, cylindrical section, tail section);
- wing: 1-2 symmetrical points for each wing part;
- empennage: one point for fin and one point for horizontal stabilizer;
- landing gear: points for both extended and retracted positions of front and main landing gear;

— power plant: one point for each symmetrical pair of nacelles;

— all equipment mass is assigned to fuselage mass points;

— engine equipment mass is assigned to nacelles points.

Wing center of mass and empennage center of mass are located at approximately (40 – 50) % of their mean geometric chords, center of mass of the fuselage part is located in the center of mass center of its projection.

All varying loads (passengers, luggage, fuel, cargo, expendable combat load) should be assigned to at least two points for each load type – in front of and behind the airplane center of mass. Mass points of cockpit and cabin are defined according to their actual locations.

The first approximation of center of mass is located in the point of $\frac{1}{4}b_A$ measured from MAC leading edge.

Mass points of varying loads:

— cockpit crew;

— cabin crew;

— passengers: according to the number of passenger cabins (but at least two points - in front of and behind the $\frac{1}{4}b_A$ point);

— luggage: according to the number of luggage compartments;

— fuel: at least two pints in front of and behind the $\frac{1}{4}b_A$ point.

9.2.2 Balance report

All mass points are listed in the balance report (Table 9.2); [1], p.205.

Table 9.2 – Airplane balance report

№	Point name	m_i	X_i	m_iX_i	Y_i	m_iY_i
1						
2						

First, the points of empty airplane are listed, then the points of varying loads are listed.

The table contains numbers of points, names of the units assigned to each point, their mass, the X and Y coordinates and static moments $m_i X_i$, $m_i Y_i$.

After filling in the balance report the X and Y coordinates of the airplane center of mass for all possible loading variants are defined:

$$X_M =;$$

$$Y_M =.$$

Each loading variant has its own combination of mass points for varying loads. They are used for summing up the masses and the static moments.

The Y coordinate can be defined only for one main loading variant of the airplane – for total take-off mass m0, as it is supposed that there is very little change of it between different loading variants.

The X coordinated is used to define the relative location of the airplane center of mass according to the mean aerodynamic chord

$$\overline{X}_M = ;$$

where X_A – the X coordinate of the mean aerodynamic chord leading edge.

9.3 The required balance variants

Balance calculations are carried out for the following required loading variants:

1) airplane take-off mass: landing gear extended (LGE), landing gear retracted (LGR);
2) airplane landing mass: LGE, LGR;
3) ferry variant take-off (no payload, additional fuel),: LGE LGR;
4) ferry variant landing: LGE, LGR;

5) empty airplane parked (LGE) – check for tipping possibility; in this case maintenance personnel in the tail section is taken into account (400 kg); the absolute coordinate $X_М$ is compared with the coordinate of the airplane tipping point;

6) forward balance limit: LGE, LGR;

7) aft balance limit: LGE, LGR.

The last two cases correspond to partial loading by payload and fuel. For the first of these two cases only the part of these loads located in front of the airplane center of mass is considered, while in the second one – only the part behind the airplane center of mass. If this causes unacceptable shift of the center of mass (i.e. outside the balancing range), then suggestions for passenger and fuel placement for these cases are given.

After calculating balance values for all of the variants the table of balance values is made, and the range of the airplane operational balance values is defined.

Balance position drawing shows the airplane forward and aft center of mass locations at the height $Y_м$. From the point of aft position, the angle of the main landing gear offset γ is plotted; also the static ground angle ψ and the tipping angle φ are shown.

The additional recommendations for calculating the airplane balance values can be found in [1], p.203–215.

9.4 Correcting the balance values

If the balance values of initial or start loading variants are outside of the range recommended in section 9.1 (or in [1], p.207), balance correction can be made by one of the following methods:

— realignment of masses;

— moving the mass m_i from its initial position $X_{iнач}$ to a new position $X_{i\,нов}$, which shifts the airplane balance by

$$\overline{\Delta X}_M = \frac{m_i}{m_0} \cdot \frac{X_{i\,на}}{};$$

— slightly changing (2-3°) the wing sweep angle;

— slightly changing the empennage parameters;

— the most radical method is to shift the whole fuselage with all its masses according to the wing.

The required value of the fuselage shift is defined in the following way. The required value center of mass shift $\Delta X_м$ is calculated, assuming that new COM located in the middle of the desired balance range. The total mass for the fuselage group $m_ф$ is calculated. This group does not contain the mass of the main landing gear as it is related to the wing by the offset angle γ, and while shifting the fuselage the landing gear stays in place even if it is attached to the fuselage. The required value of the fuselage shift is defined

$$\Delta X_ф = \frac{m}{m}\,(\mathrm{m}).$$

9.5 Balance position diagram

After calculating the balance values the balance position diagram is made ([1], p.212–214), which shows the displacements of COM according to MAC while loading the airplane or during the flight. The diagram is plotted in the coordinates $b_A - m_i$. The vertical axis shows the relative scale related to b_A, the horizontal axis shows the absolute mass values for variable loads mass points and for the total airplane mass.

The forward and aft balance limits and the airplane tipping point are marked at this diagram.

The starting point of the airplane loading is its empty mass. The COM displacement is subsequently plotted from this point as different types of varying loads are added: the crew, the luggage in each luggage compartment, the passengers in each cabin, the fuel in each tank group, the retracted landing gear.

After completely loading the airplane the COM is located in the point with the coordinates m_0 and $\bar{X}_{M0}$ (LGE). Then, after retracting the landing gear, the COM is located in the point with the coordinates m_0 and $\bar{X}_{M0}^{/}$ (LGR) – the flight starts with this balance value.

During the flight the COM location is defined by the fuel consumption program. This program should provide the least possible static stability margin as long as possible in order to minimize balance drag, so the COM position should be as close as possible to the aft balance limit. It is possible if there are balance fuel tanks in the airplane tail part (for example, in the fin).

Fuel from the wing tip tanks should be consumed at the very least, so it provides unloading the wing.

The description of the different balance position diagram is given in [3], p.499. It enables to define easily the airplane balance before the flight if all load parameters (number of passengers and their location, payload and luggage mass and location, the amount of fuel and its location) are known.

The final specification of the aerodynamic scheme, the layout and the dimensions of the airplane is carried out after calculating the airplane balance, and it provides the basis of developing the drawing of the airplane general view.

10 GENERAL DRAWING AND TECHNICAL SPECIFICATION OF THE AIRPLANE

The general drawing is made in three views; it is made according to the current standards in the electronic form and then printed.

Then the airplane technical specification is made, which comprises the list of the main airplane parameters and characteristics, also design features of the airplane units, control systems, equipment and power plant should be specified.

10.1 General view drawing

When all of the previous stages are completed and all of the parameters are specified the airplane general drawing is made in three views on white paper of the standard size (usually A1), with the standard scale (1:10, 1:20, 1:50, 1:75, 1:100, 1:200).

The main views are the side view at the left, the plan view under it, the front view to the right. The starboard wing can be shown only partially at the last two views.

The drawing shows: general contours of all airplane units, visible edges and contours of all movable elements of the main units: rudders, ailerons, flaps (only visible parts), slats, interceptors, spoilers, brake flaps, wing fences and notches, trimming and servo flaps, cockpit canopies, windows, passenger and cargo doors, emergency exits and the hatches, landing gear doors, antennas, landing gear in extended position, elements of external loads – tanks, missiles, containers and etc.

<u>**Not shown:**</u> Technological and maintenance joints of all units, skin panel edges, inscriptions at the units, axes of load-carrying elements.

All three views should show **airplane axes** and the following dimensions (in **mm**):

Side view: the airplane total length and height, fuselage length and height (at midsection), wheelbase, tipping angle, fin quarter-chord line sweep angle, static ground angle;

Side view: wing and empennage spans, fuselage midsection width, distance between engine axes, wing and empennage quarter-chord line sweep angles;

Front view: landing gear tread, propeller diameters, wing and empennage dihedral angle, allowed bank angle at landing.

The list of the following main airplane data is given under the title “The airplane performance characteristics” at the right side of the drawing:

1. The airplane name and type
2. The airplane performances:

— maximum velocity km/h;
— cruise velocity at altitude $H_{кр}$ km/h;
— flight range with full payload km;
— maximum flight range (with m1ком) km;
— maximum altitude m;
— climb rate at sea level m/s;
— landing velocity (approach speed) km/h;
— take-off run m;
— landing run m;

1. Mass characteristics

— take-off mass kg;
— landing mass kg;
— payload (number of passengers) kg (persons);
— expendable combat load kg;
— empty airplane mass kg;
— fuel mass kg;
— mass efficiency related to total load -;
— mass efficiency related to payload -;

— specific wing load daN/m^2;

2. Geometric parameters

— wing area m^2;

— wing aspect ratio ;

— wing taper ratio ;

— wing mean aerodynamic chord m;

— empennage area (horizontal and vertical) m^2;

— empennage arms (horizontal and vertical) m;

3. Engine parameters

— number and type of engines;

— net static thrust at sea level daN (kW);

— engine mass kg;

— specific engine weight daN/kW (JPE);

— fuel consumption rate kg/daN h;

— start thrust-to-weight ratio;

4. Other data

— crew;

— required runway type;

— maximum operational g-load;

— fuel efficiency ratio;

— armament and combat load.

10.2 The airplane technical specification

General data include type, scheme, operational conditions, the list of the main technical characteristics, layout description, possible modifications and production amount.

Airframe data contains the load-carrying schemes of the wing, the fuselage, the empennage and the landing gear, aerodynamic shape features, geometrical and relative parameters of the main units, wing lift augmentation devices, control surfaces, passenger accommodation, cargo placement, locations and sizes of passenger and cargo doors and emergency exits, design and kinematics of retractable landing gear, structural materials used, location and characteristics of technological and maintenance joints, airframe life-span.

The airplane control is defined by the airplane control scheme, degree of automation, backup and safety measures, controls and control links.

The airplane equipment and systems comprise the instruments, avionics, electrics, cargo handling, emergency and survival equipment, armament and its variants. The features and operation of fuel, hydraulic, fire extinguishing, anti-ice, crew and passenger life-support systems are described.

The power plant comprises the description of engine type, number and location, their main parameters and characteristics, engine mounting, thrust reversal and engine control.

11 CONCEPTUAL DESIGN PROSPECTS

Practice of the design of complex engineering system shows that the design stage and, particularly, its initial part of choosing the conception and the main parameters, is crucial for future system performance and efficiency. According to experts this stage may take up to 50-70% of the project success (Figure 11.1).

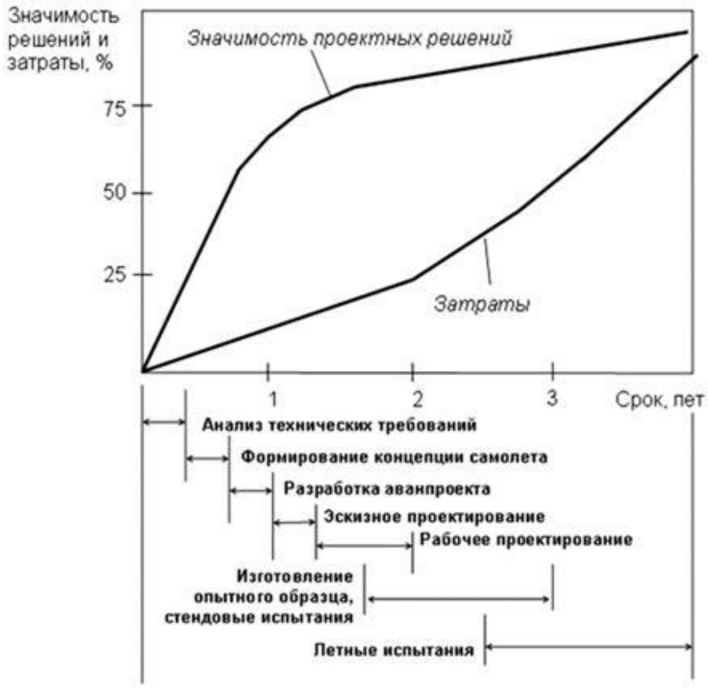


Figure 11.1 – Relative importance of design decisions and the share of design expenses

The aircraft life cycle is a long way from the intension, the existing fundamental research background in aerodynamics, thermodynamics, materials science, CAD systems and others, numerous works devoted to market study, estimation of available resources and technologies, search for advanced energy sources and new power plant operational principles, technological and design capabilities of the enterprise ... till recycling and scraping.

Simulating the complex process of the aircraft "life" according to the inevitable changes in the market, including the advent of new systems, changing priorities and logistics, implementation of new technologies, materials, equipment and systems and etc. with a high degree of accuracy is almost impossible. Project information uncertainty, sometimes its redundancy (or the impossibility of its processing and structuring) and inconsistency pose problems for making decisions.

The current design methods are aimed at clarification and removal of uncertainty, and at researching of stability of the made choices to the possible variation of initial data, priorities and effectiveness criteria. Increase of the reliability of the future aircraft effectiveness estimate is mostly determined by the experience that is specific to each company that creates high technology products. This experience comprises design and technological background, gathered experience in developing and refining high technology products, production and financial bases, information and human resources. Here, as elsewhere, the human resources are all-important. A “beautiful” aircraft is made by the experience, the knowledge, the talent and the "taste" of the designer, and they are the keys to success.

The other important thing is the integral criterion: the cost of the airplane life cycle, which takes into account all costs of marketing, R&D, design, production, operation and recycling. But the forecasting type of estimate, based on the retrospective, competes with the result accuracy. The relationship between the airplane technical parameters and the life-cycle cost is implicit and vague, it is mediated by the airplane performance characteristics, technologies employed and etc., and sometimes it is not recognized or not taken into account while designing the airplane. It is also important to see the unpredictable nature of human factor, people’s addictions, responsibilities and abilities.

The decomposition inherent in the design process usually reduces the aircraft evaluation criteria to the level at which they can be calculated as numerical values. Therefore, the level of the civil aircraft conceptual design is often estimated by weight and aerodynamic efficiency, including transportation costs and flight hour cost, noise and emission environmental requirements. For military and special-purpose aircraft there are criteria such as stealth, agility, mission cost and etc.

The Central Aerohydrodynamics Institute named after N.E. Zhukovskii (CAI) is well known as the aeronautical science center of our country. Its ongoing research projects of the aircraft development are based on the application of the effective conceptual design technology. The basis of these researches is the consistently growing scientific and technical background, the search for new engineering solutions, the widespread use of CAD methods and tools (Figure 11.2) and their enhancement by the principles of CALS-technologies in order to develop three-dimensional layout composition system.

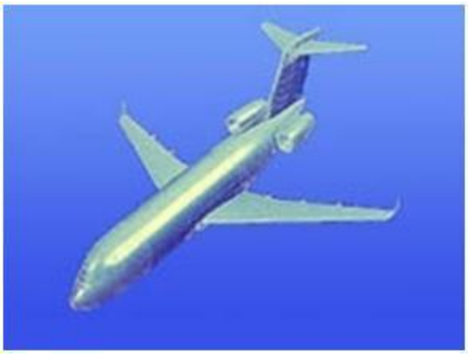


Figure 11.2 – Civil airplane conceptual design in CAI

New ways of developing the aviation are researched in CAI in addition to researches aimed at increase of the efficiency of the traditional airplane schemes, their airframes, power plants and systems. Comparing with the evolutionary improvement the development of alternative aircraft can provide the quantum leap. The research of the passenger flying wing aircraft concept conducted at CAI has shown the opportunity for the significant reduction of the maintenance costs.

In search for new conceptual solutions much attention is paid to estimating their practical efficiency, which is important for the designer. Mathematical modeling of different variants and numerous experiments are carried out, including the experiments in wind tunnels, test rigs and laboratories, with flight test models. For example, the model of advanced Boeing flying wing aircraft is shown at Figure 11.3.

Figure 11.3 – Boeing conceptual airplane X-48B

According to some experts, the search for new schemes that differ from normal or conventional aerodynamic configuration, suggests the conceptual crisis, as most of passenger and transport aircraft are designed in this configuration. Though there is a variety of new aircraft shown at exhibitions and air show, they are basically equivalent and differ from each over only in operational and technological characteristics. But they all have common conceptual solutions, and as a result - common disadvantages. The new aircraft design concept of the Airbus company presents smart solutions for the wing, the empennage, the power plant and etc., but nevertheless, it still has the traditional aerodynamic design (Figure 11.4, a).

Figure11.4 – Conceptual projects:

a) future passenger airplane of the Airbus company;

б) Brazilian MSJ «business -jet».

Brazilian Embraer also continues to use well-known traditional solutions in the layout of new projects. The company has started development of two advanced planes to bridge the gap between two popular models: Phenom 300 and Legacy 600 that have a big difference in price (7 and 26 million dollars). The cost of the two new “business jets” - the midsize MSJ shown at Figure 11.4b and the semi-light jet MLJ - will be in the average price range. The midsize modification MSJ will be 1.5 meter longer than the semi-light MLJ with the equal wing span. MSJ provides 8 passenger seats, its flight range is up to 4480 km, cruise velocity corresponds to M = 0.8. MLJ has flight range of 3520 km, its cruise velocity corresponds to M = 0.78 and passenger capacity and flight altitude are similar to MSJ, but it has shorter take-off run.

Search for the aerodynamic advantages of the new aircraft continues. According to local developers (www.yuanaircraft.ru) the so-called "feather canard" allows to realize the concept of an affordable and safe private jet. Now the project of such aircraft is already under development: it will be a six-seat YuAN-7 "Quick Flyer" (Figure 11.5, a), with a flight range up to 3000-4000 km at an altitude of 13-15 km and with M = 0.7-0.8. According to the first estimates the price of such aircraft can be equal to 1.2-1.5 million dollars. This scheme is also used in the light two-seat airplane YuAN-4 "Quick Bird" (The Figure 11.5 b).

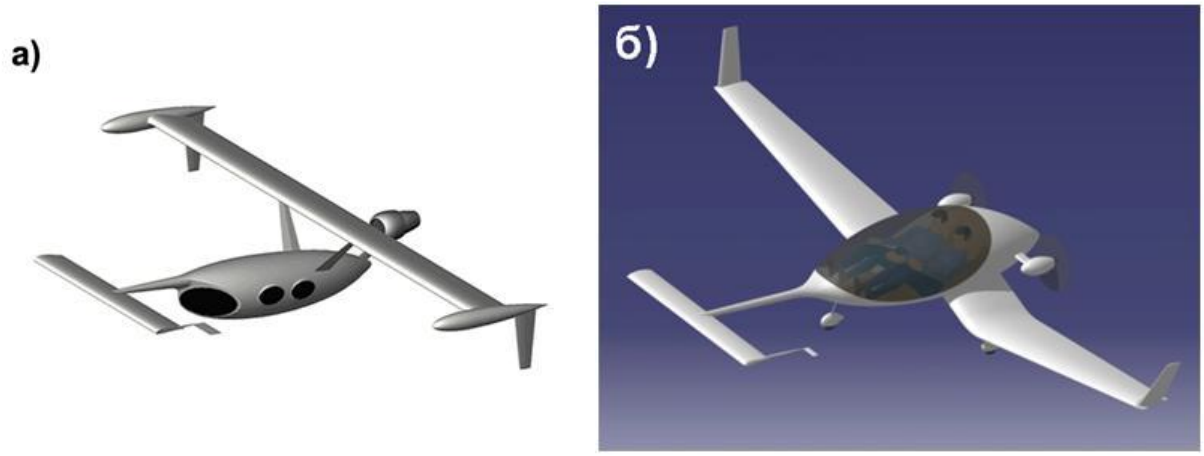


Figure11.5 – "Feather canard":

a) six-seat YuAN-7 "Quick Flyer"

б) light two-seat YuAN-4 "Quick Bird".

Experts from Massachusetts Institute of Technology and Cambridge University presented the conceptual design of the eco-friendly quiet passenger aircraft SAX-40 (Figure 11.6), which is largely similar to the Boeing X-48B concept. Developers plan to create the first aircraft in 2030. However, for this they will have to solve a number of serious technical problems, the most important of which is to develop a new engine system, which can be integrated into a new airplane concept.

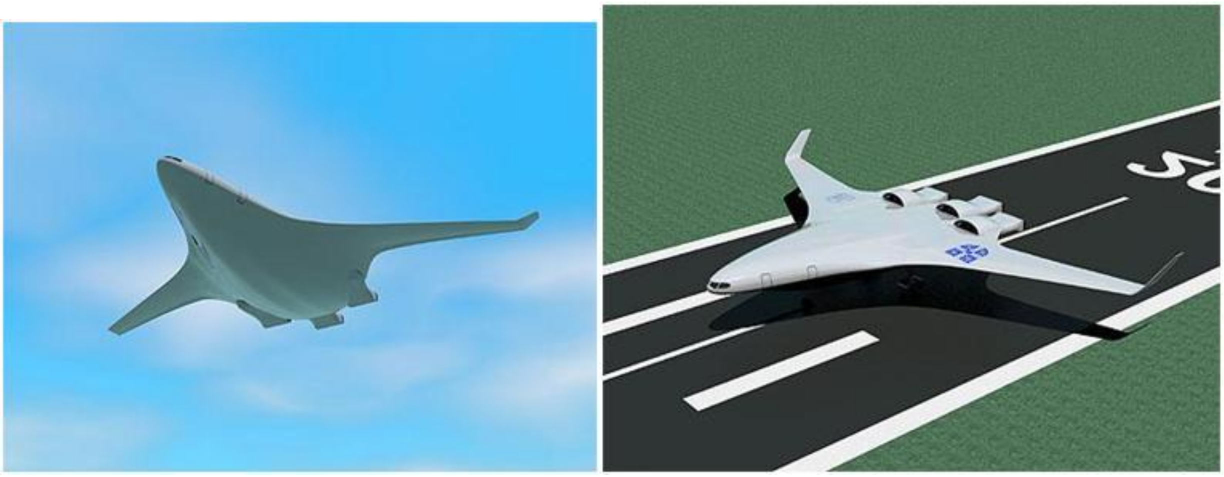


Figure 11.6 – Conceptual project of the eco-friendly quiet passenger aircraft SAX-40

Development of the conceptual design for the aircraft that will be almost silent beyond an airfield have been started by a group of scientists from well-known universities and more than 30 companies, including Boeing and Rolls Royce, in 2003. It is planned to combine the wing and the fuselage into a single structure, so it will allow take-off and landing at lower speeds, thus it will reduce the noise and the fuel consumption. This aircraft will have no flaps – which are the main source of noise during take-off and landing, and its engines will be integrated into the fuselage unlike the traditional method of placing engines under the wing. In addition, the engine nozzle will be able to change its size in flight, so it will decrease the jet stream speed during take-off and landing and increase the jet stream speed in climb. The new aircraft will be less noisy and will consume less fuel. According to its developers, the aircraft, which is designed to carry 215 passengers, will exceed the current airplane performance by up to 25%.

Research of new schemes at the stage of aircraft conceptual design is carried out using high-accuracy models, when the area of design variables variation is narrowed and various estimates of hypothetically efficient schemes are made (Figure 11.7).

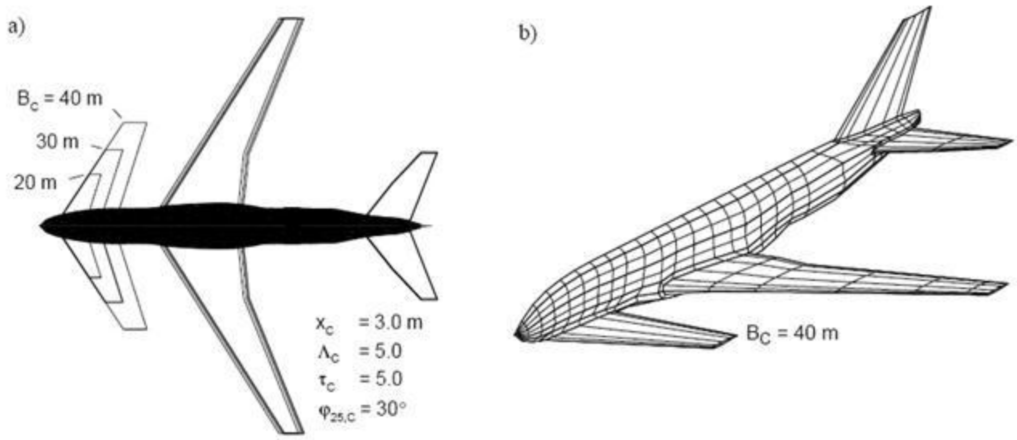


Figure 11.7 – Research of the passenger airplane with “canard” aerodynamic scheme [33]

A new advanced vehicle called “Transition” is shown at Figure 11.8. It was developed by specialists of American company Terrafugia (State of Massachusetts). “Transition” is a flying car that can be easily driven by road, fly and park in a standard car garage. The car was developed in 2006, and it made the first flight on March 5, 2009. It is able to cruise at up to 105 km/h on the highway and fly with the cruise speed equal to 185 km/h. The vehicle length is 5.7 m, the height is 2.1 m, and the width with folded wings is 2 m. The wing span is 8.4 m.

Figure 11.8 – “Transition” conceptual vehicle

The “Transition” project is designed so that the wing folds next to a door and no obstacles for driving. Also, this feature makes it easy to park it in the garage. The “Transition” is powered by Rotax 912S 75kW gasoline engine. The car is designed for only two people - a driver and a passenger. The average cost is 194 000 dollars.

The striking example of searching for new conceptual solutions is a desire of engineers to find better solutions than rigid and single-mode wings. The rigid wings, obviously, cannot perform optimally in different flight modes. This problem is known for a long time, so the idea of morphing appeared that consists in the airplane wing transformation for obtaining more similarity with living creatures. Moreover, prototypes used are birds and fishes. The morphing aircraft projects are developed by engineers and scientists from different companies and institutions for a long time. Ideally, a new generation of aircraft wings should be able change their spans by up to 50%, as well as change its sweep angles, airfoil shape, dihedral and other important geometric parameters in a wide range. There are numerous estimates for aerodynamic and weight efficiency of a rigid wing with variable span, including ones made at the department of Aircraft construction and design (ACaD) of SSAU.

University of Pennsylvania has shown the first results of their research, in which the aircraft wings change their shape like bird wings and have scales like fish (the Figure 11.9). Wings that can smoothly change its shape in a wide range are of interest for commercial aircraft, fighters and unmanned reconnaissance drones. As it is known, the task of reconnaissance drones is to reach quickly a remote area, and then fly back and forth at low speed, transfering images from their cameras.

Figure 11.9 Morphing aircraft project (University of Pennsylvania, USA).

Morphing wings developed at University of Pennsylvania can change their areas and cross-section shapes. The basis of these wings is the variable cellular load-carrying structure that is the "bones and ligaments" of the wing and the segmented scale "skin". The polygonal frame cells located along the upper and lower wing surfaces can be folded in different ways, thus the wings can be bended up and down. If they are transformed simultaneously, the wing span changes.

However, despite the research in this area that were carried out by different organizations for several years still no morphing fighters or reconnaissance drones with such wings were created.

The work in the field of the alternative fuels and power plants, as well as research of the aircrafts with flapping wings, has not stopped since the first flight. The example of the innovative development belongs to the world leader of the general purpose aircrafts - Cessna Aircraft company (USA), which together with the Bye Energy company announced development and creation of the electric engine for its Cessna 172 Skyhawk aircraft (the Figure 11.10).

Figure 11.10 – Cessna 172 Skyhawk light aircraft.

The most popular (since 1956 over 43 000 aircraft were built) and the safest airplane in aviation history can be "reborn". The first flight of the conceptual Cessna 172 Skyhawk with the electric engine is already scheduled towards the end of 2010. Usage of alternative aviation fuels has its own prospects in Russia because of the aviation gasoline high cost and low off-the-shelf availability in remote regions of the country.

The important direction of the conceptual design is the possibility to use the results obtained at this stage at subsequent stages without reformatting the data, and also the ability to make easy and quick changes of the already developed concept. Utilization of CALS-technologies and CAD/CAE/CAM systems in conjunction with data- and knowledge-bases will allow creating intelligent CAD systems for the aircraft preliminary design [32]. The ontological analysis of the "airplane" knowledge domain, the structuring and formalization of the aircraft creation process will enable developing methods for filling in an information matrix, which describes this complex technical system, and, as a result, it will allow automating the stage of the airplane conceptual design by turning the computer from a calculator to an intellectual assistant.

CALS-technologies use the means that provide the collaboration capabilities when working with complex assemblies, controlling connections and changes; also they manage associative relations between the assembly parts. These technologies are the basis of parametric modeling for products of any complexity. The mechanism of the controlled associative relation between the geometric models allows combining the conceptual design and the detailed design, so that changes of the conceptual level would automatically propagate at the level of the secondary technological models. The "conceptual" template, which is called a control structure, defines the most important product parameters, and the product functional characteristics depending on these parameters. Using this template for creating separate parts, the model can be built, which allows carrying out parametric researches with a high specification level. It gives the means of carrying out quick and accurate analysis of the influence of various parameters on the product performance.

ACaD Department of Samara State Aerospace University works on three-dimensional aircraft simulation using CATIA CAD system at the conceptual design stage. Figure 11.11 shows the surface model of the passenger airplane project built on the basis of technical specifications. The initial data that were used are the dimensionless parameters of the wing, the fuselage, the empennage and the calculated values of wing area and fuselage diameter.

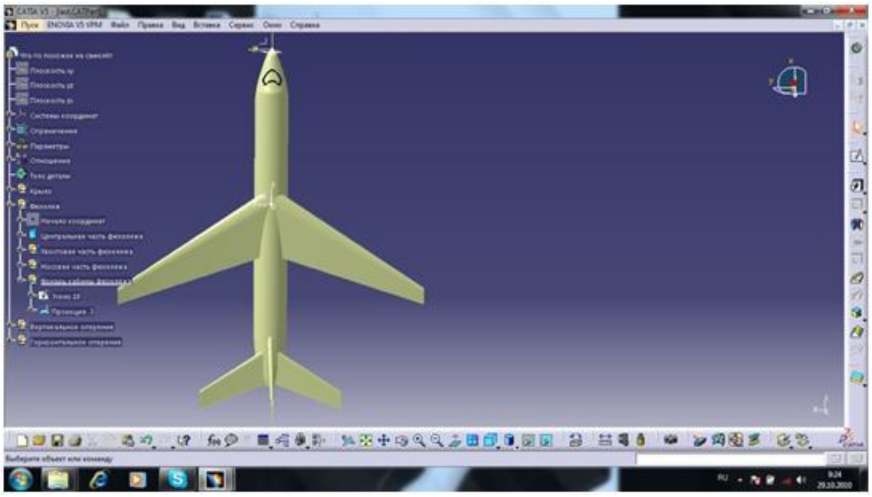


Figure 11.11 – Geometric model of a passenger airplane project in CATIA

The software developed in Moscow Aviation Institute (State Technical University - MAI) allows creating the external fuselage contour on the basis of its internal layout; developing longitudinal cabin layout that meets the requirements for passenger comfort; data transfer to SolidWorks CAD-system for further development of the airplane project (Figure 11.12).

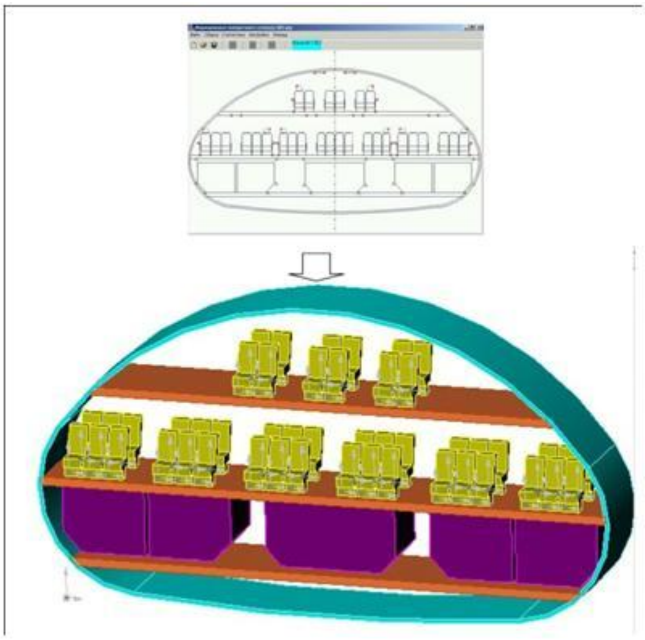


Figure 11.12 – Cabin layout in SolidWorks [34]

Management of the design process of a complex technical object using CAD/CAE/CAM systems is made with the help of PDM-systems, based on the usage of parallel design technologies at all design stages. Methods and means of PDM-systems allow organizing the collaboration between specialists from different departments and technical directions during the airplane layout design, i. e. applying the parallel design technology. For that purpose a model of the design space is created, which supports design decisions justification and can be used by designers, collaborators and suppliers of systems and equipment (Figure 11.13). This model allows performing following activities at earlier design stages:

- involve Customer representatives into specification of final technical requirements for the design;
- make all the necessary changes and specifications without wasting the large industrial resources;

— meet the requirements for prototype and mass production, and maintenance.

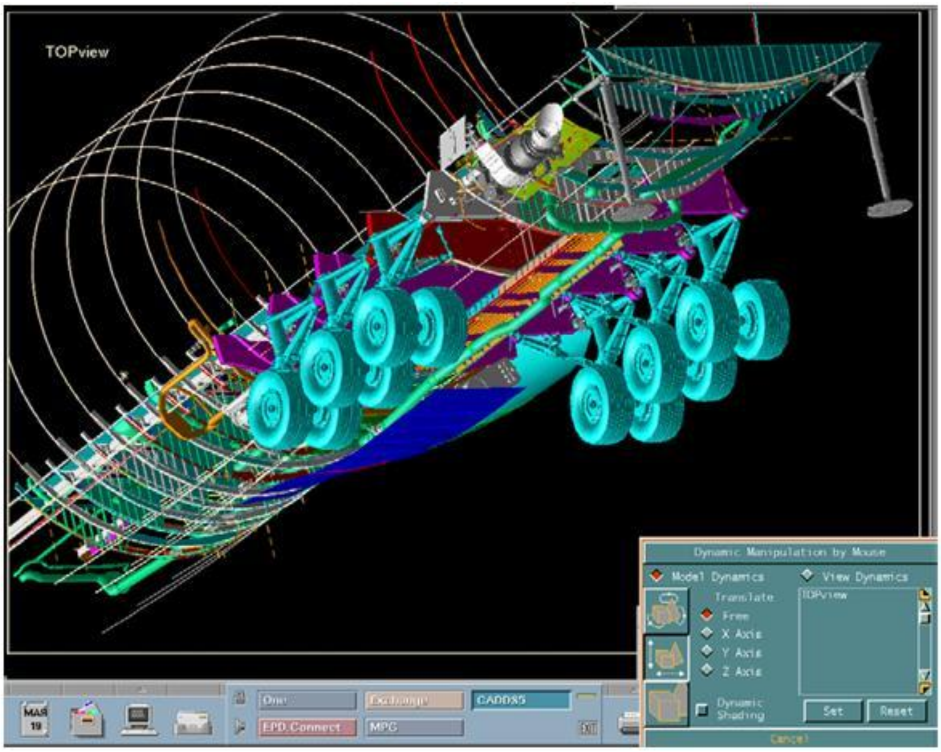


Figure 11.13 – Visualization of the model for the airplane space distribution in CAD/CAE/CAM [35]

A full-featured e-learning course designed to acquaint students and undergraduates with aircraft conceptual design has not yet been developed in Russia. Although some parts of it are computerized and available in aviation universities: SSAU, MAI, Kazan State Technical University named A.N. Tupolev (KSTU). For students it is recommended to take Stanford University free online course of the aircraft conceptual design (Aircraft Design: Synthesis and Analysis) that contains all the major topics discussed in this manual, but has its own features specific for this American university. The course is structured so that after choosing and defining all main aircraft parameters and characteristics it is possible to obtain a simplified aircraft appearance and its three-dimensional image (Figure 11.14) [29].

This material is based on course notes for a graduate level course in aircraft design at Stanford University. The course involves individual aircraft design projects with problem sets and lectures devoted to various aspects of the design and analysis of a complete aerospace system. Students select a particular type of aircraft to be designed and, in two academic quarters, define the configuration using methods similar to those used in the aircraft industry for preliminary design work. Together with the vehicle definition and analysis, basic principles of applied aerodynamics, structures, controls, and system integration, applicable to many types of aerospace problems are discussed. The objective of the course is to present the fundamental elements of these topics, showing how they are applied in a practical design.

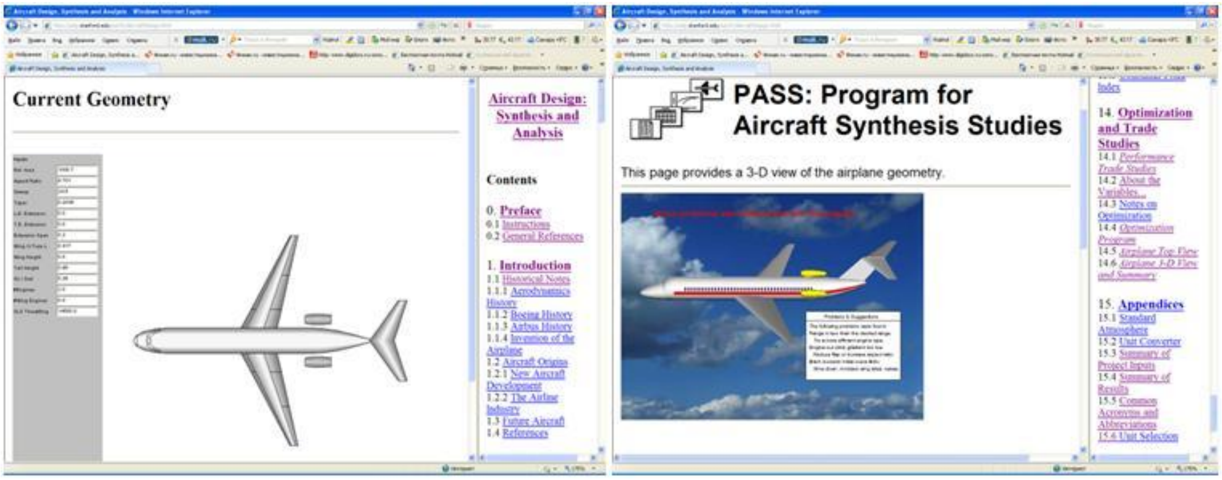


Figure 11.14 – The results of conceptual design (Aircraft Design: Synthesis and Analysis)

This internet-based version of Aircraft Design: Synthesis and Analysis is an experiment. It is a new type of textbook whose pages may be distributed throughout the world and access able via the world-wide-web. The text will be evolving and new items will be added continually.

Advanced Aircraft Analysis (AAA) software is an industry standard for the aircraft preliminary design software. It was developed and now maintained by American company DARcorporation. It is used in more than 45 countries (Russia is not included) by large aviation institutes, aircraft manufacturers and defense contractors all over the world. Generally, AAA is used to design small civil, fighter and transport airplanes (Figure 11.15). http://www.darcorp.com/Software/AAA/.

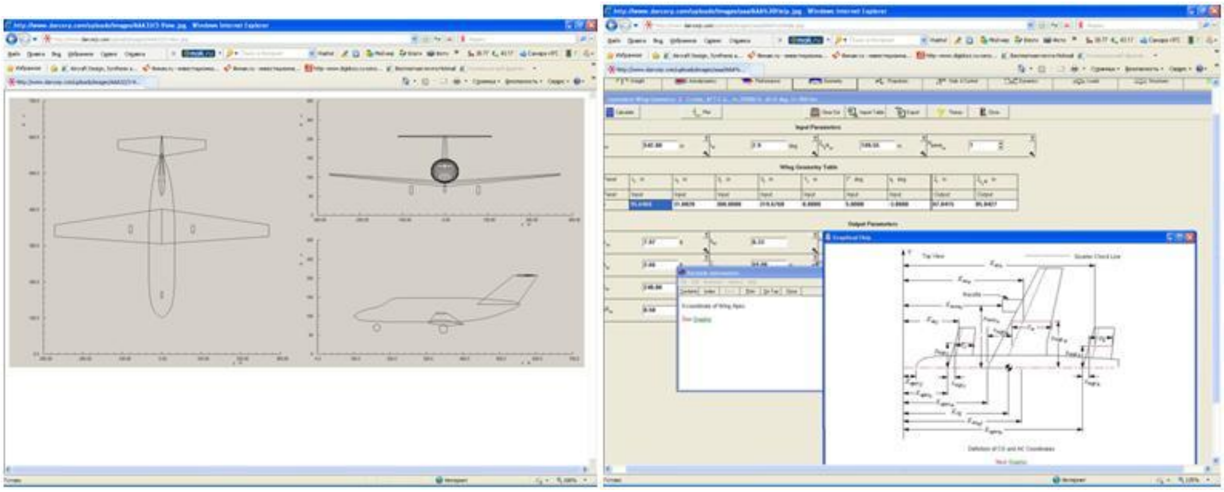


Figure 11.15 – The results of civil airplane conceptual design in AAA

AAA software has all the modules that are necessary for preparing, calculating and estimating the first airplane drawing; also it contains the module for estimate of the airplane life-cycle cost.

State-of-the-art achievements in computer simulation, applied aviation science fields and design experience allow significant decrease of time and cost of development of a new aircraft. Nevertheless, a desire for finding the most efficient solution leads to widening the search range that in turn leads to increasing costs. The resource concentration at the science-driven fields is the key for success in this field. Abroad these tasks can be solved by well-known consortiums, universities and large companies with government support. In Russia CAI, United Aircraft Corporation (UAC) and also industrial research institutes and design enterprises, national research universities play the important role in the aviation science development.

APPENDIX A

Table A.1 – Main aircraft parameters

№	Airplanes	1	2	..i...	n
1	Airplane model, manufacturer, year and country				
2	Crew				
	Power plant characteristics				
3	Engine type, number (n), thrust P_0 (daN), power N_0 (kW)				
4	Fuel consumption rate C_{p0} (кг/даНч), C_{e0} (кг/кВтч)				
5	By-pass ratio m				
6	Specific engine weight $\gamma_{дв}$; (γ ;, daN/kW)				
	Weight characteristics				
7	Take-off mass m_0, kg				
8	Payload (combat load) mass $m_{ком}$, kg				
9	Empty airplane mass $m_{пуст}$, kg				
10	Fuel mass m_T, kg				
11	Specific wing load p_0 , daN/m^2				
12	Weight efficiency $K_{полн} = \frac{m_c}{}$ or $K_{ком}$				
13	Thrust-to-weight ratio (power-to-weight ratio) $\overline{P}_0$; ($\overline{N}_0$) (kW/daN)				
	Geometric characteristics				
14	Wing area S, м^2				
15	Wing span ℓ, м				
16	Wing aspect ratio λ / wing taper ratio η				
17	Wing sweep angle χ^0				

18	Relative thickness $\bar{C}_0$				
19	Fuselage diameter $D_ф$, м / fuselage aspect ratio $\lambda_ф$				
20	Fuselage nose part aspect ratio / fuselage aft portion aspect ratio $\lambda_{н ч}$ / $\lambda_{х ч}$				
21	Relative distance from fuselage nose to wing central chord				
22	Horizontal tail (HT) area $S_{г о}$, $м^2$/ $\bar{S}_{г о}$				
23	HT aspect ratio / HT taper ratio $\lambda_{г о}$ / $\eta_{г о}$				
24	HT sweep angle $\chi_{в о}$				
25	HT arm $L_{г о}$, m / $\bar{L}_{г о}$				
26	Coefficient of HT static moment $A_{г о} =$				
27	Vertical tail (VT) area $S_{в о}$, $м^2$ / $\bar{S}_{в о}$				
28	VT aspect ratio / VT taper ratio $\lambda_{в о}$ / $\eta_{в о}$				
29	VT swept angle $\chi_{в о}$				
30	VT arm $L_{г о}$ м / $\bar{L}_{в о}$				
31	Coefficient of VT static moment $A_{в о} = \bar{S}$				
32	Landing gear tread				
33	Main landing gear offset				
	Performance characteristics				
34	Maximum velocity over altitude V_{max}/H, km/(h*m)				
35	Cruise velocity over altitude $V_{кр}/H_{кр}$, km/(h*m)				
36	Landing velocity $V_{пос}$ ($V_{з п}$) , km/h				

37	Flight range with full payload L_p, km				
38	Flight range with reduced payload L_{max}, km				
39	Take-off run (or runway length $L_{ВПП}$), m				
40	Climb rate V_{y0}, m/s				
41	Maximum altitude H_n, m				
	Others				
42	Number of passengers $n_{пас}$				
43	Cargo compartment dimensions $BxHxL$, mxmxm				
44	Airfield type				
45	Fuel efficiency $k_{топ}$, g/pass km (g/t km)				
46	Armament				
47	Calculated g-load n_{max} (n_A)				
48	Airplane cost				

APPENDIX Б

WEIGHT FORMULAS OF FOREIGN COMPANIES

Weight formulas, which are used by some leading foreign aviation design companies, are listed below [30].

Fighters/ low-flying attack aircraft

(the list of symbols is given in the end of the appendix)

$$m_{крыло} = 0{,}0334 K_{dw} K_{vs} (m_0 n_p)^{0{,}5} S^{0{,}622} \lambda^{0{,}785} (\bar{c}_0)^{-0{,}4} (1+\eta)^{0{,}05} (\cos\chi)^{-1} S_{упр.кр}^{0{,}04};$$

$$m_{го} = 12{,}541 \left(1 + \frac{B_ф}{\ell_{го}}\right)^{-2} (0{,}001 m_0 n_p)^{0.26};$$

$$m_{во} = 0{,}506 K_{rht} \left(1 + \frac{h_{го}}{h_{во}}\right)^{0{,}5} (m_0 n_p)^{0.488} S_{во}^{0{,}718} M^{0{,}341} L_{во}^{-1} \left(1 + \frac{S_{PH}}{S_{во}}\right)^{0{,}348} \lambda_{во}^{0{,}223} (1+\eta)^{0{,}25} (\cos\chi_{во})^{-0{,}323};$$

$$m_{фюзеляж} = 3{,}345 K_{dwf} m_0^{0{,}35} n_p^{0{,}25} L_{кф}^{0{,}5} H_ф^{0{,}849};$$

$$m_{осн.опоры} = 19{,}706 K_{cb} K_{tpg} (m_{пас} n_{p\ пас})^{0{,}25};$$

$$m_{нос.опоры} = 3{,}579 (m_{пас} n_{p\ нос})^{0{,}29} h_{но}^{0{,}5};$$

$$m_{крепление\ двигателей} = 0{,}0093 n_{дв}^{0{,}795} (n_{дв} P_0)^{0};$$

$$m_{группа\ двигателей} = 0{,}008 m_{дв}^{0{,}717};$$

$$m_{система\ подвода\ воздуха} = 42{,}458 K_{vg} L_D^{0{,}643} K_D^{0{,}182} n_{дв}^{1{,}498} \left(\frac{L_S}{L_D}\right)^{-0{,}};$$

where KD, LS и LD are defined according to Figure Б.1.

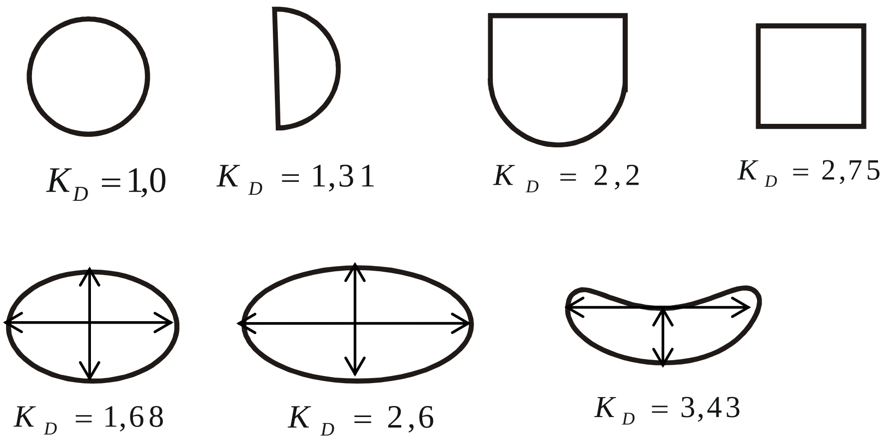


Figure Б.1 – Air intake geometry

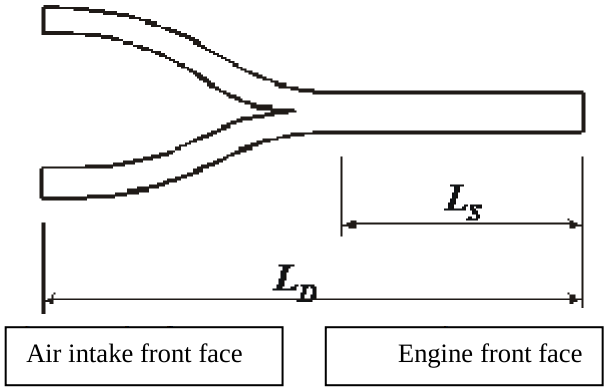


Figure Б.2 – The conduit channel

$$m_{система\ выхлопа} = 17{,}089 D_{дв};$$

$$m_{система\ охлаждения\ двигателя} = 22{,}215 D_{дв} L;$$

$$m_{масляная\ система} = 17{,}155;$$

$$m_{управление\ двигателями} = 6{,}2 n_{дв}^{1{,}008};$$

$$m_{система\ запуска} = 0{,}0207 P_0^{0{,}7};$$

$$m_{топливная\ система\ и\ баки} =$$
$$56{,}575 V_T^{0{,}47} \left(1 + \frac{V_Б}{V_T}\right)^{-0{,}095} \left(1 + \frac{V_{БΣ}}{V_T}\right) N_Б^{0{,}066} n_{дв}^{0{,}052} \left(0{,}001 \sum P_0 \cdot C_{p0}\right)^{0{,}249}$$

;

$$m_{противопожарная\ система} = 5;$$

$$m_{управление\ полетом} = 52{,}6M^{0{,}003}S_{\Sigma P}^{0{,}489}N_{су}^{0{,}484};$$

$$m_{гидросистема} = 16{,}89K_{vsh};$$

$$m_{электрооборудование} = 87{,}96K_{тс}N^{0{,}152}n_{эк}^{0{,}1}L_{пров}^{0{,}1};$$

$$m_{измерительная\ аппаратура} = 3{,}63 + 16{,}5n_{дв}^{0{,}676}N_{Б}^{0{,}237} + 11{,}98(1 + n_{эк};$$

$$m_{авионика} = 2m_{a}^{0};$$

$$m_{отделка} = 9;$$

$$m_{ситема\ кондиционирования\ и\ противообледенительная\ система} = 163{,}5[(m_{ав.нетто} + 200n_{эк}) \cdot 0{,}001]^{0{,}735}$$

;

$$m_{погрузочно-разгрузочное\ оборудование} = 0{,}00(;$$

Cargo/transport airplanes.

$$m_{крыло} = 0{,}0213(m_0 n_p)^{0{,}557}S^{0{,}649}\lambda^{0{,}5}(\bar{c}_0)^{-0{,}4}(1+\eta)^{0{,}1}(\cos\chi)^{-1};$$

$$m_{го} = 0{,}051K_{го}(1 + \frac{B_{ф}}{\ell_{го}})^{-0{,}25}m_0^{0{,}639}n_p^{0{,}1}S_{го}^{0{,}75}L_{го}^{-0{,}296}(\cos\chi_{го})^{-1}\lambda_{г.т.}^{0{,}166}(1 + \bar{S}_{рв})^{0{,}1}$$

;

$$m_{во} = 0{,}0094(1 + \frac{h_{го}}{h_{во}})^{0{,}225}m_0^{0{,}556}n_p^{0{,}536}L_{во}^{0{,}375}S_{во}^{0{,}5}(\cos\chi_{во})^{-1}\lambda_{во}^{0{,}35}(\bar{c};$$

$$m_{ф} = 0{,}6093K_{двер}K_{ш}\left(m_0 n_p\right)^{0{,}5}L_{кф}^{0{,}25}S_{ф.ом}^{0{,}302}(1 + k_{ws})^{0.04}(.$$

For the fuselage with the middle cylindrical part

$$S_{ф.ом.} = \pi D_{ф}L_{ф}\left(1 - \frac{2}{\lambda_{ф}}\right)^{\frac{2}{3}}(1.$$

For the fuselage with non-circular cross section the calculation of $S_{ф\ ом}$ is carried out according to 6.3 [2, p.488].

$$m_{осн\ опора} = 0{,}0396 K_{тр} m_{пос}^{0{,}888} n_{р\ пос}^{0{,}25} h_{оо}^{0{,}4} N_{коо}^{0{,}321} N_{оо}^{-0};$$

$$m_{нос\ опора} = 0{,}155 K_{пр} m_{пос}^{0{,}646} n_{р\ пос}^{0{,}2} h_{но}^{0};$$

$$m_{группа\ гондол} = 1{,}3444 K_{ng} L_{гонд}^{0{,}1} B_{гд}^{0{,}294} n_{р}^{0{,}119} m_{дв\Sigma}^{0{,}611} n_{дв}^{0{,}984}.$$

The calculated value takes into account the air supply system. $S_{гд\ ом}$ can be calculated according to 6.3 [2, p.488]:

$$m_{управление\ двигателями} = 2{,}27 n_{дв} + 1;$$

$$m_{система\ запуска} = 34{,}22(0{,}001 n_{дв} m_{д};$$

$$m_{топливная\ система} = 32{,}024 V_{T}^{0{,}606} \left(1 + \frac{V_Б}{V_T}\right)^{-1} (1 + \frac{V_Б}{V_T}.$$

It should be mentioned that the fuel tank volumes $V_Б$ should exceed the total fuel volume up to 5% because of the fuel expansion. The fuel tank volume can be approximately defined according to 6.3 [2, c.490]:

$$m_{управление\ полетом} = 132{,}86 N_{ф}^{0{,}554} (1 + \frac{N_{аф}}{N_{ф}})^{-1} S_{\Sigma p}^{0{,}2} (I_y \times 10^{};$$

$$m_{ВСУ\ установленная} = 2{,}2 m_{ВСУ\ постав};$$

$$m_{измерит.аппаратура} = 3{,}705 K_{r} K_{tp} n_{эк}^{0{,}541} n_{дв} (L_{ф} +;$$

$$m_{гидросистема} = 0{,}3691 N_{ф} (L_{ф} + 1;$$

$$m_{электрооборудование} = 4{,}989 N^{0{,}782} L_{пр}^{0{,}3};$$

$$m_{авионика} = 1{,}707 m_{a}^{0};$$

$$m_{отделка} = 0{,}2122 n_{эк}^{0{,}1} m_{нагр}^{0{,}39};$$

$$m_{система\ кондиционирования} = 263{,}56 n_{чел}^{0{,}25} (0{,}001 V_{герм})^{0{,}604} m_{a}^{0};$$

$$m_{противообледенительная\ система} = 0{,}0;$$

$m_{погрузочно-разгрузочное\ оборудование} = 0,0$ – для гражданских грузов;

$m_{погрузочно-разгрузочное\ оборудование} = 11,72$ – для военных грузов.

General aviation aircraft

$$m_{крыло} = 0,1427 S^{0,758} m_{T\ кр}^{0,0035} \left(\frac{\lambda}{cos^2 \chi}\right)^{0,6} q^{0,006} \eta^{0,04} \left(\frac{100\bar{c}}{\cos\chi}\right)^{-0,3} (n_p n;$$

$$m_{го} = 0,044 (n_p m_0)^{0,414} q^{0,168} S_{го}^{0,896} \left(\frac{100\bar{c}}{\cos\chi}\right)^{-0,12} \left(\frac{\lambda}{cos^2 \chi_{го}}\right)^{0,043};$$

$$m_{во} = 0,221 (1 + 0,2 h_{го}/h_{во}) (n_p m_0)^{0,376} q^{0,122} S_{го}^{0,873} \left(\frac{100\bar{c}}{\cos\chi_{во}}\right)^{-0,49} \left(\frac{\lambda}{cos^2 \chi_{во}}\right)^{0,357} \eta_{во}^{-0,02}$$

;

$$m_{ф} = 0,126 S_{ф.ом}^{1,086} (n_p m_0)^{0.177} L_{ф}^{-0,051} (L_{кф}/H_{ф})^{-0,072} q^{0,241};$$

$$m_{осн.опора} = 0,355 (n_{p\ пос} m_{пос})^{0,768} (L_{ф}/1;$$

$$m_{нос.опора} = 1,976 (n_{p\ пос} m_{пос})^{0,566} (L_{ф}/1;$$

$$m_{установленные\ двигатели} = 2,421 m_{дв}^{0,};$$

$$m_{топливная\ система} = 64,74 V_T^{0,726} \left(1 + \frac{V_Б}{V_T}\right)^{-0,363} N_Б^{0,242};$$

$$m_{управление\ полетом} = 0,436 L_{ф}^{1,536} l^{0,371} (0,0001 n_p;$$

$$m_{гидросистема} = 0,0;$$

$$m_{авионика} = 2 m_a^{0,};$$

$$m_{электрооборудование} = 8,53 (m_{топливная\ система} + m_{авиони};$$

$$m_{система\ кондиционирования\ и\ противообледенительная\ система} = 0,207 m_0^{0,52} n_{чел}^{0,68} m_{авионика}^{0,17} M^{0,08}$$

;

$$m_{отделка} = 0{,}0264 m_0 - .$$

Symbols in formulas:

$\bar{c}_0$ – relative thickness of wing root section;

η – wing taper ratio;

λ – wing aspect ratio;

$\lambda_ф$ – fuselage aspect ratio;

χ - wing sweep angle at quarter MAC;

$B_{гд}$ – nacelle width, m;

$B_ф$ – fuselage construction width, m;

$B_ф^{го}$ – fuselage width at the location of horizontal empennage, m;

C_{p0} – engine fuel consumption rate (maximum);

$D_{дв}$ – engine diameter, m;

$D_ф$ – fuselage diameter, m;

$h_{во}$ – vertical empennage vertical location, m;

$h_{го}$ – horizontal empennage vertical location, m;

$h_{го}/h_{во}$ = 1,0 – for T-shaped tail; 0,0 – for other schemes;

$h_{но}$ – nose landing gear height, m;

$h_{оо}$ – main landing gear height, m;

$H_ф$ – fuselage construction height, m;

$I_x =$ – rolling moment of inertia, kg·m^2;

$I_y = (\frac{1+L_{кф}}{2})$ – yawing moment of inertia, kg·m^2;

$I_z = \frac{L}{}$ – pitching moment of inertia, kg·m^2;

where $\bar{R}_x$, $\bar{R}_y$, $\bar{R}_z$ – dimensionless inertia radiuses. Values of dimensionless inertia radiuses are given in Table Б.1.

Table Б.1 – Dimensionless inertia radiuses

Airplane type	$\overline{R}_x$	$\overline{R}_y$	$\overline{R}_z$
One propeller engine	0,25	0,38	0,39
Two propeller engines	0,34	0,29	0,44
Administrative jet airplane with two engines	0,30	0,30	0,43
Transport airplane with two turbo-prop engines	0,22	0,34	0,38
Transport jet airplane:			
— engines at the fuselage	0,24	0,36	0,44
— 2 engines under the wing	0,25	0,38	0,46
— 4 engines under the wing	0,31	0,33	0,45
Military training jet airplane	0,22	0,14	0,25
Jet fighter	0,23	0,38	0,52
Heavy jet bomber	0,34	0,31	0,47
Flying wing airplane (the type B-49)	0,32	0,32	0,51
Flying boat	0,35	0,32	0,41

$K_{\text{го}}$=1,143 for movable stabilizer, 1,0 in other cases,

$K_{\text{двер}}$=1,0 if there are no cargo doors, 1,06 if cargo doors located on one side, 1,12 if cargo doors located on both sides; 1,12 if cargo ramp, 1,25 if cargo doors located on both sides and cargo ramp;

$K_{\text{ш}}$ =1,12 if landing gear is fixed at the fuselage, 1,0 for other cases;

K_{cb}=2,25 for strut scheme of the landing gear (F-111), 1,0 for others;

K_{D} – channel coefficient (see the Picture Б.1);

K_{dw} =0,768 for delta wing, 1,0 for other cases;

K_{dwf} =0,774 for delta wing, 1,0 for other cases;

K_{mc}=1,45, if in case of failure the flight should be cancelled, 1,0 for other cases;

K_{mp}=1,126 for retracting landing gear, 1,0 for other cases;

K_{ng}=1,017 for nacelles located at pylons, 1,0 for other cases;

K_{np}=1,15 for retracting landing gear, 1,0 for other cases;

K_p=1,4 for propeller engines, 1,0 for other cases;

K_r=1,133 for piston engines, 1,0 for other cases;

K_{rht}=1,047 for movable empennage, 1,0 for other cases;

K_{tp}=0,793 for turbo-prop engines, 1,0 for other cases;

K_{tpg}=0,826 for tricycle-type landing gear, 1,0 for other cases;

K_{tr}=1,18 if thrust reversal installed, 1,0 for other cases;

K_{vg}=1,62 for adjustable air intakes; 1,0 for other cases;

K_{vs}=1,19 for variable wing sweep, 1,0 for other cases;

K_{vsh}=1,425 for variable wing sweep, 1,0 for other cases;

$$K_{ws} = 0{,}75[(1+2\eta)/(1+\eta)](l \tan\chi;$$

K_y – radius of airplane pitching inertia, $K_y \approx 0{,}3 L_{г\,о}$ m;

K_z – radius of airplane yawing inertia, $K_z \approx L_{в\,о}$ m;

l – wing span, m;

$L_{бан}$ – turbine bandage length, m;

$L_{в\,к}$ – exhaust channel length, m;

$L_{гд}$ – nacelle length, m;

$l_{г\,о}$– horizontal empennage span, m;

$L_{го}$, $L_{во}$ – arms of horizontal and vertical empennage, m; distance from wing quarter MAC point to empennage quarter MAC point;

$L_{дв}$ – distance from engine front face to cockpit, cumulative in case of several engines, m;

$L_{кф}$ – fuselage construction length, m (tail fairing excluded);

$L_{пров}$ – electric wiring length, from generators to the cockpit, m;

L_D – channel length, m (see. the Picture Б.2);

L_S – length of a single channel, m (see. the Picture Б.2);

$L_ф$ – total fuselage length, m;

M- Mach number;

m_0 – calculated airplane mass, kg;

$m_{ав\ нетто}$ – mass of unset avionics, kg (usually 244-427 kg);

$m_{дв}$ – mass of one engine, kg;

$m_{дв\Sigma}$ – mass of engine and its components, kg (for one nacelle), equal to $2{,}156 m_{дв}^{0{,}901}$;

$m_{герм}$ – mass increase due to pressurization; $m_{герм} = 5{,}4 + 4{,}6(V_{герм}\Delta l$, where ΔP – cabin excess pressure, MPa (usually 0,055 MPa);

$m_{нагр}$ - maximum payload mass, kg; $m_{боев}$ – for fighters, low-flying attack aircraft, bombers, $m_{ком}$ – for passenger airplanes, $m_{гр}$ - for transport airplanes;

$m_{пос}$ – calculated landing mass, kg, usually $m_{пос}$=0,85m_0;

$m_{т\ кр}$ – in-wing fuel mass, kg;

$N_{а\ ф}$ – number of automated functions (usually 0-2);

$N_Б$ – number of fuel tanks;

$n_{дв}$ – number of engines;

$n_{ген}$ – number of generators (usually equal to $n_{дв}$);

$N_{кно}$ – number of nose landing gear wheels;

$N_{коо}$ – number of main landing gear wheels (for one leg);

$N_{оо}$ – number of main landing gear legs;

$n_р$ – calculated g-load; $n_р$=1,5$n_э$, $n_э$ – operating g-load;

$n_{р\ пос}$ - calculated g-load at landing; $n_{р\ пос}$=1,5$n_{шасси}$; for heavy airplanes $n_{шасси}$=2,5;

$N_{с\ у}$ – number of flight control systems;

$N_ф$ – number of functions executed by control systems, (usually 4-7);

$N_{фгс}$ – number of functions executed by hydraulics (usually 5-15);

$n_{чел}$ – number of people onboard (crew and passengers);

$n_{эк}$ – number of crew members;

$n_{экi}$ =1,0 for one pilot; 1,2 for one pilot plus one empty seat behind; 2,0 for a pilot with a passenger;

N_{kva} – electrical equipment power consumption, (usually 40-60 W for transport airplanes, 110-160 W for fighters and bombers);

P_0 – single engine thrust, daN;

q – dynamic pressure at cruise, N/m^2;

S – total wing area (including in-fuselage area but without chines), m^2;

$S_{в\ о}$ – vertical empennage area, m^2;

$S_{гд\ ом}$ –nacelle wetted surface area, m^2;

$S_{гр\ пола}$ – cargo floor area, m^2;

$S_{г\ о}$ – horizontal empennage area, m^2;

$S_{о\ з}$ – area of fire-protective surface, m^2;

$S_{р\ в}$ – elevator area, m^2;

$S_{р\ н}$ – rudder area, m^2;

$S_{\Sigma р}$ – total area of control surfaces, m^2;

$S_{упр\ кр}$ – area of control surfaces located on the wing (ailerons, interceptors), m^2;

$S_{ф\ ом}$ – fuselage wetted surface area, m^2;

$V_{Б}$ – useful volume of fuel tanks, m^3;

$V_{\Sigma Б}$ – total volume of fuel tanks, m^3;

$V_{герм}$ – pressurized cabin volume, m^3;

$V_с$ – stall velocity, $V_с=V_{зах}/1{,}3$ km/h;

$V_т$ – total fuel volume, m^3.

APPENDIX B

Table B.1 – Aviations wheel catalog. Brake wheels

product number	tire dimension, mm	tire operational pressure, kgs/sm^2	Stationary load from take-off mass, kg	Allowable take-off velocity, km/h	Allowable landing velocity, km/h	Operational load of the brake, kgs m	Operational brake torque, kgs m	wheel weight, kg	brake weight, kg
КТ239	476x178-6	3,5	935	126	123	54000	52	7,8**	-
КТ235	500x150-9	7,0	1400	140	126	39500	30	14,0	7,8
КТ236	500x150-9	3,0	560	150	130	23000	30	7,8**	-
КТ245	500x150-9	4,5	950	126	128	30500	60	6,3	4,7
КТ217	600x180	7,0	3210	-	80	46500	90	12,0**	-
КТ254	610x185-305	5,5	2080	196	220	294000	350	28,5**	-
КТ176	660x200	10,0	2600	290	270	490000	180	15,8	24,1
КТ240	660x200-356	12,0	3300	275	240	290000	265	42,0**	-
КТ251	680x260	12,0	2730	275	275	420000	355	58,0**	-
КТ228*	680x260	10,5	2900	360	310	-	9,9	22,0**	-
КТ231	810x320	5,5	4300	250	250	275000	500	20,5	22,0
КТ211М	840x290	21,0	9300	305	270	1200000	1050	43,5	69,5
КТ209	840x290	15,0	8800	330	310	1100000	720	33,0	61,5
КТ197*	840x290	11,0	6000	320	310	-	-	28,0**	-
КТ207	840x360	11,0	8800	310	342	1650000	650	34,0	75,0
КТ163Д	840x360	9,5	8800	300	265	430000	650	37,0	72,0
КТ218	880x315	6,5	5700	255	235	540000	510	26,0	36,0
КТ141Е	930x305	10,0	8000	325	280	750000	650	47,0	52,0
КТ263	950x300	12,0	8400	330	300	1100000	1200	40,7	43,0
КТ172	950x300	12,0	9100	380	320	800000	750	130,0**	-
КТ175	950x300	13,0	10000	405	350	1580000	740	55,8	67,2
КТ232	950x300 Р-468	10,0	8370	200	175	652000	940	45,0	75,0
КТ229	950x300	6,0	6530	80	80	160000	265	44,0	19,1
КТ206	950x400	12,0	11000	420	300	1600000	1000	106,0**	-
КТ159Д	1030x350	17,0	15450	400	280	1650000	1250	60,9	63,6
КТ213	1030x35	19,0	19900	400	308	25000000	1700	134,0*	-

	0							*	
KT196	1070x390-480P	14,0	12000	325	280	1500000	1550	55,0	68,0
KT186*	1080x400	14,5	15500	410	330	-	-	50,0	10,5
KT159*	1100x330	7,0	5830	286	236	-	-	90,0	4,0
KT216	1120x450	8,0	9500	300	300	2200000	1700	52,0	56,0
KT166	1270x510	11,0	18375	330	300	3100000	2700	80,0	95,0
KT158	1300x480	6,5	10500	330	280	926000	900	64,3	71,7
KT171	1300x480	9,0	16470	350	300	200000	2000	90,0	127,0
KT185*	1300x480	9,0	14700	350	300	-	-	80,0	12,0
KT204	1300x480-560	11,5	187000	330	280	2300000	2300	83,3	91,0
KT205*	1300x480	11,5	16300	330	280	-	-	90,0**	-
KT106/3	1450x450	11,0	20000	330	260	2100000	2260	140,0	111,0

* nose wheel with slowdown brake,

** weight of the wheel with the brake.

Table B.2 – Aviation wheels catalog. Non-brake wheels

product number	tire dimension, mm	tire operational pressure, kgs/sm^2	stationary load from take-off mass, kg	Allowed take-off velocity, km/h	wheel mass, kg
KH52	380x150-5	3,0	310	126	2,0
KH55	400x150-5	3,0	320	125	2,3
KH47	400x150-5	4,0	450	165	2,5
KH58	430x150-165	4,5	570	196	5,0
KH54	500x150-9	5,0	654	230	5,0
KH51	500x170-10	7,5	1000	235	7,5
KH36	570x140	17,0	2300	365	11,5
KH44	600x200	5,0	1600	240	7,8
KH46	620x180	7,5	1830	185	13,0
KH35	620x180	18-20	3000	335	13,0
KH38	620x180	5,0	1280	255	7,3
KH41	680x260	14,0	5600	350	25,0
KH39	1120x450	8,0	9500	300	36,0

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