Algorithm for Optimizing the Design Parameters of a Light Transport Aircraft at the Stage of Preliminary Design

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Abstract. In this paper, the optimization of design parameters of light transport aircraft has been carried out. The proposed algorithm, in this paper, provides the calculation of the optimal values of take-off weight and fuel efficiency coefficient taking into account the geometric parameters of the aircraft wing, i.e., aspect ratio and taper ratio using genetic algorithm for multi-objective optimization. The design parameters obtained by the Pareto front are presented and compared with the similar type of aircraft.

1 Introduction

A critical aspect of aircraft design is the selection of rational parameters that ensure optimal performance, safety, and economic efficiency. In the case of light transport aircraft, this is particularly important due to their unique mission requirements, which often involve short-haul flights and the transport of passengers and cargo to remote locations. The selection of rational parameters at the preliminary design stage is crucial as it establishes the foundation for subsequent design decisions and ultimately determines the aircraft's overall performance. The academic literatures on this topic focus on several key areas, including aircraft performance, structural design, weight estimation, and optimization methods [1-6].

One of the primary concerns in aircraft design is optimizing the aircraft's performance, including its speed, range, and fuel efficiency. Aerodynamic considerations play a vital role in this process, and the work of Cai Y et al. [7] emphasizes the importance of selecting appropriate wing geometry, aspect ratio, and air foil profiles. Other key factors include the choice of engine and propeller, as well as the overall weight and balance of the aircraft.

Structural design is another critical consideration in aircraft design, and the designers must emphasize the importance of selecting appropriate materials, analysing loads and stresses, and designing a robust and reliable structure that can withstand the rigors of flight. Weight estimation is also important, as the weight of an aircraft directly affects its performance, fuel efficiency, and range. So, the designers are suggested to use empirical methods, statistical analysis, and computer-aided design tools to estimate weight accurately.

Finally, optimization methods play a crucial role in the selection of rational parameters for a light transport aircraft. The study of Komarov. V. A. highlights the importance of using optimization algorithms to identify optimal designs that meet multiple objectives, such as

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minimizing weight, maximizing performance, and ensuring structural integrity [8]. These techniques can help designers explore a wide range of design alternatives quickly and efficiently, leading to better aircraft designs.

In summary, the selection of rational parameters for a light transport aircraft at the stage of preliminary design emphasizes the importance of considering multiple disciplines, including aerodynamics, structures, propulsion, and systems. Key considerations include optimizing aircraft performance, selecting appropriate materials and structures, accurately estimating weight, and using optimization methods to identify optimal designs.

2 Overview of current studies in aircraft design

Aircraft design is in a constant state of evolution, with constant improvements and advancements being made in the design, materials, and technology used in aircraft. The study by Cai Y, Rajaram D and Mavris DN. [7] describes a method for simultaneously sizing and optimizing the performance of an aircraft during the early design phase, taking into account off-design mission scenarios. The method uses a multi-objective optimization approach to balance conflicting design objectives such as fuel efficiency, range, payload, and other factors. The authors propose a new algorithm called the "design space exploration" method that is capable of generating a set of Pareto-optimal solutions that provide optimal trade-offs between different design objectives. The approach is demonstrated through a case study of a small regional turboprop aircraft, showing how the design can be optimized for various mission scenarios, including different altitudes and ranges. The results suggest that the proposed approach can significantly improve the overall performance of the aircraft compared to traditional design methods.

Most recently, Jimenez H and Mavris D. [9] developed a study on the application of multi-objective optimization to aircraft design for environmental benefits. The study aims to identify the Pareto-optimal solutions for aircraft design considering multiple objectives such as fuel consumption, noise, and emissions. The authors applied a methodology that combined the use of high-fidelity aircraft performance models, computational fluid dynamics, and a multi-objective genetic algorithm. They evaluated the trade-offs between objectives and identified the Pareto-optimal solutions for a range of aircraft designs. The results show that the Pareto-optimal solutions can significantly reduce fuel consumption, noise, and emissions compared to current aircraft designs. The study also identified the importance of considering all objectives simultaneously to achieve optimal solutions.

In the work of Hoburg W and Abbeel P., the authors discussed the use of geometric programming (GP) for aircraft design optimization, a technique that allows the optimization of nonlinear problems with convex objectives and constraints [10]. The authors demonstrate the use of GP for several design problems, including wing and fuselage sizing, and discuss the advantages of this approach over traditional optimization methods. They also present a case study that shows how GP can be used to optimize the design of a hybrid-electric aircraft, resulting in significant improvements in fuel efficiency and emissions. The authors conclude that GP is a powerful tool for aircraft design optimization, allowing designers to find optimal solutions quickly and accurately while accounting for multiple design objectives and constraints.

The research paper [11] presents an approach for the conceptual design of aircraft that optimizes environmental performance, including reduced noise, fuel consumption, and emissions. The authors discuss the development of a multidisciplinary design optimization framework that includes aerodynamics, structures, and propulsion systems, as well as environmental performance metrics. They demonstrate the approach through case studies that show how it can be used to design aircraft that meet specific environmental goals, such as reducing fuel consumption by 50% and noise by 10 dB. The authors also discuss the importance of considering environmental performance early in the design process, as it can have a significant impact on the overall design and cost of the aircraft. They conclude that the approach presented in the paper can help aircraft designers create more sustainable and environmentally friendly aircraft.

3 Algorithm for design parameters determination of a light transport aircraft

In this section, we describe the algorithm for optimizing the conceptual design of a light transport aircraft by selecting design parameters, constraints, and objectives. Optimization is an important aspect of the early engineering design process. This is especially true in aerospace engineering where systems are a combination of multiple disciplines. One example of an aerospace application of optimization is a conceptual aircraft design problem where the designer uses simulations to size an aircraft.

Many algorithms exist for optimization, as well as the gradient method, non-linear simplex, genetic algorithms, etc. In this study, a multi-criteria genetic algorithm was used to find a compromise between competing goals. At each iteration, a set of solutions is searched and a Pareto set is formed for this iteration (generation). The Pareto set obtained from the finite population is the set of optimal solutions to the problem [12]. The block diagram of the algorithm used in the process of solving the problem is shown in Fig. 1. The program for calculating using the presented algorithm is written in the MATLAB program.

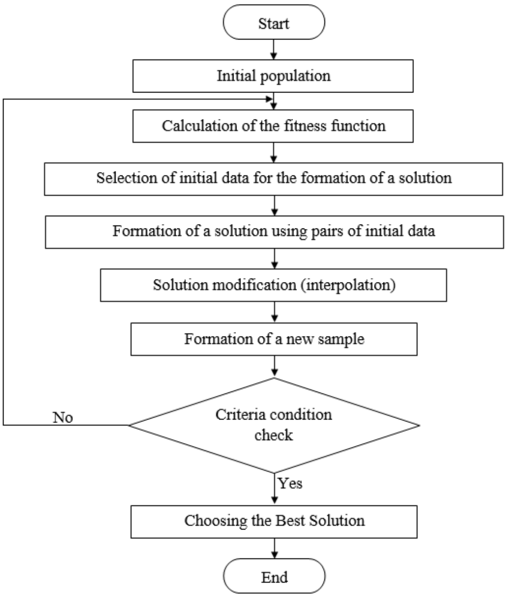

Fig. 1. Block diagram of multi-objective optimization based on genetic algorithm.

The general form of a multi-objective design problem can be expressed by the following equation (1):

$$\begin{array}{lll} \text{minimize} & \mathrm{F}(\mathrm{x}) = \left[f_1(\mathrm{x}), f_2(\mathrm{x}), \ldots, f_n(\mathrm{x})\right]^{\mathrm{T}} & \\ \text{w.r.t} & \mathrm{x} \in \mathrm{R}^{\mathrm{n}} & \\ \text{subject to} & \mathrm{g}_j(\mathrm{x}) \leq 0, & j = 1, \ldots, l \\ \text{and} & \mathrm{h}_k(\mathrm{x}) = 0, & k = 1, \ldots, m \\ \text{and} & \mathrm{x}^L \leq \mathrm{x} \leq \mathrm{x}^U, & \end{array} \tag{1}$$

where $\mathrm{F}(\mathrm{x})$ is the objective function that needs to be optimized with $\mathrm{x} = (x_1, x_2, \ldots, x_n)^T$ stands for a vector of n design variables which has limits with lower and upper bound vectors $\mathrm{x}^L$and x^U, respectively. And then, $g_j(\mathrm{x})$ and $h_k(\mathrm{x})$ are inequality and equality constraints functions. In performing the multi-objective optimization, a nondominated solution is superior compared to a dominated solution [13]. It improves one objective and causes a degradation in another or has the same superior effect on both objectives than the dominated solution. The set of all the nondominated solutions is called the Pareto front.

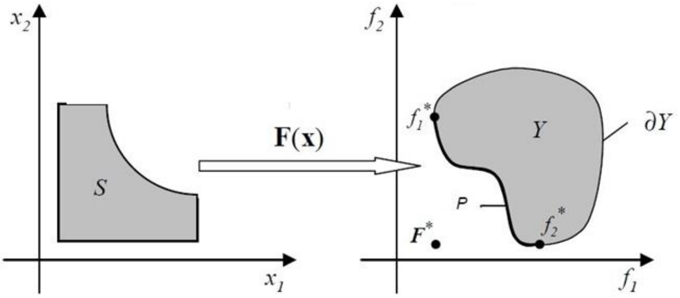

Fig. 2. Design space, objective space and Pareto frontier for a minimization problem.

If the final solution is selected from the set of Pareto optimal solutions, there would not exist any solutions that are better in all attributes. It is clear that any final design solution should preferably be a member of the Pareto optimal set. Pareto optimal solutions are also known as non-dominated or efficient solutions [14]. Fig. 2. provides a visualization of the presented nomenclature.

4 Mathematical formulation of design process

Requirements for the aircraft include the ability to quickly climb and descend steep glide paths, as well as to make several intermediate landings without refueling. It is supposed to operate on D-class runways - 1000 × 28 m and on E-class runways - 500 × 21 m [15], and on unpaved airfields with soil strength of more than 7 $\mathrm{kgf/cm^2}$. The results of preliminary calculations performed using a multicriteria genetic algorithm show that the designed aircraft with a maximum load of 2300 kg (takeoff weight $\leqslant$ 8000 kg), runways 1000 meters long will be needed. At the same time, with a lower load, the aircraft can be operated from an unpaved airfield with a runway of less than 800 meters.

For development, the concept of a twin-engine high-wing aircraft, similar to those used in agriculture, was adopted. MATLAB, SOLIDWORKS, and ANSYS programs are used to solve design problems. Using the programs of the ANSYS package, the calculation of the aerodynamic characteristics of the airfoil is carried out, as well as the calculation of the structural-power scheme.

The value of the specific load on the wing p_0 is determined by the condition of providing a given cruising flight speed v_{cruise} (M_{cruise}).

$$p_0 = \frac{C_{l\ cruise} q_{M=1} M^2_{cruise}}{1 - 0.6\bar{m}_f} \tag{2}$$

where p_0 = specific load on the wing;
$C_{l\ cruise}$ = lift coefficient in cruise flight
M_{cruise} = Mach number in cruise flight
$q_{M=1}$ = dynamic pressure ($q_{M=1}$) is taken for the speed corresponding to the number M = 1 at a given flight altitude or corresponds to the value "a" - the speed of sound at this altitude)
$\bar{m}_f$ = relative mass of fuel

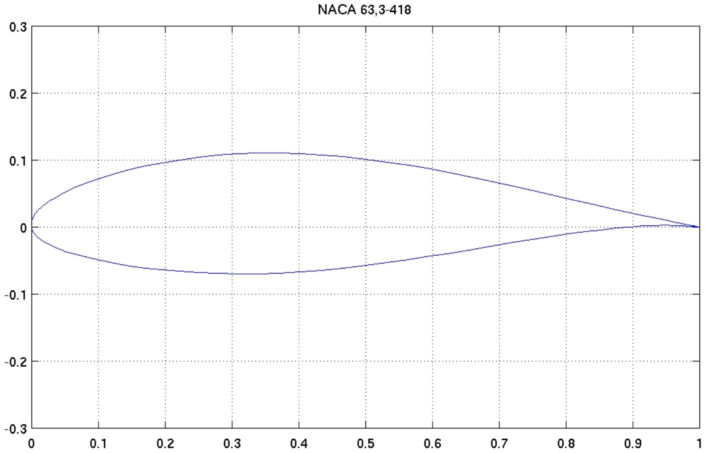

Fig. 3. NACA 633-418 Air foil.

NACA 633-418 was chosen as the aerodynamic profile of the wing (Fig. 3), its characteristics obtained from the results of numerical simulation in ANSYS, in comparison with the reference characteristics [16,17], are shown in Fig. 4.

Table 1. Geometric characteristics of the NACA 633-418 profile.

Upper surface		**Lower surface**	
Station	**Ordinate**	**Station**	**Ordinate**
0.0000	0.0000	0.0000	0.0000
0.2670	1.4840	0.7330	-1.2840
0.4870	1.8330	1.0130	-1.5530
0.9450	2.4100	1.5550	-1.9820
2.1400	3.4550	2.8600	-2.7110
4.5930	4.9750	5.4070	-3.7110
7.0770	6.1390	7.9230	-4.4430
9.5770	7.0870	10.4230	-5.0190
14.6020	8.5600	15.3980	-5.8680
19.6450	9.6320	20.3550	-6.4480
24.6990	10.3850	25.3010	-6.8050
29.7600	10.8540	30.2400	-6.9660
34.8230	11.0580	35.1770	-6.9380

39.8860	10.9860	40.1140	-6.7020
44.9460	10.6720	45.0540	-6.2920
50.0000	10.1480	50.0000	-5.7360
55.0460	9.4460	54.9540	-5.0660
60.0830	8.5960	59.9170	-4.3120
65.1100	7.6260	64.8900	-3.5060
70.1250	6.5640	69.8750	-2.6760
75.1280	5.4380	74.8720	-1.8580
80.1190	4.2800	79.8810	-1.0960
85.0990	3.1300	84.9010	-0.4380
90.0690	2.0170	89.9310	0.0510
95.0320	0.9780	94.9680	0.2860
100.0000	0.0000	100.0000	0.0000
L.E. radius			2.120
Slope of radius through L.E.			0.1685

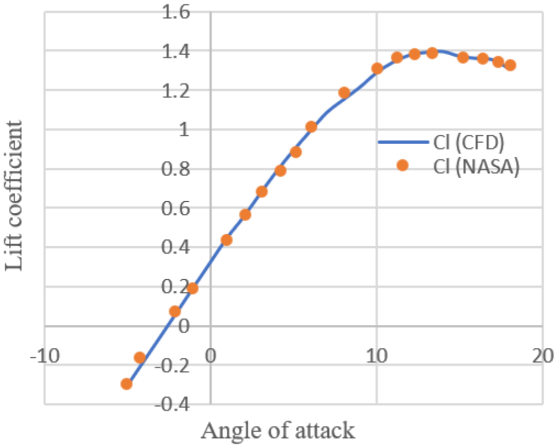

Fig. 4. Airfoil aerodynamic characteristics obtained from the results of numerical simulation in ANSYS in comparison with reference data.

When determining the take-off mass (m_0) of the aircraft, equation (3) was used in the first approximation, the initial data for solving which are the characteristics of the project aircraft.

$$m_0 = m_{str} + m_{p.p} + m_{equ} + m_f + m_{payload} + m_{service}$$

$$1 = \bar{m}_{str} + \bar{m}_{p.p} + \bar{m}_{equ} + \bar{m}_f + \frac{m_{payload} + m_{service}}{m_0}$$

$$(m_0)_1 = \frac{m_{payload} + m_{service}}{1 - \bar{m}_{str} - \bar{m}_{p.p} - \bar{m}_{equ} - \bar{m}_f} \tag{3}$$

where m_0 = take-off mass of the aircraft

m_{str} = structural mass of the aircraft

$m_{p.p}$ = mass of power plant

m_{equ} = mass of equipment and control system

m_f = mass of fuel

$m_{payload}$ = mass of payload

$m_{service}$ = service load mass

As a first approximation, the aircraft takeoff mass $(m_0)_1$ is determined using statistical data. In the second approximation, the values of the relative mass of the structure, power plant, equipment, and control systems, as well as fuel were determined by the formulas from the book [18].

$$\bar{m}_{str} = m_{str} / m_0 = \bar{m}_W + \bar{m}_F + \bar{m}_E + \bar{m}_L \tag{4}$$

where $\bar{m}_W$ = relative mass of wing

$\bar{m}_F$ = relative mass of fuselage

$\bar{m}_E$ = relative mass of empennage

$\bar{m}_L$ = relative mass of landing gear

Depending on the initial power-to-weight ratio ($\bar{N}_0$), to ensure a given takeoff run, the relative mass of the power plant ($\bar{m}_{p.p}$) was calculated using formula (5):

$$\bar{m}_{p.p} = 1.36 k_{p.p} \gamma_{En} \bar{N}_0 \tag{5}$$

where $k_{p.p}$ = coefficient showing how many times the mass of the power plant is greater than the mass of the engines (engine)

γ_{En} = specific mass of engine

$\bar{N}_0$ = initial power-to-weight ratio

The relative mass of the equipment and control system ($\bar{m}_{equ}$) can be obtained from the formula (6):

$$\bar{m}_{equ} = \frac{200}{m_0} + 0.2\bar{m}_{payload}\left(\frac{1+0.1L_e}{V_F}\right) + 0.08 \tag{6}$$

where $\bar{m}_{equ}$ = relative mass of equipment and control system

V_F = flight speed

L_e = estimated flight range

The calculation formula (7) for the relative mass of fuel ($\bar{m}_f$) has the form:

$$\bar{m}_f = \left(\frac{Vt}{270}\frac{c_e}{\eta_p K}\right)_{cruise} + \frac{1}{75K_{\max}}\left(\frac{c_e V t_n}{\eta_p}\right)_{K_{\max}} + 0.006 \tag{7}$$

where V = cruise speed

t = flight time

C_e = specific fuel consumption

η_p = propeller efficiency

t_n = flight time of the navigation reserve

K, K_{max} = cruise and maximum aerodynamic efficiency.

5 Results

In this research work, both the minimum takeoff weight and the minimum fuel efficiency coefficient of light transport aircraft are simultaneously optimized. With each generation, the Pareto front is moving towards lower takeoff weight and lower fuel efficiency. Eventually, the Pareto front no longer progresses and an optimal compromise between takeoff weight and fuel efficiency is established. During the optimization, the aspect ratio λ and the taper ratio η of the wing are taken as design variables. The variables were changed according to the following sets of discrete values: λ = [7 8 9 10 11 12], η= [1 2 3]. The constraints are shown in Table 2.

Table 2. Constraints for optimization problem.

Constraints	**Value**
Takeoff weight	≤ 8000 kg
Takeoff distance	≤ 1000 m
Landing distance	≤ 1000 m

Fig. 5 and Fig. 6 show take-off weight and fuel efficiency as a function of aspect ratio (λ) and taper ratio (η) of the wing.

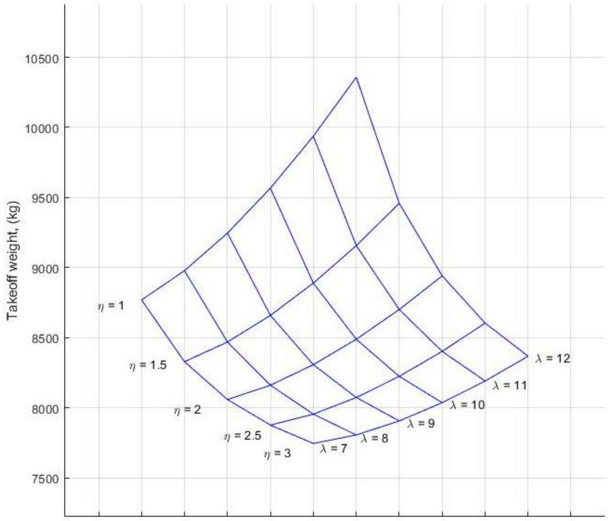

Fig. 5. Dependence of the take-off weight on the aspect ratio (λ) and taper ratio (η) of the wing.

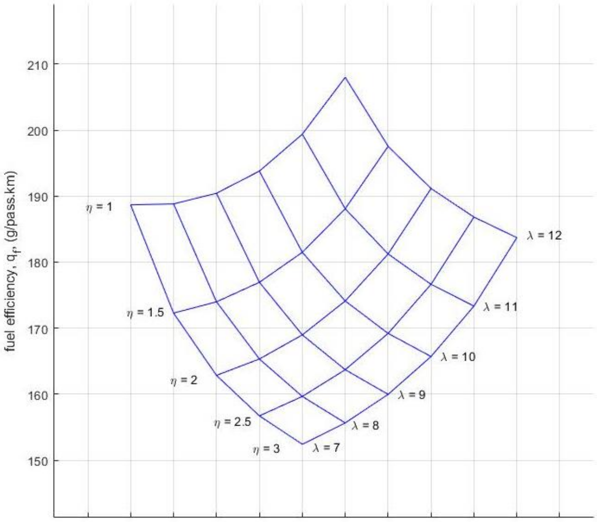

Fig. 6. Dependence of fuel efficiency on aspect ratio (λ) and taper ratio (η) of the wing.

In the process of optimization for 25 iterations, the minimum takeoff weight is obtained at aspect ratio $\lambda = 7$ and taper ratio $\eta = 3$, and the minimum value of the fuel efficiency coefficient is obtained at aspect ratio $\lambda = 9.72$ and taper ratio $\eta = 2.9999$.

According to the obtained results, shown in figures (5, 6), it is obvious that takeoff weight and fuel efficiency coefficient are more sensitive to wing aspect ratio than to its taper ratio. The optimal aspect ratio obtained under the condition of the minimum fuel efficiency coefficient is greater than that under the condition of the minimum takeoff mass, because the fuel efficiency ratio is more sensitive to the aerodynamic characteristics of the aircraft, which increases alongside with aspect ratio. The resulting Pareto front is shown in Fig. 7.

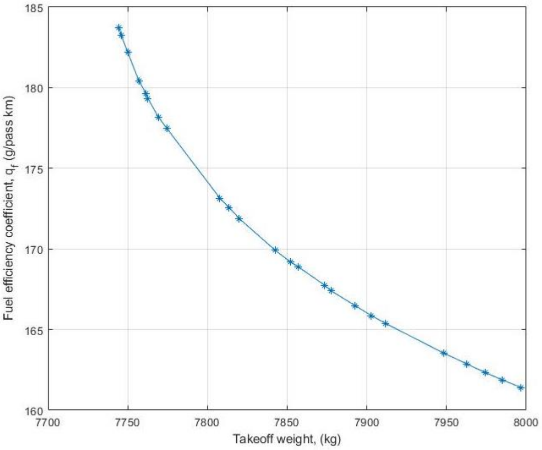

Fig. 7. Pareto front of takeoff weight and fuel efficiency coefficient.

Based on the obtained geometric data, a general view drawing of a light transport aircraft is developed (Fig. 8), and its geometry is created using SOLIDWORKS.

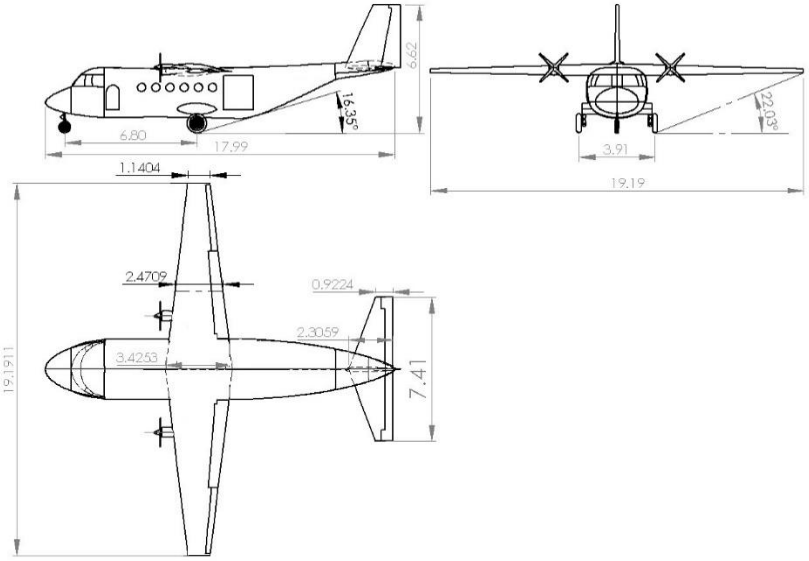

Fig. 8. Drawing of a general view of the aircraft under study.

Table 3. Comparison of the obtained results with prototype the aircraft.

Characteristics	Prototype aircraft, Cessna 408 Sky Courier	Projected aircraft
Load capacity	19 passengers or 2722 kg	19 passengers or 2300 kg
Wing span	22.02 m	19.1911 m
Wing area	40.97 m^2	43.771 m^2
Maximum takeoff weight	8616 kg	7842.57 kg
Cruise speed	390 km/h	400 km/h
Maximum ceiling flight	7600 m	6000 m
Takeoff distance	1116 m	844.927 m

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6 Discussion and conclusion

The main design parameters of light transport aircraft at the stage of preliminary design for operation in remote regions are determined:

a. The adoption of the most important decision in the design of light transport aircraft on the continuation of work on the project allows to obtain the results at the preliminary approximation stage of the developed method for determining the take-off weight and fuel efficiency coefficient of the aircraft;
b. The criterion for optimality is chosen as the minimum takeoff weight of the aircraft. Its value is achieved by studying the influence of its geometric parameters on the aerodynamic, energetic and mass characteristics;
c. The obtained results meet the basic tactical and technical requirements of a light transport aircraft for operation in remote regions.

The obtained results, in this research work, ensure the optimal geometric parameters of the wing. The wing will further be used for strength parameter optimization based on numerical simulation.

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