МІНІСТЕРСТВО ОСВІТИ ТА НАУКИ УКРАЇНИ
Національний авіаційний університет
Кафедра конструкції літальних апаратів

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«___» ____________ 2024 р.

КВАЛІФІКАЦІЙНА РОБОТА

ЗДОБУВАЧА ОСВІТНЬОГО СТУПЕНЯ
«БАКАЛАВР»

Тема: «Вантажний люк конвертованого літака»

Виконав: _________ **Назар ЯРМОЛЕНКО**

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Київ 2024

MINISTRY OF EDUCATION AND SCIENCE OF UKRAINE
National Aviation University
Department of Aircraft Design

PERMISSION TO DEFEND
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Associate Professor, PhD
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"___" ____________ 2024

BACHELOR DEGREE THESIS

Topic: "Cargo door for converted aircraft"

Fulfilled by: _________ **Nazar YARMOLENKO**

Supervisor:
PhD, Associate professor _________ **Tetiana MASLAK**

Standards inspector:
PhD, associate professor _________ **Volodymyr KRASNOPOLSKYI**

Kyiv 2024

НАЦІОНАЛЬНИЙ АВІАЦІЙНИЙ УНІВЕРСИТЕТ

Аерокосмічний факультет
Кафедра конструкції літальних апаратів
Освітній ступінь «Бакалавр»
Спеціальність 134 «Авіаційна та ракетно-космічна техніка»
Освітньо-професійна програма «Обладнання повітряних суден»

ЗАТВЕРДЖУЮ
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«___» ____________ 2024 р.

ЗАВДАННЯ
на виконання кваліфікаційної роботи здобувача вищої освіти

ЯРМОЛЕНКА НАЗАРА АНДРІЙОВИЧА

1. Тема роботи: «Вантажний люк конвертованого літака», затверджена наказом ректора від 15 травня 2024 року № 794/ст.

2. Термін виконання роботи: з 20 травня 2024 р. по 16 червня 2024 р.

3. Вихідні дані до роботи: кількість пасажирів – 124, дальність польоту з максимальним комерційним навантаженням 1650 км, крейсерська швидкість польоту 835 км/год, висота польоту 11,5 км.

4. Зміст пояснювальної записки: вступ, основна частина, що включає аналіз літаків-прототипів і короткий опис проектованого літака, обґрунтування вихідних даних для розрахунку, розрахунок основних льотно-технічних та геометричних параметрів літака, компонування пасажирської кабіни, розрахунок центрування літака, спеціальна частина, яка містить процес проектування вантажного люка для конвертованого літака.

5. Перелік обов’язкового графічного (ілюстративного) матеріалу: загальний вигляд літака (А1×1), компонувальне креслення фюзеляжу (А1×1), модель CAD середовища «SOLIDWORKS», діаграми FEA аналізу середовища «Ansys».

6. Календарний план-графік:

№	Завдання	Термін виконання	Відмітка про виконання
1	Вибір вихідних даних, аналіз льотно-технічних характеристик літаків-прототипів.	20.05.2024 – 21.05.2024	
2	Вибір та розрахунок параметрів проектованого літака.	22.05.2024 – 23.05.2024	
3	Виконання компонування літака та розрахунок його центрування.	24.05.2024 – 25.05.2024	
4	Розробка креслень по основній частині дипломної роботи.	26.05.2024 – 27.05.2024	
5	Огляд літератури за проблематикою роботи. Проектування та створення моделі вантажного люку конвертованого літака.	28.05.2024 – 29.05.2024	
6	Перевірка витривалості дверей під дією надлишкового тиску.	30.05.2024 – 31.05.2024	
7	Оформлення пояснювальної записки та графічної частини роботи.	01.06.2024 – 02.06.2024	
8	Подача роботи для перевірки на плагіат.	03.06.2024 – 06.06.2024	
9	Попередній захист кваліфікаційної роботи.	07.06.2024	
10	Виправлення зауважень. Підготовка супровідних документів та презентації доповіді.	08.06.2024 – 10.06.2024	
11	Захист дипломної роботи.	11.06.2024 – 16.06.2024	

7. Дата видачі завдання: 20 травня 2024 року

Керівник кваліфікаційної роботи ___________ Тетяна МАСЛАК

Завдання прийняв до виконання ___________ Назар ЯРМОЛЕНКО

NATIONAL AVIATION UNIVERSITY

Aerospace Faculty
Department of Aircraft Design
Educational Degree "Bachelor"
Specialty 134 "Aviation and Aerospace Technologies"
Educational Professional Program "Aircraft Equipment"

APPROVED BY
Head of Department,
Associative Professor, PhD
_______ Sviatoslav YUTSKEVYCH
"___" ____________ 2024

TASK

for the bachelor degree thesis

Nazar YARMOLENKO

1. Topic: "Cargo door for converted aircraft", approved by the Rector's order № 794/ст from 15 May 2023.
2. Period of work: since 20 May 2024 till 16 June 2024.
3. Initial data: number of passengers 124, flight range with maximum capacity 1650 km, cruise speed 835 km/h, flight altitude 11.5 km.
4. Content introduction, main part: analysis of prototypes and brief description of designing aircraft, selection of initial data, wing geometry calculation and aircraft layout, landing gear design, engine selection, center of gravity calculation, special part: cargo door for converted aircraft design.
5. Required material: general view of the airplane (A1×1), layout of the airplane (A1×1), "SOLIDWORKS" CAD model and "Ansys" FEA analysis diagrams.

6. Thesis schedule:

№	Task	Time limits	Done
1	Selection of initial data, analysis of flight technical characteristics of prototypes aircrafts.	20.05.2024 – 21.05.2024	
2	Selection and calculation of the aircraft designed parameters.	22.05.2024 – 23.05.2024	
3	Performing of aircraft layout and centering calculation.	24.05.2024 – 25.05.2024	
4	Development of drawings on the thesis main part.	26.05.2024 – 27.05.2024	
5	Cargo door design and modeling.	28.05.2024 – 29.05.2024	
6	The test of the door under excess pressure loadings.	30.05.2024 – 31.05.2024	
7	Explanatory note checking, editing, preparation of the diploma works graphic part.	01.06.2024 – 02.06.2024	
8	Submission of the work to plagiarism check.	03.06.2024 – 06.06.2024	
9	Preliminary defense of the thesis.	07.06.2024	
10	Making corrections, preparation of documentation and presentation.	08.06.2024 – 10.06.2024	
11	Defense of the diploma work.	11.06.2024 – 16.06.2024	

7. Date of the task issue: 20 May 2024

Supervisor: ___________ Tetiana MASLAK

Student: ___________ Nazar YARMOLENKO

РЕФЕРАТ

Пояснювальна записка кваліфікаційної роботи бакалавра
«Вантажний люк конвертованого літака»

67 с., 18 рис., 12 табл., 27 джерел

Дана кваліфікаційна робота присвячена розробці аванпроєкту пасажирсього літака для середньомагістральних польотів і подальша його конвертаці у вантажний літак з детьальним описом і розробкою вантажних дверей.

В роботі було використано методи аналітичного розрахункуб компьютерного проєктування за допомогою CAD/CAM/CAE систем, чисельного МСЕ моделювання для аналізу створенеої моделі. Практичне значення результату кваліфікаційноїх роботи полягає в створенні невеликого вантажного літака з вантажопідйомністью у 12276 кг, з герметичною кабіною. Ця модель потенційно може збільшити потенціал для регіональних вантажних авіаперевезень.

Матеріали кваліфікаційної роботи можуть бути використані в навчальному процесі та в практичній діяльності конструторів спеціалізованих установ.

Дипломна робота, аванпроєкт літака, компонування, центрування, конвертація, вантажний люк, пружно-деформаваний стан

ABSTRACT

Bachelor degree thesis "Cargo door for converted aircraft"

67 pages, 18 figures, 12 tables, 27 references

This qualification work is devoted to the development of a preliminary design of a passenger plane for short-haul flights and its subsequent conversion into a cargo plane with a detailed description and development of cargo doors.

The work used methods of analytical calculation, computer design using CAD/CAM/CAE systems, and numerical MCE modeling to analyze the created model. The practical significance of the result of the qualification works is the creation of a small cargo plane with a carrying capacity of 12,276 kg, with an airtight cabin. This model could potentially increase the potential for regional air freight.

The materials of the qualification work can be used in the educational process and in the practical activities of designers of specialized institutions.

Bachelor thesis, preliminary design, layout, center of gravity position, conversion, cargo hatch, stress-strain analysis

LIST OF ABBREVIATION

CAD – Computer-aided design.

CAM – Computer-aided manufacturing.

CAE – Computer-aided engineering.

LG - Landing gear.

ULD – Unit load device.

LD – Loading device.

FEA – Finite element analysis.

TU – tail unit.

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Cargo door for converted aircraft
(List of qualification work)

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INTRODUCTION

Nowadays, aviation is one of the most scientifically progressive branches. Every manufacturer fights for the most fuel-efficient design to get the most orders by airlines companies. This race led them to awareness that the profit generated by one of the biggest aircraft such as Boeing 747 or Airbus A380 is low, comparing to their operational costs. Especially in the context of COVID-19 pandemic that provoked one the biggest crisis in history of aviation. It forced manufacturers to stop the production of these types of aircraft in favour of smaller ones even with lower range.

Such airplane types are not only cheaper in operation but also easier in manufacturing and maintenance, which allows their production to be more massive. Great examples of this aircraft type are:

- Embraer 195 with maximum capacity up to 124 passengers and flight range with maximum payload of 12276 kg up to 2650 km [1].
- Bombardier CRJ900 with maximum capacity up to 90 passengers and flight range with maximum payload of 10247 kg., up to 2500 km [2].
- Airbus A220-100 with maximum capacity up to 110 passengers and flight range with maximum payload of 15150 kg., up to 3970 km [3].

These aircraft types are popular due to their mobility and low operational costs. That’s what makes them so popular for domestic and regional flights. Moreover, they can also be used not only for commercial passenger flights, but also for cargo transportation. In some cases, even for medical or military purposes, such as troops delivery or evacuation. That is exactly why the development of such aircraft type is so relevant.

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1. ANALYSIS OF PROTOTYPES AND SHORT DESCRIPTION OF DESIGNING AIRCRAFT

1.1. Statistic data of prototypes

Choosing a model for a medium-haul airplane design requires balancing varied considerations. These align with intended use, goals for performance, and the market's desires. First, the mission profile should be defined. Talking about medium-haul aircraft it should be capable of flying 1500 - 3500 kilometres. Let's consider that the aircraft being developed should be able to carry a payload of at least 10000 – 15000 kilograms and about 130 passengers. Then, important technical characteristics should be considered. The aerodynamics of the aircraft should offer an optimal combination of flight stability, fuel efficiency and speed. The powerplant should also be efficient and light but at the same time, it should provide necessary thrust giving enough speed during takeoffs and landings. It should also be capable of operating in a variety of airports even with shorter runaways. Since the aircraft is passenger one, some innovations in context of passenger`s comfort and flight experience should be introduced: advanced entertainment systems, more comfortable seats, and modern interior design. Moreover, the aircraft should meet the regulatory compliances and safety regulations to get all necessary certifications. Considering the above requirements for medium-haul aircraft design, three airplane models can be presented as prototypes for this project. Those are: Embraer 195, Bombardier CRJ900 and Airbus A220-100. All three combine good and reasonable performances for medium-haul aircraft. Their specific parameters are listed in Table 1.1.

The typical location of constructional elements, principal aerodynamic schemes of listed prototypes became the baseline for designed aircraft outline. For layout formation the mix of the most effective characteristics from all three prototypes are used. Besides the Embraer 195 is chosen as a main prototype because it meets almost all requirements for middle-range economy class passenger airplane.

Table 1.1

Performance of prototypes

#	Parameters	Prototypes		
		Embraer 195	Bombardier CRJ900	Airbus A220-200
1	Purpose	Passenger	Passenger	Passenger
2	Max take-off weight, kg	50300	38330	69900
3	Crew/flight attendants	5	5	5
4	Seats	124	90	160
5	Wing load, kN/m^2	5.33	5.33	6.11
6	Range, km	2650	2500	3970
7	Cruising height, m	12500	12497	12500
8	Number of engines and their type	2/CF34-10E	2/CF34-8C5	2/PW1500G
9	Take off thrust, kN	82.3	59.4	103.6
10	The shape of the fuselage cross-section	circular	circular	circular
11	Fineness ratio	12.8	13.48	10.45
12	Fineness ratio the nose and rear part	4.2	4	5.3
13	Sweepback angle at 1/4 chord line	23	25	25

1.2. Short description of the designing aircraft

Consider a one-of-a-kind concept pulling together the Airbus A220-200, CRJ900, and Embraer 195's top traits for a refreshing design.

Chosen model merges the A220-200's cutting edge materials aiming at passenger ease. It uses carbon composite-s and featherlight stuff to cut down on fuel wastage and emissions — a major goal for today's aircraft structure. The inside of the aircraft matches the A220-200's roomy layout, boasting more- expansive seats and larger windows for a superior travel experience. Adopting the CRJ900's region specific efficiency and stretched body model, the aircraft design has been refine-d for economical travel and lower seat per mile cost-making it a practical pick for airlines.

Perfect for linking less-populated regions or accommodating fewer passengers while- keeping comfort and efficiency. The Embraer 195 brought versatility and adaptability to this model with its adaptable cabin layout. The unique design does away with the middle seat, amplifying the passengers' sense of space and ease. This feature allows the plane to navigate many different routes, from quick local trips to longer, region-wide journeys, granting airlines the ability to adjust according to shifting market needs. Mixing these components, the model marks a huge leap in airplane design. It's set to surpass today's fuel saving, traveller comfort, and ve-rsatile operation standards. This plane could change the game for regional and single isle aircraft. Its unique mix of efficie-nt user comfort and versatility for different tasks stands out. This sort of design will show off the creative and visionary aspects of current aviation.

The designing aircraft is a single aisle narrow-body aircraft for the transportation of 124 passengers. The fuselage features a sleek, cylindrical shape with a cross section that supports a comfortable 4 seats configuration. It is manufactured from light aluminum alloys like 2024 T4 and 2024 T3, ensuring both durability and light weight of th3e structure. It includes round windows, four entry and two doors to access front and back cargo compartments.

The wing structure feature aerodynamic efficiency and sweepback design. It also contributes to fuel saving. Wing structure includes some aerodynamic features like winglets that reduce drag that improves fuel efficiency. There are high-lift devices in its structure, such as slats and flaps, that improve takeoff and landing performance of the aircraft. The wing structure consists of lightweight materials like aluminum alloys and composites, that gives the wing strength and reduces its weight at the same time.

The tail unit presents itself as a conventional empennage with vertical and horizontal stabilizers. The vertical stabilizer provides stability and houses rudder which is responsible for the yaw moment of an aircraft. The horizontal stabilizer which houses elevators provides horizontal stability and pitch control during the flight. The main task of this unit is to provide stable and balanced flight of an aircraft with the ability of yaw and pitch control. It is manufactured from lightweight aluminum alloys and composites.

The landing gear is a retractable tricycle-type system, that features two main landing gear units and a single nose gear. It is made from high-strength materials to withstand landing stresses and to support aircraft during ground operation. It also has an equipped advanced braking system and can be retracted into the fuselage after takeoff, to reduce drag during the flight.

Analytical part conclusions

As a result, three different passenger jet aircrafts: Embraer 195, Bombardier CRJ900and Airbus A220-100 were analysed. Their benefits were considered. The priority was an aircraft which combined good passenger capacity and relatively small size to design its converted version for cargo transportation, to create a small but at the same time efficient and profitable freighter. From all prototypes these parameters belong to the Embraer 195, despite the Airbus A220-100 can haul bigger number of passengers. Though Bombardier is the smallest aircraft among the presented prototypes, Embraer 195 is somewhere in the middle by its performances which is perfect for the task of the work. Considering all other characteristics the Embraer 195 is an appropriate prototype for conversion process. Its fuselage geometrical characteristics and payload would make it a profitable and efficient middle-range freighter.

2. AIRCRAFT GEOMETRY CALCULATION

In the context of aircraft preliminary design, the main geometrical parameters of all parts of the designing aircraft need consideration.

The wing design and high lift devices calculations, the fuselage geometry and cabin layout, landing gear design, tail unit design will be calculated in this paragraph. The engines will be chosen from the list of engines which are used nowadays in operation.

2.1. Wing geometry calculation

For the design of the aircraft, the initial data were calculated with the help of a special computer program developed by the Aviation Design Department of NAU.

1.1. The data are presented in Appendix A.

1.2. At the preliminary design stage, a profile is usually chosen from many profiles whose geometric and aerodynamic characteristics are available in aeronautical literature.

1. Wing airfoil: For designing aircraft Eppler E195 low Reynolds number airfoil was taken.

2. Relative thickness of the airfoil is 0.118.

3. Location of the wing on fuselage: low wing.

4. Aspect ratio of the wing $\lambda_w = 8$.

5. Taper ratio of the wing η_w 2.5.

The taper ratio influences the following quantities: induced drag, structural weight, ease of fabrication.

6. Sweep back angle of a wing is 25 degrees.

7. Wing area: 145 m^2.

Wing area (S_{wing}): This is calculated from the wing loading and gross weight which have been already decided, (in appendix A)

$$S_{wing} = \frac{m_0 \cdot gc}{P_0} = \frac{54678 \cdot 9.8}{3899} = 137.43 \quad \mathrm{m}^2,$$

$$S_{wcruise} = \frac{54678 \cdot 9.8}{3508} = 152.75 \quad \mathrm{m}^2,$$

where m_o – take off mass of the aircraft.

g – gravitational acceleration,

P_o – wing loading at cruise regime of flight.

The average number should be taken as a wing area $S_{wing} = 145\ \mathrm{m}^2$.

After the calculation, the area of the wing can be compared with a wing area of prototypes and if it necessary we could recalculate it.

8.Wingspan is:

$$l = \sqrt{S_{wing} \cdot \lambda}_w = \sqrt{145.8} = 34 \quad \mathrm{m},$$

9. Root chord is:

$$C_{root} = \frac{2S_w \eta_w}{(1+\eta_w) \cdot l} = 6.09\,\mathrm{m},$$

10. Tip chord is:

$$C_{tip} = \frac{C_{root}}{\eta_w} = 2.44\,\mathrm{m},$$

11. Wing construction and spars position.

To choose the structure scheme of the wing it is necessary to determine the type of its internal design. The torsion box type with two spars was chosen to meet the requirements of strength and at the same time to make the structure comparatively light.

Relative coordination of the spar's position is equal for a wing with two spars: x_{1spar}=0.2 C_i; x_{2spar}=0.6 C_i from the leading edge of current chord in the wing cross-section.

Mean aerodynamic chord definition. The geometrical method of mean aerodynamic chord determination has been taken. The mean aerodynamic chord is calculated graphically and equals to B_{MAC} = 4.16 m. It is shown in (Fig. 2.1).

Ailerons design.

The main purpose of the ailerons is to create rolling moment and provide adequate rate of roll. Ailerons geometrical parameters are determined by the next formulas:

Ailerons span

$$l_{aileron} = (0.3...0.4) \cdot \frac{l_{wing}}{2},$$

Ailerons chord

$$C_{aileron} = (0.22...0.26) \cdot C,$$

Aileron area

$$S_{aileron} = (0.05...0.08) \cdot \frac{S_{wing}}{2},$$

Ailerons are equipped by secondary control surfaces (aerodynamic balance).

Inner axial balance:

$$S_{in\,axial} = (0.3...0.31) \cdot S_{aileron},$$

Area of aileron's trim tabs:

For the aircraft with two engines

$$S_{trim\,tabs} = (0.04...0.06) \cdot S_{aileron},$$

Range of aileron deflection: upward $\delta_{aileron} \geq 25^{\circ}$ downward $\delta_{aileron} \geq 15^{\circ}$

So, the results are:

Ailerons span:

$$l_{aileron} = 0.35\frac{l_w}{2} = 0.35\cdot\frac{34}{2} = 5.95 \text{ m},$$

Aileron area:

$$S_{aileron} = 0.36\frac{S_w}{2} = 0.06\cdot\frac{145}{2} = 4.35\,\text{m},$$

Area of aileron’s trim tab for four engine airplanes:

$$S_{trim\,tab} = 0.6\cdot 4.35 = 0.216\,\text{m},$$

13. High lift device of a wing: 0.93 – double slotted flaps with fixed deflector, together with slats.

The relative coordination of high lift on the wing chord are:

$$C_f = (0.28...0.3)C_i,$$

for one slotted and two slotted flaps.

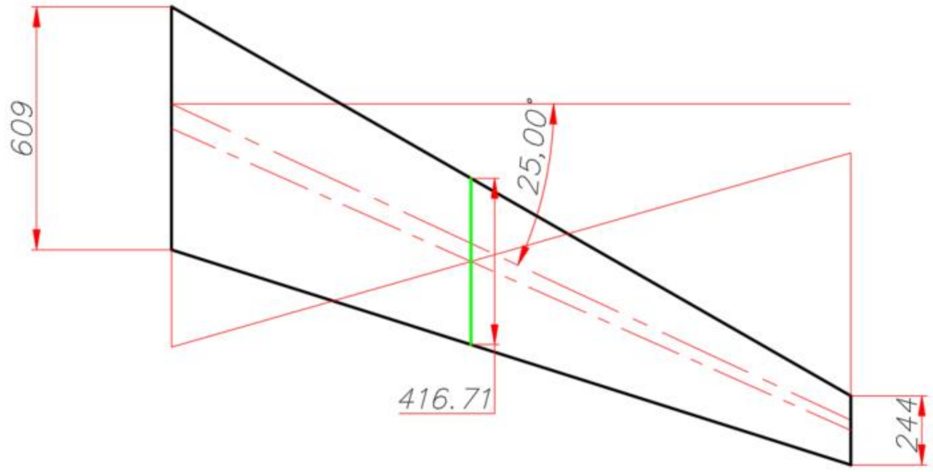

Fig. 2.1 – Geometrical method of determination of mean aerodynamic chord

2.2 Fuselage layout

Fuselage layout consists of comfortable accommodation of passengers in the cabin (for passenger aircraft) or correct position of the cargo on pallets or in unit load devices (for cargo aircraft).

At the preliminary design of the fuselage structure, we are based on the typical semimonocoque structure design. The fuselage structure consists of bulkheads (formers and frames), stringers (and longerons) and skin. Formers give the shape for the fuselage, supports the stringers with the skin. Formers are installed parallel to each other and relate to stringers. Frames take the main loads, all concentrated loads from other parts (from a wing, from tail, from landing gear attachment, near the entrance door, emergencies exit, cargo doors). At the beginning of the fuselage the first frame is the pressurized bulkhead, which provides the sealing for the cabin. At the rear part of the fuselage the aft pressure bulkhead is located before the auxiliary power unit to close the pressurized cabin.

Technologically the fuselage is divided into some parts: front (cockpit compartment), middle (passenger compartment or cargo cabin), rear part (tail unit).

The front part is the cockpit, the space under the cockpit accommodates many electrical instruments and other devices and the landing gear nose wheel.

The central part of the fuselage is the passenger compartment (or cargo compartment), baggage compartment under the floor, center wing box with fuel tanks and main landing gear wheel well.

The tail of the fuselage consists of the compartment for equipment of systems, smaller forms, spars and stringers. As the formers are smaller but their thickness is constant, they are more rigid so that there are no structural problems to support both the horizontal and vertical stabilizers. The APU (auxiliary power unit) is usually placed at the tail.

In selecting the fuselage parameters, we need to consider the aerodynamic requirements of the streamline and cross section.

The circular cross-section of fuselage is the most efficient because it provides the minimum weight and maximum strength, meeting strength requirements and reducing weight are important for aircraft design.

We also concentrate on the geometrical parameters, such as: fuselage diameter, length of fuselage, fineness ratio of fuselage, nose part and tail unit geometry. The design of the length of the aircraft fuselage is considered by the aircraft purpose, number of passengers, cabin layout, and characteristics of the aircraft's center of gravity position and the landing angle of attack.

$$FR = \frac{L_{f\,us}}{D_{f\,us}},$$

$$L_{f\,us} = FR_f \cdot D_{f\,us} = 12.8 \cdot 3.01 = 38.53\,\text{m},$$

where: FR – fineness ratio of the fuselage

D_{fus} – diameter of the fuselage

Let's find the fineness ratio of the fuselage nose part of prototype (nose part from the beginning to the end of cone part, after the pilot part) and take it for the

$$L_{f\,wd} = FR_{np} \cdot D_{f\,us} = 1.27 \cdot 3.01 = 3.82\,\text{m},$$

Length of the fuselage tail part:

$$L_{f\,wd} = FR_{tu} \cdot D_{f\,us} = 1.27 \cdot 3.01 = 9.93\,\text{m},$$

For passenger aircraft fuselage, the size of passenger cabin is important.

The underdeveloped aircraft cabin is going to be a single class one. The correct split of passenger sits is chosen and presented in Table 2.1.

Table 2.1

Characteristics of passenger cabin

Number of seats in one row, m	Seats Possibilities	Number of aisles, width of the aisle, mm	Width of armrest in mm, number of armrests in a row	Fuselage diameter in the cross section with passengers' seats, m
4	2+2	1x(400…470)	≥ 50 (3+3)	2.80…2.90

The cabin width of passenger aircraft in a place where we have passenger's seats can be found by the formula:

$$B_{cabin} = n_2 b_2 + n_3 b_3 + n_{aisle} b_{aisle} + 2\delta + 2\delta_{wall},$$

$$B_{cabin} = 2\cdot 1040 + 1\cdot 400 + 2\cdot 30 + 2\cdot 30 + 2\cdot 87 = 2714 \text{ mm},$$

where: n_2; n_3 – number of blocks of seats with 2 or 3 seats in a cross section;

b_2; b_3 – width of block of 2 seats or 3 seats, mm;

n_{aisle}– number of aisles;

b_{aisle} – aisle width, mm;

δ – distance between external armrests to the decorative panels, mm;

δ_{wall} = 80…120 – width of the wall, mm;

Aisle width is defined in FAR 25.815.

According to the recommendations and on the base of statistical data of prototypes the width of aisle can be taken from the next table 2.

Table 2.2

Statistic data for the width of aisle for transport category of the aircraft

Class of passenger cabin	Economy	Business	First	
Flight duration, hours.	Up to 4	Up to 10	Up to 6	6…12
Aisle width at the level of 635 mm from the floor, mm	400…510	500…600	600	800

After the definition of the cabin width, we should define the height of the cabin, which is also very important for comfort.

For domestic and short-long range passenger aircraft the minimum height of the cabin is 1950 mm.

For narrow-body planes with number of seats in one row less than 6:

$$H_{cabin} = 1.48 + 0.17 B_{cabin} .$$

For wide body planes with number of seats in one row more than 6:

$$H_{cabin} = 0.296 + 0.383 B_{cabin} .$$

For domestic airlines

$h_1 - 1.75...1.9$ m,
$h_2 - 1$ m,
$h_4 - 0.6...0.9$ m,
$h_5 - 1.4...1.55$ m.

For short-mid-long-range planes:

$h_1 - 1.9...2.11$ m,
$h_2 - 1$ m,
$h_3 - 0.9...1.68$ m,
$h_4 - 1.58...1.73$ m.

The pitch of the frames is in the range of 360…550 mm and depends on the fuselage size and class of passenger cabin. The windows are in one row (or in two for double-deck cabin). The shape is circular D=300 …400 mm or rectangular with rounding. Windows pitch is equal as usual to the frame pitch.

$$H_{cab} = 1.48 + 1.17B_{cab} = 1.48 + 0.17 \cdot 2.714 = 1.94\,\mathrm{m},$$

Windows are placed in one row on each side of the fuselage. The shape of the windows is rectangular with rounded corners. Because aircraft windows easily lead to stress concentration, the corners of the windows are rounded. The windows are located between two bulkheads and in my design, the distance between two windows is about 400 mm.

The passenger seats are installed along the length of the passenger cabin with correct seat pitch, which depends on the flight duration and class of the cabin. Seat pitch must be divisible to one inch. (25,4 mm).

Cabin length $L_{cab.}$ for typical accommodation with constant seat pitch L_{seat}

$$H_{cab} = 1.48 + 1.17B_{cab} = 1.48 + 0.17 \cdot 2.714 = 1.94\,\mathrm{m},$$

where:

L_1- distance from the wall to the back of the seat in first row, mm;

L_2- distance from the back of the seat in the last row to the wall, mm.

The length of economic passenger cabin:

$$L_{econ} = L_1 + (N-1)L_{seatpitch} + L_2,$$

$$L_{econ} = 1200 + (31-1)850 + 235 = 23635\,\mathrm{mm},$$

Baggage compartments are placed under the floor of the passenger cabin. It is important in the flight which will influence gravity center of the aircraft. Incorrect placement of cargo and passengers can lead to emergency situations in flight, that is why we have to calculate exactly cargo placement and limit their weight.

Given the fact that the unit of load on floor K = 500 kg/m^2

The area of cargo compartment is defined:

$$S_{cargo} = \frac{M_{bag}}{0.4K} + \frac{M_{cargo\&mail}}{0.6K} = \frac{10 \cdot 124}{0.4 \cdot 500} = \frac{21 \cdot 124}{0.6 \cdot 500} = 14.88\,\mathrm{m}^2,$$

where:

M_{bag} – mass of baggage of all passengers, $M_{bag}=m\ n_{pass}$, m- mass of baggage for one passenger for free, n_{pass} – number of passengers.

$M_{cargo\ \&mail}$ – mass of additional cargo and mail on the board of aircraft., approximately 15 kilograms for each passenger.

Cargo compartment volume is equal:

$$V_{cargo} = v \cdot n_{pass} = 0.2 \cdot 124 = 24.8\,\mathrm{m}^3,$$

Let's assume that the cargo compartment design is similar to Embraer 195 prototype.

International standards provide that if the plane has a mixed layout, be sure to make two dishes. If the flight duration is less than 3 hours the food to passengers is not issued in this case providing only water and tea. Tickets to the flight time less than one hour, buffets and toilets cannot be done. Kitchen cupboards must be placed at the door, preferably between the cockpit and passengers or cargo, have separate doors. Refreshments and food cannot be placed near the toilet facilities or connected with a wardrobe. According to international standards, the volume of the galleys should be about 0.1 cubic meter per passenger, so the volume of galley should be:

$$V_{galley} = 0.1 \cdot n_{pass} = 0.1 \cdot 124 = 12.4\,\mathrm{m}^3,$$

The total area of galley floor:

$$S_{galley} = \frac{V_{galley}}{H_{cab}} = \frac{12.4}{1.94} = 6.39\,\mathrm{m}^2$$

If food is organized once it is given a set number 1 weighing 0.62 kg. Food passengers appear every 3.5-4-hour flight.

Number of meals per passenger breakfast, lunch, and dinner – 0.8 kg; tea and water – 0.4 kg, the total weight of food for passenger and crew number is about 190 kg. Buffet design like prototype.

Number of toilet facilities is determined by the number of passengers and flight duration: with t = 2-4 hours and one lavatory for 50 passengers

$$t = \frac{Range_{flight}}{V_{cruise}} + 0.5 = \frac{2650}{835} + 0.5 = 3.67\ \text{h},$$

$$N_{lavatory} = \frac{n_{pass}}{40} = \frac{124}{40} > 4.$$

The number of lavatories is chosen by prototype, and it equals 3.

Area of lavatory:

$$S_{lav} = 1.5\ \text{m}^2,$$

Width of lavatory: 1m. Toilets design similar to the prototype.

The aircraft chosen as a prototype has 3 galleys and 2 lavatories by designed. Galley and lavatory design are similar to the prototype.

2.3 Layout and calculation of basic parameters of tail unit.

One of the most important tasks of the aerodynamic layout is the choice of tail unit (TU) position.

For ensuring longitudinal stability of the aircraft during manoeuvring flight its centre of gravity should be placed in front of the aircraft focus (aerodynamic centre) and the distance between these points (arm for aerodynamic moment of the lift force), related to the mean value of wing aerodynamic chord, determines the rate of longitudinal stability.

$$m_x^{Cy} = \bar{x}_{cg} - \bar{x}_F < 0,$$

where $m^{Cy}{}_x$ –is the moment coefficient; $\bar{x}_{cg}, \bar{x}_F$ – center of gravity and focus coordinates.

Statistic range of static moment coefficient of horizontal tail unit A_{htu}, and vertical tail unit A_{vtu} are given in the table with typical arms for HTU and VTU in ratio to mean aerodynamic chord of the wing. Using table, we may find the first approach of geometrical parameters determination.

Table 2.3

Range of TU static moments

#	Airplane type	A_{htu}	A_{vtu}	L_{htu}/B_{MAC}, and L_{vtu}/lw
1	Long range passenger, turbo prop engine	0.8....1.1	0.05...0.08	2.0...3.0
2	Long range passenger, turbo jet engine	0.65...0.8	0.08...0.12	2.5...3.5
3	Large, not manoeuvrable, with swept wing	0.5...0.6	0.06...0.1	2.0...3.0
4	Large, not manoeuvrable, with straight wing	0.45...0.55	0.05...0.09	2.0...3.0
5	High speed, manoeuvrable	0.4...0.5	0.05...0.08	1.5….2.0

Determination of the TU geometrical parameters.

Usually, the areas of vertical S_{VTU} and horizontal S_{HTU} of TU is:

$$S_{HTU} = (0.18..0.25)\,S$$

$$S_{VTU} = (0.12..0.20)\,S$$

According to prototype:

$$L_{htu} = 16\text{ m},$$

$$L_{vtu} = 13\text{ m}.$$

More exactly:

$$S_{HTU} = \frac{b_{mac} \cdot S}{L_{htu}} \cdot A_{HTU,},$$

$$S_{HTU} = \frac{4.16 \cdot 145}{16} \cdot 0.6 = 22.6 \text{ m}^2,$$

$$S_{VTU} = \frac{l \cdot S}{L_{vtu}} \cdot A_{VTU},$$

$$S_{VTU} = \frac{34 \cdot 145}{13} \cdot 0.09 = 34.13 \text{ m}^2,$$

where: L_{HTU} and L_{VTU} - arms of horizontal TU and vertical TU.

l, S – wingspan and wing area.

A_{HTU}, A_{VTU} – coefficients of static moments, values of which may be taken from the table.

Values L_{HTU} and L_{VTU} depend on some factors. Firs of all, their value is influenced by the length of the nose part and tail part of the fuselage, sweptback and wing location, and also from the conditions of stability and control of the airplane.

Determination of the elevator area and direction:

elevator area:

$$S_{el} = (0.3..0.4)\ S_{HTU},$$

$$S_{el} = 0.3 \cdot 22.6 = 6.78 \text{ m}^2,$$

Rudder area:

$$S_{rudder} = (0.2...0.22) S_{VTU},$$

$$S_{rudder} = 0.22 \cdot 34.13 = 7.5 \text{ m}^2.$$

Choose the area of aerodynamic balance.

For speed of the flight $M \geq 0.75$:

$$S_{ad\ el} = (0.18..0.2)\ S_{el},$$

$$S_{ab\ el} = 0.2 \cdot 6.78 = 1.35,$$

$$S_{ad\ rudder} = (0.18..0.2)\ S_{rudder},$$

$$S_{ab\ rudder} = 0{,}2 \cdot 7.5 = 1.5.$$

If the, then

$$S_{ab\ el} \approx S_{ad\ rudder} = (0.18..0.2)\ S_{control\ surface}.$$

The area of trim tab

$$S_{stabs} = (0.8..0.12)\ S_{rudder}.$$

Determination of the TU span

TU span is related to the following dependence:

$$l_{HTU} = (0.32..0.5)\ l_{wing},$$

$$l_{HTU} = 0.45 \cdot 34 = 15.3 \text{ m}.$$

In this dependence the lower limit corresponds to the turbo jet engine aircraft, equipped with all-moving stabilization.

The height of the vertical TU h_{VTU} is determined according to the location of the engines. Taking it into account we assume:

Engine in the root part of the wing

$$h_{VTU} = (0.13...0.165),$$

$$h_{vtu} = 0.15 \cdot 134 = 5.1\ m,$$

For high wing airplanes we need to set the upper limit.

Tapper ratio of horizontal and vertical TU we need to choose:

For planes M<1

$$\eta_{HTU} = 2...3,$$
$$\eta_{VTU} = 1...1.33.$$

TU aspect ratio

It is recommended recommend:

For transonic planes

$$\lambda_{vtu} = 0.8...1.5$$
$$\lambda_{htu} = 3.5...4.5$$

Determination of TU chords b_{end}, b_{root}:

$$b_{tipv} = \frac{2s_{htu}}{(\eta_{vtu}+1)h_{vtu}} b_{mac} = \frac{2\cdot 22.6}{(1.33+1)\cdot 5.1} = 3.8\text{ m},$$

$$b_{tiph} = \frac{2s_{htu}}{(\eta_{vtu}+1)l_{vtu}} b_{mac} = \frac{2\cdot 34.13}{(2.5+1)\cdot 15.3} = 1.27\text{ m},$$

$$b_{root} = b_{tip}\cdot\eta_{VTU} = 3.8\cdot 1.33 = 5.05\text{ m},$$

$$b_{root} = b_{tip}\cdot\eta_{HTU} = 1.27\cdot 2.5 = 3.175\text{ m}.$$

Width/chord ratio of the airfoil.

For horizontal and vertical TU in the first approach,

$$\overline{C}_{TU} \approx 0.8\overline{C}_{w}.$$

For more accurate:

Subsonic

$$\overline{C} = 0.08..0.1.$$

If the stabilizations fixation is on the fin, we need to use upper limit of $\overline{C}_{TU}$, to provide fixation base on the fin.

TU sweptback is taken in the range 3...5°, and not more than wing sweptback. We do it to provide the control of the airplane in shock stall on the wing.

2.4. Calculation of basic parameters and layout of landing gear.

In the primary stage of design, when the airplane center-of-gravity position is not defined and there is no drawing of airplane general view, only the part of landing gear parameters may be determined.

The distance from the centre of gravity to the main LG

$$Bm = (0.15..0.20)\, b_{MAC}.$$

Let’s take 0,17

$$B_m = 0.17 \cdot 4.16 = 0.7072 \text{ m}.$$

With the large distance the lift of the nose gear during take of is complicated, and with small, the strike of the airplane tail is possible, when the loading of the back of the airplane comes first. Besides the load on the nose LG will be too small and the airplane will be not stable during the run on the slickly runway and side wind.

Landing gear wheel base comes from the expression:

$$B = (0.3..0.4)\, l_f = (6..10)\, Bm,$$

$$B = 0.4 \cdot 38.53 = 15.421\, m.$$

Large value belongs to the airplane with the engine on the wing.

The last equation means that the nose support carries 6…10% of aircraft weight.

The distance from the centre of gravity to the nose LG

$$B_n = B - B_m = -13.32 \text{ m},$$

Wheel track is:

$$T = (0.7..1.2)\,B \leq 12m$$

On a condition of the prevention of the side nose-over the value T should be > 2H, where H – is the distance from runway to the center of gravity.

Wheels for the landing gear is chosen by the size and run loading on it from the take-off weight; for the front support we consider dynamic loading also.

The type of tires and the pressure in it is determined by the runway surface, which should be used. We install brakes on the main wheel, and sometimes for the front wheel also.

The load on the wheel is determined:

$$F_n = \frac{B_m}{B} W,$$

$$F_m = \frac{B_n}{B} W.$$

$$\sum F_z = 0 \rightarrow F_n + F_m = W,$$

$$\sum M_0 = 0 \rightarrow F_n B + W B_m = 0.$$

$$F_{main} = \frac{(B - Bm) m_0 \cdot 9.81}{B \cdot n \cdot z},$$

$$F_{nose} = \frac{Bm \cdot m_0 \cdot 9.81 \cdot K_g}{B \cdot z},$$

where *n*, and *z* – is the quantity of the supports and wheels on the one leg.

K_g = 1.5...2.0 – dynamics coefficient.

By calculated F_{main} and F_{nose} and the value of $V_{take\ off}$ and $V_{landing,}$ pneumatics is chosen from the catalogue, the following correlations should correspond.

$$P^{K}_{slmain} \geq P_{main};\, P^{K}_{s\ln ose} \geq P_{nose};\, V^{K}_{landing} \geq V_{landing};\, V^{K}_{takeoff} \geq V_{takeoff}.$$

Where K is the index designated the value of the parameter allowable in catalogue. Pneumatics data is in appendixes 6, 7, 8.

For ensuring airplane pass ability, used on the ground runways, pressure in the wheel pneumatics should range in

$$P = (\ 3..5)\ 105\ Pa.$$

2.5. Choice and description of powerplant

The power plant is one of the main elements of an aircraft, because it provides thrust which is a vital component in lift generation. Moreover, the powerplant choice also determines the flight performance of an aircraft, such as cruise speed and altitude of flight. The best choice for current aircraft prototype will be two General Electric CF34-10E turbofan engines, as a real prototype Embraer 195. These engines are known for their reliability and fuel efficiency. One of the most important benefits is their very low noise level. This engine can generate up to 89 kN of thrust. Two of this engine types will provide enough power for takeoff, climb and cruise.

2.6. Determination of center of gravity

2.6.1 Equipped wing center of gravity determination

The distance from the main aerodynamic chord to the centre of gravity of the airplane is called the centering. Due to changing of the aircraft loading variants or the weight during flight the position of aircraft centre of gravity is changing. The moving of the cargo inside the aircraft leads to changing of centre of mass position too. Centering is an important aircraft characteristic as it affects balancing, stability, and controllability of the aircraft. That is why it is necessary to keep it to strict limits. To calculate the centering, it is necessary to determine the mass of main structural units and devices. The list of masses for aircraft is given in Table 3.1.

The longitudinal static stability of the aircraft is determined by the location of its centre of mass relative to the focuses. The closer the centre of mass is to the nose part of the aircraft, the more longitudinal stability the aircraft has.

Formula for calculation of coordinates of center of gravity of the equipped wing is:

$$X'_w = \frac{\sum m'_i \cdot x_i}{\sum m'_i},$$

Table 2.4

List of equipped wing masses

#	object name	Mass		C.G coordinates *Xi*, m	Mass moment, $X_i * m_i$
		units	total mass m_i, kg		
1	wing (structure)	0.12193	6666.88854	1.7888	11925.73022
2	fuel system	0.0055	300.729	1.768	531.688872
3	Power plant	0.0931	5090.5218	-2.94	-14966.13409
4	Flight control system, 30%	0.00219	119.74482	2.496	298.8830707
5	electrical equipment, 10%	0.00333	182.07774	0.416	75.74433984
6	anti-ice system, 40%	0.0096	524.9088	0.416	218.3620608
7	hydraulic systems, 70%	0.01344	734.87232	2.496	1834.241311
8	equipped wing without landing gear and fuel	0.24909	13619.74302	-0.005982801	-81.48421757

2.6.2 Determination of center of gravity of equipped fuselage

The list of fuselage units and their calculated coordinates is given in Table 3.2.

All calculations are performed by this formula:

$$X_f' = \frac{\sum m_i' \cdot x_i}{\sum m_i'},$$

Table 2.5

Calculation of center of gravity position variant

#	Objects names	Mass		C.G coordinates, m	Mass moment, kgm
		Units	Total mass		
1	2	3	4	5	6
1	Fuselage	0.12591	6884.50698	19.265	132630.027
2	Horizontal tail	0.01585	866.6463	35.53	30791.94304
3	Vertical tail	0.01558	851.88324	32.76	27907.69494
4	Radar	0.0033	180.4374	0.5	90.2187
5	Radio equipment	0.0025	136.695	1.5	205.0425
6	Instrument panel	0.0058	317.1324	2	634.2648
7	Aero navigation equipment	0.005	273.39	2	546.78
8	Flight control system 70%	0.00511	279.40458	19.265	5382.729234
9	Hydraulic system 30%	0.00576	314.94528	26.971	8494.389147
10	electrical equipment 90%	0.02997	1638.69966	19.265	31569.54895
11	Not typical equipment	0.0031	169.5018	17.65	2991.70677
12	Lining and insulation	0.00274	149.81772	19.265	2886.238376

Ending of table 2.5

13	Anti ice system, 20%	0.0048	262.4544	30.824	8089.894426
14	Airconditioning system, 40%	0.009600	524.9088	19.265	10112.36803
15	Passenger seats (economic class)	0.0136	743.6208	20	14872.416
16	Seats of flight attendence	0.000384	20.996352	1.82	38.21336064
17	Seats of pilot	0.000768	41.992704	2.87	120.5190605
18	Emergency equipment	0.0018	98.4204	17.6	1732,.9904
19	Lavatory1, galley 1	0.0055	300.729	4.7	1413.4263
20	Lavatory2, galley 2	0.0055	300.729	30.4	9142.1616
21	Operational items	0.00095	51.9441	17.6	914.21616
22	Additional eguipment	0.001	54.678	17.6	962.3328
23	Equipped fuselage without payload	0.264522	14463.53392	20.15609269	291528.3302

2.6.3. Determination of center of gravity positioning variants

Table 2.6

Determination of center of gravity of fuselage

#	objects names	Mass		C.G coordinates x_i, m	mass moment
		units	total mass		
1	2	3	4	5	6
1	fuselage	0.12591	6884.50698	19.265	132630.027
2	horizontal tail	0.01585	866.6463	35.53	30791.94304
3	vertical tail	0.01558	851.88324	32.76	27907.69494
4	radar	0.0033	180.4374	0.5	90.2187
5	radio equipment	0.0025	136.695	1.5	205.0425
6	instrument panel	0.0058	317.1324	2	634.2648
7	aero navigation equipment	0.005	273.39	2	546.78
8	Flight control system 70%	0.00511	279.40458	19.265	5382.729234
9	hydraulic system 30%	0.00576	314.94528	26.971	8494.389147
10	electrical equipment 90%	0.02997	1638.69966	19.265	31569.54895
11	not typical equipment	0.0031	169.5018	17.65	2991.70677
12	lining and insulation	0.00274	149.81772	19.265	2886.238376
13	anti ice system, 20%	0.0048	262.4544	30.824	8089.894426
14	airconditioning system, 40%	0.009600	524.9088	19.265	10112.36803

1	2	3	4	5	6
15	passenger seats (economic class)	0.0136	743.6208	20	14872.416
16	seats of flight attendence	0.000384	20.996352	1.82	38.21336064
17	seats of pilot	0.000768	41.992704	2.87	120.5190605
18	Emergency equipment	0.0018	98.4204	17.6	1732.19904
19	lavatory1, galley 1	0.0055	300.729	4.7	1413.4263
20	lavatory2, galley 2	0.0055	300.729	30.4	9142.1616
21	Operational items	0.00095	51.9441	17.6	914.21616
22	additional eguipment	0.001	54.678	17.6	962.3328
23	equipped fuselage without payload	0.264522	14463.53392	20.15609269	291528.3302

The list of mass objects for center of gravity calculation options presented in Table 3.3 and the center of gravity calculation options presented in Table 3.4 are completed based on both previous tables. Formula for determination of position of mean aerodynamic chord from the nose of the fuselage is:

$$X_{MAC} = \frac{m_f \cdot X_f + m_w \cdot X_w - m_0 \cdot c_n}{m_0 - m_w}$$

where m_0 – aircraft take-off mass, kg; m_f – mass of equipped fuselage, kg; m_w – mass of equipped wing, kg.

Table 2.7

Calculation of center of gravity position variants

#	Name object	mass $m_{i,}$, kg	coordinate X_i, m	mass moment kgm
1	equipped wing (without fuel and landing gear)	13619.74	17.27	235201.04
2	Nose landing gear (extended)	471.76	5	2358.81
3	main landing gear (extended)	1887.05	17.86	33702.66
4	fuel reserve	1932.87	19.06	36848
5	fuel for flight	8490.40	19.06	161860.19
6	equipped fuselage (without payload)	14463.53	20.16	291528.33
7	Passengers(economy)	9548	20	190960
8	Passengers(bussiness)	0		0
9	on board meal	150	30	4500
10	baggage	1240	18	22320
11	cargo, mail	2541	18	45738
12	flight attend	180	17	3060
13	crew	154	2.4	369.60
14	Nose landing gear (retrected)	471.76	4	1887.05
15	main landing gear (retrected)	1887.05	17.86	33702.66

Table 2.8

Aircraft`s center of gravity position variants

#	Name	Mass, kg	Moment of mass, m	Center of mass	Centering, %
1	Take off mass (L.G. extended)	54678.35	1028446.64	18.80902732	36.8730793
2	Take off mass (L.G. retracted)	54678.35	1027974.87	18.80039938	36.66567679
3	Landing weight (LG extended)	46187.95	866586.44	18.76217458	35.74681145
4	Ferry version (without payload, max fuel, LG retracted)	41019.35	761396.87	18.56189379	30.93236941
5	Parking version (without payload, without fuel foe flight, LG extended)	32374.95	599638.84	18.52168983	29.96592805

Project part conclusions

As a result of the project part of the work, the preliminary design of a middle-range passenger aircraft was completed. This work illustrated the intricate relationship between various aircraft parameters, such as area of a wing, geometrical parameters of the fuselage, tail unit configuration and landing gear placement. The optimal values were determined for each of these parameters, ensuring that that the aircraft structure integrity, aerodynamic efficiency and operational versatility. The aircraft center of gravity was also calculated using methodological guide. As a result, the position of aircraft center of gravity varies in a range between 29.96 % and 36.87 %.

3. DESIGN OF THE CARGO DOOR OF THE CONVERTED AIRCRAFT

3.1. Possibilities of converting the passenger aircraft to freighter

Nowadays passenger aircraft to a freighter conversion is a typical procedure. There are several reasons why airlines are doing that. Flexibility. Cargo aircraft have fewer restrictions and requirements on operation than passenger ones. Conversion process makes an aircraft much more flexible in scheduling and routing as fighters can operate on destinations not common for passenger flights. The market demands. There are periods when the demand for cargo transportation is higher than for passenger transportation . Aircraft converting process allows airlines to adapt to changing market conditions. Economic reasons. Older aircraft that are not cost-efficient on passenger travel can gain more revenue doing cargo transfers. It can extend the economic life of an aircraft. During Covid-19 pandemic a lot of airlines converted some of their fleet for cargo transfers, that helped to survive the crisis . Generally, cargo aircraft require lower operating costs [10, 11]. The reason is that they require fewer crew members, and they have simple cabin configurations. They also do not require passenger services and in-flight entertainment. The conversion process itself increases the cargo capacity of an airline and makes it capable of serving a broader range of cargo transportation needs. There are several examples of the most successful freighters that originally were passenger aircraft: Bombardier CRJ200SF is a converted version of Bombardier CRJ200 passenger aircraft design for accommodation of up to 50 people. The Cargo version can transport up to 6.7 tons of payload [12]. Embraer 195F is a freighter aircraft conversion built on the Embraer 195 regional jet design for transportation of up to 120 passengers [13]. It is designed to meet the growing demand for air freight with a maximum structural payload of 12300 kg and a sizable volumetric capacity of 4.170 cubic feet. Airbus A321

Passenger-to-Freighter (P2F) converted from the popular A321 passenger jet originally designed for transportation of up to 236 passengers is intended to fulfill the increasing demand for aviation freight [14]. With its containerized loading system on both the main and lower decks, this effective and adaptable freighter offers a considerable cargo capacity of up to 28 tons and a generous volumetric capacity. The A321P2F is a desirable choice for airlines and operators looking for an affordable and environmentally friendly solution for regional and express cargo operations since it keeps the remarkable range and fuel efficiency of the original A321. Boeing 737-800 Boeing converted freighter (BCF) also known as 737 freighter has earned a considerable reputation in online cargo and express markets [15]. Its passenger version can transport up to 162 passengers. This aircraft is a great choice for both short-haul and medium-haul transportation. Its popularity is gained by an ample cargo area and great cargo capacity of up to 24 tons. The conversion design provides easy loading and unloading capabilities for a variety of cargo.

3.2. Requirements for conversion process and changes in aircraft systems

Generally, the passenger to cargo conversion is a complex process which requires a whole set of different works and modifications. Before the conversion, a set of tests should be performed on the passenger aircraft to collect necessary data such as: fuselage pressurization, wing deflection, and different systems performances [16]. Collected data helps engineers and designers understand the aircraft's performance in different conditions and simulate its behaviour as a freighter [17]. This process is vital, especially for models undergoing conversion for the first time. The next step is the conversion itself. It starts with the complete interior disassembly. In the passenger cabin, all seats, galleys, lavatories, and sidewalls are removed. The passenger cabin floor is also disassembled, and the illuminators are replaced with aluminium stubs. The cockpit is commonly disassembled as well, often to modernize outdated avionics equipment. One of the most critical aspects is the cargo door. It is usually installed behind the main passenger door at the front left of the fuselage, or in some models, at the back left. This requires cutting out a fuselage half-section, which is then replaced with a section containing the cargo door cutout. Skin and structural elements like stringers and ribs are riveted to the original fuselage structure, and this section is reinforced to withstand pressure loads during flight. A new cargo door is then installed. The passenger cabin floor is then reinforced to sustain heavy cargo loads, and additional loading equipment like rollers, pallet/container locks, and tie-down rings is installed. Newly modified systems and communications, such as a fire extinguishing system for the main cargo deck, are also added at this stage. The wall between the main cargo deck and cockpit is reinforced to protect pilots from potential cargo detachment during hard landings. In some cases, aircraft engines are modified for increased power. After all assembly and modification work is completed, the aircraft undergoes a series of ground and flight tests to verify compliance with airworthiness requirements and obtain new certification and registration as a freighter. Some companies can complete the entire conversion process within 90-120 days [16, 18, 19].

Fig. 3.1. The installation process of fuselage section with cargo door cutout on Boeing 767-300ER [20].

3.3. Cargo aircraft layout calculation

To calculate cargo aircraft layout the geometrical parameters of the main cargo deck are needed. According to calculated passenger cabin parameters we got cabin length = 23.64 m, cabin height = 1.94 m and cabin width on the floor level = 2.71 m.

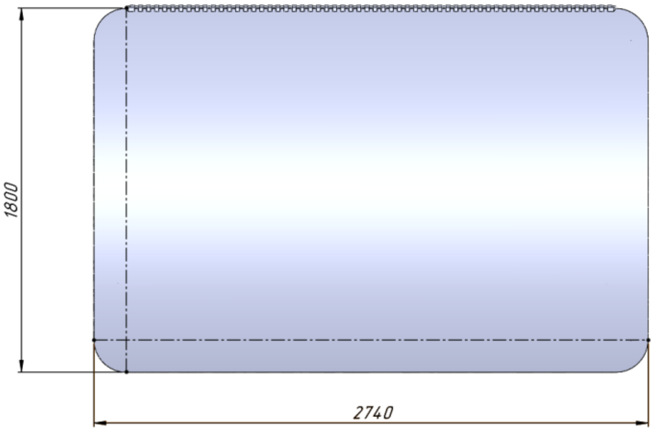

Fig. 3.2. Main cargo door geometrical parameters in millimeters.

Geometrical parameters for the main cargo door shown in Fig. 3.2 were taken from Embraer 195F which is a cargo version of a prototype aircraft. Using these parameters, we can calculate the layout for the main cargo deck. Size limits for cargo containers will be 1.8 m height and 2.71 m width. The maximum payload of prototype is equal to 12276 kg.

Table 3.1

Main cargo deck parameters				
	H, m	W, m	L, m	V, m^3
Main cargo bay	1.94	2.71	23.64	124.28
Max payload, kg	12276			
Floor area, kg	64.06			

This table represents parameters of the main cargo deck of converted prototype with calculated volume and floor area.

Table 3.2

	by Height	By Length	By Width
LD-2	Fits	Fits	Fits
LD-6	Fits	Fits	Does not fit
LD-7	Fits	Fits	Does not fit
LD-8	Fits	Fits	Does not fit
LD-9	Fits	Fits	Does not fit
PL	Fits	Fits	Does not fit
PA	Fits	Fits	Does not fit
PM 2W	Fits	Fits	Does not fit
PM 2H	Fits	Does not fit	Does not fit
PG	Fits	Does not fit	Does not fit

This table represents the displacement of different types of unit load devices and whether they fit the main cargo deck or not. If the ULD does not fit by width but fits by length this means that it is still able to be placed in cargo cabin but only along the fuselage.

Table 3.3

LDs placement for converted prototype

		Available number of LDs if they are located along	Lower number of LDs to meet the available payload	Total weight (LD+Cargo), kg	Max payload (without LD weight), kg	Corresponds to max available payload	Floor Area Left, %	Volume left, %
1	LD-2	15.13	10	12250	11650	Yes	62.6	72.64

Ending of table 3.3

2	LD-6	5.82	3	9525	8985	Yes	70.81	83.25
3	LD-7	7.45	2	12066	11666	Yes	77.85	84.05
4	LD-8	7.45	5	12245	11645	Yes	61.99	72.08
5	LD-9	7.45	2	12066	11666	Yes	77.85	84.05
6	PL	7.45	3	9525	9255	Yes	77.19	83.25
7	PA	7.45	2	9252	9012	Yes	77.85	84.05
8	PM 2W	7.45	2	10070	9810	Yes	75.83	74.57
9	PM 2H	6.36	1	6804	6674	Yes	85.86	82.97
10	PG	3.90	0	0	0	Yes	100	100

According to this table the most efficient ULD for converted prototype aircraft are Lower Deck container-IATA Type 8D-IATA Prefix: APA-APA: LD-2, upper Deck Container-IATA Type 5-IATA Prefix: AAK-ATA: LD-7, lower Deck container-IATA Type 6B-IATA Prefix: AQ-ATA: LD-8 and container-IATA Type 5-IATA Prefix: AAP-ATA: LD-9. The cabin volume and floor area of the main cargo deck were also considered. Therefore, the most efficient ULD among presented above for current aircraft will be lower Deck container-IATA Type 6B-IATA Prefix: AQ-ATA: LD-8, because it uses the cargo deck in the most efficient way. With 61.99 % of floor area and 72.08 % of cabin volume left, it is possible to transport 11645 kg of pure payload using 5 containers of such type.

It is also possible to combine different types of the ULDs at the same time depending on the types and sizes of transported cargo. Front and back lower cargo compartments could not be used for commercial payload transfer due to their small sizes. It is possible to use them for transporting some small cargo or personal items of the flight crew. Information about unit load devices and their geometrical parameters was taken from an official IATA source [21].

3.4. Designing a cargo door for a convertible aircraft

The cargo door for a freighter aircraft is one of the main constructional and functional elements. It provides access to the main cargo deck and makes it possible to place cargo pallets inside the fuselage. It combines two opposite functions: access for big cargo pallets and containers and aircraft cabin pressurization on higher altitudes of flight. According to CS25 [22] cargo door requirements the cargo door itself and its surrounding structure must be able to withstand pressure loads and different stresses that occur during flight and ground operation. It should also be able to sustain hard landing loads. Door structure must also be able to withstand repeated loading cycles without fatigue failures. Cargo doors should also be designed in a way it can sustain a certain level of damage without losing structural integrity or catastrophic failure. The door locking and latching mechanism should be designed in a secure and reliable way, so it would not open accidentally during the flight. There should be an ability to open the door from both inside and outside, it is vital for emergency situations and evacuation process. It should also have a pressure relief mechanism to prevent excessive pressure buildup. The door should be easy in operation both manually and with powered mechanisms. The opening of a cargo door should provide sufficient clearance for cargo loading and unloading process. There should be access for maintenance too. Finaly the newly designed cargo door should be tested and certified and approved by the responsible authorities. Those are the European Union Aviation Safety agency (EASA) [23] and/or Federal Aviation Administration (FAA) [24]. If the aircraft is registered and operated in EU member countries the EASA will be the main certification authority. If it is registered and operated in the USA, the FAA will be the main certification authority. In case an aircraft is certified by one authority, and it is going to be operated in another authority jurisdiction, this second authority would need to validate the certification. This will ensure that the aircraft meets the safety and certification standards of both authorities. Therefore, the design process of such a door is not a simple task.

3.4.1. Determination of door types and their dimensions

In the case of a converted freighter an outward-opening door is the most suitable option, considering the dimensions of typical cargo carried by freighters. This door type offers a wide opening which is suitable for fast loading of different types of cargo such as palettes and LDs. The door dimensions of height of 1.8 m and width of 2.74 m are chosen according to the prototype aircraft Embraer 195F which is converted version of Embraer 195 passenger jet. These dimensions also align with the standard of some ULDs which are commonly used in aircraft cargo transfer operations. [25]

3.4.2. Desing of the door structure

The design process of cargo door model was performed using SolidWorks 3D CAD software [26]. First the fuselage section was modeled according to geometrical parameters of the prototype.

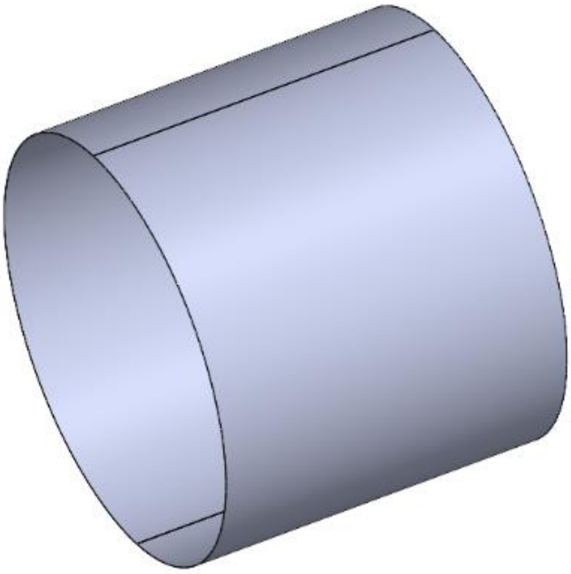

Fig. 3.3. Fuselage skin section.

Next step is to cut the cargo door in this fuselage section.

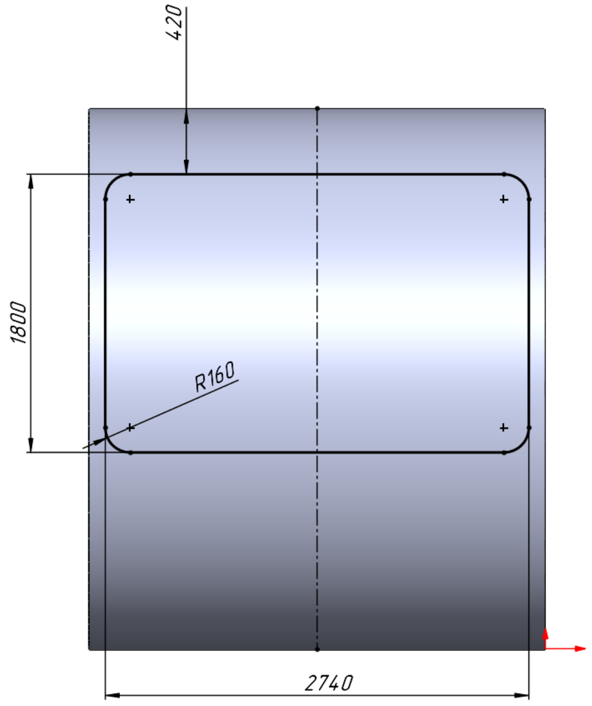

Fig. 3.4. Sketch of the door cutout.

All dimensions were taken from the prototype Embraer 195F.

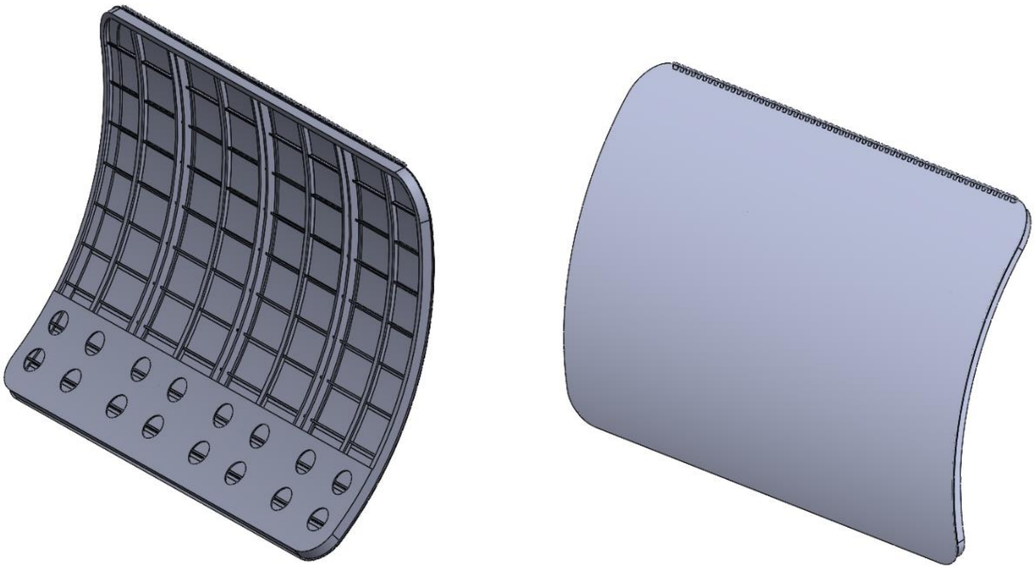

Fig. 3.5. Cargo door model from inside and outside.

After the fuselage skin model was cut, the door frame was modeled according to prototypes frame with stringers, ribs and latch plate with additional holes to make the structure lighter.

3.4.3. Door latch and hinge design

Latch and hinge are both very important elements of the door. Their task is to hold the door in close position during the flight and sustain different stresses from excess pressure. At the same time, they should provide easy door opening and closing during ground operation while loading and unloading process.

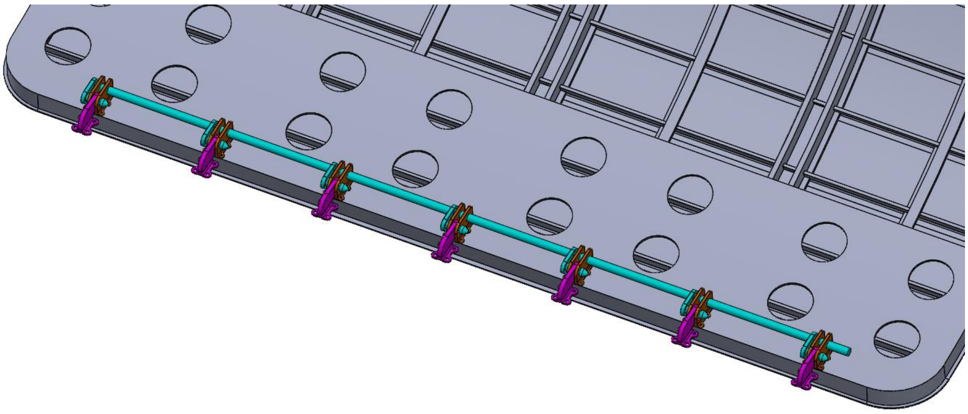

Fig. 3.6. Door locking mechanism. Consist of fuselage lock lug -pink, door lock lug – brown, latch – blue.

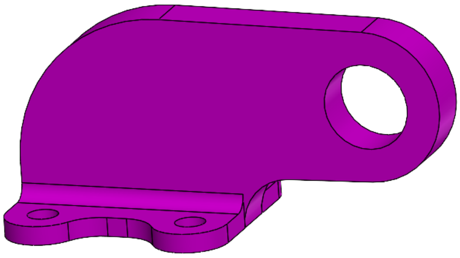

Fig. 3.7. Fuselage lock lug.

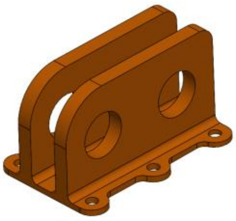

Fig. 3.7. Door lock lug.

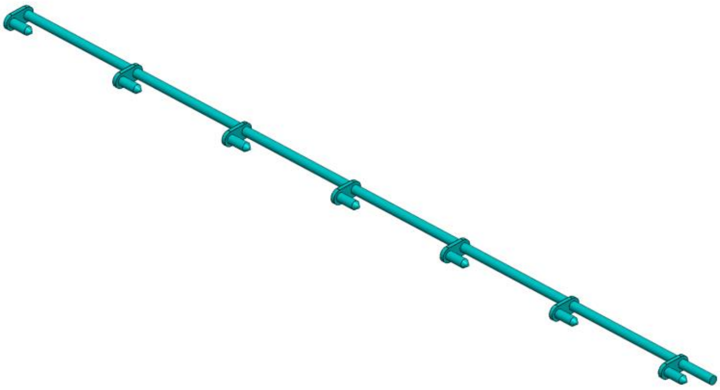

Fig. 3.8. Lutch.

Lutch is normally connected to the door handling mechanism which isn't shown on this model.

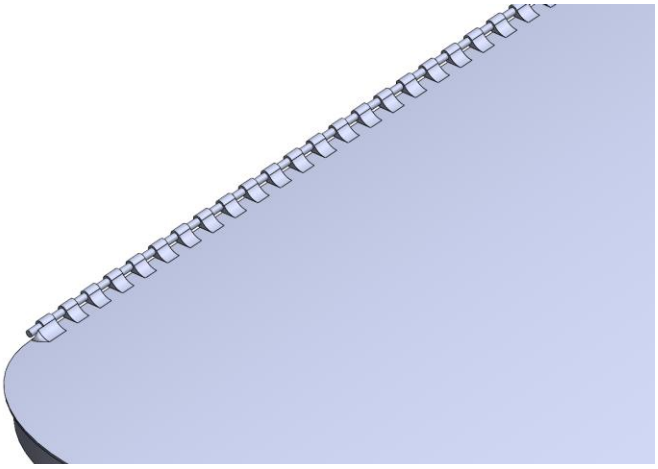

Fig. 3.9. Hinge and hinge pin.

Hinges are welded to the skin of the cargo door, which provides better structural integrity and sustainability during operation.

3.4.4. Door structure analysis under pressure loads

During the flight the pressure level inside the aircraft cabin is sustained between 0.075 MPa and 0.082 MPa. This creates a comfortable environment for passengers and flight crew. This puts a significant amount of pressure on the cargo door from inside the cabin. The maximum flight altitude of prototype aircraft is 12500 m above sea level. At this altitude the air pressure equals about 0.018 MPa.

Let’s calculate excess pressure:

$$\Delta P = 0.082 - 0.018 = 0.064 \text{ MPa}.$$

So, the door should be able to sustain 0.064 MPa of pressure load from inside. This simulation was performed in Ansys software in static structure module. To perform this simulation, it is necessary to choose the material. For this model the aluminum 2024-T3 was chosen as the most common aluminum type for prototype aircraft due to its good stress resistance in combination of light weight. After that it is necessary to fix the door in a correct way. All structural elements of the door should be bonded to the skin and to each other. The fuselage lock lugs should be fixed to simulate their connection to the fuselage airframe. The door lock lugs should be bonded to the door structure. The hinge pin and latch mechanism parts should have revolute type joints. This will accurately simulate door attachment in close position inflight. After that we should apply a pressure load of 0.064 MPa to the door from inside.

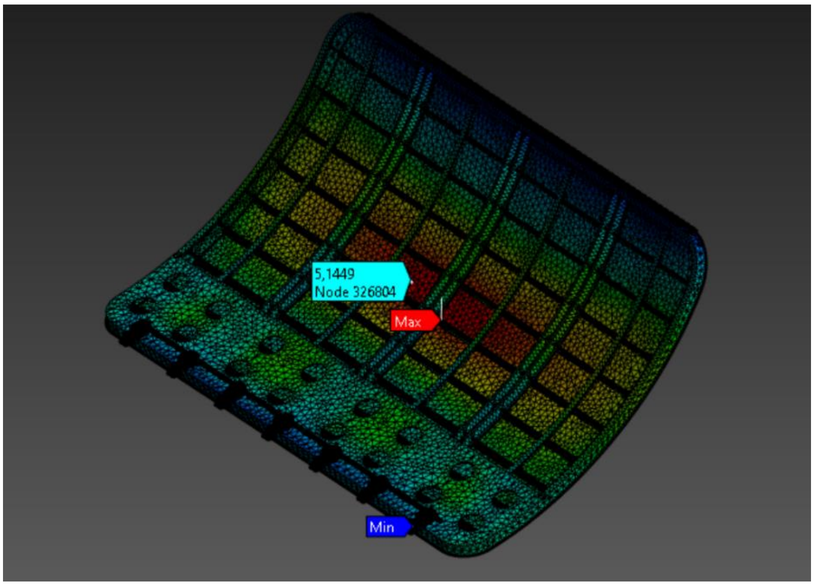

Fig. 3.10. Representation of the first simulation, total deformation diagram. Maximum displacement is 5.21 mm.

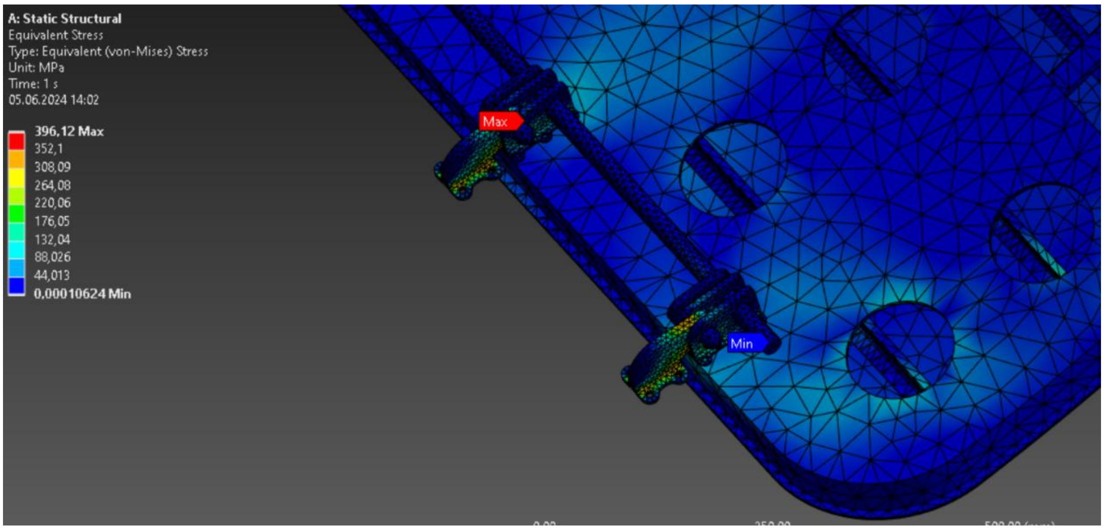

Fig. 3.11. Representation of the first simulation, equivalent stress diagram.

The maximum value is 396.12 MPa.

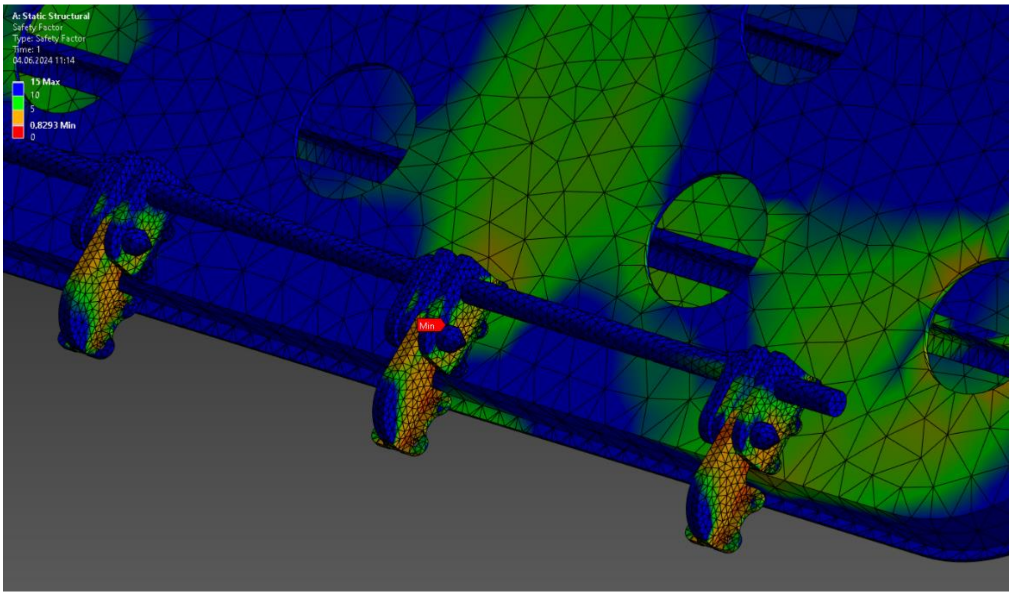

Fig. 3.12. Representation of the results of the first simulation, safety factor diagram.

As is shown on fig. 3.10, the minimum safety factor number is 0.83 means the structure starts to deform at concentration points which is not acceptable. The safety factor should be in the range from 1.5 to 2.5 units. Therefore, some changes should be made to the 3D model and simulation should be repeated. Using Space Claim module the 3D model has been changed. Moreover, it is decided to change the material for lock lugs. There are two possible variants of metallic alloys used during prototype aircraft manufacturing. These are SAE-AISI 4340 steel and Ti-6Al-4V titanium alloy. Both are one of the most common for especially stressed parts of an aircraft like engine mounts and landing gear. But for this application the best will be Ti-6Al-4V titanium alloy. It combines both high strength-to-weight ratio and excellent corrosion resistance, which is very important for lock lugs, as they are extended to the weather conditions during ground operation. Among its disadvantages are significantly higher cost and difficulties while machining and manufacturing.

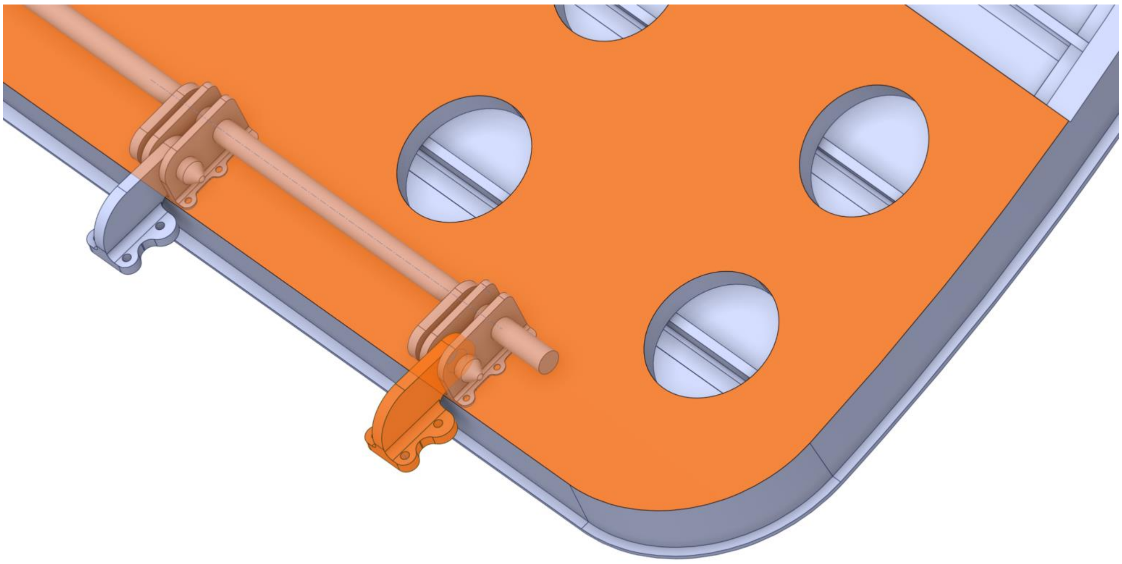

Fig. 3.13. Representation of structural changes, modified parts are orange.

The fuselage lock lugs mount was thickened together with door lock lugs plate, which also become two times thicker.

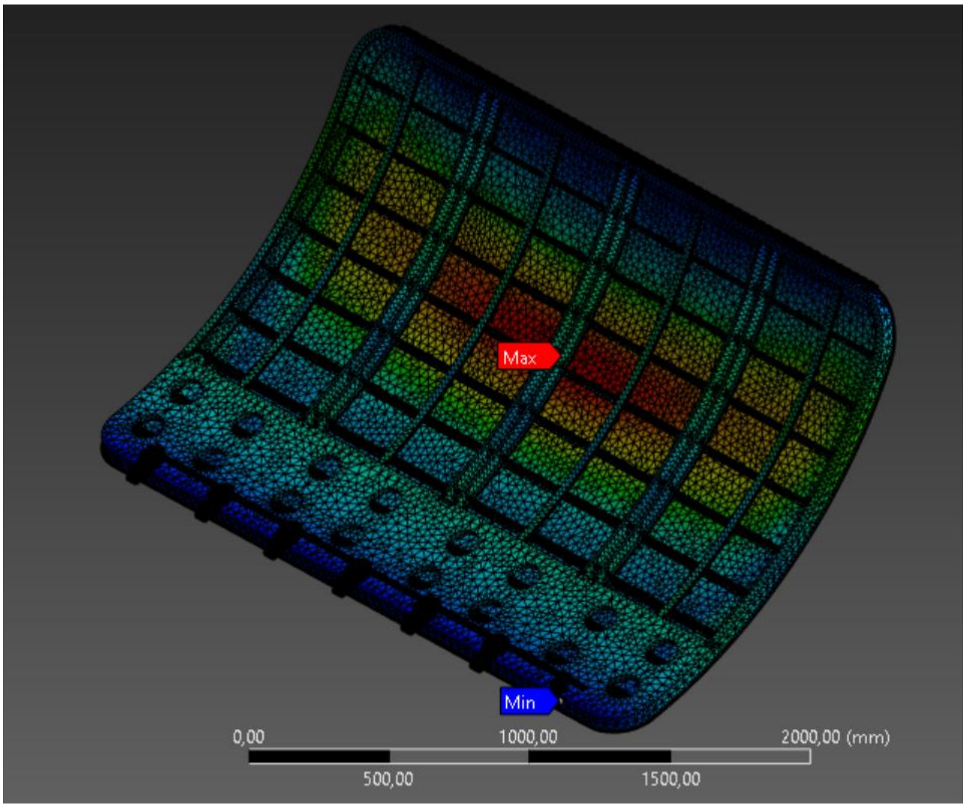

Fig. 3.14. Representation of second simulation. Total deformation diagram.

Maximum displacement is 1.8 mm, which is significantly better when in first simulation.

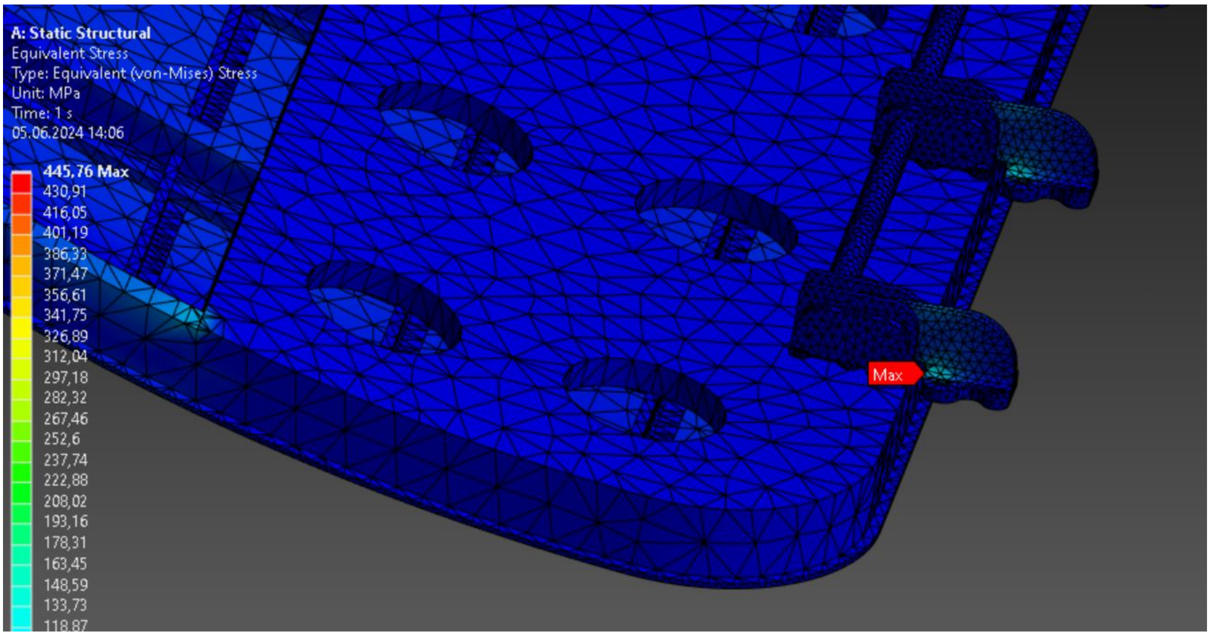

Fig. 3.14. Representation of second simulation. Equivalent stress diagram. Maximum stress is 445.76 MPa.

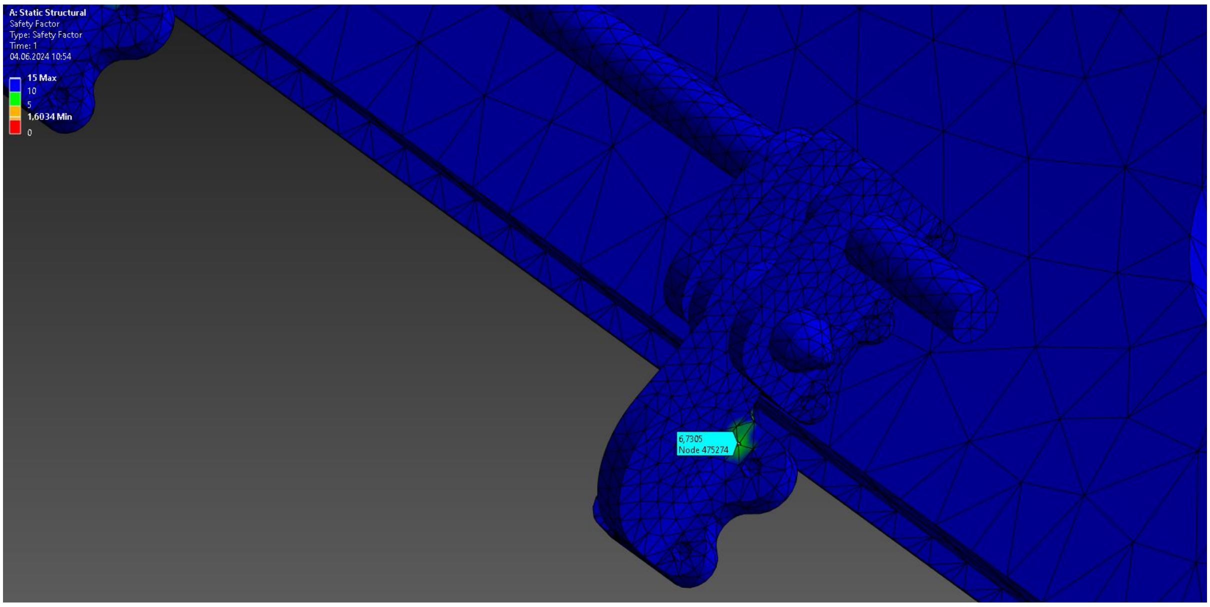

Fig. 3.12. Representation of second simulation, the safety fac tor coefficient.

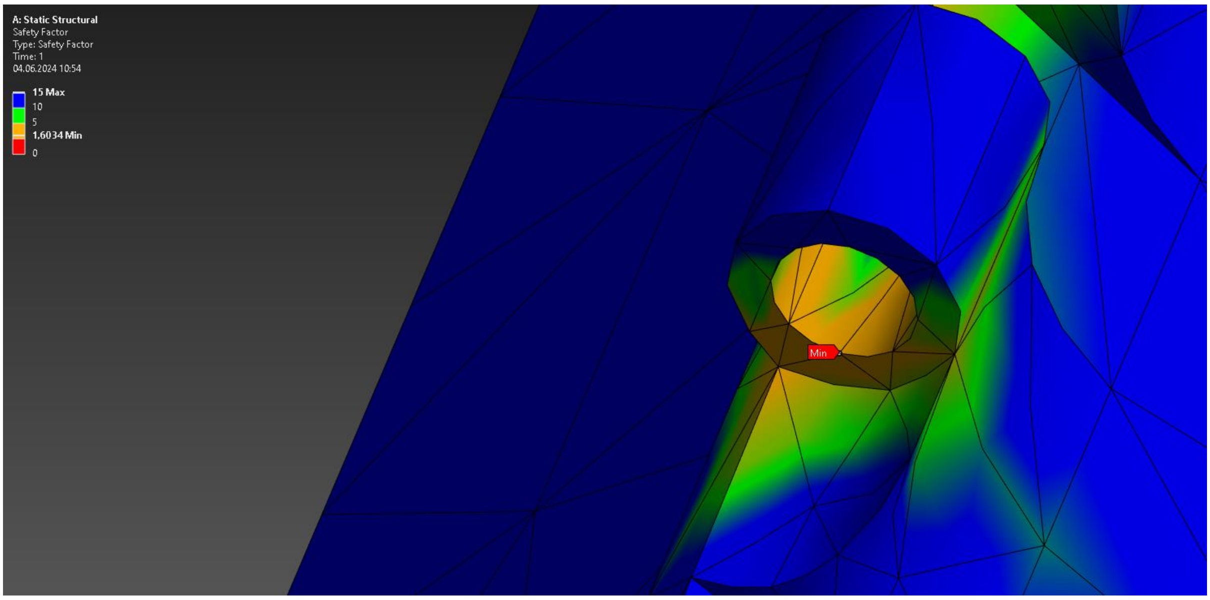

Fig. 3.13. Representation of second simulation, safety factor coefficient is 1.6 in the weakiest concentration point.

As a result of the second simulation, we have got the safety factor 1.6 (Fig. 3.12) which meets the safety factor requirements. Fig. 3.13 shows the point of concentration which is hinge with the lowest safety coefficient of 1.6. All points with load concentrations, like lock lugs and hinges must be given special attention during the maintenance procedures. They should be regularly inspected for possible fatigue cracks.

Special part conclusion

As a result of a special part, the conversion according to all necessary certifications and regulations process was detailly described and performed. The new layout for the main cargo deck was calculated in a way to use all space and payload in the most efficient way. Main cargo door was designed and modeled using SolidWorks 3D CAD software according to all necessary parameters and regulations by CS25. The latch mechanism of the door was designed and tested together with door itself in Ansys software for excessive pressure resistance. Some changes were made to the model and by incorporating advanced materials like titanium alloy. As a result, a secure and efficient cargo door was created. It can withstand the flight stresses and ground cargo operations.

GENERAL CONCLUSION

1. According to given task of the bachelor’s degree thesis, preliminary design of passenger middle-range aircraft was created. This process was detailly described and divided by chapters. Every chapter was dedicated for separate aircraft part, such as fuselage design, wing geometry calculation, tail unit calculation, landing gear placing, centre of gravity calculation and finally powerplant selection. All aircraft characteristics was designed and selected to meet all necessary requirement for safety. Different variants of centre of gravity were calculated and checked to be in allowable range.

2. The conversion process of the designed passenger aircraft was detailly describe to meet all necessary certifications and parameters. Different layouts possibilities were calculated and presented. The design process of main cargo door was also described. All door parameters were chosen according to requirements for current aircraft. As a result, a CAD 3D model was created.

3. Newly created 3D model of main cargo door was checked by series of simulations, to check its resistance to excess pressure. The results of first simulation have shown that the door structure need to be changed. Moreover, some parts material was reselected for much more durable. After all necessary changes were implemented, the next simulation has shown the significant improvement in results.

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Appendix A

INITIAL DATA AND SELECTED PARAMETERS

Passenger Number	124
Flight Crew Number	2
Flight Attendant or Load Master Number	3
Mass of Operational Items	947,59 kg
Payload Mass	12276 kg

Cruising Speed	835 km/h
Cruising Mach Number	0.7848
Design Altitude	11.50 km
Flight Range with Maximum Payload	1650 km
Runway Length for the Base Aerodrome	2.20 km

Engine Number	2
Thrust-to-weight Ratio in N/kg	3.4
Pressure Ratio	29
Assumed Bypass Ratio	5.5
Optimal Bypass Ratio	5.5
Fuel-to-weight Ratio	0.25

Aspect Ratio	8
Taper Ratio	2.5
Mean Thickness Ratio	0.11
Wing Sweepback at Quarter Chord	25 deg
High-lift Device Coefficient	0.93
Relative Area of Wing Extensions	0.01
Wing Airfoil Type	Supercritical

Winglets	Installed
Spoilers	Installed

Fuselage Diameter	3.01 m
Finess Ratio	12.8
Horizontal Tail Sweep Angle	27 deg
Vertical Tail Sweep Angle	32

CALCULATION RESULTS

Optimal Lift Coefficient in the Design Cruising Flight Point	0.38676
Induce Drag Coefficient	0.00905

ESTIMATION OF THE COEFFICIENT $D_m = M_{critical} - M_{cruise}$

Cruising Mach Number	0.78480
Wave Drag Mach Number	0.79243
Calculated Parameter D_m	0.00763

Wing Loading in kPa (for Gross Wing Area):

At Takeoff	3.899
At Middle of Cruising Flight	3.508
At the Beginning of Cruising Flight	3.751

Drag Coefficient of the Fuselage and Nacelles	0.00682
Drag Coefficient of the Wing and Tail Unit	0.00908

Drag Coefficient of the Airplane:

At the Beginning of Cruising Flight	0.02644
At Middle of Cruising Flight	0.02582

Mean Lift Coefficient for the Ceiling Flight	0.38676

Mean Lift-to-drag Ratio	14.98120

Landing Lift Coefficient	1.532
Landing Lift Coefficient (at Stall Speed)	2.297
Takeoff Lift Coefficient (at Stall Speed)	1.924
Lift-off Lift Coefficient	1.405
Thrust-to-weight Ratio at the Beginning of Cruising Flight	0.64
Start Thrust-to-weight Ratio for Cruising Flight	2.853
Start Thrust-to-weight Ratio for Safe Takeoff	2.73

Design Thrust-to-weight Ratio	2.967

Ratio Dr = $R_{cruise} / R_{takeoff}$	1.045

SPECIFIC FUEL CONSUMPTIONS (in kg/kN∗h):

Takeoff	36.0362
Cruising Flight	57.8587
Mean cruising for Given Range	58.8359

FUEL WEIGHT FRACTIONS:

Fuel Reserve	0.03535
Block Fuel	0.15528

WEIGHT FRACTIONS FOR PRINCIPAL ITEMS:

Wing	0.12193
Horizontal Tail	0.01585
Vertical Tail	0.01558

Landing Gear	0.04314
Power Plant	0.09310
Fuselage	0.12591
Equipment and Flight Control	0.13996
Additional Equipment	0.01212
Operational Items	0.01733
Fuel	0.19063
Payload	0.22451

Airplane Takeoff Weight	54678 kg
Takeoff Thrust Required of the Engine	81.11 kN

Air Conditioning and Anti-icing Equipment Weight Fraction	0.0240
Passenger Equipment Weight Fraction (or Cargo Cabin Equipment)	0.0184
Interior Panels and Thermal/Acoustic Blanketing Weight Fraction	0.0085
Furnishing Equipment Weight Fraction	0.011
Flight Control Weight Fraction	0.0073
Hydraulic System Weight Fraction	0.0192
Electrical Equipment Weight Fraction	0.0333
Radar Weight Fraction	0.0033
Navigation Equipment Weight Fraction	0.0050
Radio Communication Equipment Weight Fraction	0.0025
Instrument Equipment Weight Fraction	0.0058
Fuel System Weight Fraction	0.0055

Additional Equipment:

Equipment for Container Loading	0.0091
No typical Equipment Weight Fraction	0.0031

(Build-in Test Equipment for Fault Diagnosis, Additional Equipment of Passenger Cabin)

TAKEOFF DISTANCE PARAMETERS

Airplane Lift-off Speed	239.81 km/h
Acceleration during Takeoff Run	2.34 m/s^2
Airplane Takeoff Run Distance	943 m
Airborne Takeoff Distance	578 m
Takeoff Distance	1522 m

CONTINUED TAKEOFF DISTANCE PARAMETERS

Decision Speed	227.82 km/h
Mean Acceleration for Continued Takeoff on Wet Runway	0.34 m/s^2
Takeoff Run Distance for Continued Takeoff on Wet Runway	1473.74 m
Continued Takeoff Distance	2052.12 m
Runway Length Required for Rejected Takeoff	2126.22 m

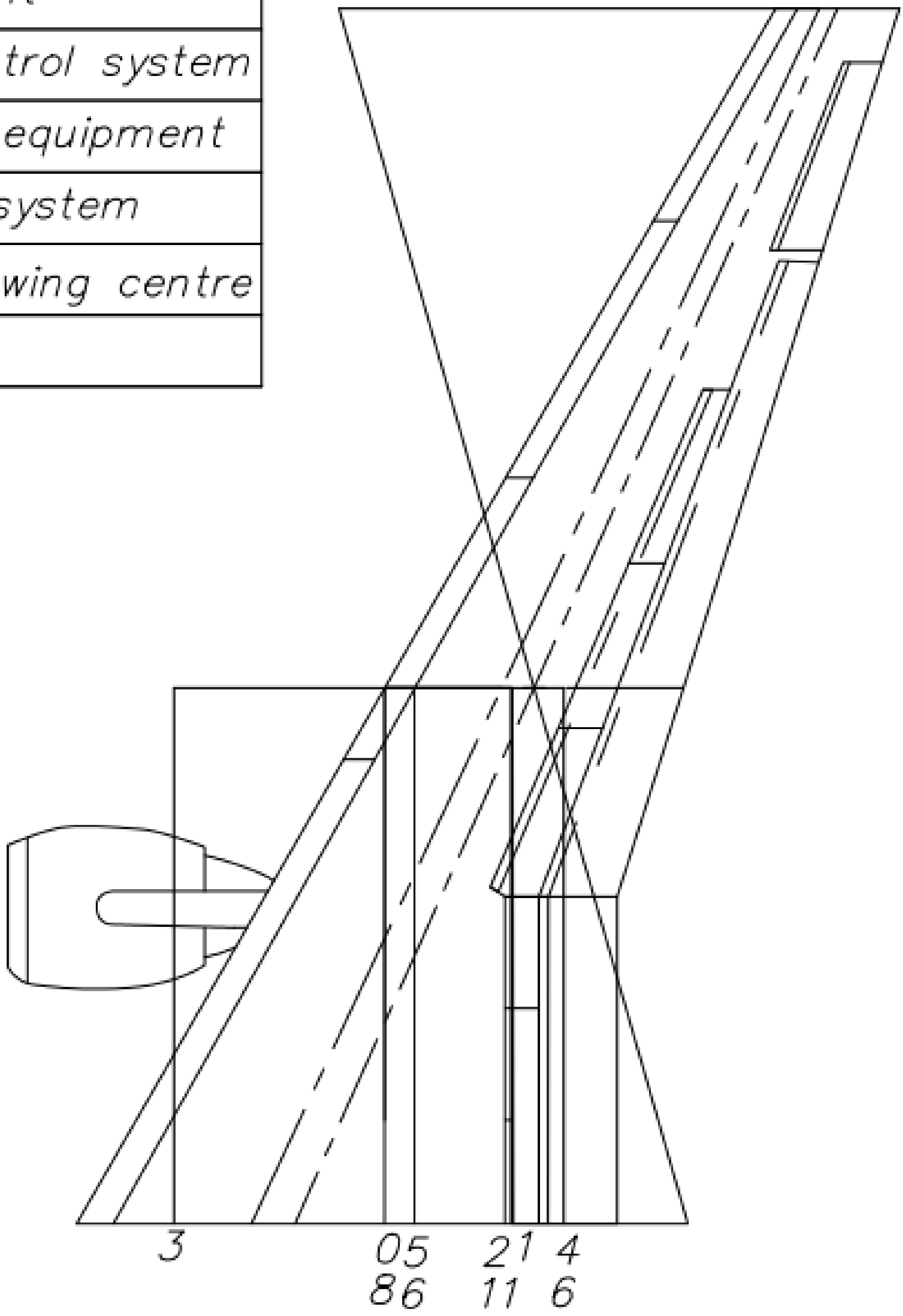
LANDING DISTANCE PARAMETERS

Airplane Maximum Landing Weight	48623 kg
Time for Descent from Flight Level till Aerodrome Traffic Circuit Flight	22.2 min
Descent Distance	51.54 km
Approach Speed	232.88 km/h
Mean Vertical Speed	1.9 m/s
Airborne Landing Distance	510 m
Landing Speed	217.88 km/h
Landing run distance	668 m
Landing Distance	1177 m
Runway Length Required for Regular Aerodrome	1966 m
Runway Length Required for Alternate Aerodrome	1672 m

ECONOMICAL EFFICIENCY

THESE PARAMETERS ARE NOT USED IN THE PROJECT

1	Wing structure
2	Fuel system
3	Power plant
4	Flight control system
5	Electrical equipment
6	Anti-ice system
8	Equipped wing centre
11	Fuel



Ch.	Sheet	Document#	Sign.	Date
Performed		Yarmolenko N.		
Checked		Maslak T.		
Tech. control				
St. controler		Krasnopolskyi V.		
Approved		Yutskevich S.		

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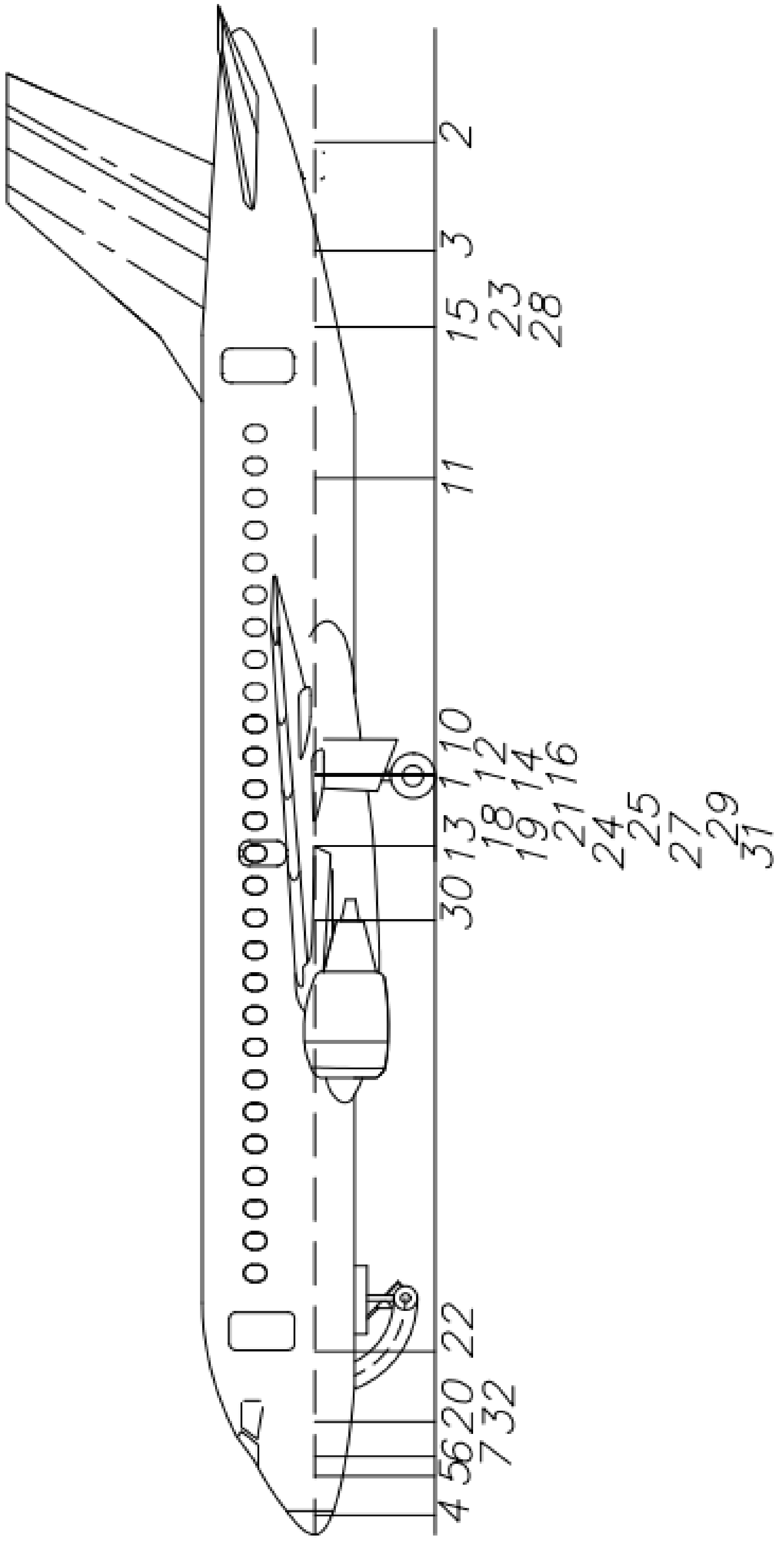
Center of gravity
of the fuselage

Letter	Weight	Scale
		1:100

Sheet 3
Sheets 4

Appendix C

404 AF 134



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Center of gravity
of the fuselage

Letter	Weight	Scale
S		1:175

Sheet	Sheets

Appendix C

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