ESCUELA POLITÉCNICA NACIONAL

FACULTAD DE INGENIERÍA MECÁNICA

DISEÑO PRELIMINAR Y ANÁLISIS TECNO-ECONÓMICO DE UN AVIÓN PERSONAL

TRABAJO DE TITULACIÓN PREVIO A LA OBTENCIÓN DEL TÍTULO DE MAGÍSTER EN DISEÑO, PRODUCCIÓN Y AUTOMATIZACIÓN INDUSTRIAL

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CERTIFICACIÓN

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APROBACIÓN DEL TRIBUNAL

DEDICATORY

This project is dedicated to those who have put their trust in me through my academic, professional and personal life.

Daniel Ponce Montenegro

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CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF APPENDIXES

ABBREVIATIONS

BEM Blade Element Momentum
BET Blade Element Theory
BPR By Pass Ratio
CER Cost Estimating Relationship
DBT Design Built Team
DFM/A Design For Manufacture and Assembly
DFSS Design For Six Sigma
EUAC Equivalent Uniform Annual Cost
GSEIS Ground Support Equipment and Initial Spares
IPPD Integrated Product and Process Development
LCC Life Cycle Cost
MEW Manufacture Empty Weight
MTOW Maximum Takeoff Weight
OEW Operational Empty Weight
PAY Maximum Payload weight
RDTE Research Development Test and Evaluation
SC Special Construction
TERA Techno-Economic Environmental Risk Assessment
TSFC Thrust Specific Fuel consumption
UAS Unmanned Aircraft System
VTOL Vertical Taking Off and landing

SYMBOLS

ROMAN SYMBOLS

Symbol	Name	Units
a	Axial induction factor	
a'	Angular induction factor	
A	Area	m^2
A_{max}	Maximum cross-sectional area	m^2
A_{out}	Outlet area	m^2
A_{DC}	Author development cost	
A_R	Aspect ratio	
A_{Rht}	Horizontal tail aspect ratio	
A_{Vht}	Vertical tail aspect ratio	
A_{PL}	Aircraft power loading	$^{kg}/_{kW}$
$\bar{C}_{\mathrm{t}}$	Mean aerodynamic chord in tails	m
$\bar{C}_{\mathrm{w}}$	Mean aerodynamic chord in wings	m
C	Chord length	m
C_{root}	Root chord length	m
C_{tip}	Tip chord length	m
C_w	Wing mean chord	m
C_D	Drag coefficient	
C_{D0}	Total parasite drag coefficient	
C_{D0f}	Parasite drag coefficient in fuselage	
C_{D0w}	Parasite drag coefficient in wings	
C_{D0t}	Parasite drag coefficient in tails	
C_{D0an}	Parasite drag coefficient in another element	
C_f	Skin friction coefficient	
C_{ff}	Skin friction coefficient in fuselage	
C_{fw}	Skin friction coefficient in wings	
C_{ft}	Skin friction coefficient in tails	
C_L	Lift coefficient	
C_P	Pressure coefficient	
C_S	Suction force coefficient	
D	Drag force	N
D_f	Fuselage structural depth	m
D_{DC}	Director development cost	
d_f	Downwash on fuselage	
e	Oswald's span efficiency factor	
f	Fitness ratio	
F	Force	N
FF_f	Form factor for fuselage	
FF_w	Form factor for wings	
FF_t	Form factor for tails	
h	Height	m
hv_{cr}	Height of cruising speed	m
h_f	Fuel energy per unit mass	$^{J}/_{kg}$
$H_{\lambda h}$	Horizontal tail taper ratio	
H_{th}	Horizontal tail height above fuselage	ft
H_{tv}	Vertical tail height above fuselage	ft

I	Moment of inertia	$^{Kg}/_{m^2}$
K	Drag due to lift factor	
k	Induced power factor	
L	Lift force	N
L_a	Length of aircraft	m
L_f	Overall length	m
L_m	Extended length of main landing gear	in
L_t	Length of tail arm	m
L_I	Angular momentum	$Kg^{m2}/_s$
m	Mass	kg
$\dot{m}$	Mass flow	$^{Kg}/_s$
$\dot{m}_0$	Free stream mass flow	$^{Kg}/_s$
$\dot{m}_c$	Core mass flow	$^{Kg}/_s$
$\dot{m}_e$	Exit mass flow	$^{Kg}/_s$
$\dot{m}_f$	Fan mass flow	$^{Kg}/_s$
$\dot{m}_{fuel}$	Fuel mass flow	$^{Kg}/_s$
$\dot{m}_p$	Propeller mass flow	$^{Kg}/_s$
M_m	Measure of merit	
N	Propeller / rotor angular speed	rpm
N_b	Number of blades	
N_l	Ultimate landing load factor	
N_z	Ultimate load factor	
p	Pressure	Pa
P_c	Power in climb	kW
P_f	Power in forward flight	kW
P_h	Power in hover	kW
P_r	Rotor power	kW
P_{tr}	Tail rotor power	kW
Q	Torque	Nm
q	Dynamic pressure	Pa
Re	Reynolds number	
Re_f	Reynolds number for fuselage	
Re_w	Reynolds number for wings	
Re_t	Reynolds number for tails	
r	Radius	m
r_{p}	Propeller radius	m
r_{r}	Rotor radius	m
Sf_{wet}	Fuselage wetted area	m^2
S_{p}	Propeller area	m^2
S_{r}	Rotor area	m^2
S_{ht}	Horizontal tail area	m^2
S_{vt}	Vertical tail area	m^2
S_{w}	Aircraft wing reference area	m^2
S_{wet}	Wetted surface	m^2
T	Thrust	N
T_{DC}	Total development cost	
t	Time	s
$^{t}/_{c}$	Average tip chord	%
U	Relative speed of the flow respect to the blade	$^{m}/_{s}$
U_p	Relative speed of air in the blade, perpendicular	$^{m}/_{s}$

U_t	Relative speed of air in the blade, tangential	$^m/_s$
v_{CL}	Climb speed	$^m/_s$
v_{CR}	Cruising speed	$^m/_s$
v_0	Axial speed of air in free stream	$^m/_s$
v_e	Speed of air at exit	$^m/_s$
v_f	Axial speed of air through the fan	$^m/_s$
v_p	Axial speed air through the propeller	$^m/_s$
v_{tip}	Blade tip speed	$^m/_s$
v_R	Rotation speed	$^m/_s$
v_S	Stall speed	$^m/_s$
v_{TAS}	True airspeed	$^m/_s$
W_{dg}	Flight design gross weight	kg
W_t	MEW	kg
W_0	MTOW	kg
W_f	Fuselage weight	kg
W_w	Wings weight	kg
W_{ht}	Horizontal tail weight	kg
W_{vt}	Vertical tail weight	kg
W_{mg}	Weight in main landing gear	kg
W_P	Propulsion system weight	kg
W_s	Wing span	m
$(^x/_c)_m$	Chordwise location of the airfoil maximum thickness point	

GREEK SYMBOLS

Symbol	Name	Units
α	Angle of attack	degrees
β	Angle of sideslip	degrees
γ	Climb angle	degrees
Λ	Wing swept	
Λ_m	Wing swept at the maximum thickness line	
λ	Taper ratio	
λ_i	Inflow ratio	
λ_t	Wing taper ratio	
η_m	Mechanical efficiency	
$\eta_{overall}$	Propulsion system efficiency	
θ	Pitch angle	degrees
ϕ	Roll angle	degrees
φ	Inflow angle	degrees
ρ	Air density	$^{Kg}/_{m^3}$
σ	Solidity	
ψ	Yaw angle	degrees
ω	Wake rotation	$^{rad}/_s$
Ω	Angular velocity	rpm

ABSTRACT

Recent developments in materials and automatic controls have allowed manufacturers to build smaller and lighter aircraft. Hence, they have developed even personal or unmanned models. These aerial vehicles show two main constraints. The first one is that they need runways to take off and landing. The second one is their high cost, which depends on the demand for the product in addition to operating costs. Three aircraft have been analyzed in this project. The first one is the Cessna 172; this aircraft was investigated to allow the comparison of equations accounting the propulsion system and airframe to ensure their suitability on the design conducted in this investigation. The other two aircraft are named as DPM-A concept and DPM-B concept. These aircraft have been designed for Quito and the Andean region based on parametric sizing, and aerodynamic and propulsion performance equations. Both concepts (DPM-A and DPM-B) shown that most of the materials required to build the airframe of these aircraft can be found in Ecuador. A TERA (Techno-Economic Environmental Risk Assessment) approach has been applied on this project. This approach focuses on an energy analysis which compares the performance of each concept with an automobile. From this assessment, it was demonstrated that an aircraft is more efficient than an automobile, due to a shorter time travel spent. Furthermore, a brief explanation about the labor analysis for manufacturing aircraft in Ecuador and a comparison between similar aircraft at DPM-A and DPM-B concepts that already exist is made.

Keywords: *Aircraft, Personal, Quito, VTOL*.

RESUMEN

El reciente desarrollo en materiales y control automático ha permitido que las personas puedan construir aviones pequeños y ligeros, incluso se han desarrollado modelos personales o no tripulados. Estos vehículos aéreos tienen dos restricciones principales, la primera es que necesitan pistas de despegue-aterrizaje y la segunda es el alto costo, el mismo que dependerá de la demanda de dichos aviones y de los costos operativos. En este proyecto han sido desarrollados tres aviones, el primero es un Cessna 172, este avión fue consultado para permitir comparar ecuaciones del sistema de propulsión y armazón para asegurar su funcionalidad en el diseño de este proyecto. Los otros dos aviones son denominados como modelo DPM-A y modelo DPM-B. Estos aviones han sido diseñados para Quito y la región andina basados en el dimensionamiento paramétrico y ecuaciones de desempeño aerodinámicas y de propulsión. Ambos modelos DPM-A y DPM-B mostraron que la mayoría de materiales, requeridos para construir el armazón de estos aviones, pueden ser encontrados en Ecuador. Una propuesta TERA (análisis tecno-económico del riesgo ambiental por sus siglas en inglés) ha sido aplicado en el proyecto. Esta propuesta se enfoca en el análisis energético, la cual compara el desempeño de cada modelo con un automóvil. De este análisis, se demostró que un avión es más eficiente que un automóvil, debido al corto tiempo de viaje empleado. Además, una breve explicación acerca del análisis en mano de obra para fabricar aviones en Ecuador y una comparación entre aviones similares a los modelos DPM-A y DPM-B que actualmente existen está realizada.

Palabras clave: *Avión, Personal, Quito, VTOL*.

PRELIMINARY DESIGN AND TECHNO-ECONOMIC ASSESSMENT OF A PERSONAL AIRCRAFT

INTRODUCTION

Ecuador is improving fields of technology and research but is still behind other countries around the world, mainly the G8 group. Some of the new fields of research are: aeronautics, genetics, and nuclear engineering, among others. Even though these disciplines have been spread in educational institutions in other countries for decades, they are still not taught in any Ecuadorian University.

All these years Ecuador has focused in fields like agriculture and commerce due to the fact that Ecuador has a perfect weather for agriculture, previous governments never tried to develop technology. In the seventies, technology in Ecuador increased quickly with the beginning of petroleum extraction. This led governments to focus the economy in the sales of raw materials. The rapid growth of global economies, mainly based on technology and gadgets, is pushing Ecuador to develop technology if it wants to make progress at the same rate than other countries.

This project proposes to contribute to the aeronautical sector through the assessment of a personal aircraft, capable to cover short travel distances and which requires to be manufactured with materials that should be easy to find in Ecuadorian markets. The feasibility of the aircraft is analyzed using the TERA method, which is a model approach to develop the design space of this project and identifies ways to minimize the overall design.

Aim

The aim of this project is to carry out a preliminary design of a personal aircraft and assess its techno-economic feasibility.

General objectives

- Develop the preliminary design of a personal aircraft and develop its motion equations.
- Define the design space for these concepts on propulsion system and airframe using parametric and bi-dimensional tools.
- Define materials for the manufacture of personal aircraft provided by national markets.
- Analyze the economic feasibility of this project using a TERA approach based on parametric tools.

Scope

- Two personals aircraft concepts are developed, based on parametric sizing and performance equations specified by their dimensions.
- A mission performance analysis for the two concepts are carried out for take-off, climb, flight, descend and landing for the personal aircraft in the airspace of Quito.
- The conceptual analysis of propulsion system is defined using parametric and empirical equations. Furthermore, parametric sizing is used for the airframe design.
- A prototype of personal aircraft is defined specifying the materials used in its manufacture, which can be easily found in local markets.
- The techno-economic feasibility is carried out using the TERA approach.
- Energy consumption and environmental impacts are assessed comparing the effect of using different materials.

Motivation

The accelerated technological development that the world is facing nowadays has centralized the economic growth of countries in the most developed cities, causing internal and external migrations towards these cities, therefore increasing their population. Thus, the demand for vehicles has also growth in these cities. Ecuador is not an exception to this trend, and its main cities are experiencing a rapid growth in traffic. In the city of Quito almost 45% of householders have at least one automobile [10].

Even though travel distances are less than 15 km on average, the journeys from the houses of citizens to their jobs or study centers last more than one hour. The majority of citizens who drive their automobiles are not sharing them with other passengers, which produces an excessive number of vehicles on the streets besides the amount of emissions that pollutes the environment. Therefore, it is necessary to find new transportation alternatives for people who want to travel short distances in less time.

This project is a new way of diminishing part of the traffic in cities such as Quito, developing a design of a prototype for a personal aircraft that allows people to move between places that are separated less than 100 km in short time and with more safety. In addition, this prototype could have other applications, such as explorations of devastated places (after natural disasters), visualization of crowded areas (demonstrations, marches, protests and so on) and urgent medical assistance among others. As a design constraint, the aircraft must be light and capable of transporting people. A main aim of this project is to propose that the aircraft have lower costs compared to similar aircraft.

This project expects to find a new fast and safe way of transportation around the city of Quito including its valleys, as well as reducing the fuel consumption produced in comparison to automobiles due to reduction in travel time.

An outcome of this project suggests that this model is a milestone for the Andean Region since similar studies have limited their scope to sea level flights. Finally, this project can benefit from the political framework of the current administration, which focuses on the transformation of the productive matrix. This can be used to promote the aviation industry as well.

1. LITERATURE RESEARCH

This section is a review of the principal aspects that are involved in the preliminary design of the aircraft. It shows equations and elements that are outstanding for design of propellers, rotors, principal aerodynamics forces, dimensions and principal weights. This section shows firstly an overview of the principal systems that commonly are considered for an aircraft design as can be seen on figure 1.1. Only the outstanding systems at this project are considered such as propulsion, aerodynamics, weights and manufacturing. The other three systems that are noise, flight control and structures are beyond the project scope.

Additionally, at the end of this section there is data of aircraft and helicopters which have been used as baseline concepts. These aircraft and helicopters have been selected for their similar characteristics to the concept which is developed.

1.1. Aircraft design

For some experts in aeronautics like Raymer [68] aircraft design is a separate discipline of aeronautical engineering, different from the analytical disciplines such as aerodynamics, structures, controls and propulsion. An aircraft designer needs to be well versed in these disciplines. Instead, the time of the designer is spent doing something called "design", creating the geometric description of a thing to be built.

Designing the actual layout requires more than a replication of a standard model. Design depends on the many calculations that determine what should be considered and how the design should be modified to better meet the requirements. In a small company, this may be done by the same person who does the layout design. In the larger companies, aircraft analysis is done by the sizing and performance specialist with the assistance of experts in aerodynamics, weights, propulsion, stability and other technical specialties [68].

According to Kroo [61] it is necessary to consider seven key systems at the moment to design an aircraft. Figure 1.1 shows these aspects for a better understanding. For this project propulsion, aerodynamics, weights and manufacturing are considered; other three systems (noise, flight control and structures) have not been assessed in detail for this work.

Below a briefly explanation of noise, flight control and structures is shown.

Noise is produced by pressure pulses generated from any vibrating source in the air. The pulsating energy is transmitted through the air and can be heard in audible frequency ranges of 20 to 20000 Hz [46]. The intensity and frequency of pulsation determine the physical limitations of human tolerance. In certain conditions, acoustic vibrations can reach natural frequency and affect an aircraft structure. Nowadays, many countries around the world consider noise as environmental pollution.

Flight controls consist in two groups: control system and avionics. A control system is a collection of mechanical and electronic equipment that allows an aircraft to fly alone with exceptional precision and reliability. A control system consists of cockpit controls, sensors, actuators (hydraulic, mechanical or electrical) and computers. Avionics is the communication inside and outside from aircraft.

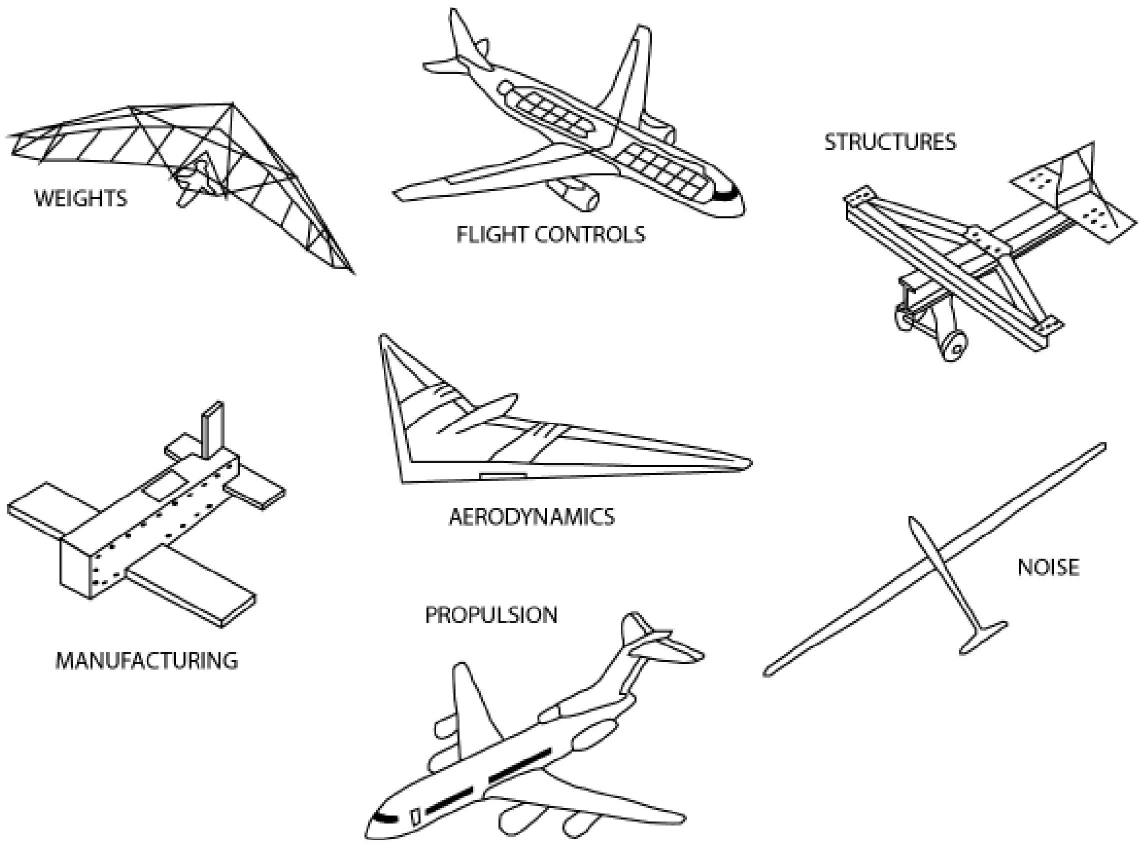

Figure 1.1 Principal aspects for design an aircraft. [61]

Structural design has critical importance to aircraft safety, but also plays a key role in aircraft cost and performance. The airplane cost is related to the structural design in complex ways, but typically aircraft end up costing \$200-\$500 per pound (with sailplanes and military aircraft such as the B-2, this last one reportedly costs more per ounce than gold) [61]. In addition to its direct impact on aircraft cost, the aircraft structural weight affects performance. Every pound of airplane structure means one less pound of fuel when the take-off weight is specified.

1.2. Propulsion systems

A propulsion system works when a fluid (air) enters the system at a speed (v_{in}) with a mass flow $\dot{m}$ (figure 1.2). The mass flow exits at a speed (v_{out}) and the fuel mass is added to the outflow at a rate $\dot{m}_{fuel}$. The force generated by the propulsion system includes a changeable rate of momentum through the system outlet area ($\mathrm{A_{out}}$) and a pressure difference ($p_{out} - p_{in}$). The equation 1.1 shows thrust and works for systems ranging from rockets to ramjets, turbojets, and propeller driven aircraft [61].

$$T = \dot{m}(v_{out} - v_{in}) + \dot{m}_{fuel} v_{out} + A_{out}(p_{out} - p_{in}) \tag{1. 1}$$

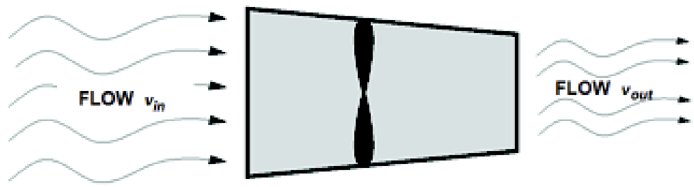

Figure 1.2 General propulsion system illustration.

- **ROCKETS**

The rocket thrust is the simplest propulsion engine type. It is produced by the application of Newton's third law of motion (for every action there is an equal and opposite reaction).

In general, a rocket engine is designed to work outside the atmosphere to avoid the use of atmospheric air as the propulsive fluid stream. Instead, it produces its own propelling fluid by the combustion of liquid or gas fuel with oxygen, which it carries inside, thus it is only suitable for operations over short periods.

- **RAMJETS**

The main characteristic of ramjets is that they do not have moving parts. Its operation is based on high speed air entering the inlet. The air is compressed as it is slowing down, it is mixed with fuel and burned out in the combustion chamber, finally it is expanded and ejected through the nozzle.

The key of this operation is that its feasibility is compromised when the Mach number exceeds 3. Thus, ramjets have been used in a few missile applications.

- **TURBOJETS**

They are like Ramjets but with an additional compression of the intake air. At the beginning, a simple compressor turbojet could increase the total pressure by 4 times. However, latest axial compressors can produce overall pressure ratios by more than 13 times, depending on the number of stages of the compression.

The relation between fuel and air is almost 50 times in weight for a typical jet engine. For example, 100 kg of air should be combined with 2 kg of fuel.

- **TURBOFAN**

They are the most modern variation of turbojets. They have a core engine that is surrounded by a fan in the front and an additional turbine at the rear of the engine. This can be seen in figure 1.3.

They have more than two shafts. If they are showing two shafts, they are called two spool engines and so on. One shaft is connected to the fan and the other one is connected to the core compressor (turbojet), the fan shaft passes through the core shaft.

When the incoming air is captured by a turbofan engine some air (almost 80%) passes around the core compressor and generates directly thrust when it is expelled by the rear engine. The rest of the intake air (20%) passes through the fan and keeps going into the core compressor and then goes into the burner, where it is mixed with fuel and the combustion occurs. The exhaust heat passes through the core and turbines and then goes out the nozzle, as a turbojet. Equation 1.2 gives the turbofan thrust.

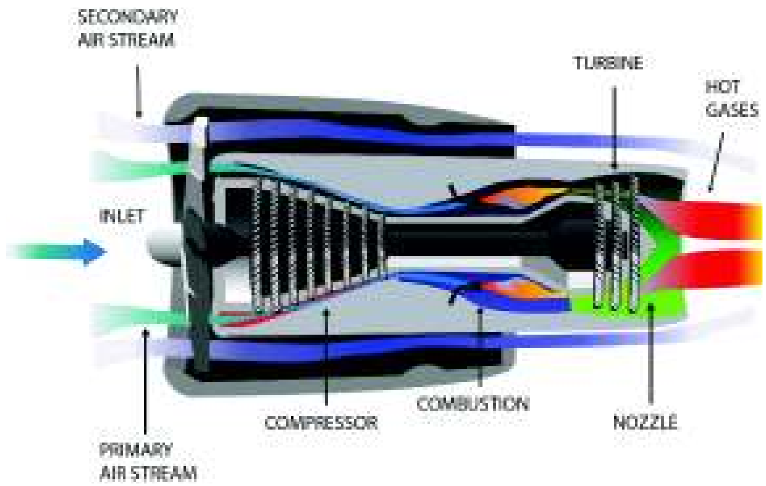

Figure 1. 3 Turbofan engine.

$$Turbofan\ thrust = F = \dot{m}_e v_e - \dot{m}_o v_o + BPR\dot{m}_c v_f \quad (1.2)$$

There is an expression called bypass ratio (BPR) that is a ratio between fan or propeller airflow ($\dot{m}_f$) and core airflow ($\dot{m}_c$), as equation 1.3 gives.

$$BPR = \frac{\dot{m}_f}{\dot{m}_c} \quad (1.3)$$

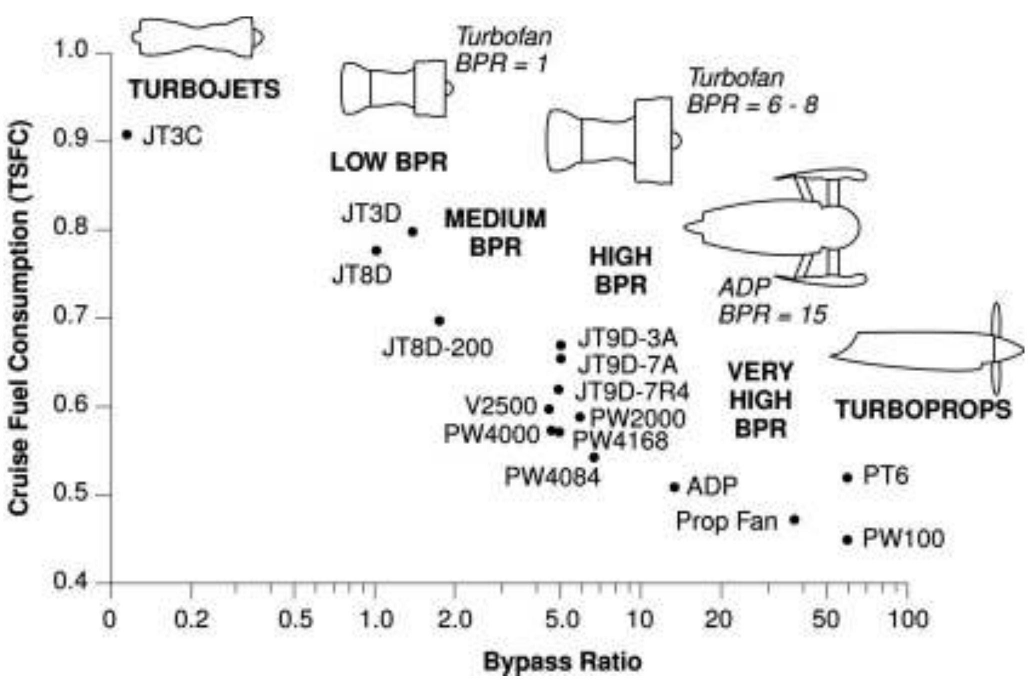

Figure 1.4 BPR vs. TSFC. [12]

A turbojet is a turbofan with a BPR of zero. The BPR needs to be higher or lower depending of the aircraft design, a BPR between 1 to 2 is generally termed low bypass ratio and if a BPR is between 5 to 8, generally termed high bypass ratio. If a BPR is very high this does not mean that the engine efficiency is the best one. If an aircraft flies at high speed a BPR between 2 to 8 is more appropriate but if an aircraft flies at low speed, a BPR over 10 is the best choice. Figure 1.4 displays the relationship between BPR and fuel consumption, as observed, a larger BPR generates smaller cruise fuel consumption.

- **TURBOPROP**

Turboprops have the same operation of turbofans but instead a fan they have a propeller. This increases the BPR from 10 to 20. A sketch of turboprop can be seen in figure 1.5. Equation 1.4 shows the thrust that a turboprop has.

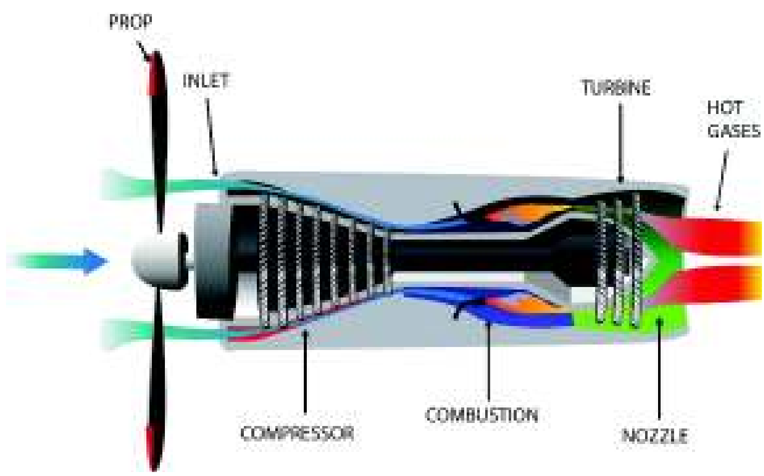

Figure 1.5 Turboprop engine.

$$Turboprop\ thrust = F = \dot{m}_o(v_p - v_0) + \dot{m}_e v_e - \dot{m}_c v_p \qquad (1.\ 4)$$

1.2.1. Momentum theory for rotors

Since aircraft should have vertical take-off and landing (VTOL), it is necessary at least one rotor and one propeller. The rotor is used for VTOL and the propeller for moving forward.

Firstly, equations for VTOL are presented, then are presented equations for a propulsion system focused in charge of moving forward the aircraft. All propulsion equations for moving forward are developed for cruising condition.

Momentum theory for rotors is adequate as a first step to find the thrust power for lifting a helicopter, this method works for hover and climb condition. The equation 1.5 shows a relationship between thrust (T), airspeed across the rotor (v_r) and rotor disk area (S_r). The principal equations are shown in this step. Further details can be found in reference [68].

$$T = 2\rho {v_r}^2 S_r \qquad (1.\ 5)$$

According to Raymer [68] losses of helicopters comprise roughly 6% due to nonuniform inflow, up to 30% for airfoil profile drag, about 3% for tip losses and less than 1% for slipstream effects. Together, the net thrust is typically 83% or less than the ideal thrust. An empirical "measure of merit" M_m that is defined as the ratio between the ideal power and the actual power required is used to adjust the theory momentum estimation, typically M_m is between 0.6 to 0.8.

Supposedly, thrust disk loading (T/S_r) equals the weight disk loading (mg/S_r), but it is necessary to add roughly 3% for downwash blowing force into the fuselage. These developed equations are considering the hover position. Equation 1.6 shows that thrust can be considered as weight with a small difference of 3%.

$$\frac{T}{S_r} = 1.03\ \frac{mg}{S_r} \tag{1. 6}$$

To analyze vertical climb in this aircraft, the momentum theory can be extended. Climb momentum theory is based on assuming that inlet speed ($\mathrm{v_{in}}$) equals to climb speed ($\mathrm{v_{CL}}$). Raymer [68] suggest that the additional power to climb is only half the time derivative of the increase in potential energy. The additional power required to climb is roughly half of helicopter's weight times the climb speed. This is added to the hover power requirements to determine total power to climb.

Combining those statements, equations and starting from the principle of $P = T * v_r$. Power required for vertical climb (P_c) according Raymer [68] is given by equation 1.7 which considers downwash on fuselage (d_f) that commonly has a value of 1.03 as equation 1.6 gives.

$$P_c = \left[\left(\frac{d_f mg}{M_m}\sqrt{\frac{d_f mg}{2\rho S_r}}\right) + \frac{mgv_{CL}}{2}\right] * \left[\frac{1+\frac{P_{tr}}{P_r}}{\eta_m}\right] \tag{1. 7}$$

Commonly in helicopters mechanical efficiency η_m is around 0,97 and ratio of rotor power and tail rotor power (P_{tr}/P_r) is around 0.14–0.22.

Leishman [62] uses equation 1.8 to find the rotor power in forward flight for helicopters, where there is a relationship between climb speed ($\mathrm{v_{CL}}$) and angle of attack (∝).

$$P_f = T(v_{CL}\, sin \propto + v_r) \tag{1. 8}$$

The first term on the right-hand side of the equation 1.8 is the power required to propel the rotor forward and to climb, the second term is the induced power.

1.2.2. Blade equations for propellers

This part describes two methods to calculate thrust and power in propellers. There are other sophisticated treatments available in the open domain but these methods have the advantage of being simple and easy to appreciate [68].

- **BLADE ELEMENT MOMENTUM**

This design method uses the blade element momentum (BEM) theory [64] to complete the design, lift and drag curves for the chosen airfoil.

Four stations are shown in figure 1.6 considering the stream tube around a propeller.

1. Propeller upstream
2. Just before the blades
3. Just after the blades
4. Propeller downstream

Energy is transferred between 2 and 3 and there is also a change of pressure. Assume p_1 = p_4 and that v_2 = v_3, then the axial force generated by the propeller is as equation 1.9 gives.

$$dF_x = (p_2 - p_3)dS_p \tag{1. 9}$$

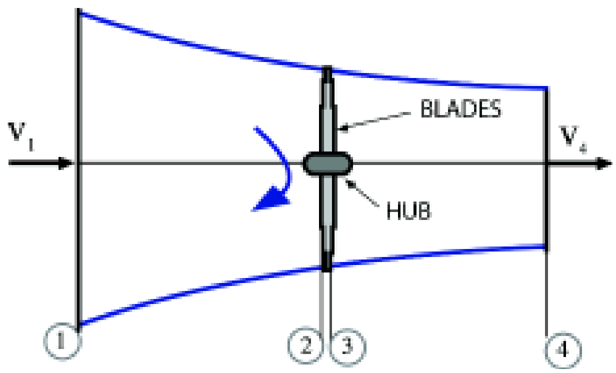

Figure 1.6 Axial Stream tube around of a propeller.

It is assumed that between 1 and 2 and between 3 and 4 the flow is frictionless so Bernoulli's equation can be applied and equation 1.9 is modified to equation 1.10.

$$dF_x = \frac{\rho(v_1^2 - v_4^2)}{2} dS_p \tag{1. 10}$$

Define a as the axial induction factor for reducing expressions, equation 1.11 gives.

$$a = \frac{v_1 - v_2}{v_1} \tag{1. 11}$$

Substituting equation 1.11 in equation 1.10 yields the axial force. Equation 1.12 shows this and now the name axial force is changed by thrust.

$$dT = \frac{\rho v_1^2[4a(1-a)]2\pi r dr}{2} dS_p \tag{1. 12}$$

Now that thrust equation (1.12) was found it is necessary to find the torque and the power equations, for this is necessary to considerate the wake into the propeller. Therefore, the rotation of propeller imparts a rotation onto the blade wake between 2 and 3.

To find the torque generated by a propeller is necessary to consider the wake that is present in a rotation. In equation 1.13, the torque (Q) that a propeller has is defined. While equation 1.14 shows the mass flow.

Equations 1.13 and 1.14 have been developed with the same four stations that figure 1.6 shown.

Consider the conservation of angular momentum in this annular stream tube. An "end-on" view is shown in figure 1.7 and axial view is shown in figure 1.8. The blade wake rotates with an angular velocity ω and the blades rotate with an angular velocity of Ω. Recall from basic physics that:

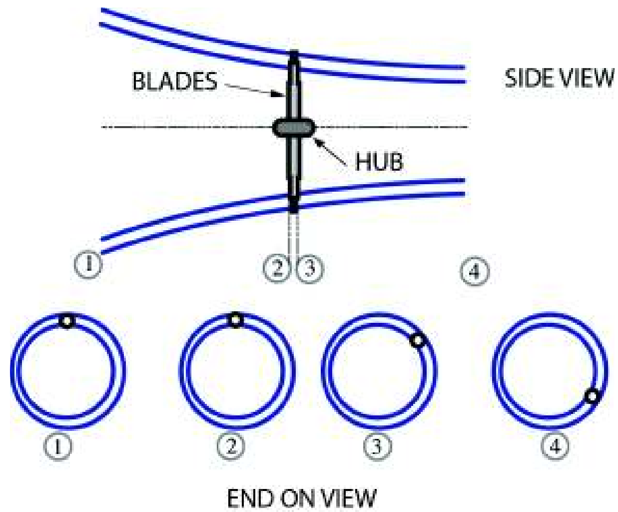

Figure 1.7 Rotating annular stream tube, side view.

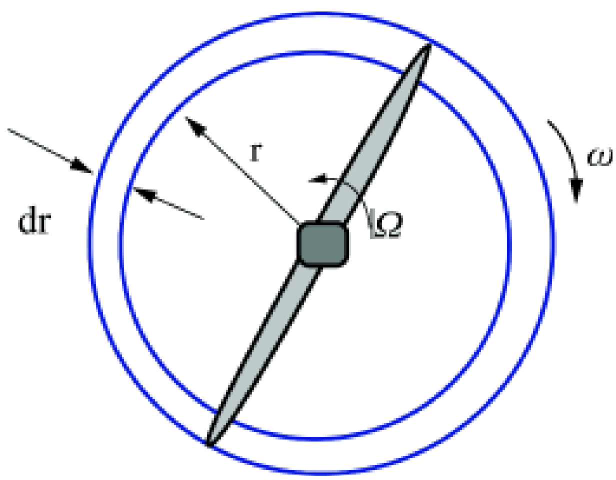

Figure 1.8 Rotating annular stream tube, axial view.

$$Q = \frac{dmr^2\omega}{dt} = d\dot{m}\omega r^2 \qquad (1.\ 13)$$

$$\dot{m} = \rho A v_2 = \rho 2\pi r dr v_2 \qquad (1.\ 14)$$

Define angular induction factor a' for reducing expressions, equation 1.15 gives.

$$a' = \frac{\omega}{2\Omega} \qquad (1.\ 15)$$

Then for a small element (dr) the corresponding torque is:

$$dQ = 4a'(1-a)\rho v_1 \Omega r^3 \pi dr \qquad (1.\ 16)$$

- **BLADE ELEMENT THEORY**

The blade element theory has two assumptions [60]:

1. There are not aerodynamic interactions between different blade elements
2. Forces on blade elements are simply determined by lift and drag coefficients

The air flow does not rotate at the inlet of the blade but at the outlet it does at rotational speed ω due to the motion generated by the blades. Therefore, the average speed over the blade due to wake rotation is $\omega/2$ which is an average between $\omega = 1$ at the tip and $\omega = 0$ at the hub. The blade rotates with speed Ω. Thus, the average tangential velocity that the blade experiences is given by equation 1.17.

$$dv_{tip} = \left(\Omega r + \frac{\omega r}{2}\right) dr \tag{1. 17}$$

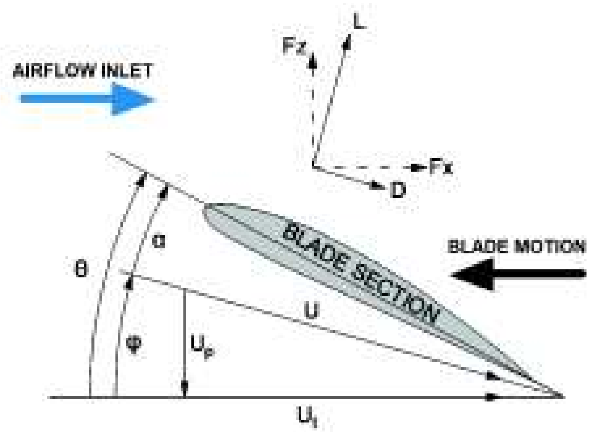

Figure 1. 9 Flow onto the propeller blade.

Equations 1.18 – 1.21 are used to derived tangential and axial forces in equations 1.22 and 1.23. A representation of the system can be seen in figure 1.9.

$$tan\, \varphi = \frac{U_p}{U_t} = \frac{v_p}{v_{tip}} = \frac{v_p(1-a)}{\Omega r(1+a\prime)} \tag{1. 18}$$

The tip speed ratio λ_t is defined as:

$$\lambda_t = \frac{v_p + v_{in}}{v_{tip}} \tag{1. 19}$$

$$tan\, \varphi = \frac{\lambda_t(1-a)}{(1+a\prime)} \tag{1. 20}$$

$$U = \frac{v_{tip}}{cos\, \varphi} \tag{1. 21}$$

Therefore, forces are:

$$F_Z = L\, cos\, \varphi - D\, sin\, \varphi \tag{1. 22}$$

$$F_X = L\, sin\, \varphi + D\, cos\, \varphi \tag{1. 23}$$

Equations 1.24 – 1.29 show the main equations that according to Raymer [68] are necessary to find the required power in a rotor blade.

Lift and drag forces are defined as:

$$L = \frac{C_L \rho U^2 c}{2} \tag{1. 24}$$

$$D = \frac{C_D \rho U^2 c}{2} \tag{1. 25}$$

The local solidity σ is defined as:

$$\sigma = \frac{N_b c}{2\pi r_r} \tag{1. 26}$$

Then the thrust, torque and power of the rotor blade yields:

$$dT = \sigma\pi\rho \frac{{U_p}^2(1+a)^2}{sin^2\,\varphi}(C_L\,cos\,\varphi - C_D\,sin\,\varphi)rdr \tag{1. 27}$$

$$dQ = \sigma\pi\rho \frac{{U_p}^2(1+a)^2}{sin^2\,\varphi}(C_L\,sin\,\varphi + C_D\,cos\,\varphi)r^2dr \tag{1. 28}$$

$$dP = dQ\Omega dr \tag{1. 29}$$

Another equation to calculate power with the blade element theory is equation 1.30, Leishman [62] obtained this equation that summarizes that theory.

$$P = kTv_p + \rho {v_{tip}}^3 S_p \frac{\sigma C_{D0}}{8} \tag{1. 30}$$

This equation for propellers and rotors can be applied, the induced power factor k depends of many factors like shape, size, position (horizontal or vertical) and so on. This factor is suggested by Leishman [62] as 1.15 for an initial designing.

1.3. Airframe

This section shows equations that are involved in an aircraft, principally drag coefficients. Two subsections have been suggested for this part, the first one is a study for an airfoil that can be a wing profile or a propeller blade; and the second one is a group of equations for the principal elements of an aircraft like fuselage, wings and tails.

1.3.1. Airfoil

An airfoil is a streamlined body, which is designed to produce lift or thrust when it passes through the air as it can be seen on figure 1.10. Samples of airfoils are airplane wings, propeller blades, helicopter rotor and tail rotor blades.

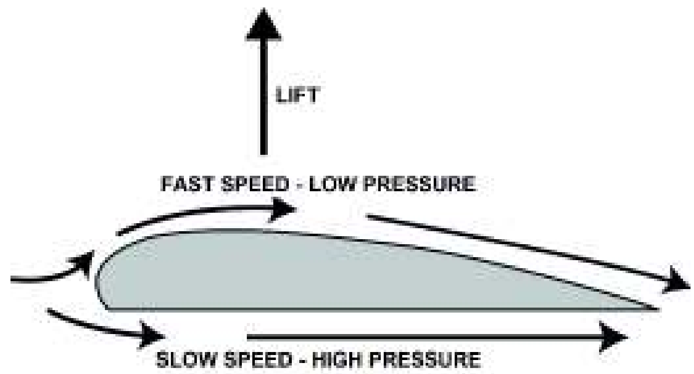

Figure 1.10 Airfoil lift.

According to Kutta-Joukowski theorem [56], there is a lifting force proportional to air density, free stream velocity and a circulation generated by the bound vortex for an airfoil with round leading and sharp trailing edge immersed in a uniform stream with an effective angle of attack. This theorem is one of the aerodynamics fundamentals. The application of this theorem gives the equation 1.31 for lifting force where (ρ) is the air density, (α) is the angle of attack, (c) is the chord line and (U) is the relative speed of the flow respect to the blade. Figure 1.11 shows the principal parts that an airfoil has, this is for understand better equations from subsection 1.3.2.

$$L = \rho \pi \alpha c U^2 \tag{1. 31}$$

Figure 1.11 Airfoil parts. [6]

Equations 1.32 – 1.34 are the same 1.24 and 1.25 equations but in this case writing from the lift and drag coefficients instead from lift and drag forces, additionally there is the pressure coefficient (C_P).

$$C_L = \frac{2L}{\rho c U^2} = 2\pi\alpha \tag{1. 32}$$

$$C_D = \frac{2D}{\rho c U^2} \tag{1. 33}$$

$$C_P = \frac{2\Delta p}{\rho U^2} \tag{1. 34}$$

It does not matter the size and operation of an airfoil. If two airfoils are geometrically similar and have the same angle of attack, they have identical coefficients C_L, C_D and C_P ; even if one of them works in a wind tunnel with high air density and the other one works in a conventional airplane wing with low air density. This effect allows designers (and engineers) to build and test small scale models, and extrapolate qualitative features, but also quantitative information, from a small-scale model to a full-size configuration [56].

1.3.2. Aerodynamic equations

This part shows useful equations, symbols and aerodynamic nomenclature. The purpose is to present an easy way to design the desired model of the personal aircraft.

The following equations describes the general drag equation for principal components of an aircraft [68]. The important coefficient for this project is the total drag coefficient that is equation 1.35, which is divided in equations 1.41, 1.46 and 1.51 for each principal aircraft element. Besides principal elements that aircraft has like fuselage, wings or tails for other drag coefficients the expression ($\mathrm{C_{DOan}}$) is used.

$$C_D = C_{D0} + KC_L{}^2 \tag{1. 35}$$

The equation 1.36 shows the total parasite drag in an aircraft.

$$C_{DO} = C_{DOf} + C_{DOw} + C_{DOt} + C_{DOan} \tag{1. 36}$$

$$e = 1.78\left(1 - 0.045A_R{}^{0,68}\right) \tag{1. 37}$$

$$K = \frac{1}{\pi A_R e} \tag{1. 38}$$

Applying the dynamic pressure $q = \frac{\rho v_{CR}{}^2}{2}$ in equations 1.24 and 1.25 it can be obtained following equations for aircraft

$$L = qS_w C_L \tag{1. 39}$$

$$D = qS_w C_D \tag{1. 40}$$

The following equations describes the parasite drag in fuselage (assuming fully turbulent flow).

$$C_{DOf} = C_{ff} * FF_f * {}^{S_{wet}}/_{S_w} \tag{1. 41}$$

$$Re_f = \frac{\rho v_{CR} l_a}{\mu} \tag{1. 42}$$

$$C_{ff} = \frac{0.455}{\left(log_{10} Re_f\right)^{2.58}(1+0.144M^2)^{0.65}} \tag{1. 43}$$

$$f = \frac{l_a}{\sqrt{\left({}^4/_\pi\right)A_{max}}} \tag{1. 44}$$

$$FF_f = 1 + \frac{60}{f^3} + \frac{f}{400} \tag{1. 45}$$

The following equations describes the parasite drag in wings

$$C_{DOw} = C_{fw} * FF_w * {}^{S_{wet}}/_{S_w} \tag{1. 46}$$

$$\overline{C_w} = \frac{2}{3} C_{root} \frac{1+\lambda_w+{\lambda_w}^2}{1+\lambda_w} \tag{1. 47}$$

$$Re_w = \frac{\rho v_{CR} \overline{C_w}}{\mu} \tag{1. 48}$$

$$C_{fw} = \frac{0.455}{(log_{10} Re_w)^{2,58}(1+0.144M^2)^{0.65}} \tag{1. 49}$$

$$FF = \left[1 + \frac{0.6}{(^x/_c)_m}\frac{t}{c} + 100\left(\frac{t}{c}\right)^4\right][1.34M^{0.18}(cos\,\Lambda_m)^{0.28}] \tag{1. 50}$$

The following equations describes the parasite drag in tails.

$$C_{DOt} = C_{ft} * FF_t * {}^{S_{wet}}/_{S_w} \tag{1. 51}$$

$$\lambda_t = \frac{\lambda_{ht}+\lambda_{vt}}{2} \tag{1. 52}$$

$$C_{root} = \frac{C_{rooth}+C_{rootv}}{2} \tag{1. 53}$$

$$\overline{C_t} = \frac{2}{3} C_{root} \frac{1+\lambda_t+{\lambda_t}^2}{1+\lambda_t} \tag{1. 54}$$

$$Re_t = \frac{\rho v_{CR} \overline{C_t}}{\mu} \tag{1. 55}$$

$$C_{ft} = \frac{0.455}{(log_{10} Re_t)^{2.58}(1+0{,}144M^2)^{0.65}} \tag{1. 56}$$

$$^t/_c = \frac{^t/_{c_H}+^t/_{c_V}}{2} \tag{1. 57}$$

$$FF_t = \left[1 + \frac{0.6}{(^x/_c)_m}\frac{t}{c} + 100\left(\frac{t}{c}\right)^4\right][1{,}34M^{0.18}(cos\,\Lambda_m)^{0.28}] \tag{1. 58}$$

1.4. Performance analysis

All aircraft need to have a performance analysis to identify which are the advantages or disadvantages between the proposed design and traditional models. Breguet range equations allow to identify the range using three principal components that are fluids, propulsion and structure/materials. This section shows the Breguet range equations [70].

This model has many approximations and assumptions. It is important for the understanding to consider some statements. First, to understand the limitations of the applicability of the model, and second, the estimations derived from it.

Figure 1.12 shows an aircraft in steady and level flight at cruising speed.

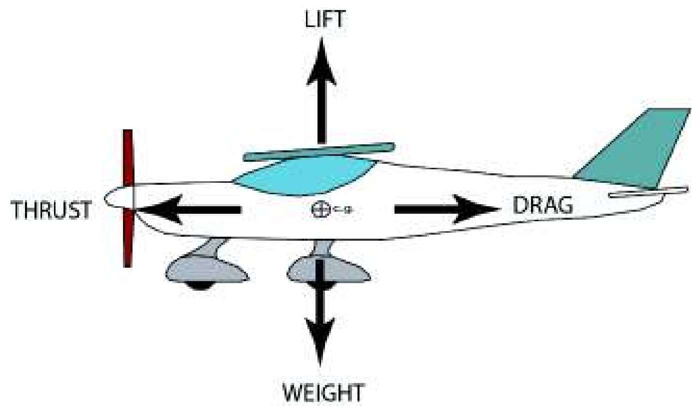

Figure 1.12 Aircraft aerodynamic forces at cruising phase.

The weight of the aircraft changes in response to the fuel that is burned (the weight change rate is equals to the negative fuel mass flow rate times gravitational constant). This expression gives the equation 1.59.

$$\frac{dW}{dt} = -\dot{m}_{fuel} * g \quad (1.\ 59)$$

Equations 1.60 – 1.62 describes how to obtain an overall propulsion system efficiency.

$$overall\ efficiency = \frac{what\ it\ get}{what\ it\ pay\ for} = \frac{propulsive\ power}{fuel\ power} \quad (1.\ 60)$$

$$propulsive\ power = thrust * flight\ velocity = T * v_{CR} \quad (1.\ 61)$$

$$fuel\ power = fuel\ mass\ flow\ rate * fuel\ energy\ per\ unit\ mass = \dot{m}_{fuel} * h_f \quad (1.\ 62)$$

Thus, expressions 1.60, 1.61 and 1.62 summarizes in equation 1.63.

$$\eta_{overall} = \frac{T*v_{CR}}{\dot{m}_{fuel}*h_f} \quad (1.\ 63)$$

The expression for the change in weight of the aircraft in terms of important aerodynamic (L/D) and propulsion system efficiency ($\eta_{overall}$) parameters based on the previous equations are defined in equation 1.65.

$$\frac{dW}{dt} = -\dot{m}_{fuel}g = \frac{-W}{W/\dot{m}_{fuel}g} = \frac{-W}{\left(\frac{L}{D}\right)\frac{T}{\dot{m}_{fuel}g}} \quad (1.\ 64)$$

$$\frac{dW}{dt} = \frac{-W*v_{CR}}{\frac{h_f}{g}\left(\frac{L}{D}\right)*\eta_{overall}} \quad (1.\ 65)$$

Rewriting and integrating gives the equation 1.67.

$$\int\frac{dW}{W} = \int\frac{-v_{CR}*dt}{\frac{h_f}{g}\left(\frac{L}{D}\right)*\eta_{overall}} \quad (1.\ 66)$$

$$ln\,W = constant - \frac{v_{CR}*dt}{\frac{h_f}{g}\left(\frac{L}{D}\right)*\eta_{overall}} \quad (1.\ 67)$$

Applying the initial conditions, at $t = 0$, $W = W_{initial}$, $ln\,W_{initial} = constant$. It gives equation 1.68.

$$t = \frac{-L}{D}\eta_{overall}\frac{h_f}{gv_{CR}}ln\left(\frac{W}{W_{initial}}\right) \tag{1. 68}$$

The time the aircraft has flown corresponds to the amount of fuel burned, therefore

$$t_{final} = \frac{-L}{D}\eta_{overall}\frac{h_f}{gv_{CR}}ln\left(\frac{W_{final}}{W_{initial}}\right) \tag{1. 69}$$

Then multiplying by the flight velocity, it arrives at the Breguet Range Equation (1.70) which is applied for situations where overall efficiency ($\mathrm{L/D}$) and flight velocity are constant over the flight.

$$Range = \left[\frac{h_f}{g} * \frac{L}{D}\right]^{Fluids} \quad [\eta_{overall}]^{Propulsion} \quad \left[ln\left(\frac{W_{final}}{W_{initial}}\right)\right]^{Structure\ and\ materials} \tag{1. 70}$$

Note that this expression is sometimes rewritten in terms of an alternate measure of efficiency. The specific fuel consumption (SFC) is defined as the mass flow rate of fuel per unit of thrust ($lbm/s/lbf$ or $kg/s/N$). In the following expression, there are the flight speed (v) and the acceleration of gravity (g).

$$Range = \frac{v(^{L}/_{D})}{g*SFC}ln\left(\frac{W_{initial}}{W_{final}}\right) \tag{1. 71}$$

1.5. Weights

The sizing and performance equations described throughout this project use parameters in aerodynamics, propulsion and weigh. All are important for the calculations, and all have a huge effect on the take-off gross weight, performance, cost, and viability of a design.

Many equations need weight data but when the design starts there is not information for aircraft weight [57]. Therefore, one needs to estimate some weights with a literature basis or information from the manufacturers in order to use the equations and calculate the weigh. After getting the weigh, the results should be compared with estimated data and recalculate these values. This becomes an iterative task.

Using equations from Raymer [68], one can calculate aircraft elements weight. These equations are displayed in imperial units (pounds). Nevertheless, they need to be changed to kilograms for the ease of calculations of this project. These equations are 1.72 – 1.77.

Weight in fuselage.

$$W_f = 0{,}052{S_f}^{1.086}\left(N_zW_{dg}\right)^{0.177}{L_t}^{-0.051}\left(^{L}/_{D}\right)^{-0.072}q^{0.241} \tag{1. 72}$$

Weight in wings.

$$W_{wing} = 0{,}036{S_w}^{0.758}\left(\frac{A_R}{cos^2\,\Lambda}\right)^{0.6}q^{0.006}\lambda^{0.04}\left(\frac{100t/c}{cos\,\Lambda}\right)^{-0.3}\left(N_zW_{dg}\right)^{0.49} \tag{1. 73}$$

Weight in tails.

$$W_{ht} = 0.016\left(N_zW_{dg}\right)^{0.414}q^{0.168}{S_{ht}}^{0.896}\left(\frac{100t/c}{cos\,\Lambda_{ht}}\right)^{-0.12}\left(\frac{A_{Rht}}{cos^2\,\Lambda_{ht}}\right)^{0.043}{\lambda_{ht}}^{-0.02} \tag{1. 74}$$

$$W_{vt} = 0.073\left(N_z W_{dg}\right)^{0.376} q^{0.122} S_{vt}{}^{0.873} \left(\frac{100t/c}{\cos\Lambda_{vt}}\right)^{-0.49} \left(\frac{A_{Rvt}}{\cos^2\Lambda_{vt}}\right)^{0.357} \lambda_{vt}{}^{0.039} \quad (1.\ 75)$$

Weight in landing gear.

$$W_{mg} = 0.095(N_l W_l)^{0.768} \left(L_m/_{12}\right)^{0.409} \quad (1.\ 76)$$

Weight in propulsion system.

$$W_P = 2.575 W_{en}{}^{0.922} N_{en} \quad (1.\ 77)$$

1.6. Cost analysis

In this section, some cost estimation methods, that commonly are applied for aircraft designing and manufacturing are explained. Additionally, the principal cost factors for manufacturing a civil and fighter aircraft are shown.

Finally, principal materials that are involved in aircraft manufacturing are shown.

1.6.1. Cost estimation methods

The basic cost estimation method for each item of an aircraft is made up of so called "Cost Estimating Relationships" (CERs) [23]. CERs are mathematical expressions relating cost as the dependent variable to one or more independent cost drivers. These relations can be simple averages or percentages, or more complex equations which result from regression analyses and which connect the cost (the dependent variable) to the physical characteristics of the product (such as the mass, the output power, the percentage of a given material and so on). Additionally, four cost estimation methods can usually be extrapolated:

1. Analogy: comparing a system to a similar system with known cost and technical data
2. Parametric: use of a database on similar elements to the item to be evaluated, to generate a cost estimate based upon parameters representative of the performance characteristics of the item
3. Engineering: bottom up estimate from lowest subcomponents of a project (work breakdown structure)
4. Extrapolation: using information from the same system early in the project to estimate costs later in the project.

1.6.2. Aircraft and operational cost

Figure 1.13 shows a typical high-subsonic civil aircraft cost at the 2000-year price level in millions of dollars, reflecting the basic (i.e., lowest) aircraft cost. This graph is generated from a few accurate industrial data that are kept commercial confidentially.

In general, exact aircraft cost data are not readily available and the overall accuracy of the graph is not substantiated. The aircraft price varies for each sale depending on the terms, conditions, and support involved. The values in the figure 1.13 are crude but offer a sense for newly initiated readers of the expected cost of the aircraft class.

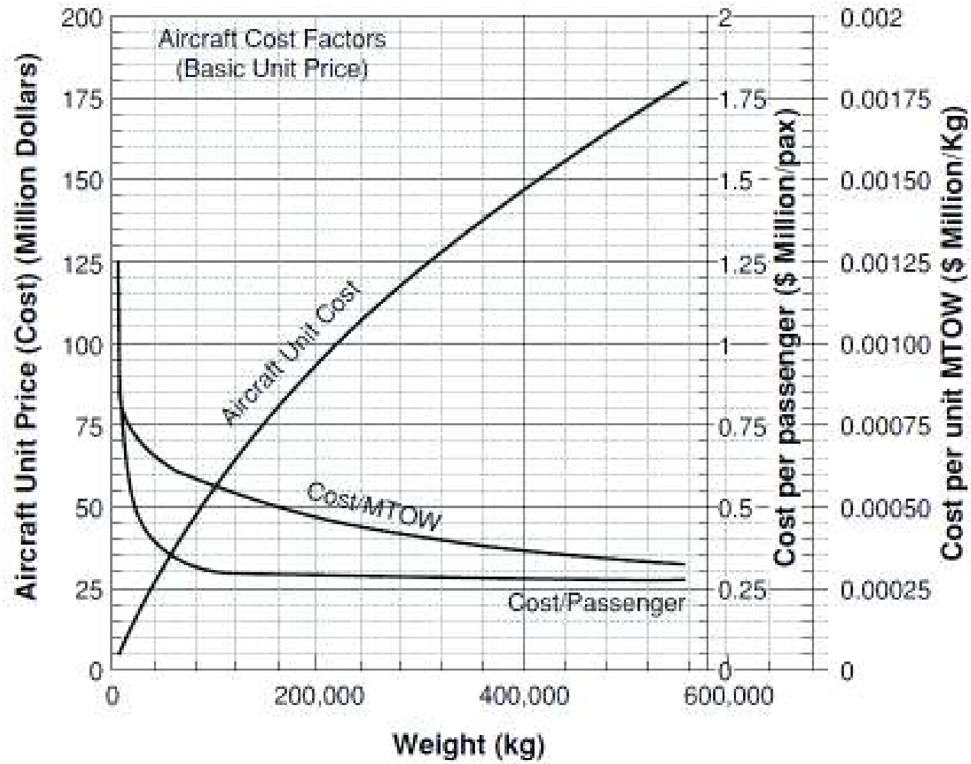

Figure 1.13 Aircraft cost factors. [46]

The basic price of a midrange, 150-passenger class, high-subsonic turbofan aircraft is $47 million (2000-year price level).

The aircraft maximum takeoff weight (MTOW) reflects the range capability, which varies among types.

Therefore, strictly speaking, cost factors should be based on the maximum empty weight (MEW).

Typical cost fractions (related to aircraft cost) of various groups of civil aircraft components are listed in table 1.1, providing preliminary information for two-engine aircraft (four-engine aircraft are slightly higher). It is best to obtain actual data from the industry whenever possible.

The AMPR weight represents the weight of an empty aircraft shell structure without any bought-out vendor items (e.g., engines, undercarriages, or avionics packages).

Table 1.1 Typical cost fractions of midsize civil aircraft (two engines) at the shop floor level. [46]

Element	**Cost fraction**

AIRCRAFT EMPTY-SHELL STRUCTURES	
Wing-shell structure	10 to 12%
Fuselage-shell structure	6 to 8%
Empennage-shell structure	1 to 2%
Two-nacelle shell structure	2 to 3%
Miscellaneous structures	0 to 1%
Subtotal	20 to 25%
BOUGHT-OUT VENDOR ITEMS	
Two turbofan dry, bare engines [39]	18 to 22%
Avionics and electrical system	8 to 10%
Mechanical systems	6 to 10%
Miscellaneous	4 to 6%
Subtotal	40 to 50%
FINAL ASSEMBLY TO FINISH (LABOR-INTENSIVE)	25 to 30%

Combat aircraft cost fractions are different: The empty shell structure is smaller but it houses sophisticated avionics black boxes for the complex task of combat and survivability. Typical cost fractions of various groups of combat aircraft components are listed in table 1.2, in which the avionics cost fraction is separate. This table provides preliminary information for two-engine aircraft; it is best to obtain actual data from the industry whenever possible.

In the United States, military aircraft costing uses AMPR weight, also known as Defense Contractor's Planning Report (DCPR) weight, for the manufacturer to bid.

Table 1.2 Typical cost fractions of combat aircraft (two engines) at the shop-floor level. [46]

Element	Cost fraction
AIRCRAFT EMPTY-SHELL STRUCTURES	
Wing-shell structure	6 to 7%

Fuselage-shell structure	4 to 6%
Empennage-shell structure	1%
Two-nacelle shell structure	part of the fuselage
Miscellaneous structures	0 to 1%
Subtotal	12 to 15%
BOUGHT-OUT VENDOR ITEMS	
Two turbofan dry, bare engines	25 to 30%
Mechanical systems	5 to 8%
Miscellaneous	1 to 2%
Subtotal	30 to 40%
AVIONICS AND ELECTRICAL SYSTEM	30 to 35%
FINAL ASSEMBLY TO FINISH (LABOR-INTENSIVE)	12 to 15%

Tables 1.3 and 1.4 show the retail price of aircraft and helicopters; these are some of the same vehicles which are shown in table 1.7 and table 1.8. These values can give an idea about how much is the cost of proposed aircraft in this project. Due to manufacturing costs of aircraft it is very hard to find, in this step it works with retail price; means that this applies the analogy cost estimation method.

As it can be seen a retail price for concepts defined in this project need to be between $40000 and $90000.

Table 1.3 Retail price of light aircraft.

Aircraft type	MTOW [kg]	MEW [kg]	Cost per unit [USD]
SD-1 Minisport [40]	240	116	54850
Kitfox S7 Super Sport [24]	600	341	60000
Evolution Revo [37]	473	250	68500
Sam LS [39]	600	377	131800

Table 1.4 Retail price of small helicopters.

Helicopter type	MTOW [kg]	MEW [kg]	Cost per unit [USD]
Eagle Helicycle [18]	386	227	38500
Mosquito Aviation XE [30]	277	136	47500
Heli-Sport CH-7 [22]	450	280	48000
Auto Gyro Calidus [9]	560	270	88060

1.6.3. Materials for building aircraft in Ecuador

This subsection intends to show the available elements in the Ecuadorian market for building an aircraft, this step is focused on components that are built and manufactured in Ecuador.

Elements like engines, rotors and propellers are not built yet in Ecuador then may need to be imported.

The most common materials to build aircraft are: wood, aluminum alloys and composite materials. This step shows a brief description of everyone.

a) WOOD

In the beginning of aviation wood has been used in aircraft construction. First aircraft often were made of ash or hickory. They were looking for a type of wood that would be relatively lightweight in addition to being very strong.

Prior World War I, Sitka Spruce was discovered by aircraft builders and found to be very well suited to their needs. The strength to weight ratio was discovered to be very favorable for aircraft use.

Several other types of wood had similar strength to weight ratios but were not as easily harvested or as plentiful. At the time, spruce proved to be the best choice, not only because of the physical characteristics, but of equal importance was the fact that spruce was readily available and easy to use as a building material. With the advantages noted, spruce became very widely accepted as the primary material to be used in building an airplane [5]. Table 1.5 shows the principal woods that have been most used in aircraft manufacturing.

Table 1.5 Chart of woods for aircraft use. [5]

Type of wood	Strength	Min rings/inch	Max grain slope

Sitka spruce	100%	6	1:15
Douglas fir	exceeds spruce	8	1:15
White pine	85-96%	6	1:15
Western hemlock	slightly exceeds spruce	6	1:15

b) ALUMINUM ALLOYS

Aluminum seems to be king in aircraft construction, though in recent years new alloys have been applied. These super alloys are still quite expensive for the aircraft homebuilder. With its good strength to weight and cost ratio, aluminum is still used very widely in the aircraft industry [2].

c) COMPOSITE MATERIALS

Manufacturing companies favor composite materials in the production of aircraft due to their high tensile strength, high compression resistance, low weight and high resistance to corrosion. Composite materials are composed by a base material and a resin that strengthens the material as a whole. Composite materials improve fuel efficiency and performance of the aircraft as well as lessen direct operating costs of aircraft. The most common composite materials used are fiberglass and carbon fiber. The disadvantages of using composite materials, however, include high cost and immediate reparations that are needed in case of damage. It is also important to avoid re when using composite materials because the resin used weakens and causes release of toxic fumes [3].

1.7. Relevant aircraft for this project

In this section, the technical features of Cessna 172 are shown, because this model has been widely researched in the aircraft market, this information is very useful to validate the suggested equations.

In table 1.6 the weight of principal components of Cessna 172 is shown for use this information and compare it with calculated weight that is on section 2.

Besides, there is information of small and personal aircraft which there are actually in the international market, this information can be compared with the results obtained at the end of this project.

Table 1.6 Weight data for Cessna 172. [65]

Element	Weight [kg]
Wing group	107
Tail group	28

Fuselage	115
Landing gear	55
Surface controls	14
Nacelle group	14
Propulsion group	194
Services/Equipment group	70
Fuel	114
Other	138
TOTAL	849

Therefore, information about similar aircraft, that market has in nowadays, is shown, these aircrafts give technical information that is very useful to compare with concepts defined through this project.

Table 1.7 Principal data for small aircraft.

Aircraft type	Engine	Gross weight [kg]	Empty weight [kg]	Cruise speed [$^{m}/_{s}$]	Wing area [m^2]	Length [m]
Van's RV-12 [43]	Rotax 912 ULS	600	336	52-60	11.8	6.07
Ran's S-19 [36]	Rotax 912 ULS	600	373	60-67	11.8	6.06
Evolution Revo [37]	Rotax 912 UL	473	250	29-45	13.5	2.7
Sam LS [39]	Rotax 912 ULS	600	377	51-56	12.8	6.5
Kitfox S7 Super Sport [24]	Rotax 912 ULS	600	341	54-56	12.3	6
SD-1 Minisport [40]	Hirth F33	240	116	44	6	4.35
Team Mini Max 1600R Sport [27]	Rotax 447	255	137	32-36	10.5	4.88

Table 1.8 Principal data for small helicopters.

Helicopter type	Engine	Gross weight [kg]	Lift power [Kw]	Power loading [$^{kg}/_{kw}$]	Main rotor diameter [m]
Heli-Sport CH-7 [22]	Rotax 914UL	450	85	5.3	6.2
LCA LH 212 Delta [26]	Rotax 914	450	85	5.3	6.7
Mosquito XE Aviation [30]	Zanzottera MZ 201	277	48	5.8	5.9
Eagle Helicycle [18]	Solar T62 Titan	386	70	5.5	6.1
Dynali H2S [17]	Subaru EJ engine	700	130	5.4	7.2
DF334 [15]	Rotax 914	500	85	5.9	6.8
Edm Aerotec CoAX 2D/2R [19]	Rotax 912 S	450	74	6.1	6.5
R22 BETA II [35]	Lycoming O-360	622	98	6.4	7.7
Auto Gyro Calidus [9]	Rotax 914	560	85	6.6	8.4

2. PRELIMINARY DESIGN

In this section is the designing process following the flow diagram that is on figure 2.1. This section is the core of project due to contains the calculus for principal aspects like propulsion, airframe, performance, weights and so on.

Firstly, the mission profile is defined and then starts with the initial sizing. This section contains three aircrafts that are: a Cessna 172 used for equations validation and two concepts named DPM-A and DPM-B. The aim of this project is to do a top-level system analysis for one aircraft able to reach the objectives suggested at the beginning: flying around the airspace of Quito with a maximum range which covers the city dimensions, take-off and landing must be with VTOL for move from and to any place in the city including the valleys and finally that could be made from materials that could be find easily in Ecuador.

The aim is to do a preliminary design for one aircraft but like this is a novel design is very difficult to find a similar aircraft to validate the equations, therefore it is done another design for a second aircraft which is similar at the Cessna 172, this is for validate all equations.

Once that those equations are validated need to be applied to design the first aircraft that is named DPM-A concept (is similar at Cessna 172), then it is designed the second aircraft that is named DPM-B concept (this aircraft has VTOL).

The equation 1.30 is applied for the design of DPM-B concept, because it can be validated for this new type of aircraft.

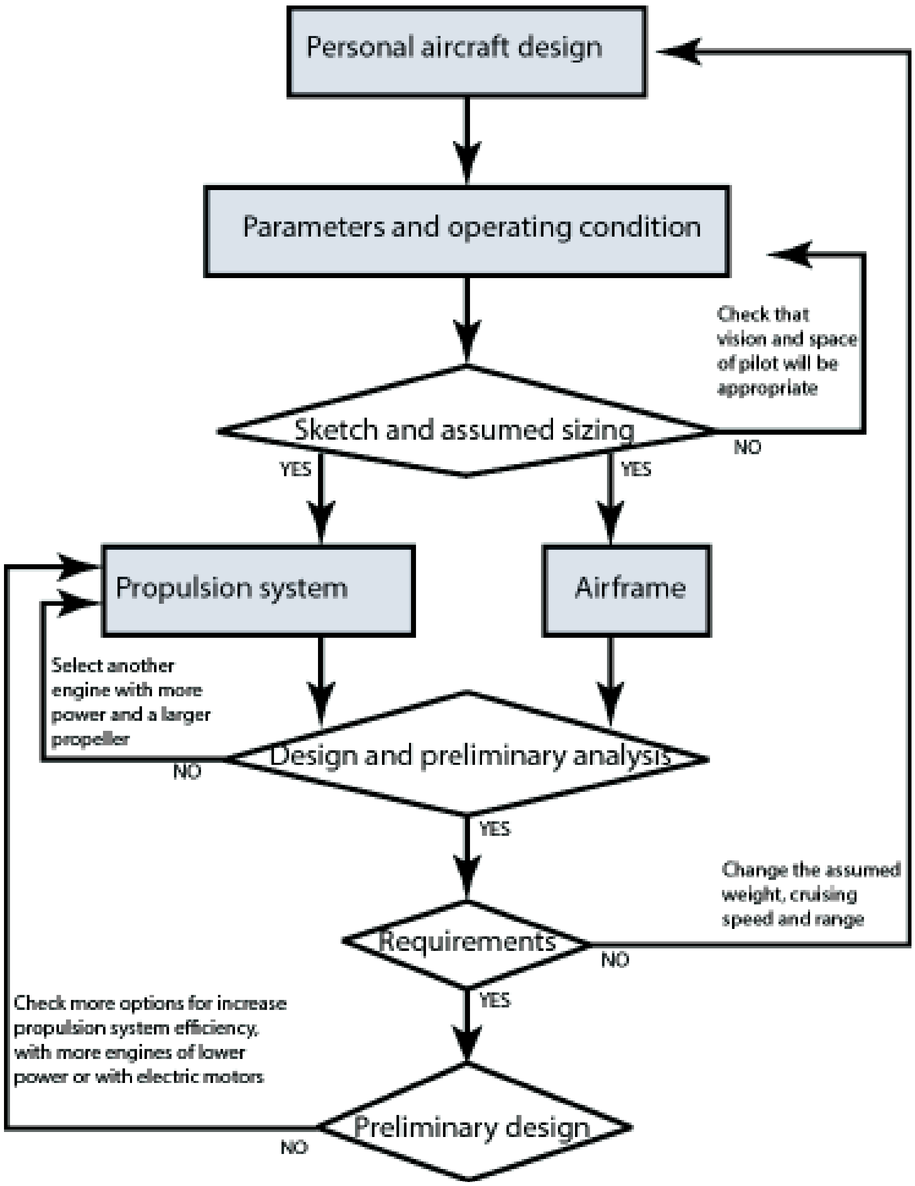

Figure 2.1 Design flow diagram for personal aircraft.

2.1. Mission profile and aircraft selection

During the beginning of the research study it is necessary to draw a sketch of the desired personal aircraft to be designed. For obtain a better selection of design three aircraft that are a Cessna 172 and two concepts are used.

The Cessna 172 uses equations from section 1 to compare obtained results with real data from appendix A, then if all obtained results are like real data the same equations for both DPM-A and DPM-B concepts are used.

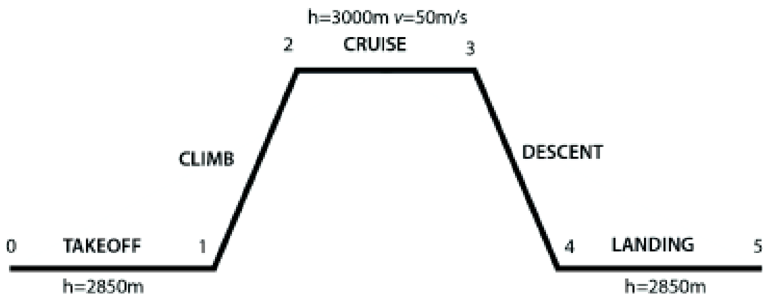

Figure 2.2 Mission of personal aircraft.

Both concepts move with mission seen in figure 2.2. The difference between them is that the first concept needs a long runway for takeoff and the second concept only requires a short runway.

The aim is to fly at speed of 50 $^{m}/_{s}$. This value is common for cruising speed in little aircraft like the models shown in table 1.7. This value is selected like the cruising speed referenced for this project.

2.2. Initial sizing

This subsection shows design features for each aircraft, specially about the two concepts developed in this investigation. In addition, the equations and calculations of propulsion system and airframe are shown.

d) CESSNA 172

This project has selected the Cessna 172 as a study case due to is historically one of the most successful mass-produced airplanes for general aviation in the world. It was first own in the year 1955 and ever since then it has continued to reach new heights and dominate the aviation industry for over half a century.

The Cessna 172 has been ruling the aviation industry since it was first manufactured and has been widely used for general rental, flight instruction and family transport. Newer models of the 172 are in popular demand since they are affordable, simple to handle and are the perfect aircraft for a small family today [13].

By all these things there is much information about Cessna 172 like it can be seen in appendix A. This information is very useful to compare the calculated values of both concepts (DPM-A and DPM-B) with a real case.

e) DPM-A CONCEPT

DPM-A concept is exactly like a Cessna 172, the sketch of this DPM-A concept is shown on figure 2.3. Due to many aspects and coefficients of Cessna are known, this allows to compare all results.

According to the figure 2.5 for slow speeds a turbo-prop propulsion system would be the best choice for this design due to high propulsive efficiency. This figure has been improved from the original, adding color and converting imperial in metric units.

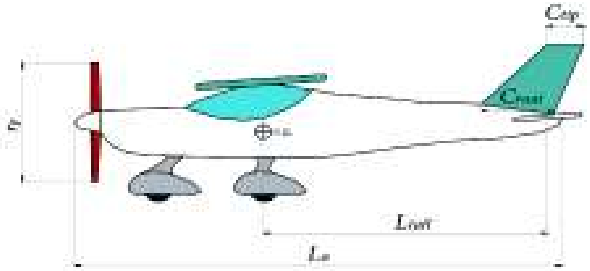

Figure 2.3 Sketch of DPM-A concept.

The principal components of DPM-A concept are: one propeller, two principal wings, two rear wings, one tail and three wheels.

Weight information from Cessna 172 is available in table 1.6 from which one can approximate for this case to know how much could weights each component of this concept taken the same basis of Cessna 172.

Most common small aircraft, with one propeller and two passengers, have an empty weight MEW between 250–380 kg, as could be seen on table 1.7. The aircraft MEW target of this project needs to be less than stated in the table 1.6. It is expected that the MEW of DPM-A is a fifth of the MEW in relation to Cessna 172. Two minis aircraft at the end of table 1.7 show that this target is reachable, these aircraft have one propeller and one passenger, which have an empty weight of 116 kg and 137 kg. This shows that nowadays there are mini aircraft with weight similar at a common motorcycle like Vespa 150 [44] for example.

f) DPM-B CONCEPT

DPM-B concept is a novel design with the expectation that does not require a runway (or at least that have a short runway), this means that need to reach the VTOL. The sketch of this model is shown in figure 2.4.

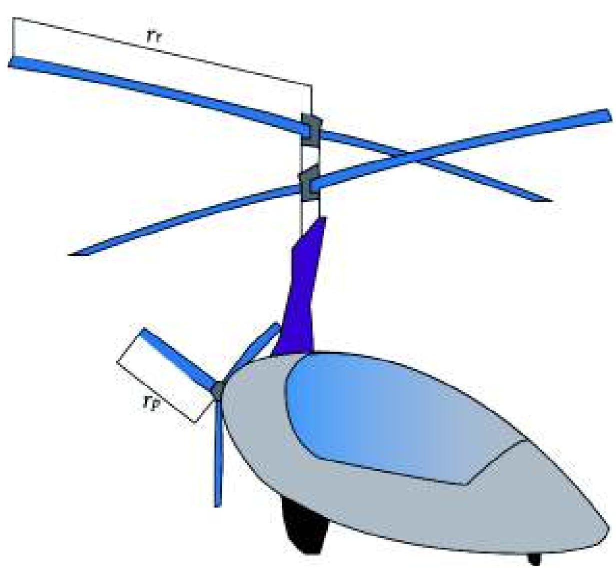

Figure 2.4 Sketch of DPM-B concept.

The principal components of DPM-B concept are: two rotors, one propeller and four wheels.

Like this concept it is expected to have VTOL, therefore it would be necessary to have a rotor like a helicopter. This is the best way to reach VTOL with high efficiency in gross weight per power in comparison to other VTOL aircraft like it could be seen in figure 2.6. This figure has been improved from the original, adding color and converting imperial in metric units.

To move forward DPM-B concept would be better if it had a propulsion system like an airplane because rotors produce more fuel consumption than a propeller.

This DPM-B concept has 2 coaxial rotors to avoid undesirable turning. The fuselage for this design should have a shape that help both movements due to downwash. Vertical movement in take-off and landing; and horizontal in forward flight. The right way for design the fuselage and get principal drag coefficients is making a sale model and subject to some tests principally into a wind tunnel, after that it can be designed more models and do the same process up to find the best one. Due to this task is out of goals form this project, find the optimal shape of DPM-B concept with drag coefficients could be the beginning of a new project by the complexity that carry out. In this project is not considered a fuselage design for this case.

To calculate take-off and landing it is used the same helicopter VTOL equations (from equation 1.5 to equation 1.8), but to calculate cruise it is used the turboprop aircraft formulas, like equation 1.30.

To define the initial sizing of DPM-B concept, it is assumed the same values of weight and size estimated in the DPM-A concept. Size meaning length and height without coaxial rotors.

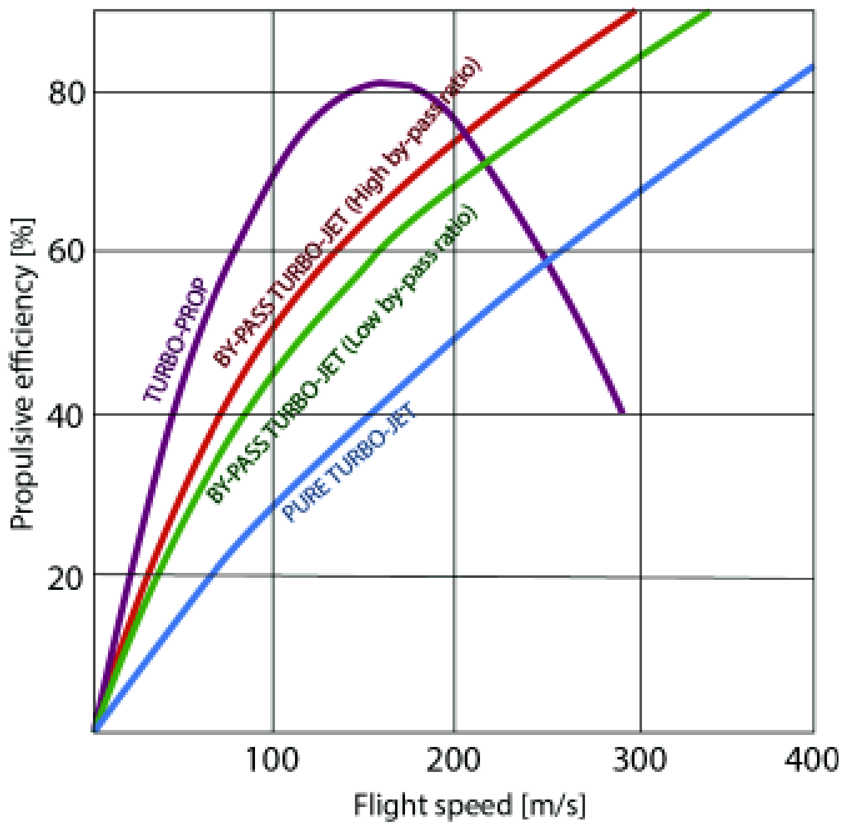

Figure 2.5 Comparative propulsive efficiencies. [69]

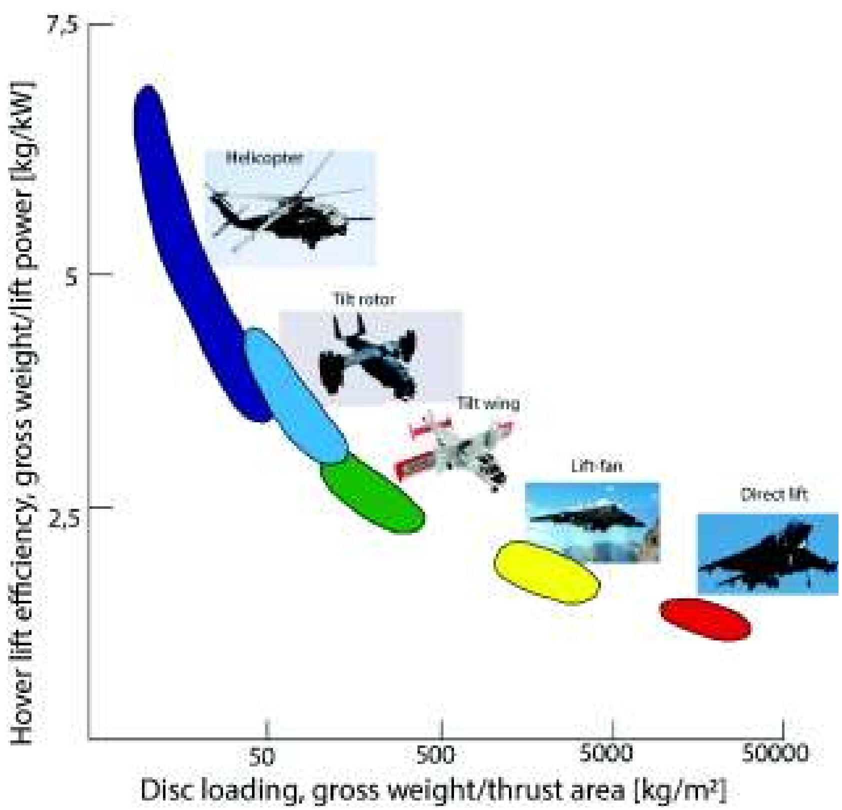

Figure 2.6 Hover vertical lift efficiency as a function of disc loading. [63]

This aircraft is designed for flying over the air space of Quito, in figure 2.7 the longest distance in Quito is shown. Approximately there is 60km from San Antonio de Pichincha to Tambillo, therefore this distance of 60km is selected as the range.

Figure 2.7 Quito map, earth view. [33]

The tables 2.1 and 2.2 show some values that are assumed for initial sizing of these aircraft.

Table 2.1 Assumed values for aircraft design.

Aspect	Value
Pilot weight [kg]	80
Aircraft weight [kg]	220
Height of take-off and landing [m]	2850
Height of flight [m]	3000
Range [km]	60
Cruising speed $\mathbf{v_{CR}}$ [$^{m}/_{s}$]	50

Table 2.2 Air properties in Quito (h=3000m). [1]

Aspect	Value
Air density ρ [$^{kg}/_{m^3}$]	0,9093

Air viscosity μ [$^{Ns}/_{m^2}$]	1,694x10^{-5}
Air Cp [$^{m^2}/_{s^2}$ k]	1010
Specific heat ratio γ	1,4
Pressure in [kPa]	70
Temperature [k]	290

2.2.1. Design methodology and model validation

This subsection calculates the propulsion system and principal dimensions for this aircraft, then is compared with real values from appendix A to confirm that used equations were appropriated.

a) Propulsion system design

The propeller design uses two types of methods, the first one works with experimental information that in this case is taken from appendix D that is a similar propeller that Cessna uses; and the second one is a theoretical method using the equation 1.30 principally. Then equations 2.4 and 2.10 are compared to see which one is closer to the real Cessna 172. Principal properties of Cessna 172 are shown in table 2.3 to compare it with properties calculated in development of this section.

Table 2.3 Properties of Cessna 172. [65]

Aspect	Value
Aircraft drag coefficient C_D	0.034
Parasite drag coefficient C_{DO}	0.1
Aircraft MTOW W_0 [kg]	1000
Propeller radius r_p [m]	0.95
Aircraft wing area S_w [m^2]	16.17
Fuselage structural depth D_f [m]	1.7 [52]
Maximum cross-sectional area A_{max} [m^2]	1.19
Overall length L_f [m]	8.2
Fuselage wetted area Sf_{wet} [m^2]	27
Root chord C_{root} [m]	1.63
Cruising speed v_{CR} [$^m/_s$]	62.6

Height of cruising speed $\boldsymbol{Hv_{CR}}$ [m]	2438
Air density at cruising speed $\boldsymbol{\rho}$ [$^{kg}/_{m3}$]	0.961
Engine Lycoming O-320	119kW @2700 rpm
Propeller speed $\boldsymbol{\Omega}$ [rpm]	2700
Number of blades $\boldsymbol{N_B}$	2
Blade model	McCauley 1C160/DTM 75 57
Blade airfoil type	Clark Y
Factor for induced power $\boldsymbol{k}$	1.15

Calculating the thrust that is the same drag by the assumptions shown in figure 1.12 which shows an aircraft in steady and level flight at cruising speed.

$$D = qS_wC_D = 1882.96 * 16.17 * 0.034 \tag{2. 1}$$

$$D = 1035.22\ N = T$$

Calculating the power coefficient, equation 2.2 was taken from Raymer [68] and works with experimental data provided from propeller companies.

$$C_P = \frac{P*1000}{\rho\left(^{N}/_{60}\right)^3 D_P{}^5} = \frac{119*1000}{0.961\left(^{2700}/_{60}\right)^3 1.9^5} \tag{2. 2}$$

$$C_P = 0{,}05416$$

Calculating the advanced ratio, equation 2.3 was taken from Raymer [68] and works with experimental data provided from propeller companies. The cruising speed need to be in *km/h* units.

$$J = \frac{v_{CR}*16.66}{N*2r_p} = \frac{225*16.66}{2700*2*0.95} \tag{2. 3}$$

$$J = 0.7307$$

According to the chart from appendix D that is a propeller which is similar to the Cessna 172 it gets the following information:

$$^{C_T}/_{C_P} = 2.7$$

$$\eta_p = 0.82$$

Calculating the power required for cruising speed, equation 2.4 was taken from Raymer [68] and works with experimental data provided from propeller companies.

$$T = \frac{0{,}9\eta_p P}{v_{CR}} \rightarrow P = \frac{Tv_{CR}}{0.9\eta_p} = \frac{1035.22*62.6}{0.9*0.82} \tag{2. 4}$$

$$P = 88\ kW$$

This Cessna 172 has a power of 90 kW [65] at parameters shown in table 2.3. Calculating the percentage error.

$$\Delta E = \frac{|P_c - P_r|}{P_r} * 100\% = \frac{|88 - 90|}{90} * 100$$

$$\Delta E = 2\%$$

This proves that the selected parameters for this aircraft are suitable. Below equations 2.5 and 2.6 show the static and dynamic thrust that aircraft has.

Calculating the static thrust *($v_{CR} = 0$)*

$$T_s = \frac{C_T}{C_P}\frac{P*1000}{nD} = 2{,}7 * \frac{119*1000}{{2700}/{60}*1.9} \tag{2. 5}$$

$$T_s = 3340\ N$$

Calculating the dynamic thrust *($v_{CR} > 0$)*

$$T_d = \frac{3600*\eta_p*P}{v_{CR}} = \frac{3600*0.82*119}{225} \tag{2. 6}$$

$$T_d = 1561\ N$$

Figure 2.8 shows the lift and drag coefficient according the angle of attack for the airfoil type Clark Y which is the airfoil type of propeller used in table 2.3.

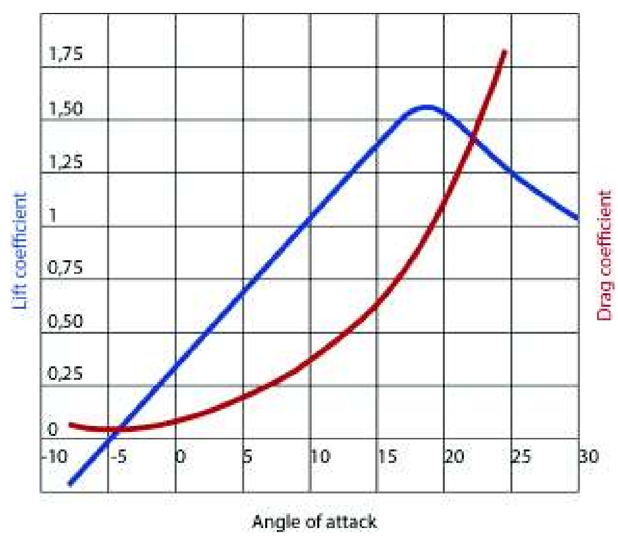

Figure 2.8 Clark Y airfoil at A_R = 6: Lift and drag coefficient according the angle of attack. [14]

Now the power is calculated using equation 2.10 that is a theoretical method, firstly equations presented in subsection 1.2 are used.

$$v_p = \sqrt{\frac{T}{2\rho S_p}} = \sqrt{\frac{1035.22}{2*0.961*2.85}} \tag{2. 7}$$

$$v_p = 13.75\, {}^{m}/_{s}$$

$$\sigma = \frac{N_b c}{\pi r_p} = \frac{2*0.15}{\pi*0.95} \quad (2.\ 8)$$

$$\sigma = 0.1003$$

$$\lambda = \frac{v_p + v_{in}}{v_{tip}} = \frac{13.75+62.6}{270} \quad (2.\ 9)$$

$$\lambda = 0.2828$$

$$P = kTv_p + \rho {v_{tip}}^3 S_p \frac{\sigma C_{D0}}{8}$$

$$P = 1.15 * 1035.22 * 13.75 + 0.961 * 270^3 * 2.85 \frac{0.1003*0.1}{8} \quad (2.\ 10)$$

$$P = 84\ kW$$

Calculating the percentage error.

$$\Delta\mathrm{E} = 7\%$$

As depicted, the results from the experimental equation (2.4) is like theoretical (BEM) equation (2.10) with a difference of 5%. According to Raymer [68], for aircraft designers it is better to work with information provided from propeller companies, like appendix D shown, than theoretical equations because there are many aspects that need to be considered at the moment of designing a propeller. One of these aspects is the nacelle blocking area (downwash) that depend on the aircraft's aerodynamics; another important aspect is the material with the propeller is made. Although the theoretical equation (2.10) seems implied physical formulas, it also uses an empirical factor (induced power factor k) to get be closer to the real life.

Every time the propeller companies make a new design, they run numerous tests and find empirical constants and correction factors for each propeller performance. This helps aircraft designers reach better values for a better aircraft design.

Appendix D shows information from one Propeller Company, where it shows correction factors and values for a propeller that are used for this project. Now that the calculated values have been compared with real values, one can confirm that equation 2.4 works properly for this propeller design.

b) Airframe design

This step uses equations from Raymer [68] that are shown in subsection 1.3. Below process uses the equations 1.35 – 1.58 and tables 2.4 and 2.5 for size the airframe, wings and tails.

- **WING GEOMETRY**

Table 2.4 Aspects for wing design. [65]

Aspect	Value
Aspect ratio $\boldsymbol{A_R}$	7.52
Taper ratio $\boldsymbol{\lambda_t}$	0.672
Thickness chord ratio $\boldsymbol{t/c}$ [%]	12
Wing swept $\boldsymbol{\Lambda}$	0
Chordwise location of the airfoil maximum thickness point $(\boldsymbol{x/c})_{\boldsymbol{m}}$	0.3
Airfoil type	NACA 2412

$$W_s = \sqrt{A_R * S_w} = \sqrt{7.52 * 16.17} \tag{2. 11}$$

$$W_s = 11\,m$$

$$\lambda_t = 0.672 = \frac{x}{x+y}$$

$$0.328x = 0.672y$$

$$y = 0{,}488x$$

If the half wing is a trapezoid rectangle as can be shown in figure 2.9.

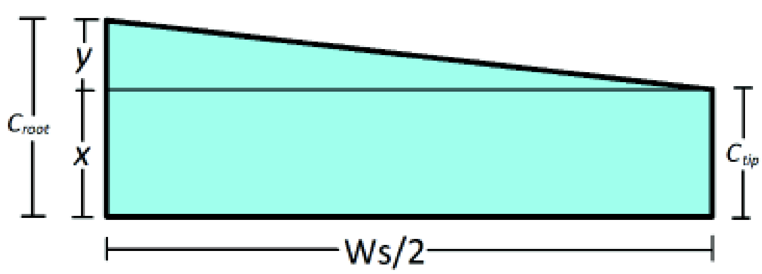

Figure 2.9 Half wing dimensions.

$$\frac{S_w}{2} = 8.1 = \frac{W_s}{2}\frac{2x+y}{2} = \frac{11}{2}\frac{2x+0.488x}{2}$$

$$x = 1.18\,m = C_{tip}$$

$$C_{root} = 1{,}76\,m$$

According to the NACA 4-digit airfoil specification, the last 2 digits are the thickness in chord percentage, then for NACA-2412

$$t_{tip} = C_{tip} * 0.12 = 1.18 * 0.12$$

$$t_{tip} = 0,14\ m$$

$$t_{root} = 0,21\ m$$

$$C_W = \frac{2 * 1.76(1 + 0.672 + 0.672^2)}{3(1 + 0.672)}$$

$$C_W = 1.5\ m$$

- **TAILS**

Table 2.5 Aspects for tail design. [65]

Aspect	Value
Horizontal tail volume coefficient $\boldsymbol{C_{ht}}$	0.6
Horizontal tail aspect ratio $\boldsymbol{A_{Rht}}$	4
Horizontal tail taper ratio $\boldsymbol{H\lambda_t}$	1
Horizontal airfoil type	NACA 0012
Vertical tail volume coefficient $\boldsymbol{C_{vt}}$	0.0411
Vertical tail aspect ratio $\boldsymbol{A_{Rvt}}$	1.41
Vertical tail tip chord [m]	0.6
Vertical tail sweep	35°
Vertical airfoil type	NACA 0009

To calculate tail position in fuselage.

$$L_a = aW_0^c = 1.6 * 1000^{0.23} \tag{2. 12}$$

$$L_a = 7.8\ m$$

$$L_{tail} = 0.6 * L_a = 0,6 * 7.8 \tag{2. 13}$$

$$L_{tail} = 4.68\ m$$

To calculate horizontal tail dimensions.

$$S_{ht} = \frac{C_{ht} C_W S_W}{L_{tail}} = \frac{0.6 * 1.5 * 16.17}{4.68} \tag{2. 14}$$

$$S_{ht} = 3.1\ m^2$$

$$HW_s = \sqrt{A_{Rht} * S_{ht}} = \sqrt{4 * 3.1} \tag{2. 15}$$

$$HW_s = 3.52\ m$$

$$C_{root} = \frac{C_{tip}}{H\lambda_t} = \frac{C_{tip}}{1} \tag{2. 16}$$

$$C_{root} = C_{tip} = \frac{S_{ht}}{HW_s} = \frac{3.1}{3.52}$$

$$C_{root} = C_{tip} = 0.88\ m$$

To calculate vertical tail dimensions.

$$S_{vt} = \frac{C_{vt}W_sS_w}{L_{tail}} = \frac{0.0411 * 11 * 16.17}{4.68}$$

$$S_{VT} = 1{,}56\ m^2$$

$$VW_s = \sqrt{A_{Rvt} * S_{vt}} = \sqrt{1.41 * 1.56}$$

$$VW_s = 1{,}48\ m$$

$$tan\,35° = \frac{C_{root}-C_{tip}}{VW_s} \tag{2. 17}$$

$$C_{root} = (tan\,35° * VW_s) + C_{tip} = (tan\,35° * 1.48) + 0.6$$

$$C_{root} = 1.64\ m$$

- **AERODYNAMIC FORCES**

The drag coefficients are calculated for the principal components of the aircraft; using equations from subsection 1.3.2 and constant values from Raymer [68]. Afterwards, the obtained value for total drag coefficient C_D is compared with assumed value that was on table 2.3 to find the error between them.

This could be an iterative task because need to be calculated again all aspects up to this step with this new drag coefficient found. Like this iterative process is not a goal in this project the calculus finish in this step.

Parasite drag in fuselage.

$$C_{DOf} = 0.0042$$

Parasite drag in wings.

$$C_{DOw} = 0.0072$$

Parasite drag in tails

$$C_{DOt} = 0.0024$$

Total parasite drag

$$C_{DO} = C_{DOf} + C_{DOw} + C_{DOt} + C_{DOan} = 0.0042 + 0.0072 + 0.0024 + 0.0096$$

$$C_{DO} = 0.0234$$

$$e = 1.78\left(1 - 0.045{A_R}^{0.68}\right) - 0.64 = 1.78(1 - 0.045 * 7.52^{0.68}) - 0.64$$

$$e = 0.82$$

$$K = \frac{1}{\pi A_R e} = \frac{1}{\pi * 7.52 * 0.82} \tag{2. 18}$$

$$K = 0.0516$$

$$L = qS_w C_L \rightarrow C_L = \frac{L}{qS_w} = \frac{mg}{qS_w} = \frac{1000 * 9.8}{1882.96 * 16.17} \tag{2. 19}$$

$$C_L = 0.322$$

$$C_D = C_{DO} + K{C_L}^2 = 0.0234 + 0.0516 * 0.322^2 \tag{2. 20}$$

$$C_D = 0.029$$

Equations 2.1 – 2.20 should be calculated again up to this step, but in this case for this new drag coefficient of 0.029 instead 0.034 that was set on table 2.3, this is an iterative process up to find the best value for drag coefficient, below shows the error between assumed value of 0.034 and the new calculated value of 0.029 for the drag coefficient.

$$\Delta E = 17\%$$

c) Performance analysis

Equations 1.72 – 1.77 are taken to find the total weight of aircraft, this weight gives an estimation of fuel tank capacity due to the range its known.

First is necessary to find the specific fuel consumption SFC. According to the manual of Lycoming O-320 [54] which is the engine of Cessna 172, the SFC is $2.3949x10^{-6}\ {}^{kg}/_{Ns}$ once that imperial units have been converted in metric units.

$$ln\frac{W_{initial}}{W_{final}} = \frac{Range * g * SFC}{v_{CR}(L/D)} \tag{2. 21}$$

$$ln\frac{W_{initial}}{W_{final}} = \frac{60000 * 9.8 * 2.3949x10^{-6}}{62.6 * 8}$$

$$W_{final} = 1043\ kg$$

This means that the Cessna 172 consumes approximately 3 kg of fuel flying across the 60km of range (cruising speed) using a MTOW of 1046 kg.

According to Cessna Skyhawk II [65] this aircraft consumes 3.3 kg of fuel for fly 60km at the same cruising speed, but this consumption could be almost the double considering the complete mission shown in figure 2.2 where is the climb and descent. This means that fuel consumption is around 7.5 kg for selected range.

These results assure that equation 2.21 works with cruising speed for this aircraft, what it means that further forward can be used for designing the DPM-A concept.

d) Weight and loading

The following formula is used to calculate power loading:

$$P/_{W_0} = \alpha V_{CR}{}^{C} = 0{,}005 * 225^{0{,}57} \tag{2. 22}$$

$$P/_{W_0} = 0.1096 \rightarrow W_0/_P = 0.1096^{-1}$$

$$W_0/_P = 9.13\, {}^{kg}/_{kW}$$

The weight of the main components should be calculated using formulas from section 1.5. These equations are shown in imperial units (pounds). Nevertheless, the units were changed to kilograms to maintain a uniform unit system (metric system) in this project. The results are compared and analyzed with information from table 1.6 and have been placed in table 2.6.

Weight of fuselage

$$W_f = 237lb = 108\ kg$$

Weight of wings

$$W_w = 239lb = 109\ kg$$

Weight of tails

$$W_{Ht} = 24lb = 11\ kg$$

$$W_{Vt} = 15lb = 7\ kg$$

Weight of main landing gear

$$W_{mg} = 119lb = 54\ kg$$

Weight of propulsion system

$$W_P = 469lb = 213\ kg$$

Table 2.6 Resume of principal aspects for Cessna 172 design.

Type	Calculated	Real	Error [%]
Propulsion			
Experimental	88 kW	90 kW	2
Equations BEM	84 kW	90 kW	7
Airframe			
Lift coefficient	0.322	1.6	80

Drag coefficient	0.029	0.032	15
Performance			
Fuel consumption in cruise speed	0.05 $^{g}/_{m}$	0.055 $^{g}/_{m}$	9
Weight and loading			
Fuselage	108 kg	115 kg	6
Wings	109 kg	107 kg	2
Tails	18 kg	28 kg	36
Main landing gear	54 kg	56 kg	4
Propulsion system	213 kg	194 kg	10
Total weight	502 kg	500 kg	0.4

Values shown in table 2.6 are a compilation of all aspects calculated in this subsection of the project, doing a comparison between calculated and real values. In the first part is the propulsion system design which shows both methods used to find the power required for fly at cruising speed.

In the second part is the airframe design, this step gives the principal dimensions of wings, fuselage and tails. Additionally, this step calculates the lift and drag coefficient. These coefficients are very difficult to calculate, aircraft designers subject those aircraft at tests in a wind tunnel to obtain the real value of these coefficients, formulas used in this project give an approximation considering parameters like cruising speed, perfect geometry, zero drag caused by components like antennas and so on.

In the third part is the performance that is principally based in fuel consumption, applying the equation 1.71 and using the range as a known data of 60 km. The fuel consumed in cruising speed was found. This allows the use of the same equations for DPM-A concept.

Finally, it can be calculated the weight of principal components as can be shown in table 2.6. The total weight of these principal components has an error of 0.4% so these equations confirm that are well suggested.

2.2.2. Design of DPM-A concept

This subsection is conducted with the equations presented in the subsection 2.2.1. the results shown for experimental and theoretical equations of the Cessna 172 reviled a moderate error around 5%.

Figure 2.10 shows the design diagram of DPM-A concept and explains the process for build this aircraft.

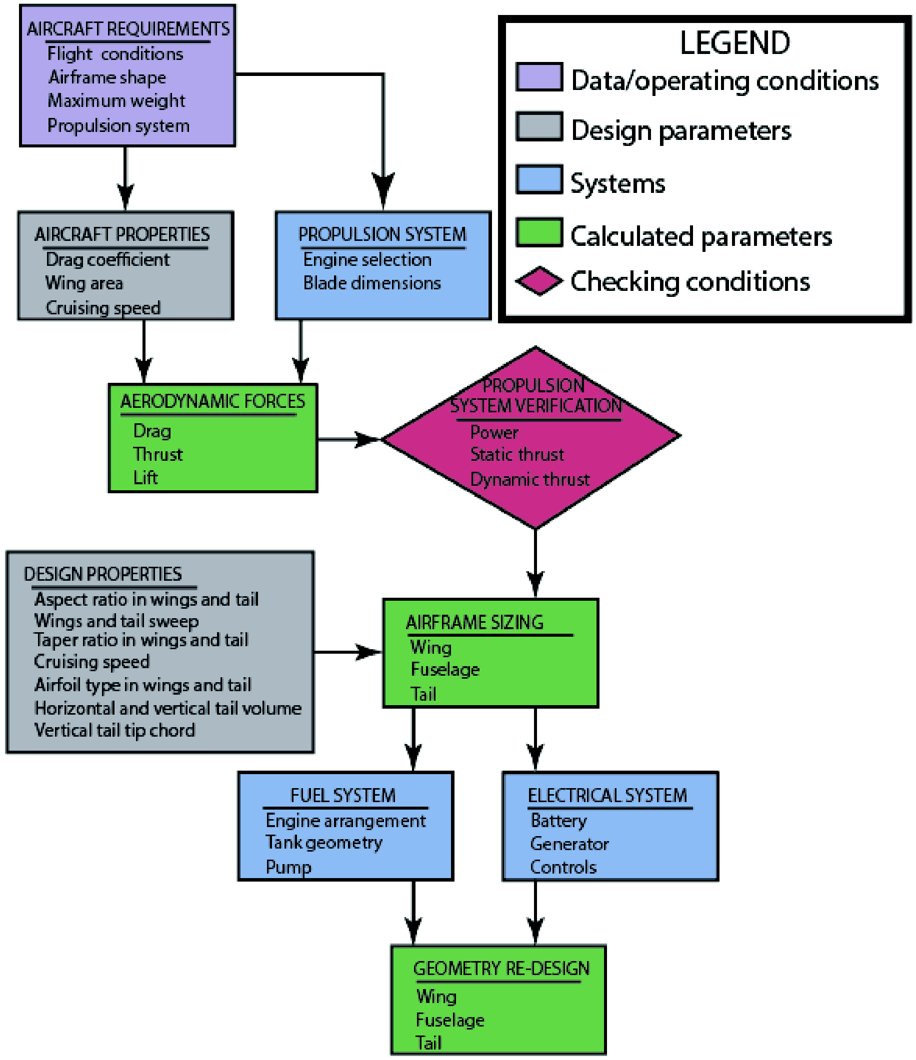

Figure 2.10 Design diagram for DPM-A concept.

a) Propulsion system design

The propeller design uses equation 2.4 which is experimental propeller data, this information can be seen in table 2.7 and appendix D.

Table 2.7 Assumed aspects for propeller design.

Aspect	Value
Aircraft drag coefficient $\boldsymbol{C_D}$ [16]	0.034
Propeller radius $\boldsymbol{r_p}$ [m]	0.82
Aircraft wing area $\boldsymbol{S_w}$ [m^2]	10
Engine Rotax 912 ULS	69kW @5500 rpm
Propeller speed $\boldsymbol{\Omega}$ [rpm]	3000

Number of blades $\boldsymbol{N_B}$	3
Chord blade $\boldsymbol{c}$ [m]	0.12
Blade mode	MTV-34-1-A/164-200
Blade airfoil type	Clark Y
Factor for induced power $\boldsymbol{k}$	1.15

Calculating the power coefficient

$$C_P = \frac{P * 1000}{\rho\left(N/_{60}\right)^3 (2r_p)^5} = \frac{69 * 1000}{0.9093\left(3000/_{60}\right)^3 (2 * 0.82)^5}$$

$$C_P = 0.05117$$

Calculating the advanced ratio

$$J = \frac{v_{CR} * 16.66}{N * 2r_p} = \frac{180 * 16.66}{3000 * 2 * 0.82}$$

$$J = 0.6095$$

According to appendix D, it gets:

$$\eta_p = 0.8$$

Calculating the power required for cruising speed.

$$P = 27\ kW$$

Calculating the thrust coefficient

$$C_T = \frac{C_P * etaP}{J} = \frac{0.05117 * 0.77}{0.6095}$$

$$C_T = 0.0646$$

Calculating the thrust static ($v_{CR} = 0$)

$$T = C_T \rho\left(N/_{60}\right)^2 (2r_p)^4 = 0.0646 * 0.9093\left(3000/_{60}\right)^2 (2 * 0.82)^4$$

$$T = 1063\ N$$

Calculating the thrust dynamic ($v_{CR} > 0$)

$$T = \frac{3600 * \eta_p * P}{V} = \frac{3600 * 0.8 * 69}{180}$$

$$T = 1104\ N$$

Now that the propulsion power of the engine has been calculated, one can move forward to design all framework and layout data.

(b) Airframe design

- **WING GEOMETRY**

The equations used for Cessna 172 in subsection 1.2.1 are employed in this step. Therefore, only the results are presented.

$$W_s = 8.7\ m$$

$$C_{root} = 1.37\ m$$

$$C_{tip} = 0.92\ m$$

$$t_{tip} = 0.11\ m$$

$$t_{root} = 0.16\ m$$

$$C_W = 1.16\ m$$

- **TAIL**

The same values from table 2.5 and 2.7 are employed in this step. Therefore, only the results are presented.

$$L_a = 6.2\ m$$

$$L_{tail} = 3.72\ m$$

Horizontal tail

$$HW_s = 2.74\ m$$

$$C_{root} = C_{tip} = 0.69\ m$$

Vertical tail

$$C_{tip} = 0.3\ m$$

$$VW_s = 1.16\ m$$

$$C_{root} = 1.11\ m$$

Figure 2.11 it shows the second sketch of DPM-A concept with all calculated measures. This is the preliminary design of DPM-A concept. For the intents and purposes of this project this sketch uses linear approximations in almost all dimensions, if a better analysis to obtain detail dimensions is required, this sketch could help to provide them.

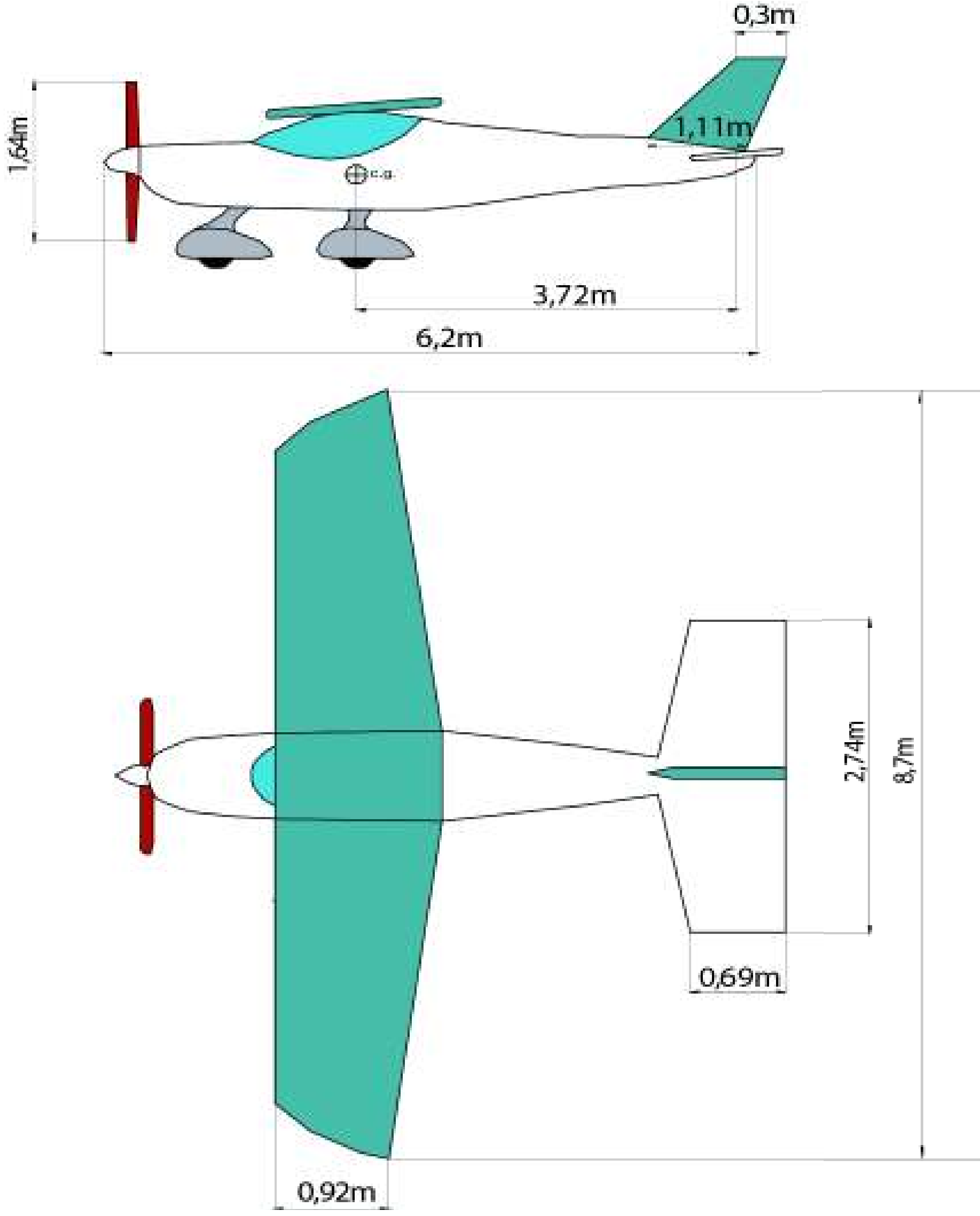

Figure 2.11 Sketch of DPM-A concept with calculated measures.

- **AERODYNAMIC FORCES**

Now the drag coefficients are calculated for the principal components of this DPM-A concept; using same equations and constant values as subsection 2.2.1. All these results are shown in table 2.8.

Table 2.8 Calculated drag and lift coefficients for DPM-A concept.

Coefficient	Value
Parasite drag in fuselage C_{DOf}	0.0049
Parasite drag in wings C_{DOw}	0.0074
Parasite drag in tails C_{DOt}	0.0025
Total parasite drags C_{DO}	0.0244
Lift coefficient C_L	0.31
Drag coefficient C_D	0.029

(c) Performance analysis

Now the same process used for the Cessna 172 in the last subsection is developed.

First is necessary to find the SFC, according information of Rotax 912 ULS in appendix B, that is the engine proposed for this DPM-A concept, the SFC is around 1.9626x10^{-6} $^{kg}/_{Ns}$

$$ln\frac{W_{initial}}{W_{final}} = \frac{Range * g * SFC}{v_{CR}(L/D)}$$

$$W_{final} = 359kg$$

This means that this aircraft theoretically has a fuel consumption of 1 kg for each 60 km that fly at cruising speed.

(d) Weight and loading

This project strives to reach this target using the latest technology in light-strength materials, reducing payload and fuel volume. The weight of DPM-A is shown in table 2.9.

Table 2.9 Weight data for personal aircraft, DPM-A concept.

Element	Weight [kg]
Wing group	50-60
Tail group	5
Fuselage	28-46
Landing gear	11
Surf ace controls	2
Nacelle group	3

Propulsion group	70-90
Services/Equipment group	14
Fuel	7-20
Other	28
TOTAL (Considering maximum weights)	280

It is difficult to define approximate size values for each aircraft component with a basis on a fifth part of Cessna 172.

The four principal components of this aircraft are explained below: wing group, fuselage, propulsion and fuel.

- **WING GROUP**

This model has two principal wings and two horizontal tail wings, the aim is that this aircraft weighs a fifth of Cessna 172 but if wings were to measure a fifth of Cessna 172 it probably could not lift the aircraft due to the small wing area. According to the table 1.7, the wing area in a little aircraft is 25% less than the Cessna 172 wing area and the mini aircraft are around 50% of the Cessna 172 wing area. Therefore, the wing group should be at least the half of weight in Cessna 172 wing group.

- **FUSELAGE**

Mini aircraft have a small design due to should be able to carry only one passenger almost without baggage. According to the table 1.7 the length of the mini aircraft is between the third and the half of Cessna 172 fuselage length. Therefore, the fuselage weight might be considered in the same order but like this is not directly proportional for this project values from 25%-40% of the Cessna 172 fuselage length are taken.

- **PROPULSION GROUP**

According to the table 1.7 most common engines in small aircraft are Rotax 912 ULS. According to appendix B this engine weighs 56.6 kg and a propeller for these aircraft like MTV-34-1-A/164-200 is made of composite materials weighing 9.5 kg; if one adds another connection and if it is also supported by a special structure this could weigh between 70-90 kg.

- **FUEL**

According to the specification of Rotax 912 ULS in appendix B this engine at maximum power has a consumption of 26 $^{l}/_{h}$. According to the table 2.1 the range is 60 km with cruising speed of 50 $^{m}/_{s}$ (180 $^{km}/_{h}$). This aircraft covers the range in 20 min. Taking this value as minimum fuel and the maximum as one hour of flight, the fuel tank should have a capacity between 9-26lt, with a density of 0,77 $^{kg}/_{l}$ [50] its weight is between 7-20 kg.

The following formula is used to calculate power loading:

$$P/_{W_0} = \alpha V_{CR}{}^{C} = 0.005 * 180^{0.57}$$

$$P/_{W_0} = 0{,}0965 \rightarrow {}^{W_0}/_{P} = 0.0965^{-1}$$

$$^{W_0}/_{P} = 10.4\ ^{kg}/_{kW}$$

The table 2.9 shows approximated weight values for this concept. Now the weight is calculated for the principal components of this DPM-A concept; using same equations and constants as subsection 2.2.1. All these results are shown in table 2.10.

Table 2.10 Calculated weights for DPM-A concept.

Coefficient	Value [kg]
Weight in fuselage $\boldsymbol{W_f}$	39
Weight in wings $\boldsymbol{W_w}$	46
Weight in horizontal tail $\boldsymbol{W_{Ht}}$	5
Weight in vertical tail $\boldsymbol{W_{Vt}}$	3
Weight in main landing gear $\boldsymbol{W_{mg}}$	18
Weight in propulsion system $\boldsymbol{W_P}$	100
TOTAL	211

All equations used for obtaining these values assume that materials for build structure, supports and fuselage are aluminum alloys.

2.2.3. Design of DPM-B concept

(a) Propulsion system design

Figure 2.12 shows the diagram which explains the design process for DPM-B concept.

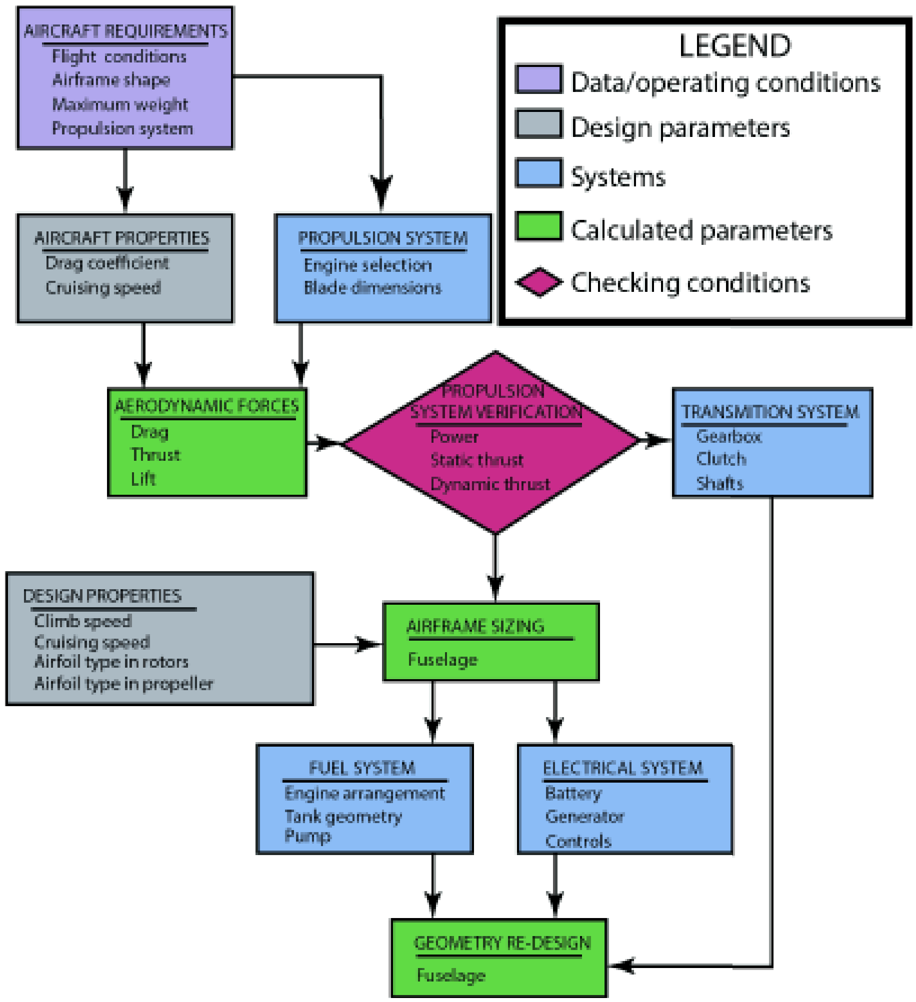

Figure 2.12 Design diagram for DPM-B concept.

Firstly, it should be designed and calculated the rotor to reach the VTOL for DPM-B. Table 2.11 details some assumed aspects for this design.

Table 2.11 Assumed aspects for rotor design.

Aspect	Value
Climb speed $\boldsymbol{v_c}$ [$^m/_s$]	5
Rotor radius $\boldsymbol{r_r}$ [m]	3,5
Engine Rotax 912 ULS	69kW @5500 rpm
Number of blades $\boldsymbol{N_B}$	2
Chord blade $\boldsymbol{c}$ [m]	0.3
Blade airfoil type [62]	NACA0012
Mean blade drag coefficient $\boldsymbol{C_{DO}}$	0.08

Factor for induced power $\boldsymbol{k}$	1.15
Downwash $\boldsymbol{d_f}$	1,03
Measure of merit $\boldsymbol{M_m}$	0,6
MTOW [kg]	360

Figure 2.13 shows the drag coefficient according the Mach number for the airfoil type NACA 0012 which is the airfoil type of propeller used in table 2.11.

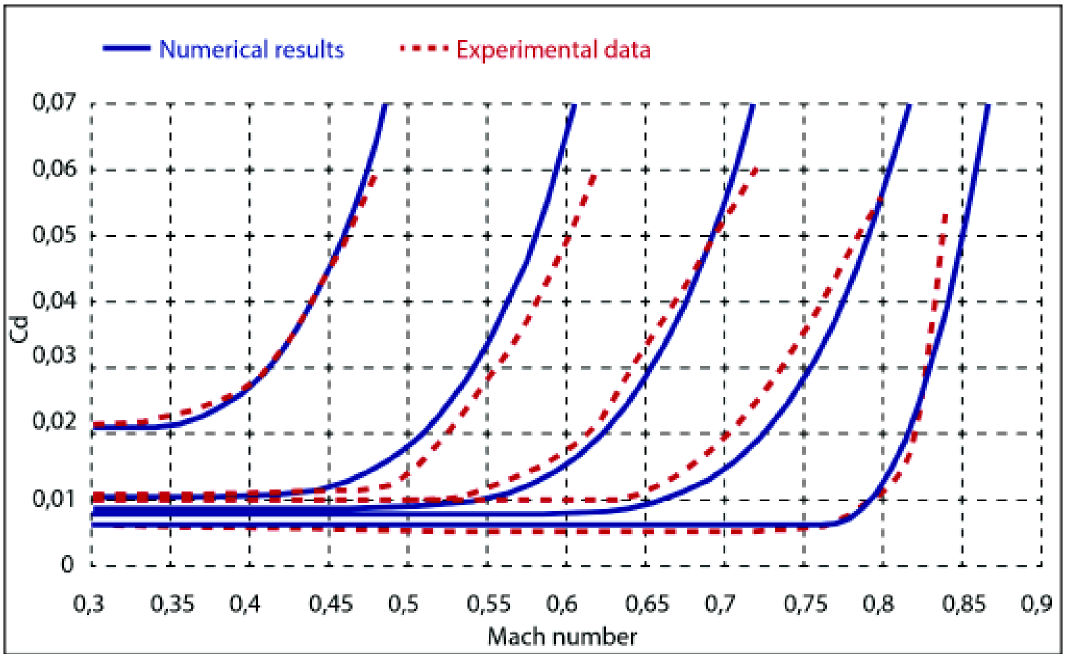

Figure 2.13 NACA 0012: Drag coefficient versus Mach number and angle of attack. [49]

Unlike the propellers, almost all helicopter manufacturers produce their own rotor blades, so it was difficult to find information and data. Therefore, for this step it is necessary to use theoretical equation 2.10. Two different methods are used to confirm that this propulsion design is suitable. As a first step, the momentum theory is used to calculate an approximation of power required to lift the aircraft. This method is a fast way to size the rotor, engine power and get an estimate gross weight. Then the blade element theory is used as a comparison.

Using rotor axial speed.

$$v_r = \sqrt{\frac{T}{2\rho S_r}} = \sqrt{\frac{mg}{2\rho S_r}} = \sqrt{\frac{360*9.807}{2*0.9093*38.5}} \quad (2.\ 23)$$

$$v_r = 7.1\, {}^{m}/_{s}$$

$$P = T * v_r = mg * v_r = 360 * 9.807 * 7.1 \quad (2.\ 24)$$

$$P = 25.1\ kW$$

This value of power was obtained assuming that there are not any losses and that both rotor disks were perfectly built. As a first calculation, the rotor power loading gives the following power loading value:

$$R_{PL} = 14.3\, {}^{kg}/_{kW}$$

According to the table 1.8 for existing small helicopters this power loading should be between 5-6.5 $^{kg}/_{kW}$. This means that this value of power loading needs to be significantly smaller to reach the VTOL.

Now one can calculate the rotor climb power using the equation 1.7, this equation assumes many losses that are present in the helicopter as is shown in subsection 1.2.1, therefore equation 1.7 is more accurate to real life values for this calculus.

This aircraft has coaxial rotors so the tail rotor power is zero; mechanical efficiency is 1 and climb speed is 5 $^{m}/_{s}$. This speed is an approximation between climb speeds of the helicopters shown in table 1.8.

$$P_c = \left(\frac{1.03*360*9.807}{0.6}\sqrt{\frac{1.03*360*9.807}{2*0.9093*38.5}}\right) + \frac{360*9.807*5}{2} \tag{2. 25}$$

$$P_c = 52.5\ kW$$

Now it is calculated the power loading with this new value of power in climb

$$R_{PL} = \frac{m}{P} = \frac{360}{52.5} \tag{2. 26}$$

$$R_{PL} = 6.9\ {}^{kg}/_{kW}$$

This rotor power loading has a value that according to table 1.8 is similar at small helicopters with the same characteristics, especially the Edm Aerotec CoAX 2D/2R that works with coaxial helix like this design. For this design, each rotor should have the half of climb power calculated.

$$P_e = \frac{P_c}{N_e} = \frac{52.5}{2} \tag{2. 27}$$

$$P_e \approx 26\ kW$$

A recommended limit value for tip speed is set at Mach 0.69 (235 $^{m}/_{s}$) by Sheddon and Newman [59], using this information an angular velocity of rotors gives.

$$N = \frac{v_{tip}}{r_r} = \frac{235}{3.5} \tag{2. 28}$$

$$\mathrm{N} = 67\, {}^{\mathrm{rad}}/_{\mathrm{s}} \approx 640\ \mathrm{rpm}$$

With this angular velocity, the torque for each shaft is

$$Q = \frac{P}{N} = \frac{26000}{67} \tag{2. 29}$$

$$Q = 388\ Nm$$

Now that it has a value for engine power, rotor radius and approach gross weight; a new calculus using blade element theory is made. With this method, some aspects that were ignored like number of blades, blade airfoil characteristics (lift, drag and angle of attack), blade twist distribution and so on are considered.

$$\sigma = \frac{N_b c}{\pi r_r} = \frac{2 * 0.3}{\pi * 3.5}$$

$$\sigma = 0.0546$$

$$\lambda = \frac{V_r + V_c}{V_{tip}} = \frac{7.1 + 5}{235}$$

$$\lambda = 0.0515$$

$$P = kmgV_r + \rho {V_{tip}}^3 S_r \frac{\sigma C_{D0}}{8} \tag{2. 30}$$

$$P = 1.15 * 360 * 9.807 * 7.1 + 0.9093 * 235^3 * 38.5 \frac{0.0546 * 0.008}{8}$$

$$P = 53.6\ kW$$

Rotor power is similar for both methods, meaning the assumed values are right for this aircraft. Until now, some losses have not been considered, with more advancements in this design is more accurate to find these losses in the rotor or framework. The propeller is the same of DPM-A concept.

For forward flight, the equation 1.8 is used, which considers the work of both rotors, this means that the propeller it does not work in this case.

$$P_f = 360 * 9.8(50 * sin\, 10° + 7.1)$$

$$P_f = 55.7\ kW$$

This means that with almost 56 kW of power in both rotors the DPM-B concept can flight at 50 $^{m}/_{s}$, without the propeller working.

This is a mathematical approximation depending upon aerodynamics of the aircraft and the angle of attack in the rotors.

(b) Airframe design

This aircraft has lack of wings and tail. Movements are produced by rotors and propeller, therefore in this step only the fuselage should be considered.

This is a novel design which is very difficult to find drag coefficients through calculus, in addition this aircraft has 2 drag considerations: first one for climb and the second one for forward advance. Commonly aircraft and helicopters manufacturers build the fuselage and find these coefficients in a wind tunnel.

(c) Performance analysis

This DPM-B concept is a novel design, therefore is not adequate to use the same equations for finding fuel consumption like Cessna 172 and DPM-A concept.

In this step of the project to find the fuel consumption the most suitable way is using the chart of fuel consumption from Rotax 912 ULS in appendix B. In that chart, it could be seen that at maximum power of 56 kW this engine consumes 14 l/h of fuel.

Flying at 56 kW and 50 $^{m}/_{s}$ this aircraft has a consume of 4,7 l in cruising the range of 60 km.

(d) Power and loading

Like take-off of this model is like a helicopter, power loading is easy to calculate. It is the relationship between MTOW and rotor climb power like was calculated before in equation 2.26. Taking this value and the maximum power that this engine can bear at normal work.

$$m = 6.9\ {}^{kg}/_{kW} * 69\ kW$$

$$m = 476\ kg$$

This means that engine power can rise a MTOW of 476 kg for this propulsion design of DPM-B concept.

After analyzing and comparing propulsion systems of both concepts (DPM-A and DPM-B). DPM-A concept has a flying power of 27 kW in cruising speed while DPM-B concept has a climb power of 53 kW that is almost double of cruising speed of DPM-A.

The aim of DPM-B concept is that cruising speed be provided with propeller, therefore rotors bring the aircraft up to reach desired height. When the aircraft be in hover position and turn on the propeller, the rotors power decreases as could be seen below. It is the same equation for power in climb but considering a climb speed of zero.

$$\mathrm{P_h} = \left(\frac{1.03 * 360 * 9.807}{0.6}\sqrt{\frac{1.03 * 360 * 9.807}{2 * 0.9093 * 38.5}}\right)$$

$$\mathrm{P_h} = 43.7\ \mathrm{kW}$$

This means that engine Rotax 912 ULS could bear the power of hover position while the propeller is working.

Therefore, DPM-B concept would be an aircraft that fulfills the aim of this project because have VTOL what lets it to taking o and landing in whichever place of Quito.

- **ENGINE ARRANGEMENT.**

As it could be seen in this section one Rotax 912 ULS engine has enough power to move this aircraft with VTOL, even though it could move it forward and reverse like a helicopter.

The motion with a propeller like an aircraft in cruising speed to become more efficient is necessary; therefore, there are two options for engine arrangement to reach this aim.

i. If it has two or three engines, the first one moves one rotor, the second one moves the other rotor and the third one moves the propeller, or in a different way one engine moves both rotors and the other one moves the propeller

ii. If it has one engine and with this engine moves both rotors and propeller.

In section 4 when starts the TERA approach it is considered these options of engine, doing an analysis about which one would have more benefits.

The engine is directly coupled to the propeller and a transmission system is coupled to the rotors, this propeller needs to be close to the engine and in the rear side of aircraft like figure 2.14 shows. This a conceptual design of the DPM-B concept.

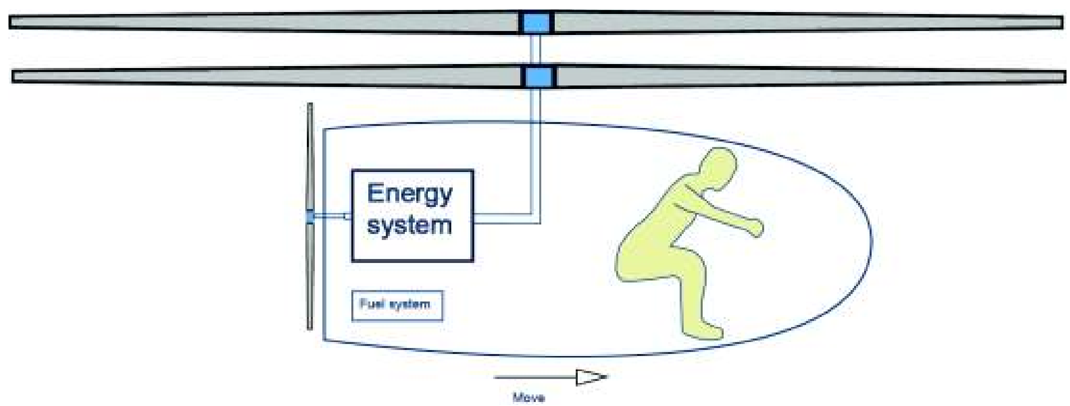

Figure 2.14 Sketch of propulsion group with rotors and propeller.

- **LANDING GEAR**

The landing gear should not be designed for advance across a length runway. These wheels do not need a sophisticated design; they simply need to guide aircraft for parking and some movement produced when takes-off or lands.

2.3. Summary of section 2

The overview for this project was defined in four steps. These are: operating conditions, initial sizing, preliminary analysis and cost analysis. First three steps were developed in this section and cost analysis is defined as an individual study in section 3.

For this section were considered the four principal aspects for design an aircraft: propulsion, aerodynamics, weights and manufacturing. These aspects were considered necessaries due to the aim of this project, to make a preliminary design. Other aspects like noise, flight controls and structures are more focused in a detail design therefore were not considered for apply in this project.

Most suggested equations in literature research are focused in propulsion systems because are directly linked with the capacity of flying and the fuel consumption. This last one turns into money.

One of the scopes for this project is that the designed aircraft has VTOL, therefore were developed some helicopter equations like momentum theory for rotors, these equations make an approximated calculus to know how much power is required to reach the climb, hover and forward flight. This is a tool that is very helpful to make a first design in a new helicopter or aircraft.

For the propeller design, were presented two types of suggested equations. The first one was the blade element momentum, which is similar to momentum theory for rotors, but in this case, is focused on propellers. The other one is the blade element theory that has two assumptions:

- There are not aerodynamic interactions between different blade elements
- Forces on blade elements are simply determined by lift and drag coefficients

From these two equations, the BET is the best one because, takes into account the proper characteristic of the propeller like chord, number of blades, propeller radius and so on. All these BET equations have been resumed in one equation that let to calculate the required power for an aircraft flying at cruising speed, this equation is 1.30.

BEM is more mathematical than BET. For a first approximation is well but is not suitable to make a preliminary design, due to its not considering chord, number of blades, airfoil and so on.

The airframe is divided in two elements, which are the airfoil and the aerodynamic equations. Airfoil makes a brief explanation about the parts and common coefficients presents in a wing or blade profile. Aerodynamic equations are principally the drag coefficients in the principal elements like fuselage, wings and tails. These drag coefficients are applicable only for a known aircraft like the Cessna 172.

The performance analysis is a group of equations that converge in equation 1.71 to calculate the range. Like the range is a known value in this project, it can be found one of the other magnitudes like speed, initial or final weight, lift or drag forces and so on.

For weigh calculation, some equations from Raymer [68] have been selected which are applicable in commercial aircraft. These equations are in imperial units, and therefore it was necessary to work in imperial system, at the end this calculus was converted into metric units.

Section 2 is the preliminary design of the aircraft, therefore this is the most important in the project. At the beginning of this project, the aim was to do the design of one aircraft that reaches the scope. However, in the path of this section, it could be seen that most of equations require some constants and values that are impossible to calculate or assume for a new type of aircraft like the DPM-B concept. Is necessary to do an approximation method to obtain constants or values useful to apply in equations for DPM-B concept, which consist of building an exact scale model and subject into a wind tunnel.

Therefore, it was necessary to design the DPM-A concept, which is an aircraft like the Cessna 172, from which could obtain many constant and values to design it. This DPM-A concept is very helpful to know about shortcomings that helps to the Ecuadorian industry at any moment build an aircraft, even if this aircraft becomes a “scale model". Additionally, this DPM-A concept helps to approximate the quantity of materials needed to build the fuselage, wings and tails; this can too give an approximated value of how much is the cost to build an aircraft in Ecuador.

The design process followed the diagram shown in figure 2.1, making a comparison between three aircraft. The first one was the Cessna 172; whose scope is to validate the equations. The second one was the DPM-A concept which applied all equations once that were validated. This aircraft is like Cessna 172, and it could be obtained the engine sizing, MEW and dimensions. The last one was the design of DPM-B concept, only the propulsion could be obtained from this aircraft design. This aircraft has not wings and tails, and for the airframe, it is necessary to apply the same calculated fuselage for DPM-A concept.

3. COST ANALYSIS FOR THE DPM-A CONCEPT

According to Gundlach [57] there are four principal phases for designing an UAS: development, manufacturing, operation and disposal. In this section, the costs to build the DPM-A concept is addressed using different cost estimation methods. The analysis of each phase is shown in figure 3.1.

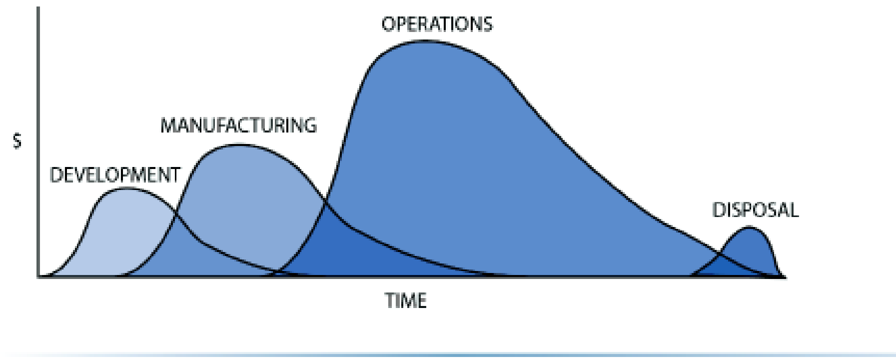

Figure 3.1 UAS LCC phases. [57]

Raymer [68] suggested another method to find the life cycle cost elements of an aircraft, which is more precise because it considers other variables and performs a meticulous analysis of operations and maintenance. Figure 3.2 shows the elements of life cycle cost; the sizes of the boxes are proportional to the magnitude of costs for a typical aircraft; it can be seen that operational and maintenance costs are larger than the others.

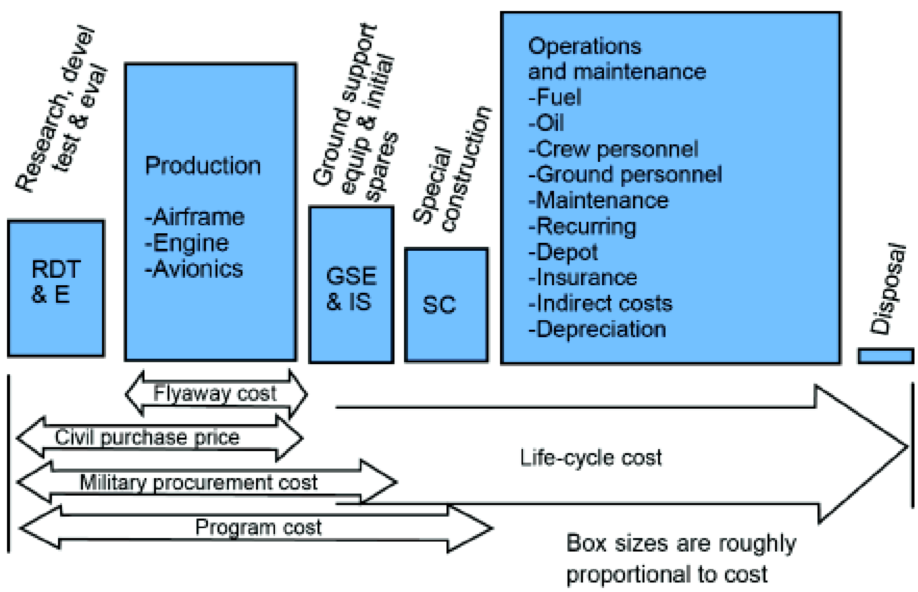

Figure 3.2 Elements of LCC. [68]

Raymer [68] outlined that aircraft are bought by the pound. In the table 3.1 the values by pound of some aircraft in the USA market are shown.

Table 3.1 Cost by pound of aircraft in year 2012. [68]

Aircraft	Cost [$^{USD}/_{pound}$]
Small general aviation	200
Airliners and businesses jets	800
Military fighter	2000
Newer F-22	3500
Fifth generation F-35	5000

3.1. Development

This section seeks the startup of the project; therefore, it includes the time spent on the design of this project, which was made by the designer and director.

The design process lasted one year, the project was developed with 60 hours of work per month, which gives a total amount of 720 hours. The designer works in the private industry with a wage of 12 $^{USD}/_{h}$, this value is taken as the cost per hour that a mechanical engineer needs for design this aircraft. The cost of designer time is:

$$A_{DC} = 720hour * 12USD/h = 8640\, USD$$

Director and designer had two meetings per months and each meeting lasted two hours, this gives a total of 48 hours for director. The director assumes the double of wage which would be 24 $^{USD}/_{h}$.

$$D_{DC} = 48hour * 24USD/h = 1152\, USD$$

This means that initial phase development for this project has a cost of

$$T_{DC1} = A_{DC} + D_{DC} = 9792\, USD$$

A complete development need to have drawings, CAD simulations, quotations of each component, manufacturing process and so on. In addition, the development time for an aircraft depending of each one. This is an ambitious task for this project, therefore is assumed like complete cost for development is the double of initial phase, this is:

$$T_{DC} = 2T_{DC1} = 19584\, USD$$

3.2. Manufacturing

White pine is widely used in the manufacturing of aircraft according the table 1.5. This type of wood is easily found in Ecuador. The price of white pine is around 1.25-1.80 $^{USD}/_{kg}$ according to EDIMCA [48] that is one of the biggest wood companies in Ecuador.

The price of aluminum in Ecuador is around 8.10-8.60 $^{USD}/_{kg}$ according to CEDAL [47] that is the biggest aluminum company in Ecuador. For composite materials, it is very difficult to find a market price because these materials are built manually and each design is different. The most common composite material in Ecuador is the fiber glass, therefore this material is taken for this study.

To find a relationship between weight and price of fiber glass it has been suggested to use the work of Rojas [55] which shows that this relationship has a cost of 9.69 $^{USD}/_{kg}$ in his sink sample. For this project is assumed that already it has an aircraft fuselage mold due to this price increases in the real life because for make composite materials firstly is necessary to build a mold. Moreover, the requirement of a structure made of aluminum or wood increases the price even more. Table 3.2 shows a comparison between these material prices in Ecuador, it considers all weights from table 2.10. The results of this table were obtained from equations that consider aluminum alloys as basis. The use of wood or composite materials instead aluminum alloys gives weight variations in results on the table. These variations are not considered for this study.

Table 3.2 uses 111 kg of aircraft elements from table 2.10 to calculate the materials price, this weight looks at all elements except propulsion system because the engine and its components have their own weights which need to be analyzed in another step.

It is difficult to find a labor price to build the DPM-A concept for each material and compare it between them. Every material listed in the table 3.2 has a different quotation method, for example labor price of metals like aluminum is quoted by weight and labor price of wood is quoted by square meter because common carpenters make furniture for homes, floors or doors. It is more difficult to find a price for composite materials because people that use composite materials quotes by work and normally this price is only based on the experience of this people. In the last column of table, it could be seen that the labor price of each material has different unit of measurement, wood is by surface, aluminum is by weight and composite material depends in the builder. This is the best approximation that could be obtained and was made consulting to some specialists in each area of aluminum and wood; for composite materials, the labor cost was adopted from Rojas work [55] that includes this price in his sank sample.

Table 3.2 Comparison between materials to build DPM-A concept.

Material	Price [$^{USD}/_{kg}$]	Material price [USD]	Labor price
White pine	1.25-1.80	138.75-199.8	200 $^{USD}/_{m^2}$
Aluminum	8.10-8.60	899.10-954.60	5 $^{USD}/_{kg}$
Fiber glass	9.69	1075.59	It is included

Two calculations are performed to have an approximated cost of the DPM-A concept. The first one is considering the engine as propulsion system and applying the parametric cost estimation method. The information presented in table 1.1 is useful for midsize aircraft. Therefore, there is variation for the results if these data are used in small aircraft like DPM-A concept.

The same calculations need to be done for the fuselage price like basis for this case. Fuselage price is calculated with the estimated MEW of 111 kg and information from table 3.2.

The Rotax engine (propulsion system) price is $17692 [4], table 1.1 shows that propulsion have a cost fraction between 18-22%:

$$Cost_{DPM-A} = 17692\ USD * 100/22 = 80418.18\ USD$$

$$Cost_{DPM-A} = 17692\ USD * 100/18 = 98288.89\ USD$$

This means that DPM-A concept has an average cost between $80418.18-98288.89 with basis in propulsion system value. This price is high according to table 1.7 for similar aircraft, in this table the prices shown are retail prices. Is the price that people would pay to get any of these aircraft. If one considers that average cost of $80418.18-98288.89 represents the manufacturing cost, this means that retail price is higher substantially.

To the have considered $17692 [4] as the propulsion system cost there are some mistakes implied, for example this is the retail price of the engine if someone wants to get it in the store. In addition, this engine is manufactured in Austria therefore need to be added taxes and importation costs to Ecuador.

If an aircraft factory wants to buy these engines probably they do a partnership with Rotax company and the price of engines drops. Information of table 1.1 is the reference taken for this project because was difficult to find manufacturing costs information of aircraft, therefore the relationship of 18-22 % about propulsion system could be higher or lower in the real life.

Working with aluminum and using results obtained from table 3.2 the cost for aircraft empty shell structures including labor price is between:

$$899.10 + 5 * 111 = 1454.10\ USD$$

$$954.60 + 5 * 111 = 1509.60\ USD$$

Averaging both prices, it has:

$$\frac{1454.10 + 1509.60}{2} = 1481.85\ USD$$

Table 1.1 shows that aircraft empty shell structures have a cost fraction between 20-25%:

$$Cost_{DPM-A} = 1481.85\ USD * 100/25 = 5927.40\ USD$$

$$Cost_{DPM-A} = 1481.85\ USD * 100/20 = 7409.25\ USD$$

Averaging both prices, it has:

$$\frac{5927.40 + 7409.25}{2} = 6668.33\ USD$$

This means that this DPM-A concept has an average cost of $6668.33 with basis in aircraft empty shell structures values.

The price is too low this time due to the structure is made in Ecuador. The difference of wage between Ecuador and countries which have a great manufacturing of aircraft is large, for example the minimum wage in USA is 7.25 $^{USD}/_{h}$ [29] whereas in Ecuador the minimum wage is 2.29 $^{USD}/_{h}$ [28] (considering a work basis of 160 $^{hours}/_{month}$). This difference shows that the manufacturing price in Ecuador to build an aircraft empty shell structure would be too low in comparison with another country like USA, therefore the fraction between 20-25% would be different.

The analysis shows that a real cost for manufacturing an aircraft in Ecuador could be cheaper than other countries due to labor price, but on the other hand this price could increase due to get some component like engine, propeller, rotors and so on that are not produced in Ecuador have expensive costs. Therefore, the importation costs and taxes increase the manufacturing cost.

This is an approximation price of the DPM-A concept. For this project, equations and price materials of a similar aircraft have been considered. Furthermore, to obtain a better approximation it is necessary to consider other aspects like energy, direct and indirect costs, taxes, transport, storage and so on. This could be an open door for future projects but is not a goal in this project.

3.3. Operation

Figure 3.2 shows that there are ten aspects to be considered in operating costs for all types of aircraft. For this study, four features are taken: fuel, oil, maintenance and depreciation.

The helicopter company Robinson has provided information about all operating costs that Robinson R22 beta II has. This vehicle could be compared with the DPM-B concept because is for one person and has VTOL. This information can be seen on appendix E.

On appendix E, it can be seen that operating costs are very high for the aircraft industry and are measured principally with the number of flight hours, it can be measured too according to road mile but it is not very accurate.

- **FUEL AND OIL**

According to appendix B proposed engine use a fuel that according to Ecuadorian norm INEN 0935 is compatible with fuel called "super" in the country.

Assuming a case where somebody uses this aircraft to fly from home to work from Monday to Friday covering a range of 20 km in one way (this means the total flight distance for a round trip is 40 km) and at power of 27 kW for cruising speed (that was calculated in subsection 2.2.2) has a fuel consumption per day of:

$$Fuel_{DPM-A} = \frac{4000\ m/day}{50\ m/s} * \frac{1h}{3600s} * 1.85\ gal/h$$

$$Fuel_{DPM-A} = 0.41\ gal/day$$

Actual price for this fuel in Ecuador is around 2.15 $^{USD}/_{gal}$ [42], this means, if a year has 280 working days, the fuel cost is:

$$Fuel_{DPM-A} = 246.82\ USD/year$$

Further forward in section 4 is explained why these values have been selected, a real-life case as example for this project is applied.

This engine uses one gallon of common engine oil like SAE 5W-40 for Ecuadorian weather, oil need to be changed each 100 working hours, this means that oil need to be changed around two times per year. Depending of oil type these values can change, there are some synthetic oils that can work much more than mineral (common) oils. The price of each oil gallon is around $25 and the oil filter is $10, this means that oil cost is:

$$Oil_{DPM-A} = 70\ USD/year$$

- **MAINTENANCE**

Maintenance is usually scheduled by flight hours, a light aircraft like this DPM-A concept require a complete inspection every 100 hour [68], like oil changing, this means around two complete inspections per year.

The main elements that are changed in maintenance are oil, air filters, fuel filters and oil filters. The maintenance cost of a Volkswagen Voyage that has an engine of 74 kW, which is like Rotax engine in power size, has been taken as reference sample. Price for a common maintenance in the Volkswagen store for mentioned automobile is around $125, with two maintenances per year this means 250 $^{USD}/_{year}$ for Volkswagen Voyage.

For a real aircraft similar to DPM-B concept like helicopter Robinson R22 Beta II price is much more expensive than a vehicle. The reason of these costs being higher corresponds to a lack of tools, hangars and professionals. This company is placed in the United States of America therefore labor price is much more expensive than Ecuador.

Appendix E shows a real maintenance cost that this helicopter has, for an engine and aircraft overhaul the cost is 64.54 $^{USD}/_{h}$ of flight (including labor price). This means, for a year that have around 200 flight hours, the maintenance cost is 12908 $^{USD}/_{year}$ for a helicopter R22 Beta II.

ARICA [7] is an Ecuadorian company that gives maintenance and commercialize aircraft and helicopters, this company gets paid $1500 for each inspection of 100 hours for a Cessna 172, if some element need to be changed the price increases. This price is high because there is few demand and uses Guayaquil airport like hangar for their operations.

If DPM-A concept generates high demand and some hangars for do the inspection and maintenance probably the price is cheaper, not like an automobile but considerably less than $1500.

For this project, the price of 1000 $^{USD}/_{year}$ is considered as maintenance for DPM-A concept.

$$Maintenance_{DPM-A} = 1000\ USD/year$$

- **DEPRECIATION**

Depreciation cost depends of each manufacturer, while an aircraft is expected to have an operating life longer, the depreciation cost is greater. According to Raymer [68] airframe and engine have different operating lives and need to be considered separate to find depreciation cost.

For this case, a depreciation of 10 years for airframe and engine is considered with a final resale value of 20% of manufacturing price. For this study, the value of aircraft with basis in empty shell structure is considered because is closer to the Ecuadorian reality than the price of aircraft with basis in propulsion system.

The depreciation cost is:

$$Airframe_{DPM-A} = 6668\ USD$$

$$DepreciationAirframe_{DPM-A} = \frac{6668 - 0.2 * 6668}{10}$$

$$DepreciationAirframe_{DPM-A} = 533\ USD/year$$

And the depreciation cost for the engine is:

$$DepreciationEngine_{DPM-A} = \frac{17692 - 0.2 * 17692}{10}$$

$$DepreciationEngine_{DPM-A} = 1415\ USD/year$$

The total depreciation cost for DPM-A concept is:

$$Depreciation_{DPM-A} = 1415 + 533$$

$$Depreciation_{DPM-A} = 1948\ USD/year$$

This is the highest cost from all operational costs for this DPM-A concept. As could be seen the engine cost is much higher than airframe cost, therefore this cost is directly linked with the engine price.

3.4. Disposal

Aircraft need to be disposed after its life expectancy has been completed, according to Gundlach [57] the disposal cost is usually neglected in modeling; therefore, is not be considered for this project.

3.5. Summary of section 3

Section 3 is about the cost analysis that the designed DPM-A concept is expected to have. DPM-B concept proved difficult to find some calculations, and therefore is difficult to find costs as well. In this section, material and labor cost is calculated. Figures 3.1 and 3.2 show the cost elements that an aircraft has from different criteria, for this project was defined the cost analysis in the four phases shown in figure 3.1.

The material cost was calculated for the three materials most used nowadays in the aircraft industry, these costs were shown in table 3.2. Selected material for this study was the aluminum. In Ecuador, the most popular composite material is fiberglass. Around the world many aircraft are built from carbon fiber as composite material, but in Ecuador, this material is very hard to find because has not been yet developed. In table 3.3 the costs obtained in this section for DPM-A concept are shown. For airframe, an analysis with basis in empty shell structures has been considered.

Table 3.3 Summary of costs for DPM-A concept.

Type	Value
Development	19584 USD
Airframe (material and labor)	6668 USD
Propulsion system	17692 USD
Fuel	247 $^{USD}/_{year}$
Oil	70 $^{USD}/_{year}$
Maintenance	250 $^{USD}/_{year}$
Depreciation	1948 $^{USD}/_{year}$

4. TECHNO-ECONOMIC ENVIRONMENTAL RISK ASSESSMENT (TERA) APPROACH

This section groups the collection from all the results obtained in sections 2 and 3, these results are compared and analyzed to understand which one is the best choice for a personal aircraft between DPM-A concept and DPM-B concept analyzing different stages with TERA approach. These concepts (DPM-A and DPM-B) are compared with other vehicles to find the performance of each one using different considerations like energy, material and operation.

Before developing this section, the concept behind TERA is briefly explained. TERA (Techno-economic, Environmental and Risk Assessment) is an approach modeling which develops the design space of engineering problems and identifies solutions minimizing overall design, time and costs, selecting an optimum solution with reduced error in the decision. This model started in Cranfield University and through the time has become an appropriate tool for improve engineering projects.

This section intends to show the impact of introducing the concepts of aeronautics in Ecuador. This aircraft design could start with the first aeronautics industry in this country.

The beginning of this industry in Ecuador could be a big step in the productive matrix change that the actual government is promoting, not only by the utility that these aircraft can generate but also opening jobs and reducing energy consumption in comparison with other means of transport. The benefits of beginning the aircraft industry in Ecuador are the reduction of CO_2 emissions, enhancing wood and aluminum industries, and generate technological improvements in the country.

4.1. Energy consumption analysis

This section is the most important from all included in this section because compares the energy required for each aircraft designed flying at cruising speed. Finally, this information is compared with Cessna 172 to see which one is more efficient in different aspects such as payload weight, range, fuel consumed per occupant, maintenance cost and manufacture cost. In this case, the concept of energy represents the propulsion system.

This step considers a real case study for making the comparison, which is analyzed the energy required using different vehicles to travel an example route (traveling from home to work by the author of this project). This can be seen in table 4.1.

Table 4.1 Information for route sample.

Data	Value
Distance in straight line	20 km
Distance by streets and highways	33 km
Working days	280 day/year

Figure 4.1 shows the difference between distance in straight line and distance by streets and highways. This is the principal advantage of using an aircraft instead an automobile, goes in straight line without stops.

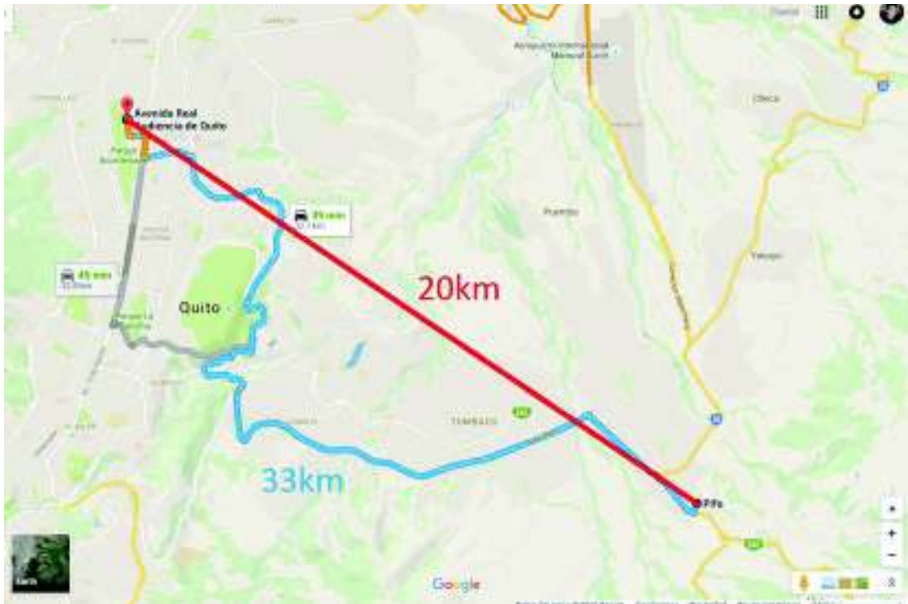

Figure 4.1 Traveling distances from home to work.

This information is compared with an automobile with similar engine characteristics, this automobile is a Volkswagen Voyage with an engine of 74 kW. Additionally, is assumed that each flight uses the same power at cruising speed for take-off and landing.

In table 4.2 the comparison between each concept and the automobile mentioned Volkswagen Voyage for traverse the same points (home and work) is shown.

For this comparison, the charts of appendix B were used.

Table 4.2 Comparison for cruising the route sample between DPM-A concept, DPM-B concept and a Volkswagen Voyage.

Element	DPM-A concept	DPM-B concept	Volkswagen Voyage
Power *	27 kW	56 kW	60 kW
Fuel consumption	1.85 $^{gal}/_{h}$	3.63 $^{gal}/_{h}$	1.05 $^{gal}/_{h}$
Total distance	40 km	40 km	66 km
Speed	50 $^{m}/_{s}$	50 $^{m}/_{s}$	20 $^{m}/_{s}$
Traveling time	0.22 h	0.22 h	1.75 h
Fuel consumed	114 $^{gal}/_{year}$	224 $^{gal}/_{year}$	515 $^{gal}/_{year}$
Fuel cost	245 $^{USD}/_{year}$	482 $^{USD}/_{year}$	1107 $^{USD}/_{year}$

*This is the power required at cruising condition, its different at the total engine power.

The Volkswagen Voyage speed shown in table 4.2 represent a traveling speed approach. However, the traffic and configuration of the road system generate time lags. Therefore, the approach presented considers the real time of traveling accounting all these delayed factors.

The main values of fuel burn and cost have been set in figures 4.2 and 4.3 to provide a better understanding of table 4.2. These figures have considered the same conditions of table 4.1.

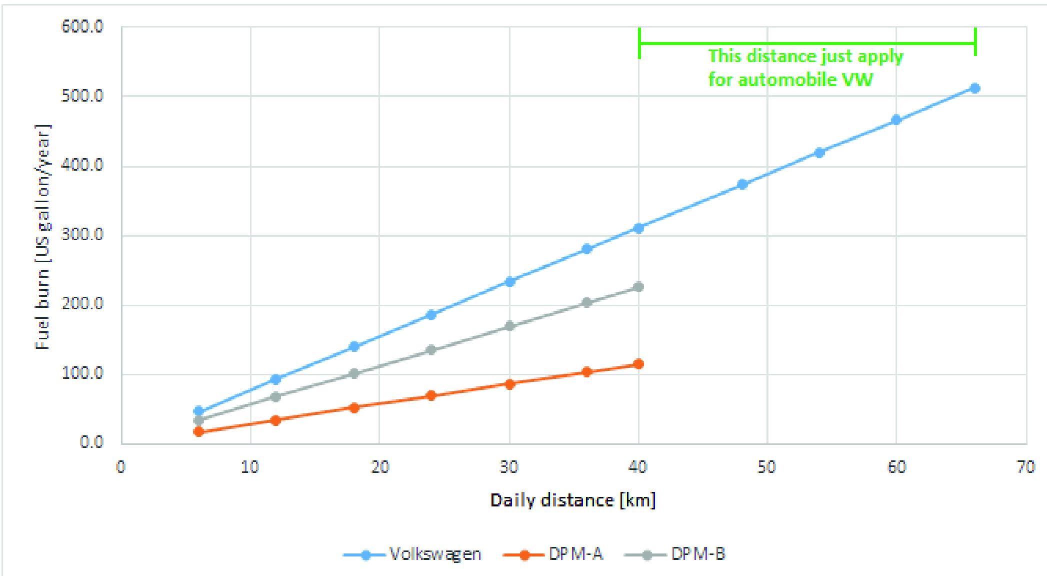

Figure 4.2 Mission fuel burn.

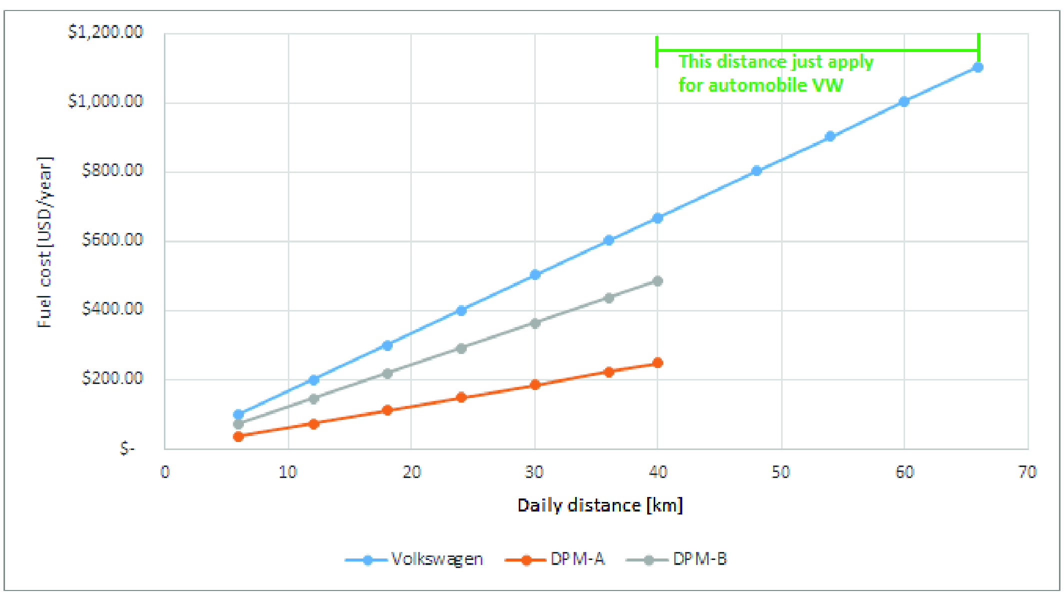

Figure 4.3 Fuel burn cost.

It can be seen from figure 4.2 that automobile traveling presents the highest fuel consumption. Indeed, this causes a direct impact in energy costs and pollution.

According to figure 4.2, the best choice is the DPM-A concept because it requires low engine power to perform one travel. However, the major restriction of this aircraft for travel inside of Quito or to another place frequently is that this DPM-A concept needs a runway for take-off and landing in each place.

Now the DPM-A concept with Cessna 172 is compared, previous table 4.2 analyzed both concepts and automobile performance. Once that DPM-A concept has been selected as the best choice between 3 vehicles this concept needs to be compared with another aircraft to see the behavior that this concept generates in a real aircraft market and analyzing the bene fits and disadvantages.

Firstly, the performance between DPM-A concept and Cessna 172 is analyzed looking two aspects, the first one is the total power required according to cruising speed and the second one is the power loading.

All data for Cessna was provided by McIver [65] and converted in metric units. The DPM-A concept requires to calculate the minimum speed for reach the aircraft lift. For this, the equation 4.1 from Raymer [68] is used.

$$v_{minT} = \sqrt{\frac{2mg}{\rho S_w}\sqrt{\frac{K}{C_{D0}}}} \tag{4. 1}$$

Using data from table 2.8 it gets.

$$v_{minT} = \sqrt{\frac{2 * 360 * 9.8}{0.9093 * 10}\sqrt{\frac{0.0516}{0.0244}}}$$

$$v_{minT} = 33.6\ m/s$$

This means that DPM-A concept needs to fly at least at 33.6 $^{m}/_{s}$ (almost 120 $^{km}/_{h}$) to reach lift in Quito.

Starting with this value and taking each airspeed data from McIver [65] it can be obtained the following charts.

It could be seen in figures 4.4 and 4.5 that the DPM-A concept has a better performance than Cessna 172 in terms of power required, this expresses directly the fuel consumption; it is more efficient at speed of 50 $^{m}/_{s}$ that was the designed speed because at high speeds consumes the same amount of fuel than the Cessna 172.

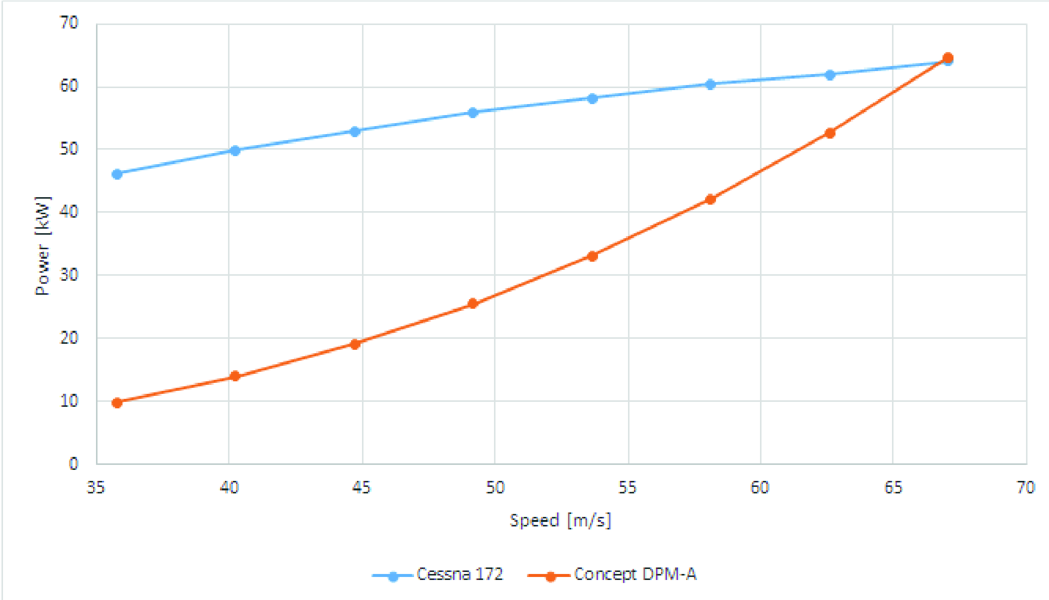

Figure 4.4 Performance speed vs power.

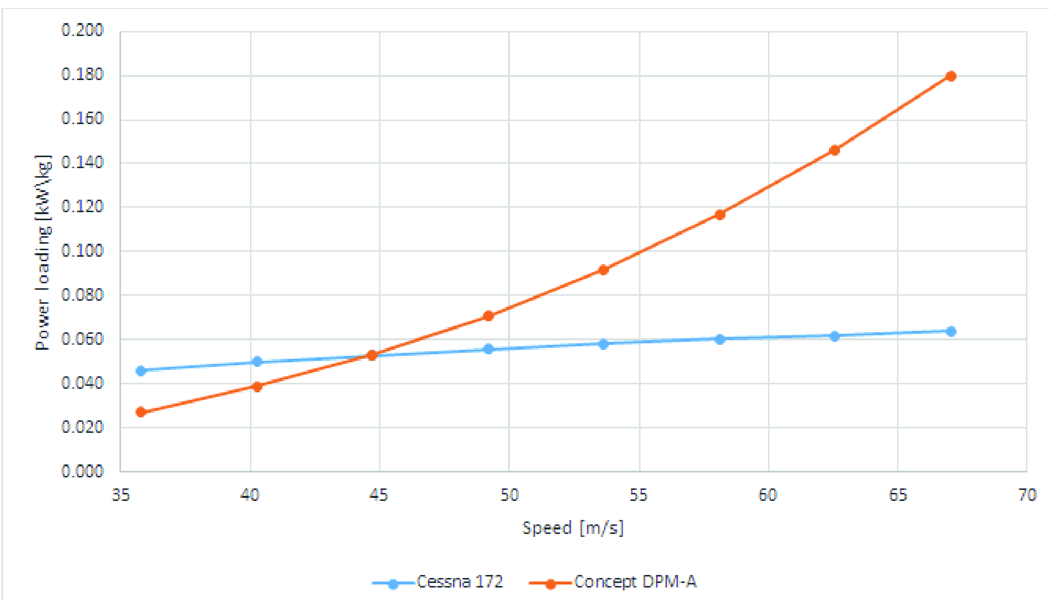

Figure 4.5 Performance speed vs power loading.

In terms of power loading Cessna 172 is more efficient because this aircraft was designed to transport four people with baggage. Power loading is around 0.04-0.06 $^{kW}/_{kg}$ whereas for DPM-A concept this value can reach up to 0.18 $^{kW}/_{kg}$, this is almost three times higher than Cessna. The principal cause is that this aircraft is designed for one person and need a medium engine like Rotax 912 for reach the take-off and landing.

The design basis of this project focuses on performing travels using the altitude of Quito with a height of 3000 m. In figures 4.6 and 4.7 the power required and the fuel burn to fly the Cessna 172 and DPM-A concept at different heights are analyzed.

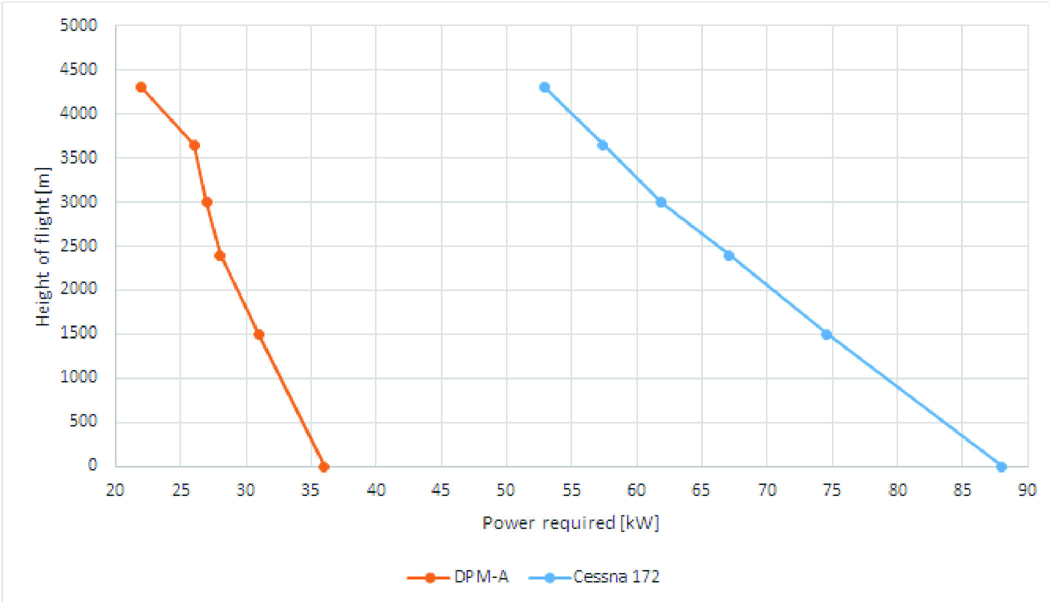

Figure 4.6 Power required according to height of flight.

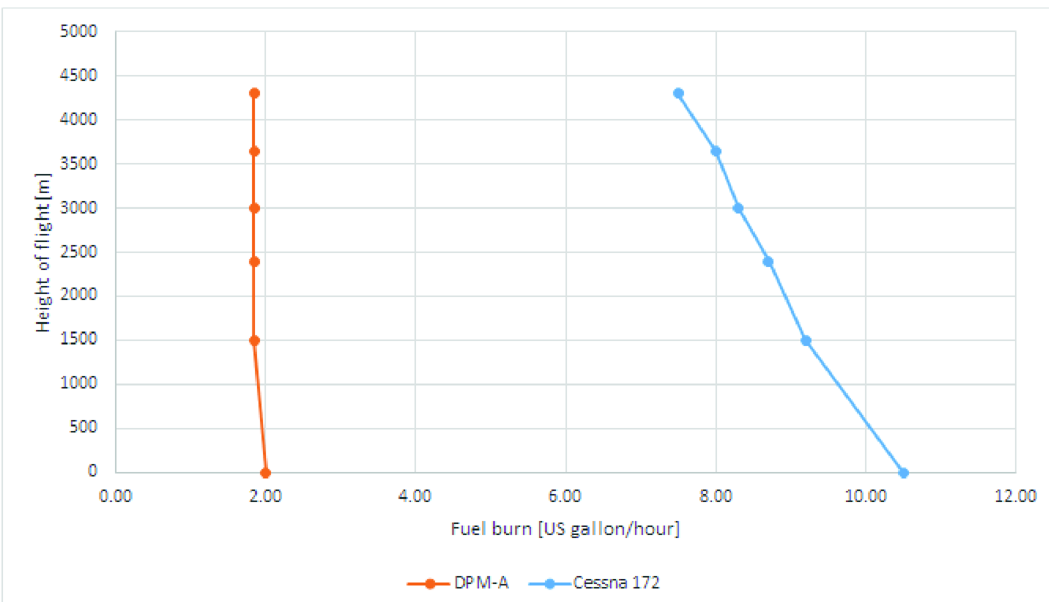

Figure 4.7 Fuel burn according to height of flight.

It could be seen in figure 4.6 that when the aircraft is closer to sea level the power required is higher because the air density increases. This indicates that Quito is a good place to apply this design because the altitude characteristics of the city reduces the power required. As the aircraft is bigger, more notorious be the difference of required power according to height of flight.

According to appendix B Rotax 912 engine burn almost the same rate of 2 gal/h for a power required up to 35 kW, therefore in figure 4.7 the line corresponding at DPM-A concept practically is a straight vertical line, therefore this DPM-A concept burns the same amount of fuel if flies in Quito or in other place at sea level like Guayaquil city.

Finally, the performance of the propulsion system for the DPM-B concept is shown as was mentioned at the end of section 2 analyzing different engine arrangements.

The propulsion system has been calculated in the DPM-B concept, leaving two options to achieve this aim.

The first option for propulsion design in the DPM-B concept is working with one engine, such as it could be seen in subsection 2.2.3. In this case, a gearbox and clutches are necessary for handling both rotors and the propeller.

The second option for propulsion design in the DPM-B concept is working with three engines, this means one engine for each rotor and one engine for the propeller, for this case the selected engine is the Rotax 447 UL which performance could be find in appendix B. In table 4.3 and figure 4.8 it can be seen the performance of each option for this DPM-B concept.

Table 4.3 Comparison for different propulsion system arrangement for DPM-B concept.

Characteristic	**Three engines Rotax 447 UL**	**One engine Rotax 912 ULS**
Total power	117 kW	69 kW
Fuel consumption at maximum power	60 l/h	25 l/h
Total cost	$10212 [38]	$17692 [4]
Total weight	80.4 kg	56.6 kg

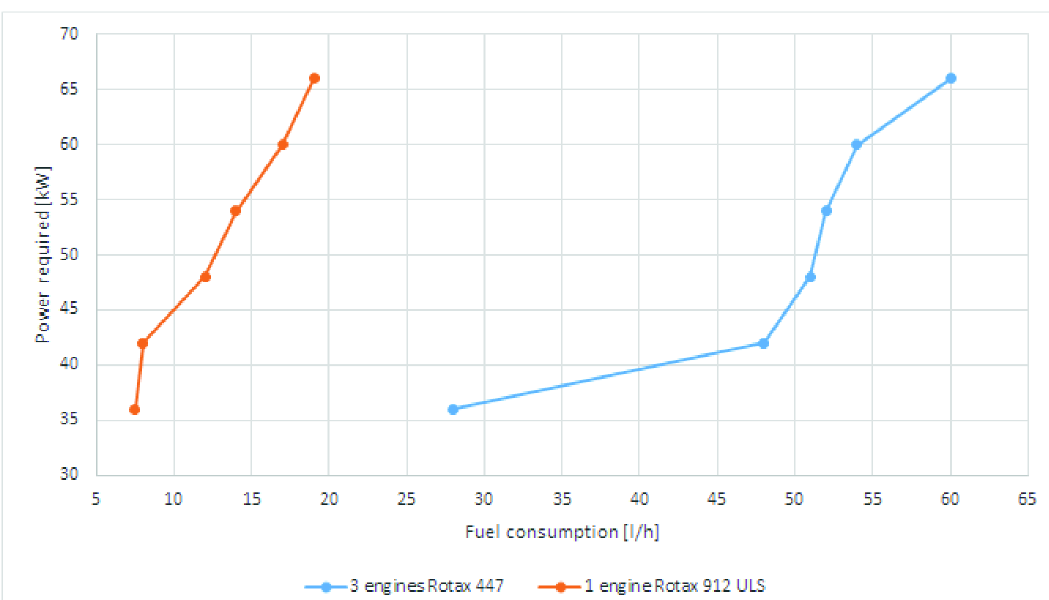

Figure 4.8 Performance comparison between 3 engines Rotax 447 UL vs. 1 engine Rotax 912 ULS.

In table 4.3 and figure 4.8 it could be seen that having three engines only provide bene fits for manufacturing cost, additionally with these engines the aircraft could have more power up to 117 kW. However, as harms it gets more weight and maintenance, due to each engine needs its own inspection. The major cost is the fuel consumption that this arrangement has. With this high fuel consumption, the aircraft increases its operational costs and pollution, specially CO_2 emissions.

The environmental analysis is essential in TERA approach, in figure 4.9 it can be seen the CO_2 emissions that each vehicle give o to the air, this means that for each automobile replaced by a DPM-A concept the air receives almost one ton of CO_2 less per year.

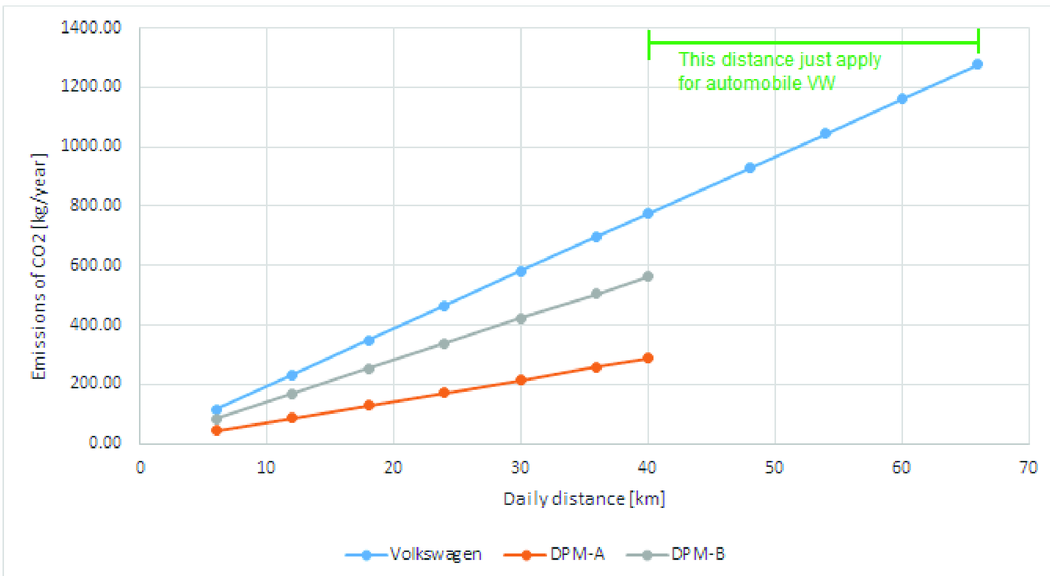

Figure 4.9 Emissions of CO_2 vs. range

About the cost of the aircraft in figure 4.10 there is a projection between three vehicles: Volkswagen Voyage, DPM-A concept and a Hyundai Tucson. This projection analyzes the price of each vehicle from the beginning through of ten years with an increase in prices of 3.66% that according to table 4.4 is the inflation average of these last seven years in Ecuador.

Hyundai Tucson has been selected because has an approaching cost of $40000 and is one of the most common automobiles in Quito. The idea is to compare the DPM-A concept with an automobile that has the same retail price. The Volkswagen Voyage is cheap for doing a good comparison.

Table 4.4 Inflation of Ecuador from 2010 up to present [11]

Year	Inflation
2010	3.56%
2011	4.47%
2012	5.11%

2013	2.73%
2014	3.59%
2015	3.97%
2016 (First semester)	2.17%
Average	3.66%

In table 4.5 the costs of Volkswagen Voyage, DPM-A concept and Hyundai Tucson with the projection of ten years is shown, the retail price of the DPM-A concept as $40000 by the author of this project has been selected. This table is for analyzing the costs that people interested in buy the aircraft should have to pay.

In this table four principal aspects have been considered: retail price, maintenance, fuel and oil. Every year the price has increased due to a 3.66% of inflation as is shown in table 4.4. A value corresponding to 10% of retail price was considered for spares that the vehicle requires every 3 years. Recordmotor (Volkswagen represent in Ecuador) suggest this projection of 10% every 3 years for spares. This cost of spares for retail price is used instead of maintenance because it is the price of the acquisition of parts.

For the Volkswagen Voyage all cost are the same that Recordmotor is handling. The same for Hyundai, costs were given by Asiacar who is one of the representatives for Hyundai in Ecuador. In table 4.5 the principal costs of Volkswagen Voyage, DPM-A concept and Hyundai Tucson through ten years are shown.

Table 4.5 Cost of each vehicle through ten years.

	2017	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**TOT. [USD]**
					Volkswagen Voyage						
Retail price	20000			2228			2481			2764	27473
Maint.	375	389	403	418	433	449	465	482	500	518	4432
Fuel	1104	1144	1186	1229	1274	1321	1369	1420	1471	1525	13044
Oil	105	109	113	117	121	126	130	135	140	145	1241
										Total	**46190**
					DPM-A concept						
Retail price	40000			4456			4963			5528	54946
Maint.	1000	1037	1075	1114	1155	1197	1241	1286	1333	1382	11819

Fuel	248	257	266	276	286	296	307	318	330	342	2925
Oil	70	73	75	78	81	84	87	90	93	97	827
										Total	**70517**
Hyundai Tucson											
Retail price	40000			4456			4963			5528	54946
Maint.	250	259	269	279	289	299	310	322	333	346	2957
Fuel	1325	1373	1424	1476	1530	1586	1644	1704	1766	1831	15660
Oil	130	135	140	145	150	156	161	167	173	180	1536
										Total	**78051**

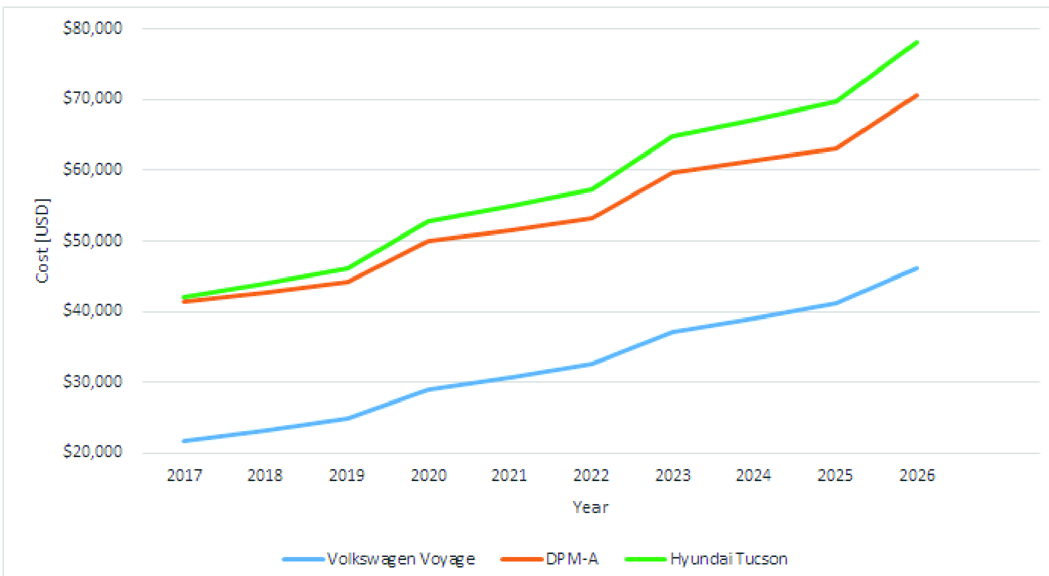

Figure 4.10 Total cost of DPM-A concept and VW Voyage through ten years of service.

The analysis shown in table 4.5 was made assuming that customers has enough money for buy the automobile Hyundai Tucson.

Below is shown another analysis for these three vehicles. In this case, the analysis if customers need to do a loan is made. Banco Pichincha has been selected for do the loan because this is the biggest bank in Ecuador, this bank has an interest rate of 16.06% for this kind of loans with a maximum term of five years. Following formulas use this interest rate and term for calculate different factors.

$$F_{EUAC} = \frac{i(1+i)^n}{(1+i)^n - 1} = \frac{0.1606(1+0.1606)^5}{(1+0.1606)^5 - 1} \tag{4. 2}$$

$$F_{EUAC} = 0.306$$

$$F_P = \frac{1}{F_{EUAC}} = \frac{1}{0.306} \quad (4.\ 3)$$

$$F_P = 3.27$$

$$F_{F/P} = (1+i)^n = (1+0.1606)^5 \quad (4.\ 4)$$

$$F_{F/P} = 2.106$$

The value of the investment at the end of five years is shown in table 4.7. For this calculus, the values of table 4.6 have been used, additionally the EUAC (equivalent uniform annual cost) and the present worth was calculated.

Table 4.6 Interest rate information.

Data for interest rate	
Years	5
Interest	16.06 %
EUAC factor	0.306
P factor	3.270
F/P factor	2.106

Following sample of calculus for the DPM-A concept is made, using the same values from the first column of table 4.5. The results of these calculus for three vehicles mentioned above are shown in table 4.7.

$$EUAC = Ret. * F_{EUAC} + (Costs) = 40000 * 0.306 + (1000 + 248 + 70) \quad (4.\ 5)$$

$$EUAC = 13552\ USD$$

$$P(A) = Ret. + Costs * F_P = 40000 + (1000 + 248 + 70) * 3.27 \quad (4.\ 6)$$

$$P(A) = 44310\ USD$$

$$Investment_{DPM-A} = P(A) * F_{F/P} = 44310 * 2.106 \quad (4.\ 7)$$

$$Investment_{DPM-A} = 93306\ USD$$

Table 4.7 Investment calculus for Volkswagen Voyage, DPM-A concept and Hyundai Tucson.

	VW Voyage	DPM-A	H. Tucson
Retail price [USD]	20000	40000	40000
Maintenance [USD]	375	1000	500
Fuel [USD]	1104	248	1325

Oil [USD]	105	70	130
EUAC [USD]	7700	13552	14189
P(A) [USD]	25178	44310	46392
Investment [USD]	53020	93306	97692

4.2. Labor analysis

As could be seen in section 3.2 the three materials that are most used in aircraft industry can be found in Ecuador, these are wood, aluminum alloys and composite materials.

The actual standards of safety and technology set a barrier to build wood aircraft, for this step the aircraft construction using aluminum and/or composite materials have been considered. The majority of aircraft are built from aluminum alloys; therefore, this material is the best choice to build an aircraft in Ecuador. Aluminum is a common material that the Ecuadorian market produces.

From table 3.2 it could be seen that total aircraft material price of aluminum or fiberglass is more than $1000, this includes labor price. This price is not too expensive if considers the aircraft fuselage construction in comparison with a retail price of aircraft like table 1.3 shows, in addition if the production increases the manufacturing costs are reduced. This new market is an opportunity to increase other industries that are involved in aircraft manufacturing, such as: painting, oil, aluminum, wheels, glass, electronics and similar industries.

In figure 4.11 it can be seen a chart with different hourly compensation cost in manufacturing for different countries, the difference is significant if compares prices between countries of first world with a great aircraft industry like Germany and countries of third world with a medium aircraft industry like Brazil. Therefore, the labor price is practically what increase or decrease the manufacturing costs in an aircraft, much more than material costs.

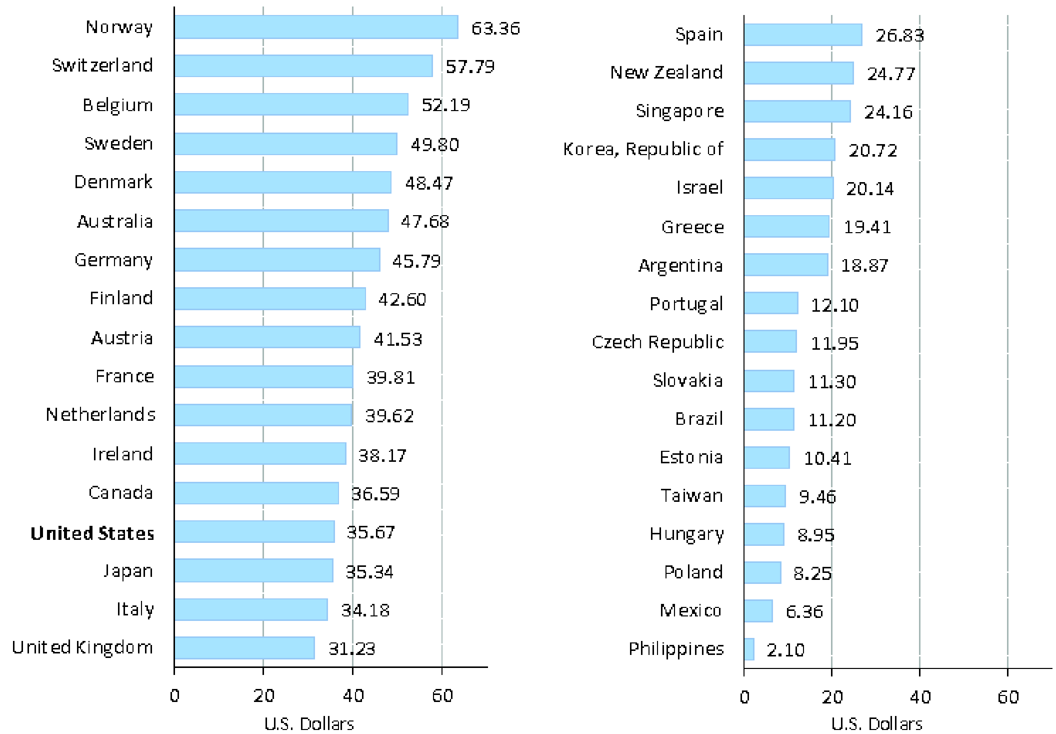

Figure 4.11 Hourly compensation cost in manufacturing, U.S dollars, 2012. [25]

4.3. Comparison between similar aircraft

Understanding the scenario and the environment in the aviation industry in terms of a future market to get in, a review of new personal aircraft models was undertaken, with an aim to establish the research conducted into understanding the applications, retail prices and effects of environmental policies.

TERA has been used widely in various EU projects to conduct design space exploration and trade-off studies, parameter sensitivity analysis, asset management, multidisciplinary optimization and to assess the effects of environmental policies [66].

The first aircraft analyzed in this step is the Calidus Auto Gyro [9], this aircraft has a rotor, propeller and does not have wings. This aircraft is produced by the German company Auto Gyro and requires a short runway of take-off; it is made of glass and carbon fiber and has one fuel engine that is the Rotax 912 ULS. Calidus can fly at cruise speed of 160 km/h.

Figure 4.12 Calidus Auto Gyro. [8]

The next aircraft analyzed is the PAL-V ONE [31], this aircraft has a rotor, propeller and does not have wings. This aircraft is produced by the Netherlands company PAL-V and requires a short runway of take-off; this aircraft has the characteristic of being an automobile too, in fact this is the first automobile/aircraft which can be used like any of two options. PAL-V ONE can fly at a cruise speed of 180 km/h.

Figure 4.13 Pal-v One. [32]

The next aircraft analyzed is the EHANG 184 [20], this aircraft has eight rotors with electrical engines and does not have wings. This aircraft is produced by the Chinese company EHANG and focuses in traveling short distances like inside of a city due to its flaying time is only 23 min at speed of 100 km/h; this aircraft has the characteristic of being used just for cities at sea level due to works under 500 m of height but is very friendly with the environment because it uses electrical energy for its motion.

Figure 4.14 Ehang 184. [21]

The next model is a type of electric motor designed for SIEMENS [41], this motor has a power of 260 kW and weights just 50 kg, with this power and weight this new age of motors can increase the design of new small aircraft with the advantage of using an electrical motor, therefore is very friendly with the environment. This motor is recently developed and not much information about it is available indeed.

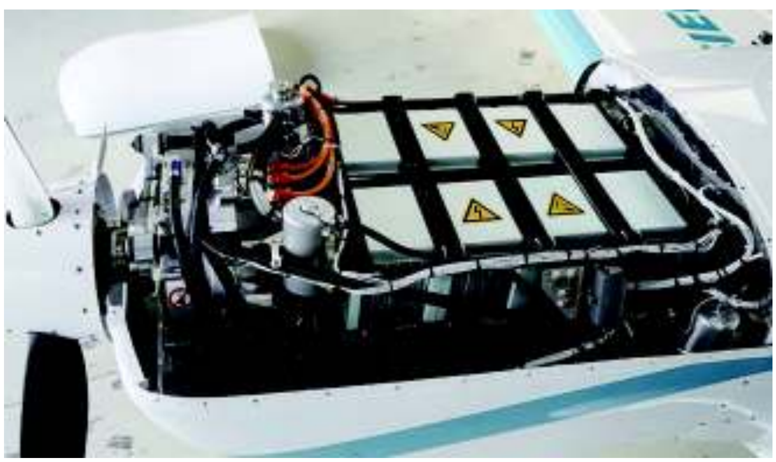

Figure 4.15 Siemens 260 kW. [41]

To conclude this section, it must be noted that these type of small or light aircraft requires the latest technology for energy and materials, therefore if the design of this project can reach the real construction and starts a new industry in Ecuador, this could help other industries to build some parts of aircraft, principally using new materials like composite materials. Hence, this generates new jobs and if may be being a new option capable of substituting the vehicles market, which is the major aim of this project, (focused in people that travel alone and through the city of Quito). Finally, these aircrafts diminish the emissions not by having a special engine but by reducing the travel time that is the time that vehicle is expelling gases to the environment. Table 4.8 shows a compilation of all characteristics from mentioned aircraft in this subsection.

Table 4.8 Comparison of DPM-A and DPM-B concepts with novel aircraft of similar characteristics.

	Calidus	Pal-V	E-hang184	DPM-A	DPM-B
Origin country	Germany	Nether lands	China	Ecuador	Ecuador
Power source	Fuel	Fuel	Electric	Fuel	Fuel
Cruising speed [km/h]	160	180	100	180	180
Range [km]	800	400	38	60	60
Load capacity [kg]	110	245	100	149	*
MTOW [kg]	560	910	200	360	476
Power output [kW]	55	150	106	27	56
Energy consumption	15 $^{l}/_{h}$	28 $^{l}/_{h}$	14.4 $^{kW}/_{h}$	2.3 $^{l}/_{h}$	14 $^{l}/_{h}$

* Due to this aircraft was a conceptual design MEW was not calculated.

4.4. Summary of section 4

Section 4 shows the TERA approach through a comparison between DPM-A concept, DPM-B concept, automobile Volkswagen Voyage and the Cessna 172 was made to see the energetic performance. An example of a daily journey from home to work of projects author was made to analyze the fuel consumption that each vehicle would have if the author would use those aircraft to travel. These results were compared with the authors automobile to see the benefits and harms of traveling with an aircraft or an automobile. Additionally, the DPM-A concept was compared with the Cessna 172 to see which one would have the best performance and fuel consumption, in the case that there were no restrictions for travel in aircraft. This comparison has allowed to see the benefits of having a personal aircraft built in Ecuador against a commercial family aircraft like Cessna 172. From figure 4.2 to figure 4.9 different comparison between mentioned vehicles were shown. These comparisons cover aspects like fuel burned, fuel cost, performance power, power loading, height of flight, different engines for DPM-B concept and CO_2 emissions.

Other important aspect considered in this section was the environmental contribution, as it could be seen on figure 4.9 the DPM-A concept gives o less than one ton per year of CO_2 in comparison with a Volkswagen Voyage that is a common vehicle in Ecuador.

Tables 4.5 and 4.7 show a comparison between the costs of DPM-A concept and two automobiles which are very common in Ecuador, these automobiles are the Volkswagen Voyage which was used in this project; and the Hyundai Tucson because is a popular with a retail price similar at selected for DPM-A concept.

Table 4.5 shows the costs that each vehicle has in a term of ten years, considering the principal aspects and an approach inflation of 3,66% as table 4.4 shown. This step considers as customer has the enough money for purchasing the vehicle without a loan.

Table 4.7 shows the costs that each vehicle has in a term of five years. For this case, a bank loan has been considered with an interest rate of 16.06%. This table shows the investment that each customer need to do for acquire each vehicle at the end of five years that loan ends.

Figure 4.10 shows the behavior of values from table 4.5. It could be seen that the DPM-A concept is more expensive than the Volkswagen Voyage but is not as expensive as the Hyundai Tucson through the term of ten years. DPM-A concept and Hyundai Tucson starts almost with the same costs but in the time with aircraft fuel saving this price gap is increasing at the end of ten years. At the first year the cost difference was almost 0% but at the end of ten years the difference is more than 10%. Price of Volkswagen Voyage is considerably cheaper than aircraft, the principal causes are the retail price and the maintenance costs.

Finally, a comparison between DPM-A and DPM-B concepts with other novel aircraft was made. The idea of this comparison is affording knowledges about the new personal aircraft that worldwide market offers. These aircraft have different shape at common airplanes or helicopters. In table 4.8 it can be seen this comparison for principal aspects.

5. CONCLUSIONS AND FUTURE WORK

A preliminary design based in propulsion system and airframe for a personal aircraft has been developed successfully with it respectively techno economic analysis. The advantage of this design is low fuel consumption due to a quicker time traveled.

This section summarizes the work accomplished during the preliminary design for a personal aircraft. Observations and conclusions based on the results of this project are also presented. Finally, recommendations for future work are given.

5.1. Conclusions

A preliminary design for two concepts DPM-A and DPM-B was made focused in propulsion system, airframe and weight of principal elements. All motion and sizing equations for concept DPM-A are developed but only propulsion equations are developed for concept DPM-B because is a novel design which needs a prototype into a wind tunnel to obtain the required coefficients for develop sizing and weight. Similar aircraft like DPM-B concept are scarce. Only the CALIDUS and the PAL-V ONE are similar but it is not easy to find information to make a preliminary design in airframe or aerodynamics. Therefore, to build a DPM-B concept it is necessary to make a scale prototype and subject it to laboratory tests to obtain the drag and lift coefficients. Then it can start designing the airframe. This task is trial and error until it obtains a model with high performance.

The dimensions and weight of defined elements, shown that Ecuador is a country with enough technology to carry out the construction of DPM-A concept. These types of aircraft, like DPM-A concept, could be used for patrolling remote zones, like mountains or jungles. Another niche market for these type of aircraft is the fumigation of banana plantations because is the principal exportation fruit of Ecuador. Most of elements which make up DPM-B concept are feasible to build in Ecuador, except rotors and engine. DPM-B concept involves a concept that does not require a long runway for take-off and landing. This becomes the DPM-B concept better to achieve the aim of flying over the Quito airspace. The best arrangement for propulsion system in the DPM-B concept is to have one engine because at maximum power three engines consume 60 l/h which is triple in comparison to flying with one engine that is 20 l/h. On the other hand, the design requires more mechanical elements to drive each rotor and propeller with the same engine. Even so, having one engine and more mechanical elements like gearboxes and clutches is more profitable than having more engines.

The DPM-A concept is feasible to build in Ecuador due to most of the elements which make up the fuselage and structure, even the propellers, could be built in Ecuador. Unfortunately, Ecuador is not ready yet to build its own engines which requires certain expertise. Ecuador has a large market for aluminum alloys and fiberglass. These materials supply enough components to build the structure and airframe of aircraft. Carbon fiber is a new material that it is currently being developed around the world to build aircraft because is stronger and lighter than fiber glass. However, this material is not produced in Ecuador and it is also quite difficult to find it in the market. Aluminum alloys would be the best choice of material to build aircraft in Ecuador because it has high resistance, low weight, low price and it is easy to be manipulated compared to fiberglass. There are hybrid materials that can be developed to produce some components of the aircraft, these hybrid materials are not easy to find in the Ecuadorian market but studies show that they have more resistance than fiberglass. For example, Delgado, Galeas and Guerrero [51] show the increasing of resistance, principally to bending, of hybrid composites like polyester matrix reinforced with coconut and glass fibers. The cheap labor price in Latin American countries makes Ecuador a strategic place to put an industry of this nature. The beginning of an aircraft industry can make competition against aircraft factories around the world, with lower prices, not only in manufacturing but also in maintenance.

An automobile is the vehicle which most fuel consumes in comparison to both concepts because people choose to travel alone in their own vehicles instead to use public transportation or sharing their vehicles. The DPM-B concept promises to be an option for singular drivers that travel long distances throughout Quito every day, like the author of this project. DPM-A concept is the vehicle with less fuel consumption. The most important constraint for this aircraft is that it requires a runway. The DPM-B concept has VTOL and spend less than 50% of fuel than an automobile burns in a year. The fuel savings become money and produces less pollution. The goal of reducing travel time is reached by run in a straight line without stops. DPM-B concept generates savings more than 600 $^{USD}/_{year}$ in comparison to an automobile and directly reduce the CO_2 emissions. In fuel cost, an aircraft is the best choice but in operational cost an aircraft is more expensive. Automobiles with low retail price like Volkswagen Voyage are more convenient than DPM-A concept economically, but other vehicles with the same or higher retail price than DPM-A concept are not economical or environmentally friendly.

5.2. Shortcoming of the DPM-A and DPM-B concepts

With all these positive conclusions that have been made, these concepts may seem to be a solution for traveling through Quito without traffic in a short time while reducing fuel consumption in comparison with an automobile. The preliminary design is the right way but it is not a detail design.

While the aim to obtain a preliminary design of a personal aircraft has been reached with reasonable accuracy, further work is needed to estimate the final manufacturing and operational costs. As Raymer [68] indicates in his book, an aircraft production begins with the design and fabrication of the production tooling. Historically, this has been a massive and expensive undertaking, with hundreds or thousands of expensive jigs and fixtures being built.

Quito is a city placed in the middle of mountains, therefore, in certain seasons, especially August [45] is under strong winds that reach sometimes a speed of 70 km/h. This situation could become an important factor to be considered now that this type of industry begins. A wind or weather study in Ecuador is not a goal of this project and therefore was not considered for this purpose.

5.3. Recommendations for future work

As mentioned throughout this project, a preliminary design is the right way to begin a production of these aircraft, but it is just the first step. More aspects need to be considered to make a better design closer to reality. For example, weather considerations, socioeconomic study for the acceptance of this project into society of Quito, permission from the Ecuadorian civil aviation or Quito transit agency, safety and security system for the aircraft and so on.

The next step is to make a detail design including the airframe and structure analysis for DPM-B concept. Once that detail design has been developed is feasible to build a prototype to find all weighs with accuracy and then propulsion system could be calculated with real values.

Nowadays, with CAD tools, some of these elements can be simulated. Reducing time and saving money in comparison with last decades.

Future thesis may take this project as incentive and starting with a detailed design of each aircraft element, designers or students could carry out a scale model or a prototype.

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Appendix A. Cessna 172 information

This appendix shows information about aircraft Cessna 172 [65] that is very useful in this project to compare calculated results with real values.

This information is shown In table A.1.

Table A. 1. Technical information of Cessna 172

Principal information	
Engine	160 HP Lycoming O-320-H (max. power at 2700 rpm)
Propeller	Two bladed fixed pitch metal propellers
Fuel capacity	43 US gallons (38 US gallons usable)
Baggage capacity	120 pounds
Principal dimensions	
Wing span	35 feet 10 inches
Wing root chord	5 feet 4 inches
Wing tip chord	3 feet 8.5 inches
Wing aspect ratio	7.52
Length overall	26 feet 11 inches
Height overall	8 feet 9.5 inches
Tailplane span	11 feet 4 inches
Propeller diameter	6 feet 3 inches
Wing area	174 square feet (gross)
Aileron area	18.3 square feet
Flap area	21.2 square feet
Vertical tail area	11.24 square feet
Rudder area	7.43 square feet
Horizontal tail area	21.56 square feet
Elevator area	14.53 square feet

Weight data	
Weight-Empty equipped	1403 pounds
Max. takeoff weight	2300 pounds
Max. wing loading	13.2 pound per square feet
Max. power loading	14.4 pounds per horsepower
Performance data	
Never exceed speed	174 mph
Max. level speed	144 mph (at SL)
Max. cruising speed	140 mph (75% power at 8000 feet)
Stalling speed	57 mph CAS (flaps up)
Stalling speed	51 mph CAS (flaps down)
Max. rate of climb	770 feet per minute (at SL)
Service ceiling	14200 feet

Appendix B. Rotax engines information

This appendix shows the principal information about engine Rotax 912 ULS [53] and Rotax 447 UL [53] that is used in the design of this project.

Following figures show principal features of each engine and the features at maximum power has been shown in table B.1 and table B.2.

Engine Rotax 912 ULS

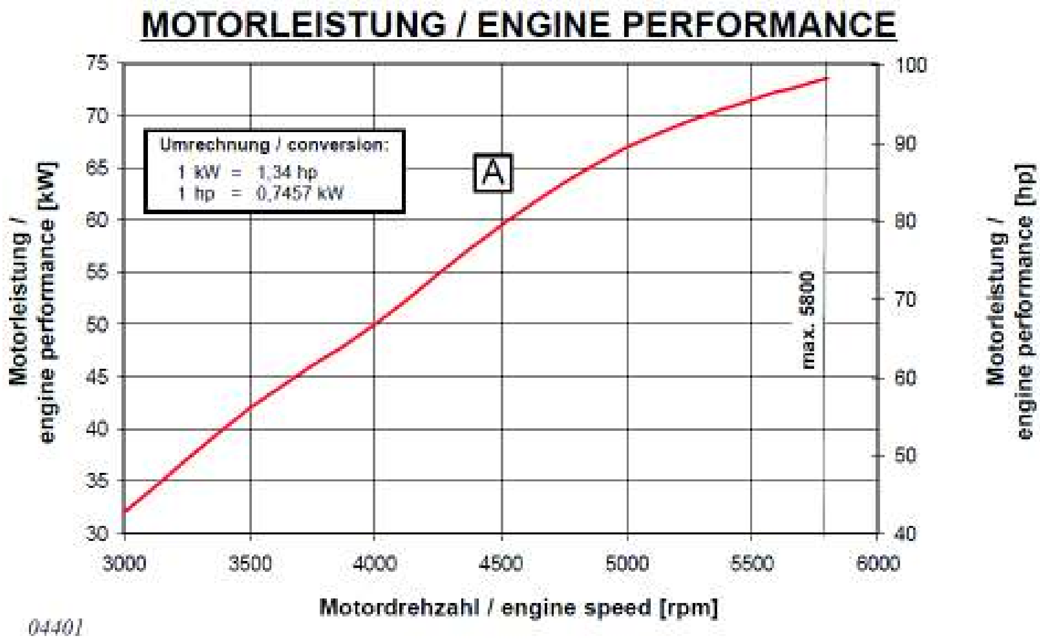

Figure B. 1. Power vs. engine speed for Rotax 912 ULS

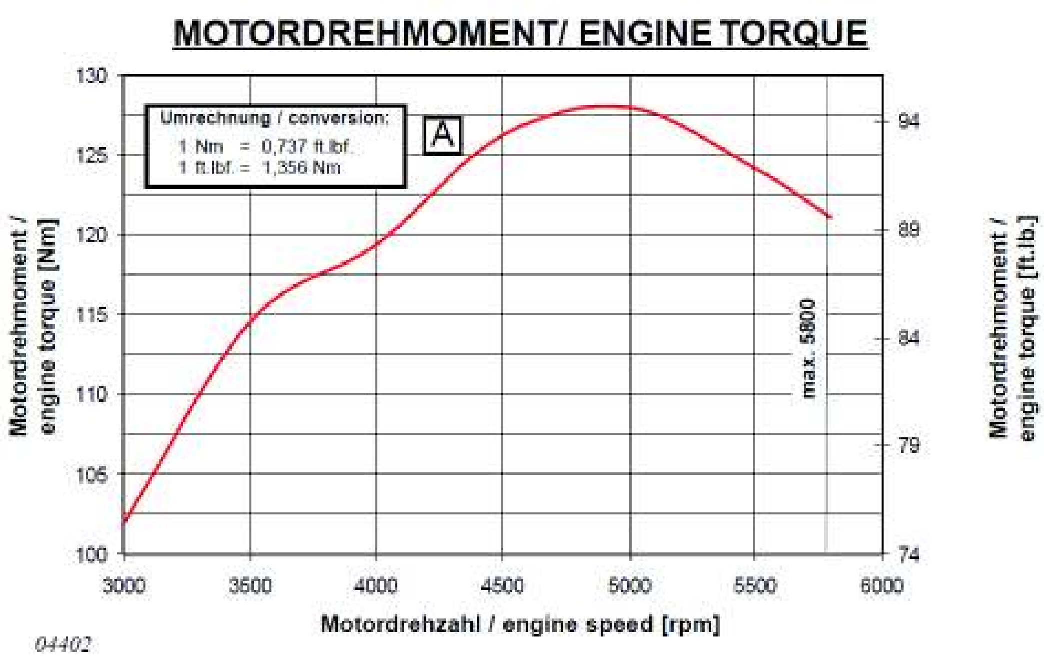

Figure B. 2. Torque vs. engine speed for Rotax 912 ULS

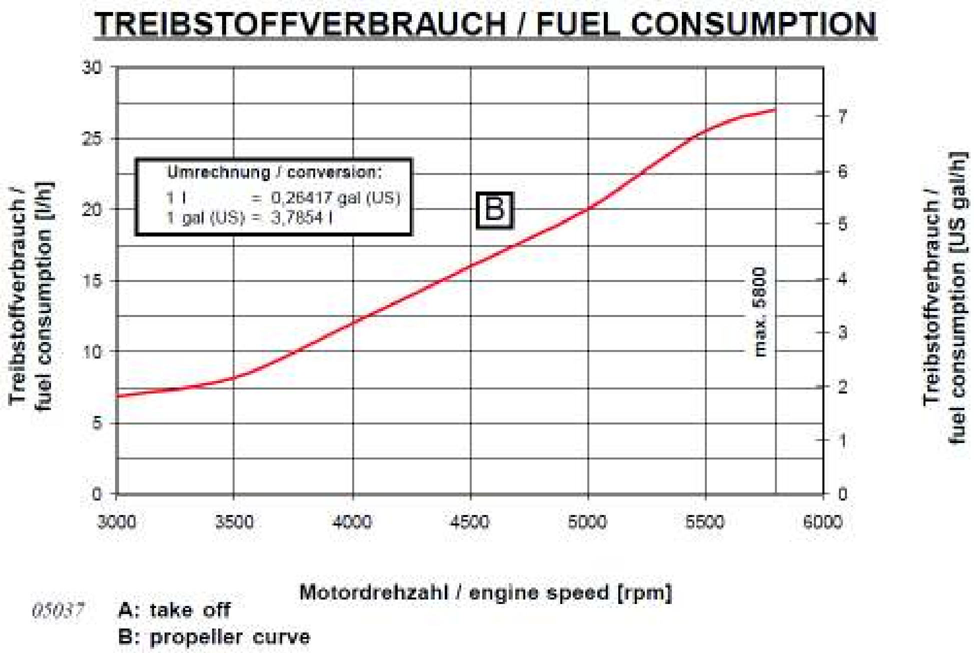

Figure B. 3. Fuel consumption vs. engine speed for Rotax 912 ULS

Table B. 1. Performance of Rotax 912 ULS according to power of 69 and 73.5 kW

Power	Velocity	Time	Torque	Gearbox	Weight
69 kW	5500 rpm	Continuous	128 Nm	i=2.43	56.6 kg
73.5 kW	5800 rpm	Max. 5 min.			

Engine Rotax 447 UL

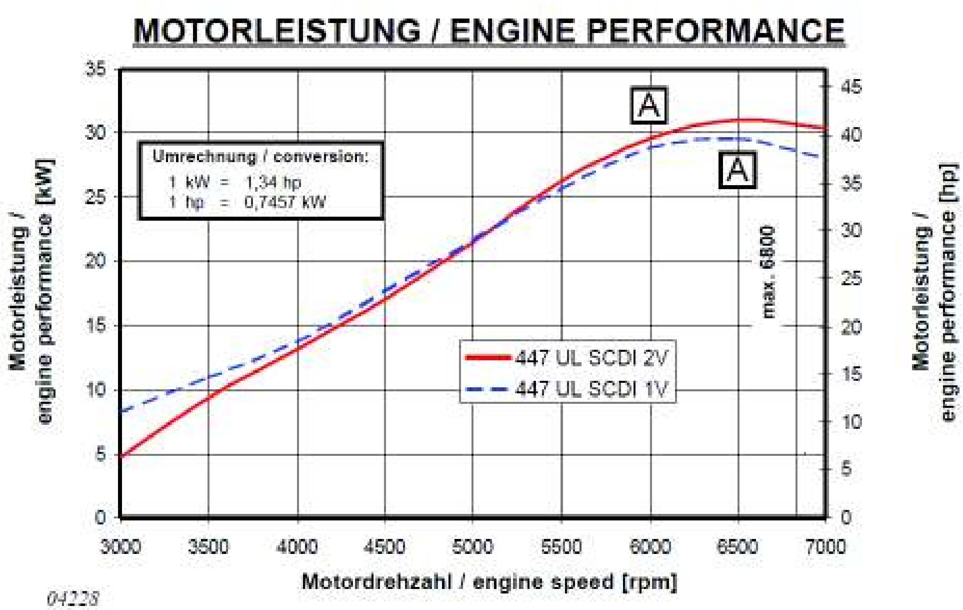

Figure B. 4. Power vs. engine speed for Rotax 447 UL

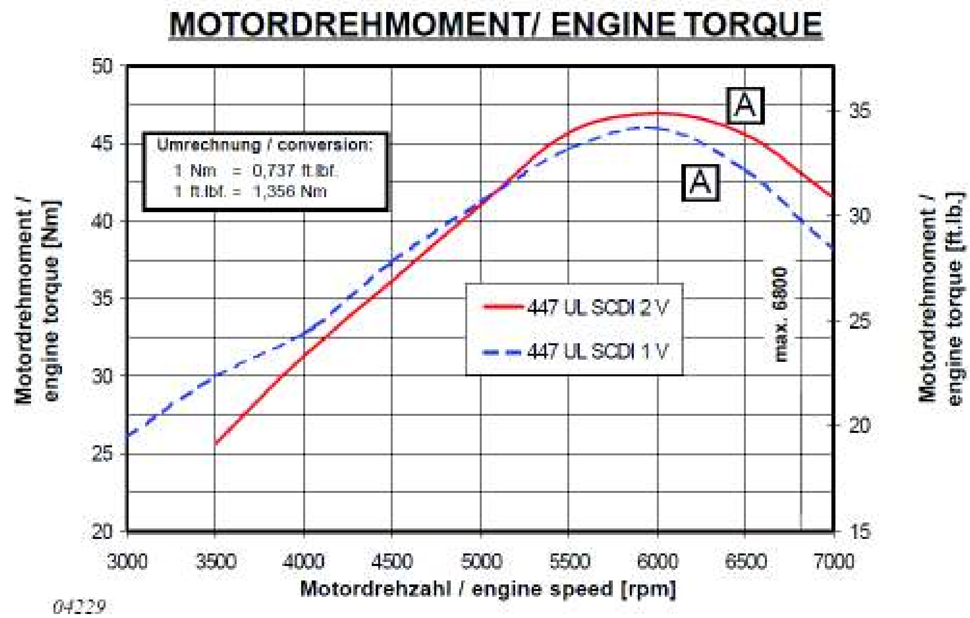

Figure B. 5. Torque vs. engine speed for Rotax 447 UL

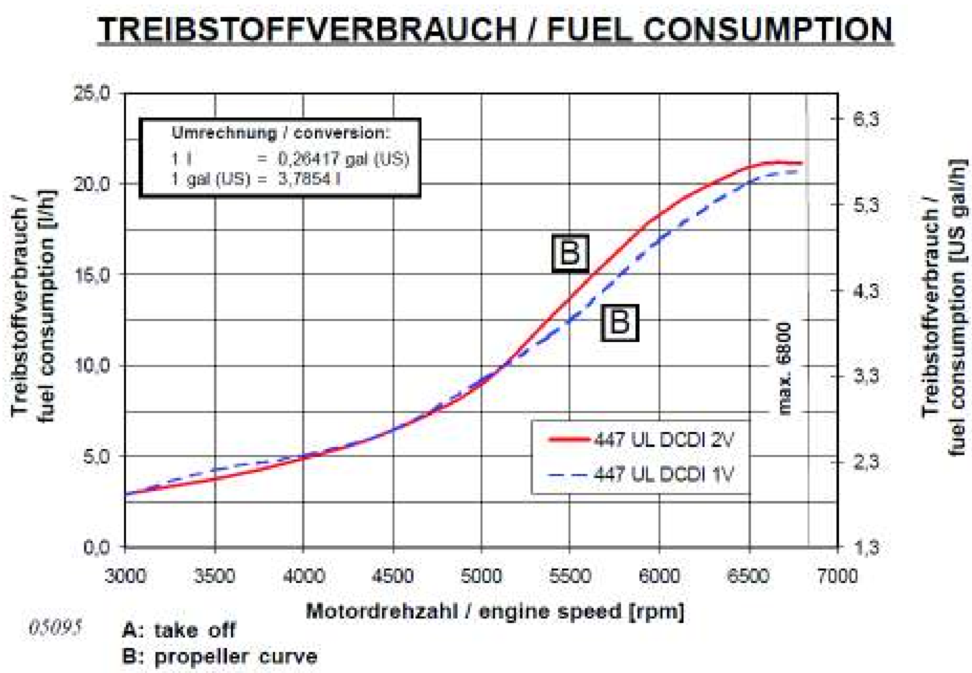

Figure B. 6. Fuel consumption vs. engine speed for Rotax 447 UL

Table B. 2. Performance of Rotax 447 UL according to power of 29.5 and 31 kW

Power	Velocity	Time	Torque	Gearbox	Weight
29.5 kW	6500 rpm	Continuous	46 Nm	i=2	26.8 kg
31 kW	6800 rpm	Max. 5 min.			

Appendix C. Scale model

This appendix shows the scale model that has been built to illustrate how it is like the DPM-B concept. In addition, the equation 1.30 is used to find the power that this scale model uses and compare it with real power. The purpose of this scale model is to show that it is possible to have an aircraft that has VTOL and a propeller in the rear side, this model confirms that an aircraft with this shape can fly, takeoff and land with-out a runway.

Figure C. 1. Scale model

In table C.1 technical data that this scale model has are shown. Additionally, there are constant values like downwash on fuselage and induced power factor that have been assumed like 1 due at the little size that scale model has.

Table C. 1. Technical data of scale model

Component	Value
Rotor radius r_r	0.1 m
Rotor surface S_r	0.03142 m^2
Number of blades N_b	2
Rotor blade chord c	0.023 m
MTOW W_0	0.04 kg
Induced power factor k	1
Angular speed ω	9000 rpm
Total parasite drag coefficient C_{D0}	0.008

Using values from table C.1 and applying equation 1.30 it gets for each rotor:

$$P_r/2 = 2.78\ W$$

This scale model works with independent motors. Therefore, total power for rotors is:

$$P_r = 2.78 * 2 = 5.56\ W$$

This scale model works with three motors. Each motor moves a rotor and the last one moves the propeller. The design of DPM-B concept shows that has one engine with a gearbox and clutches for handling each rotor and propeller. According to battery description of this scale model has a rating of 6,68 W, this means that around 6 W is real power consumption. Equations shown in subsection 1.2.1 are focused in real aircraft because has factors and constants obtained from laboratory tests and statistics data. Therefore, calculated power is not close from real power value. In table C.2 the features for calculate propeller power in scale model are shown.

Now the same calculus for the propeller is developed.

Table C. 2. Features for calculate propeller power in scale model

Component	**Value**
Propeller radius r_p	0.018 m
Propeller surface S_p	0.00102 m^2
Number of blades N_b	3
Rotor blade chord c	0.009 m
Thrust T	0.1 N
Induced power factor k	1
Angular speed ω	5500 RPM
Total parasite drag coefficient C_{D0}	0.1

Applying the equation 1.30 it has:

$$P_p = 0.74\ W$$

Total power for this scale model is:

$$P = P_r + P_p = 5.56 + 0.74$$

$$P = 6.3\ W$$

Following equations shows the error between the calculated and the real value.

$$\Delta E = \frac{|P_c - P_r|}{P_r} * 100\% = \frac{|6.3 - 6.68|}{6.68} * 100$$

$$\Delta E = 6\%$$

This means that used equations has an error of 6% for this scale model in comparison to battery information.

Appendix D. MTV propeller information

This appendix shows information about propeller MTV-34-1-A/164-200 [67] that was used in the design of DPM-A concept, this information was provided from MTV propeller company.

The “etaP” which is a propeller factor own of MTV company is shown in table D.1 according to other factors which are J (advanced ratio) and Cp (power coefficient).

Table D. 1. Performance of etaP in dependence of J and Cp for propeller MTV-34-1-A/164-200

>HELIX SYSTEM< *CP*	MTV-34-1-A/164-200	R0295M20 26.01.15
	*Adv.R. J von= 0,20 - bis= 2,00 - (= 20 Intervalle)	entsp. V von= 43,3 km/h bis= 433,0 km/h
	*Cp*E-2 von= 2,0 - bis= 16,0 - (= 20 Intervalle)	>> P_eff von= 19,4 % bis= 154,9 %
Copyright: MT-Propeller Entwicklung GmbH & Co. KG, Postfach 0720, D-94307 Straubing		

Wirkungsgrad etaP in Abhängigkeit von J und Cp

J =	Cp*E-2 = 2,00	2,70	3,40	4,10	4,80	5,50	6,20	6,90	7,60	8,30	9,00
0,200	0,414	0,446	0,443	0,432	0,418	0,405	0,391	0,377	0,364	0,349	0,335
0,290	0,479	0,555	0,568	0,562	0,550	0,537	0,524	0,511	0,498	0,485	0,472
0,380	0,516	0,622	0,650	0,653	0,646	0,636	0,625	0,613	0,602	0,591	0,579
0,470	0,544	0,665	0,705	0,716	0,714	0,707	0,699	0,689	0,680	0,670	0,660
0,560	0,570	0,693	0,740	0,757	0,761	0,758	0,752	0,745	0,737	0,729	0,721
0,650	0,592	0,712	0,763	0,785	0,792	0,793	0,790	0,785	0,779	0,773	0,766
0,740	0,610	0,725	0,778	0,803	0,813	0,817	0,816	0,813	0,809	0,805	0,800
0,830	0,621	0,733	0,786	0,813	0,826	0,832	0,833	0,833	0,831	0,828	0,824
0,920	0,625	0,735	0,789	0,818	0,834	0,841	0,845	0,846	0,845	0,844	0,842
1,010	0,576	0,731	0,789	0,819	0,837	0,846	0,851	0,854	0,855	0,855	0,854
1,100	0,029	0,722	0,783	0,816	0,836	0,847	0,854	0,858	0,861	0,862	0,862
1,190	-0,084	0,705	0,773	0,809	0,831	0,845	0,854	0,859	0,863	0,865	0,867
1,280	-0,274	0,152	0,758	0,799	0,825	0,841	0,851	0,858	0,863	0,867	0,869
1,370	-0,244	0,081	0,738	0,785	0,815	0,833	0,845	0,854	0,860	0,866	0,869
1,460	1,095	1,215	0,729	0,770	0,802	0,823	0,839	0,849	0,857	0,863	0,867
1,550	1,058	1,276	1,230	0,753	0,788	0,812	0,829	0,842	0,851	0,858	0,864
1,640	1,297	1,301	1,193	0,733	0,770	0,798	0,817	0,832	0,843	0,852	0,858
1,730	0,999	1,240	1,262	1,216	0,752	0,782	0,804	0,821	0,834	0,844	0,851
1,820	1,318	1,122	1,246	1,234	0,730	0,764	0,789	0,809	0,824	0,835	0,844
1,910	0,944	1,566	1,219	1,220	0,763	0,745	0,774	0,795	0,811	0,825	0,835
2,000	-1,334	-1,018	-0,241	-0,094	0,110	0,719	0,756	0,779	0,798	0,813	0,825

Cp = P/(rho*n^3*D^5)	J = v/(n*D)	Ct = Cp*etaP/J

Figure D.1 shows the relationship between power coefficient and advanced ratio according to propeller efficiency.

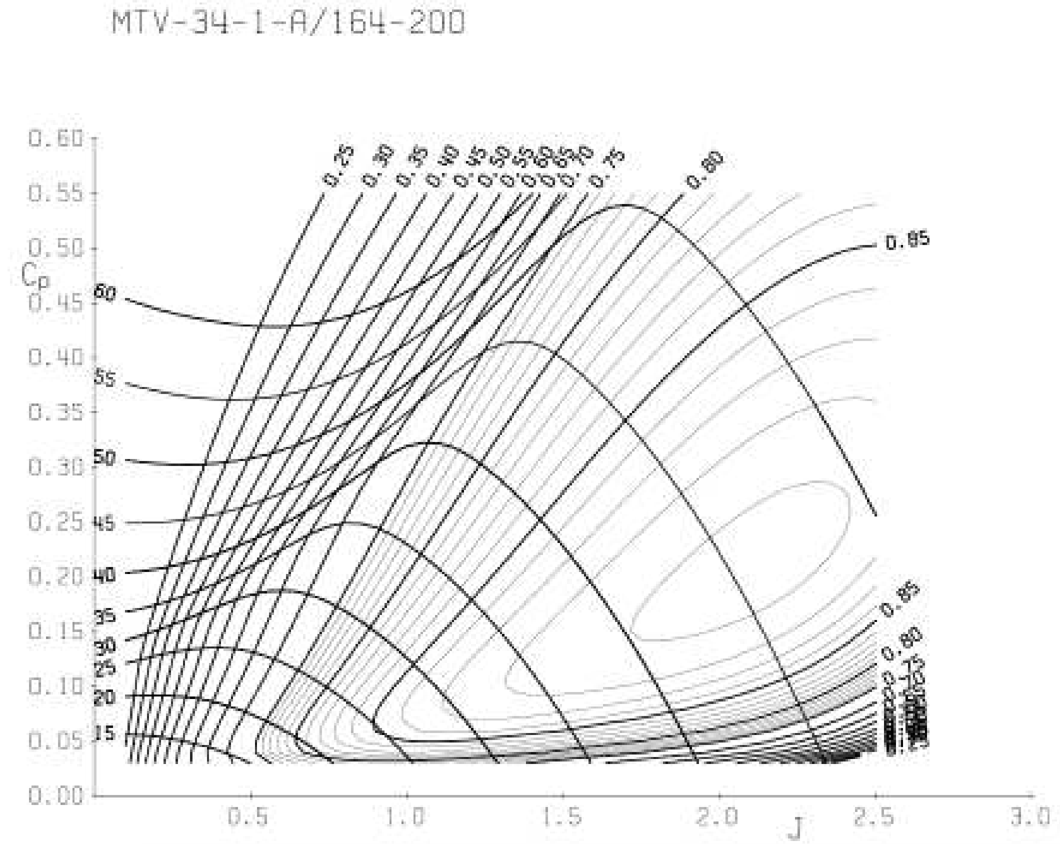

Figure D. 1. Cp (power coefficient) vs. J (advanced ratio) according to efficiency for propeller MTV-34-1-A/164-200

Appendix E. Robinson R22 beta II estimated operating cost

This appendix shows information about estimated operating cost that helicopter Robinson R22 beta II has, this information was provided from Robinson company [58].

Retail price of R22 Beta II is around 300000 USD [58].

Table E. 1. Fixed annual costs for helicopter Robinson R22 bet II

Fixed annual costs	
Depreciation (Negligible, freshly overhauled R22s typically sell for more than original costs)	N/A
Insurance based on a pilot with 200 hours logged helicopter time, including 40 PIC hours in an R22, with a good safety record and RHC Safety Course Certificate	
Liability Insurance	1920 USD
Hull Insurance	6130 USD
FIXED COST PER YEAR	8050 USD

Table E. 2. Reserve for overhaul for helicopter Robinson R22 bet II

Reserve for overhaul	
2200 Hour Engine Overhaul ($29,000 RHC exchange)	13.18 USD/h
2200 Hour Aircraft Overhaul Parts Kit ($85,000) (Includes new bearings, seals, belts, etc., and life-limited components with less than 2200 hours remaining.)	32.64 USD/h
Labor (225 Man-hours @ $95 per hour)	9.72 USD/h
RESERVE	61.54 USD/h

Table E. 3. Direct operating cost for helicopter Robinson R22 bet II

Direct operating cost	
Fuel @ $5.50 per gallon and 8.0 gph for average use	44.00 USD/h
Oil	0.90 USD/h
Periodic Inspections, Labor @ $95 per hour	11.40 USD/h
Unscheduled Maintenance, Parts and Labor @ $95 per hour	7.03 USD/h
DIRECT OPERATING COST	63.33 USD/h

Table E. 4. Total operating cost for helicopter Robinson R22 bet **II**

Total operating cost	
Fixed Cost per Flight Hour Based on 500 Hours per Year	16.10 $^{USD}/_{h}$
Overhaul Reserve Per Hour	61.54 $^{USD}/_{h}$
Direct Cost per Flight Hour	63.33 $^{USD}/_{h}$
TOTAL OPERATING COST	140.97 $^{USD}/_{h}$