THEORETICAL BACKGROUND

This report describes the theoretical principles and algorithms as implemented in the modelling module of your ADS software [1]. After a description of the general approach, you will find more detailed information about the iterative algorithms and the various models used.

TABLE OF CONTENTS

1. Methodology

ADS allows you to do your Conceptual design in 3 stages:

1. Designing with fixed constraints
2. Designing with fixed means
3. Designing with fixed geometry

1.1 Designing with fixed constraints

For designing a new aircraft, the designer may start with a set of specifications and use this information as input data. His goal is to find the parameters of the most optimized aircraft configuration which will meet the design specification.

Initially, the designer should start without prejudice and keep all options open. He should consider any imaginable and possible solution (fixed or retractable landing gear, two stroke or four stroke engine, rotary or turbine engine, taildragger or tricycle landing gear, canard or tandem configuration, etc…), including those which may appear unconventional.

To achieve this, he will study a limited set of parameters. Only "1st order parameters" will be evaluated, i.e. those parameters which will significantly affect the results. For example, he will not assume a predetermined engine, but instead he will assume an engine of a predetermined technology.

The level 1 analysis uses a "flexible engine" (rubber engine) The engine power required to meet the design specification will be calculated. At a later stage, the designer will search in an engine database to find "the real engine" which will best match the "flexible engine".

The results of the level 1 design process will allow the designer to define an aircraft configuration which will meet the design specification. The geometry (wing and tail sizing, etc…) of the aircraft is calculated as well as the thrust (engine power, propeller properties). Only the main flight condition (typically cruise flight) will be explored, as the input data are not accurate enough to explore other flight conditions (climb, take-off, descent).

1.2 Designing with fixed means

Once satisfied with the results obtained, the designer proceeds to the second stage of the process: the Design with fixed means.

The number of parameters used will increase and the input data will become more accurate. Certain information will be sourced directly from product databases. The "flexible engine" is substituted by a real engine which closely matches the properties of the "flexible engine". Values, which in the previous stage were selected by statistical analysis, will be verified by extensive algorithms. The increase in lift for the type of flaps used will be computed. The total drag will be defined more precisely as the sum of distinct drag components. A weight estimate will be made. All flight conditions will be explored. The stability will be checked. Finally, a virtual 3D scale model will be generated which will enable the results of the design process to be verified and appreciated visually.

1.3 Designing with fixed geometry

The final stage in the process is the design with fixed geometry.

One goal is to show what the effect would be of parameters that are “off-target”. What will be the impact on the aircraft performance if the weight of the aircraft turns out to be slightly different? What margins are acceptable? Where is the limit to be set?

It is also possible to show the impact of modifications to an existing aircraft. What is the overall impact on the aircraft of a wing modification? Change in weight, change in drag, change in performance,… The improvements obtained in reality can often be very different from what was initially expected or aimed for.

2. Algorithms

Each stage of the Design process is detailed below. The input data required for each stage is listed in [2]. When progressing through the different levels, the software will gradually ask you to insert additional information and data.

2.1 Definition

Let's first define the parameters we will use in this section:

Symbols	**Definition**
BHP	Engine power
Cl_{Max}	Maximum lift coefficient
Cl	Lift coefficient
CS	Climb slope
ΔCl_{Max}	Maximum lift coefficient increment
D	Drag
L	Lift
M_{fuel}	Fuel weight
M_{mot}	Engine weight
M_{prop}	Propeller weight
M_{ut}	Useful weight
M_d	Maximum takeoff weight
M_v	Empty weight
RC	Rate of climb
R_h	Propeller efficiency
Sa	Wing area
Tob	Propeller thrust (gross)
Ton	Propeller thrust (net)
V	Flight speed
WA	Wetted area

2.2 Level 1

The iterative process at level 1 is shown in Figure 1. The process starts with the initialisation of constants linked to the selection of input data. Then, only the iterations related to the weight are performed. Finally, the various parameters for the resulting configuration are derived.

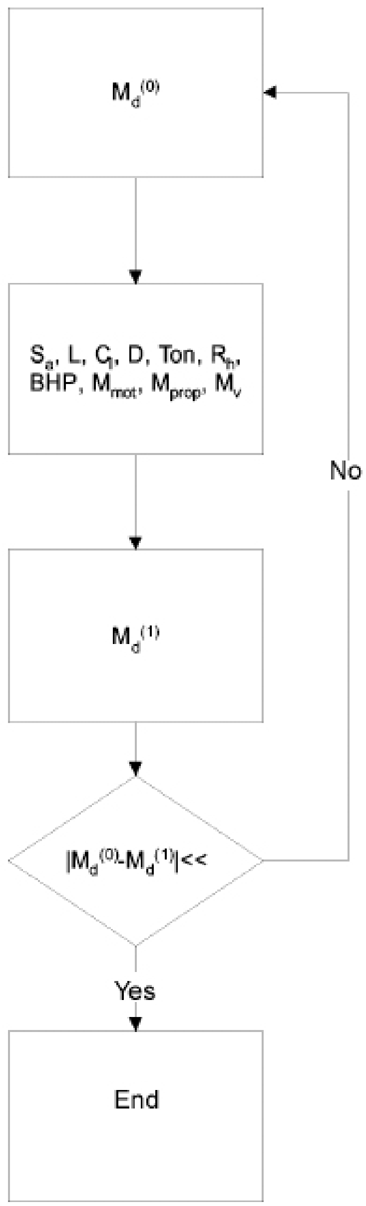

Figure 1: iterative process at level 1

2.3 Level 2

The iterative process at level 2 is shown in Figure 2. As before, the process begins with the initialisation of constants linked to the selection of input data. However, now the iterations performed are related to weight and speed. Once again, various parameters for the resulting configuration are derived, as well as the different types of drag. The drag and thrust curves are plotted (RC, Cs and the propeller performance for speeds ranging from 0 to V_{max}). The take-off distance, best climb rate and climb angle are also computed.

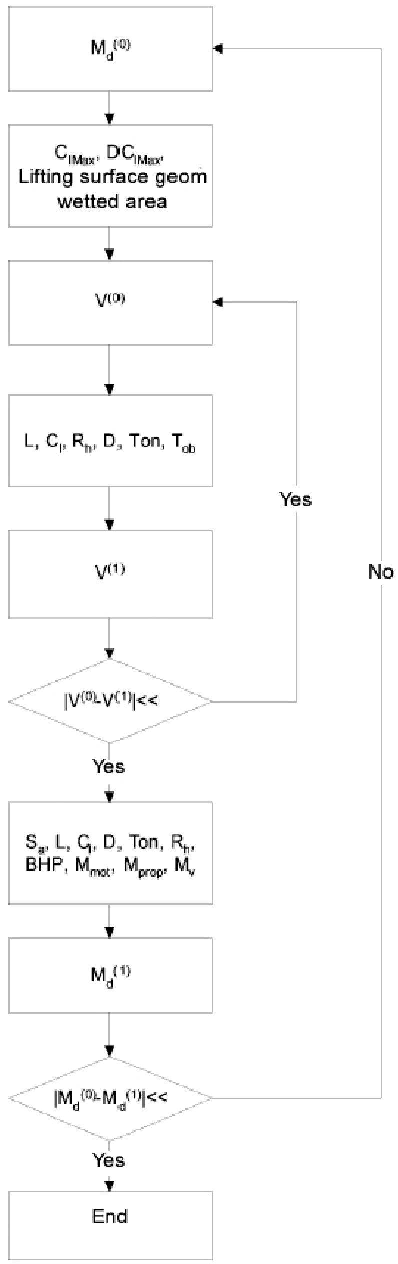

Figure 2: iterative process at level 2

2.4 Level 3

At this level , the process is no longer iterative, since the geometry is now fixed. The goal is not to find the performance for a given configuration.

ADS will perform the level 3 as follows:

1. Initialisation of constants linked to the selection of input data
2. Computation of information related to the geometry of wing, empennage, fuselage, WA, C_{LMax}, ΔC_{lMax}
3. Computation of specific weights, M_v, V
4. Computation of different type of drag, including interference drag
5. Computation of drag and thrust curves (for speeds ranging from 0 to V_{max}, calculation of RC, CS, drag, propeller performance)
6. Calculation of best rate of climb
7. Calculation of best climb angle
8. Calculation of take-off distances

3. Principles

The theory, principles and models which have been implemented in the algoritms which are used for estimating parameters (lift, drag, etc…) are given below .

3.1 Aerodynamics

3.1.1 Lift

Source : [3].

Wing lift is found by computing the spanwise distribution of the lift coefficient, based on the theory of a “loaded line”. The local lift is computed taking into account the wing planform and other properties, such as twist and incidence. The maximum wing lift is generated when somewhere along the span, the local lift coefficient reaches the maximum lift coefficient of the wing section.

3.1.2 Lift increment (ΔC_{lMax})

Source :[4].

$$\Delta C_{lMax} = base k_1 k_2 k_3 k_4 K_S wp$$

with :

- base : [4] p240, fig.8.31
- k_1 : correction coefficient [4]p240, fig.8.32
- k_2 : correction coefficient [4]p241, fig.8.33
- k_3 : correction coefficient [4]p241, fig.8.34
- k_4 : ratio of the flapped wing area to the total wing area
- K_Swp : effect of wing sweepback on the correction coefficient for maximum lift due to the flaps [4]p263, fig.8.55
- DC_{lMax} is computed for different flap types (Fig.3) :
    - plain flap,
    - split flap,
    - single slotted flap,
    - double slotted flap,
    - fowler flap.

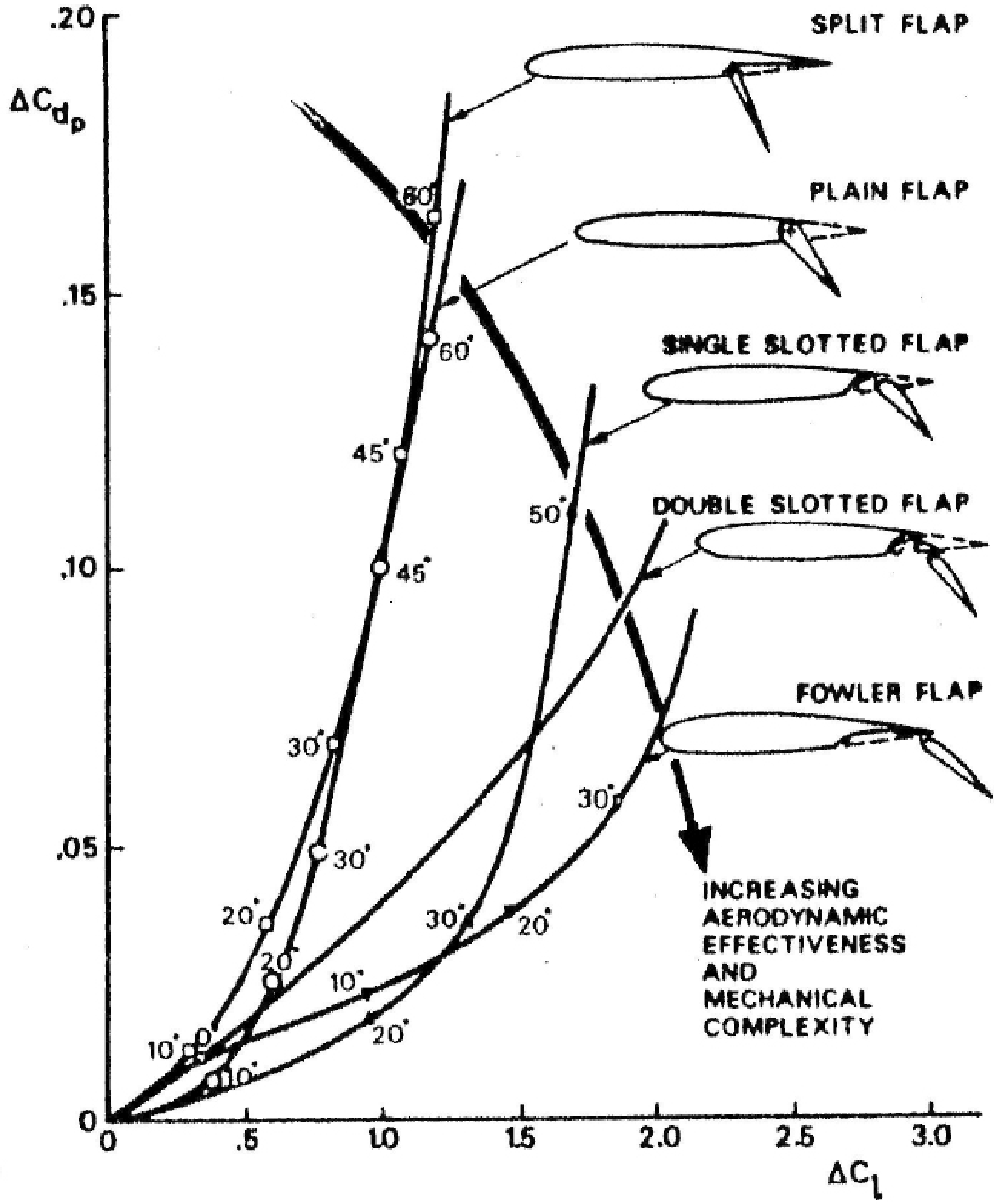

Figure 3: different flaps types and their effect on lift (C_L) and drag (C_D) coefficients [5]

3.1.3 Drag

A traditional drag breakdown is made as follows:

- ☐ C_{D0} : zero-lift drag (friction drag),
- ☐ C_{DL} : induced drag,
- ☐ C_{Dint} : interference drag caused by interaction of the different parts of the aircraft.

The drag coefficient is therefore: $C_D = C_{D0} + C_{DL} + C_{Dint}$.

Figure 4 shows a more physical drag breakdown of the total drag in pressure drag, friction drag, induced drag, profile drag, form drag, vortex drag, wave drag and wake drag.

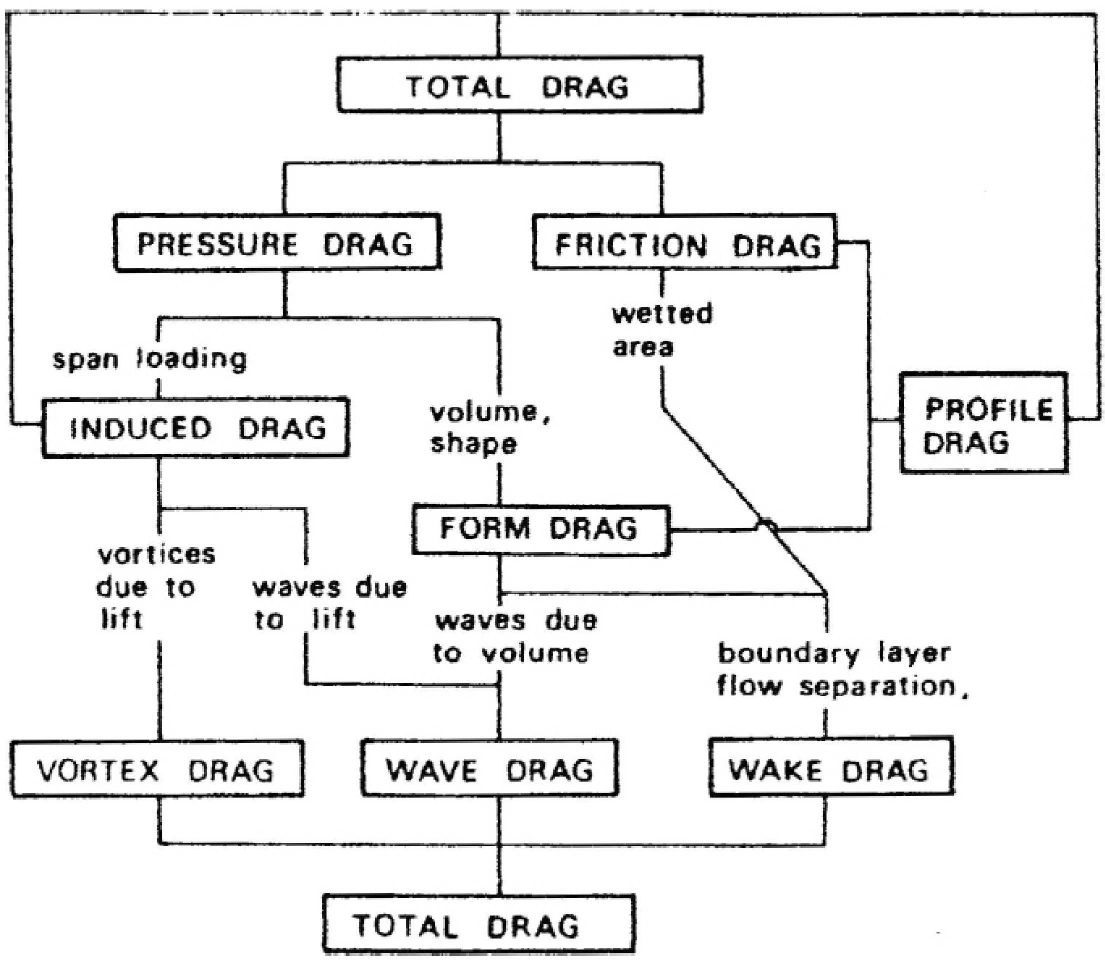

Figure 4: Physical drag breakdown [5]

The total drag of the aircraft is calculated as the sum of the drag of each major part of the aircraft:

- wing,
- trailing edge devices,
- horizontal tailplane,
- vertical tailplane,
- foreplane (canard),
- fuselage,
- propulsion (engine installation),
- propeller,
- nacelle,
- landing gear,
- interference.

The different drag components making up the total drag breakdown are computed with the formulas listed below.

3.1.3.1 Wings, horizontal tailplane and canard surface (foreplane) Source : [4].

The drag of these three components is computred in the same way: $C_D = C_{D0} + C_{DL}$

C_{D0} is found by processing information from the wing section database. If this data is not readily available, then C_{D0} is found by using the second equation (which is less accurate than the first).

$$C_{D0} = R_{wf}\ RLS\ C_{D0Airfoil}$$
$$C_{D0} = R_{wf}\ RLS\ C_f\ L_2^* \frac{WA}{S_a}$$
$$C_{DL} = \frac{C_L^2}{\pi\, AR\, e} + 2\pi\, C_L\, Twist\, IDFLT + 4\pi^2\, Twist^2\, \frac{ZLDFLT}{\sqrt[2]{1-MachN^2}}$$

with :

Rwf	Wing / Fuselage interference factor
RLS	Lifting surface correction factor
CD0Airfoil	Zero lift drag coefficient from the wing section database
L2*	Airfoil thickness location parameter
Twist	Twist angle
IDFLT	Induced Drag Factor due to Linear Twist
ZLDFLT	Zero Lift Drag Factor due to Linear Twist
Mach N	Mach number

3.1.3.2 Trailing edge devices Source : [4].

$$C_D = C_{D0} + C_{DL} + C_{Dint}$$

C_{D0} is function of the type of the trailing edge device

C_{DL}

$$C_{DL} = (k\Delta C_L)^2\, Cos(Swp25Prct)$$

C_{Dint} is function of the type of the trailing edge device

$$C_{Dint} = K_{int}\, C_{D0}$$

3.1.3.3 Vertical tailplane Source : [4].

The calculations are the same as for the wing, with $C_{DL} = 0$.

3.1.3.4 Fuselage and nacelles Source : [4].

$$C_D = C_{D0} + C_{DL}$$
$$C_{D0} = R_{wf}\, C_f\, \left(1 + \frac{60}{\frac{Length}{MD}^3} + 0.0025\frac{Length}{MD}\right)$$
$$C_{DL} = 2 \cdot ArpInc^2\, \frac{BasArea}{WngArea} + \eta\, C_{Dc}\, ArpInc^3\, \frac{TArea}{WngArea}$$

with :

C_f	Friction coefficient
Length	Length of the fuselage [m]
MD	Fuselage mean diameter [m]
Arp_{Inc}	Fuselage angle of incidence [°]
BasArea	Fuselage base area [m²]
Tarea	Fuselage top area [m²]

3.1.3.5 Engine installation Source : [4].

$$C_D = C_{Dcooling} + C_{DMisc}$$
$$C_{Dcooling} = 0,00000006 \cdot EBHPavail\, \frac{OAT^2}{\frac{OAD}{1,225}\, V\, WngArea}$$

$$C_{DMisc} = 0,000025 \cdot \frac{EBHPavail}{WngArea}$$

with :

$C_{Dcooling}$	Cooling drag coefficient
C_{DMisc}	Miscellaneous drag coefficient
OAT	Outside Air Temperature [°C]
OAD	Outside Air Density [kg/m³]
EBHPavail	Available engine power [W]

3.1.3.6 Propeller Source : [4].

$$C_D = C_{Dwindmilling} + C_{Dstop}$$
$$C_{Dwindmilling} = 33 \cdot \frac{1}{0.5 \cdot OAD\, PropV^2\, PropWngArea} * \frac{PropEBHP}{PropV}$$

$$Cdstop = 0,00125 \cdot BladeNumber \frac{\frac{Dia}{0,3048}^2}{PropWngArea}$$

with :

$C_{Dwindmilling}$	propeller drag coefficient when windmilling
C_{Dstop}	propeller drag coefficient when stopped
PropV	Propeller tip speed [m/s]
PropWngArea	Wing area lying in the propeller slip stream [m²]
PropEBHP	Propeller power available [W]
Dia	Propeller diameter [m]

3.1.3.7 Landing gears Source : Didier Breyne.

For a landing gear with fairings:

$$Cd0 = 1,5 \cdot 0,14 \cdot WheelNumber\, \frac{TireFArea}{WngArea}$$

For a landing gear without fairings:

$$Cd0 = 1,5 \cdot 0,24 \cdot WheelNumber\, \frac{TireFArea}{WngArea}$$

with:

WheelNumber	Number of wheels,
TireFArea	Frontal area of one wheel [m²]

3.1.3.8 Interference drag

During the conceptual design of the aircraft, the interference drag is difficult if not impossible to determine. ADS uses a method based on reference aircraft as described below:

The designer has specified the “aerodynamic quality” of the aircraft for the design flight condition being considered. This value was determined from the analysis of similar aircraft. As a reminder, the “aerodynamic quality” is the total drag coefficient of the aircraft.

During the design process, the drag breakdown for the major aircraft components is initially worked out for the design flight condition.

Next, the interferene drag is computed for the design flight condition by subtracting the total drag (the “aerodynamic quality” specified by the designer) and the sum of the drag breakdown calculated above.

Then, the relative interference drag is calculated and expressed as a fraction of the total drag.

It is assumed that the relative intereference drag is constant for all flight conditions.

3.2 Weights

An estimate of the empty aircraft weight is made by making a weight breakdown for the major components of the aircraft:

- Wing,
- Engine installation,
- Propeller,
- Fuselage,
- Horizontal tailplane,
- Vertical tailplane,
- Foreplane (canard),
- Main landing gear,
- Nose or tail landing gear,
- Fuel system,
- Hydraulic system,
- Control systems,
- Electrical systems,
- Instruments.

The weight breakdown is made by using the formulas below. Most often these formulas were derived in an empirical way from the analysis of a large number of existing aircraft. Each result is mulitplied by a correction coefficient in order to take into account several aspects, such as materials used, the ability of the designer to build lighter, etc… These correction coefficients are generally found after a detailed analysis of existing aircraft which are similar in concept to what the designer has in mind.

3.2.1 Wings Source : [6], equation 15.46.

$$M_{ailes}(lb) = 0,036 \cdot S_a^{0,758} M_{fuel\ ailes}^{0,0035} \frac{AR}{(\cos\Lambda)^2} q^{0,006} \lambda^{0,004} (\frac{100\ t/c}{\cos\Lambda})^{-0,3} (N_z W_{dg})^{0,49}$$

with:

$M_{fuel\ ailes}$	Weight of fuel stored in the wing [lb]
AR	wing aspect ratio
b	wing span [ft]
q	Dynamic Pressure Ratio (lb/ft²]
c	Wing aerodynamic mean chord [ft]
t/c	Wing airfoil relative thickness [%]
Λ	Sweep angle at 25% of the mean aerodynamic chord [°]
nz	ultimate load factor
W_{dg}	Flight design gross weight [lb]

3.2.2 Propulsion Source : [7], Table 14-5.

Single engine (4 strokes, 2 strokes, Diesel 2 strokes)	Meng = 1.3 x Mdry
Twin engine (4 strokes, 2 strokes, Diesel 2 strokes)	Meng = 1.4 x Mdry
4 strokes Diesel	Meng = 1.3 x Mdry
Rotary	1.9 x Mdry
Turbo propeller	1.7 x Mdry

The coefficients include the propeller. By subtracting the weight of the propeller, the weight of the installed engine is found.

3.2.3 Propeller Sources : Technical Notes from manufacturers. Analysis by D.Breyne.

Figure 5 shows propeller weight versus power for a given propeller type. The different propeller types are:

HVP : variable pitch propellers with hydraulic pitch control system;

EVP : variable pitch propellers with electric pitch control system;

FP : fixed pitch propellers.

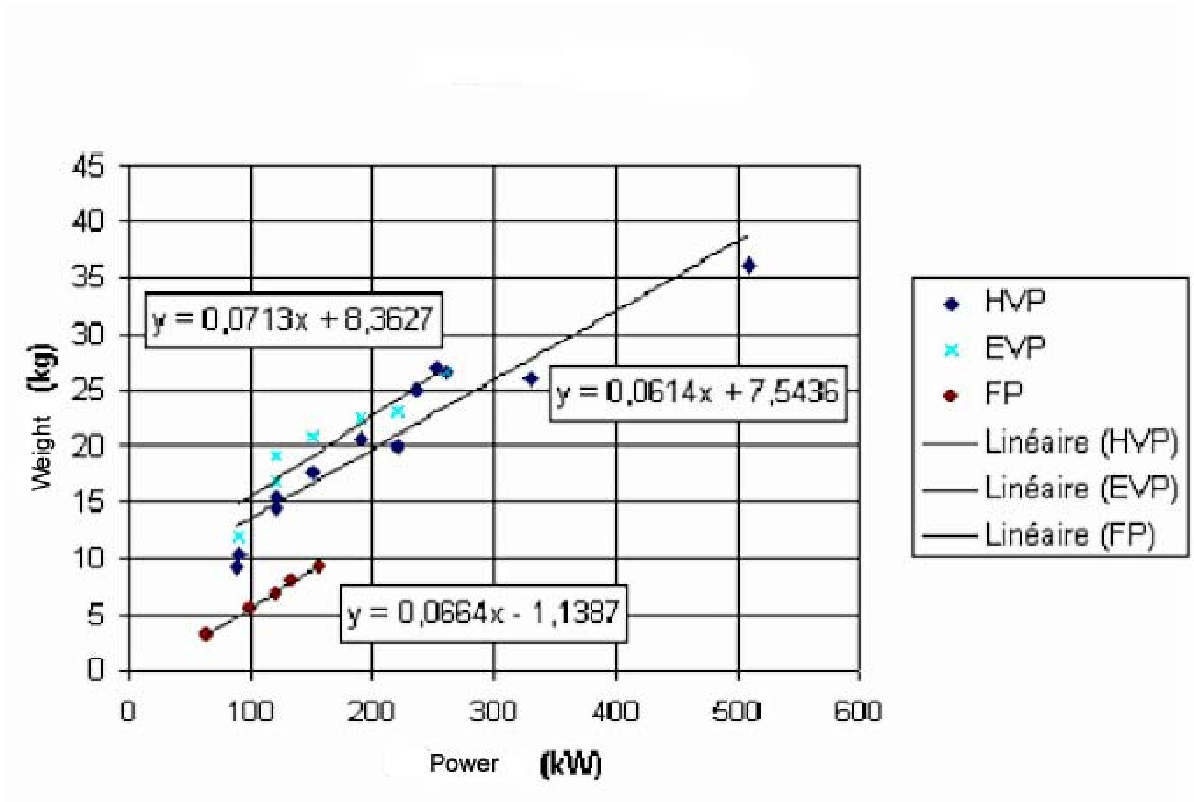

Figure 5: Weight of the propeller

3.2.4 Fuselage Source : [6], equation 15.49.

$$M_{fuselage}(lb) = 0,052 \cdot S_f^{1,086}(N_z W_{dg})^{0,177} L_t^{-0,051}\left(\frac{L}{D}\right)^{-0,072} q^{0,241} + M_{pressurisation}$$

with:

S_f	Fuselage wetted area [ft²]
Lt	Tail length [ft]
L	Total length [ft]
D	Fuselage mean diameter [ft]
$M_{pressurisation}$	Weight penalty due to pressurisation [lb]

3.2.5 Horizontal tailplane and foreplane (canard surface) Source : [6], equation 15.47.

$$W_{HT}\ (lb) = 0,016 \cdot (N_z W_{dg})^{0,414} q^{0,168} S_{ht}^{0,896}\left(\frac{100t/c}{\cos \Lambda_{vt}}\right)^{-0,12}\left(\frac{AR}{(\cos \Lambda_{vt})^2}\right)^{0,043} \lambda_h^{-0,02}$$

with:

Sht	Horizontal tail area [ft²]
Dht	Sweep angle at 25% of the mean aerodynamic chord [°]
λ	Tail tapered ratio

3.2.6 Vertical tailplane : [6], equation 15.48.

$$W_{VT}\ (lb) = 0,073 \cdot (N_z W_{dg})^{0,376} q^{0,122} S_{vt}^{0,873}\left(\frac{100t/c}{\cos \Lambda}\right)^{-0,12}\left(\frac{AR}{(\cos \Lambda)^2}\right)^{0,043} \lambda_h^{-0,02}\left(1 + 0,2\frac{H_t}{H_v}\right)$$

with:

S_{vt}	Vertical tail area [ft²]
Λ	Sweep angle at 25% of the mean aerodynamic chord [°]
λ	Tail tapered ratio
H_t / H_v	0 for conventional tail, 1 for T-Tail

3.2.7 Main landing gear Source : [7], equation 14-22a.

Fixed tail dragger	Weight = 0.8 x 0.045 x M_d
Retractable tail dragger	Weight = 1.5 x 0.8 x 0.045 x M_d
Fixed tricycle	Weight = 0.7 x 0.055 x M_d
Retractable tricycle	Weight = 1.5 x 0.7 x 0.055 x M_d
Fixed single wheel	Weight = 0.4 x 0.045 x M_d
Retractable single wheel	Weight = 1.5 x 0.4 x 0.045 x M_d

3.2.8 Nose or tail landing gear Source : [7], equation 14-22a.

Fixed tail dragger	Weight = 0.2 x 0.045 x M_d
Retractable tail dragger	Weight = 1.5 x 0.2 x 0.045 x M_d
Fixed tricycle	Weight = 0.3 x 0.055 x M_d
Retractable tricycle	Weight = 1.5 x 0.3 x 0.055 x M_d
Fixed single wheel	Weight = 0.1 x 0.045 x M_d
Retractable single wheel	Weight = 1.5 x 0.1 x 0.045 x M_d

3.2.9 Fuel system Source : [6], equation 15.53.

$$W_{Fuel}\ (lb) = 2,49 \cdot V_t^{0,726} \left(\frac{1}{1+V_i/V_t}\right)^{0,363} N_t^{0,242} N_{en}^{0,157}$$

with:

V_t	Total fuel volume [gal]
V_i	Integral tanks volume [gal]
N_t	Number of fuel tanks
N_{en}	Number of engines

3.2.10 Hydraulic system Source : [7], equation 14-35.

Mhyd = 0.03 x Md

3.2.11 Control systems Source : [6], equation 15.54

$$W_{control}\ (lb) = 0,053 \cdot L^{1,536} B_w^{0,371} (N_z W_{dg} \cdot 10^{-4})^{0,8}$$

with:

B_w	Wing span [ft]

3.2.12 Electrical systems Source : [7], equation 14-36.

Welec = 0.03 x Md

3.2.13 Instruments Source : [7], equation 14-38b.

Winst = 0.015 x Md

3.3 Propeller

The propeller properties (diameter, pitch, number of blades, blade section) are determined with the method described in report [8] and by processing the information in the charts in this report (Figure 6).

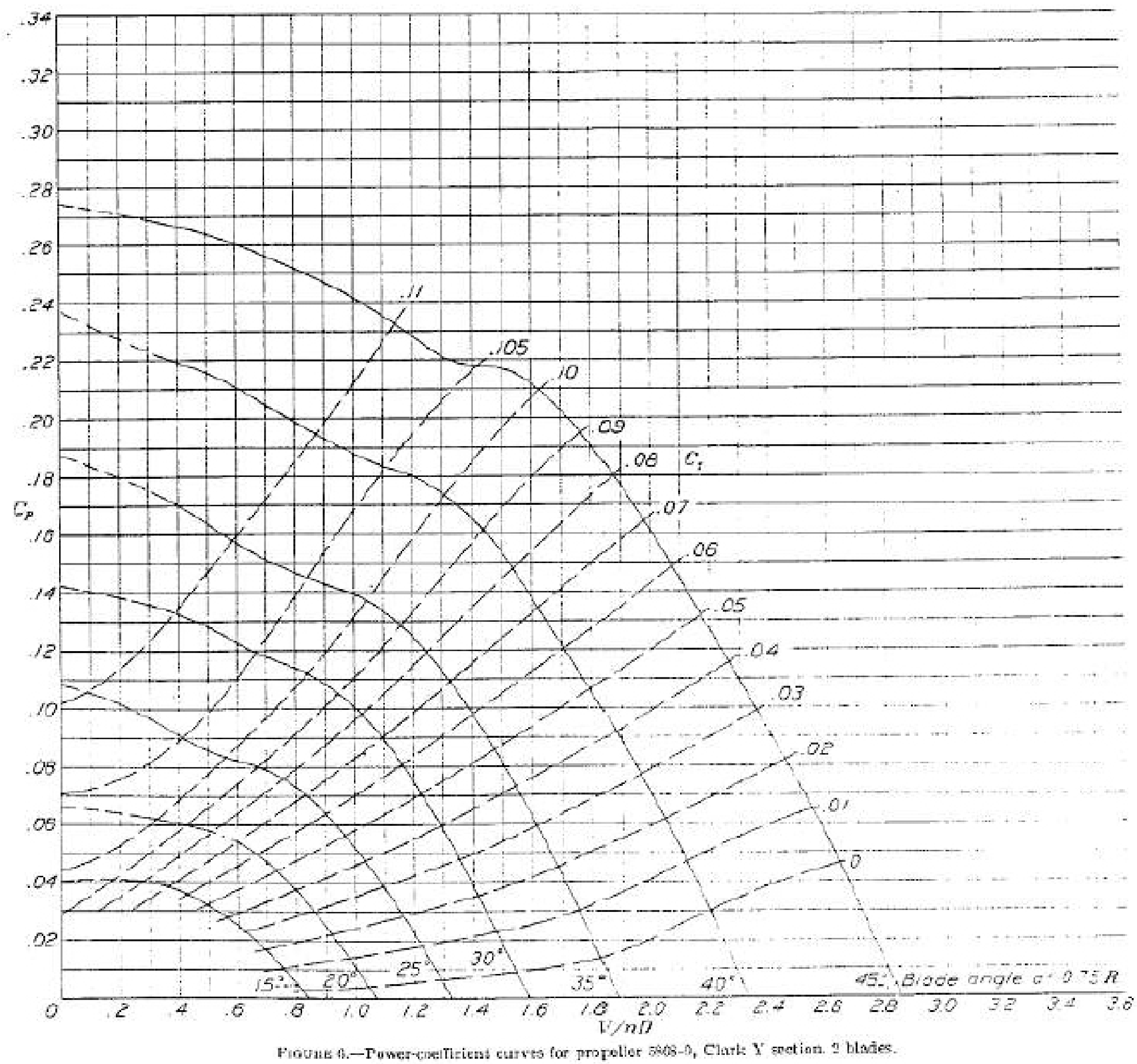

Figure 6: Propeller chart extracted from [8]

3.4 Engine

Engine data is processed in 2 different ways, depending on the level of the Design process.

3.4.1 Level 1

At level 1, the algorithms will process statistical curves (Figure 7) in order to determine the weight of the "ideal" engine, as well as its specific fuel consumption for the type of engine selected (two stroke, four stroke, rotary, turbine,...). The engine power necessary to achieve the specified performance is calculated.

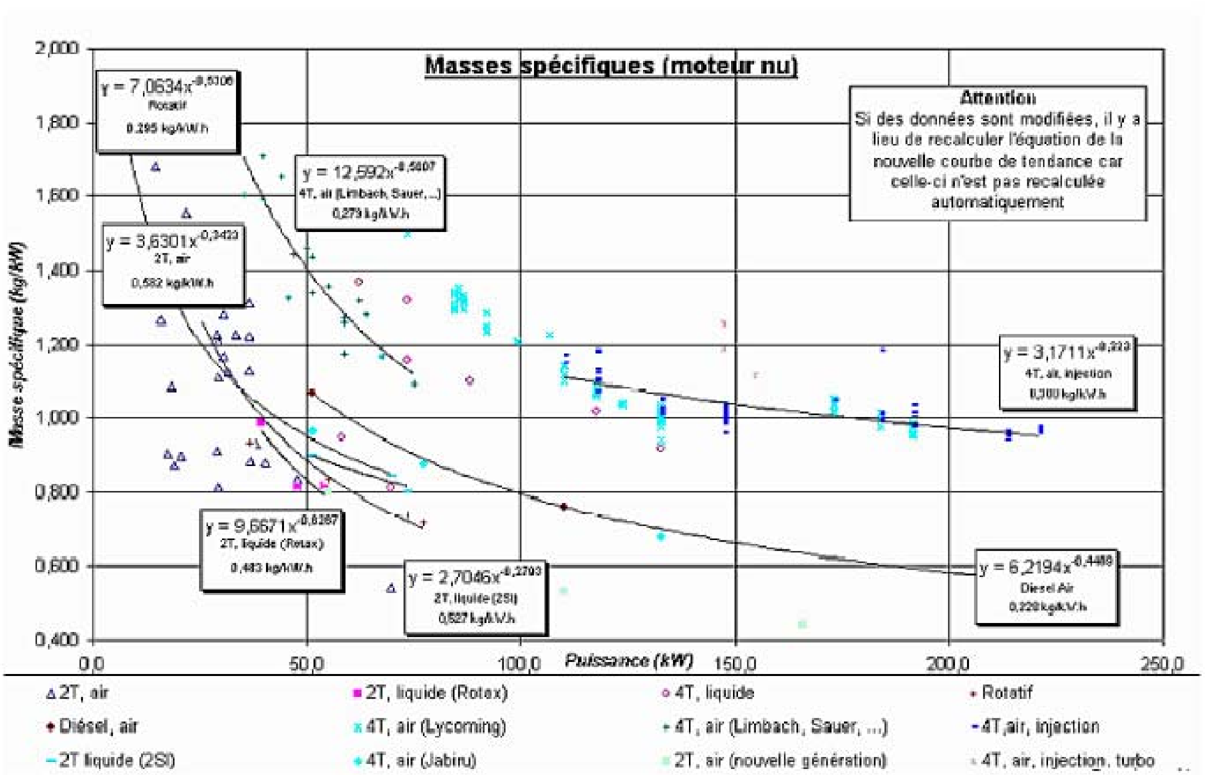

Figure 7 Speific weight of engines (M=P) as a function of engine power

3.4.2 Level 2 and 3

At level 2 or level 3, the designer made a selection of one or more engines which closely match the "ideal" engine. Now, the algorithms will process information from the engine database, which contains information provided by the engine manufacturers, such as:

- ☐ Dimensions,
- ☐ Weights,
- ☐ General performance (engine speed, power and specific fuel consumption),
- ☐ Power and fuel consumption curves.

4. Références

[1] PCA2000. http://www.pca2000.com.

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