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A user-friendly method for small UAV sizing and performance estimate

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Abstract

This paper is to implement respectively a program for fixed-wing UAVs (Unmanned Aerial Vehicle) and for quadcopters weighing less than 15 kg. This program enables to calculate the payload margin of a drone, the parameters of each component as well as the power consumed for each phase according to takeoff weight. It may also estimate the recommended takeoff weight quickly by iterative method based on fixed payload and endurance. The results show that the drone main weight contributor comes from its structure, as for a quadcopter drone, the propulsion part is the heaviest, as it consumes more power to sustain flight compared to fixed-wing systems.

1. Introduction

In recent years, the application domain of small drones is expanding, such as in agriculture, express transport, surveillance, aerial photography, etc. [1] [2]. The first step in drone manufacturing is its design. Given that the drone maximum takeoff weight and the weight of each component affect each other [3], the selection of components usually requires repeated calculations or is just based on large experience with previous designs. The aim of this work is to implement respectively a program for fixed-wing UAVs and for quadcopters weighing less than 15 kg. This program enables to calculate the payload margin of a drone, the parameters of each component as well as the power consumed for each phase according to takeoff weight. It may also estimate the recommended takeoff weight quickly based on fixed payload and flight time (endurance).

2. Fixed-wing UAV

2.1 Presentation of calculation method

Prior to the selection of components, it is essential to impose certain conditions on the drone studied, in order to concretize the problem, such as the mass, autonomy and desired speed. Then, the choice of the components is conducted in the following order: Propeller, Motor, ESC (Electronic Speed Controller), and Batteries. The goal of each part is not only to select the component, but also to model a relationship between the mass of the component and the total mass. Finally, a python program realization allows displaying directly the parameters found by this method for any initial mass without going through all the calculations.

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Table 1. Assumptions of the Fixed-wing UAV

Phase	Symbol	Parameter	Value
	t	Endurance	1h
	M_{to}	Takeoff weight	2 kg
Cruise	V_c	Cruising speed	60 km/h
	$C_{l(c)}$	Cruising lift coefficient	0.4
	$C_{d(c)}$	Cruising drag coefficient	0.026
Horizontal flight in Max speed	V_{max}	Max speed	80 km/h
	$f_{(max)}$	Finesse at Max speed in horizontal flight	13
Climb	h	Altitude	100 m
	$f_{(climb)}$	Finesse during the climb	13
	$C_{l(climb)}$	Lift coefficient during the climb	1.5

Taking a drone of 2 kg as an example, Table 1 lists all its parameters of three phases of flight. The mission of this drone is to climb up to 100m of altitude, and then to realize a cruise flight in 1 h (60 km/h) or a horizontal flight in maximum speed in 1h (80 km/h). The power consumed during the cruise should be minimal, in order to save energy. The objective of this work is to choose the most adapted components to answer this need.

2.2 Modeling of the propeller of different materials

The reference propellers in fiberglass composite in this part are APC model aircraft propellers and the reference propellers in wood are Xoar propellers. The test results and datasheets of all propellers can be found on their official website. A relationship between propeller mass and diameter can be established by taking 15 examples of each material.

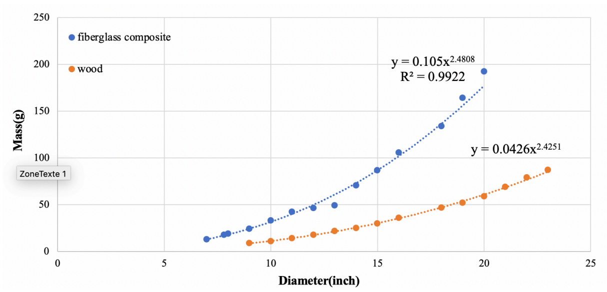

Figure 1. Effect of diameter on mass of propeller

$$M_{propeller\_fiber} = 0.105D^{2.48} \quad (1)$$

$$M_{propeller\_wood} = 0.04D^{2.42} \quad (2)$$

As shown in Equation (1) and (2), the mass of the propeller increases with its diameter and there is a power trend curve between these two parameters in both cases. Indeed, the advantage of a wooden propeller is its light mass, which is at least twice as light as a fiberglass composite propeller of the same diameter. However, its output is also smaller.

In the cruise flight, the power equation can be expressed as follows:

$$P_c = \frac{M_{to} g V_c}{f_{(c)}} \quad (3)$$

The propeller power has:

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$$P_{propeller} = \rho C_p n^3 D^5 \quad (4)$$

$f_{(c)}$: Finesse during the cruise
C_p: 0.04 power coefficient.
n: 4000 propeller rotation rate in revolutions per minute
D: Propeller diameter in m
ρ: The density of the air in kg/m^3 i.e 1.21 kg/m^3 at 100 m
g: Gravitational acceleration

Assuming that P_c is the cruising power which depends on M_{to}. By combining equation (1)(3)(4), the propeller mass can be expressed as a function of M_{to}.

2.3 Modeling of motor brushless

The maximum power of the motor must be greater than the maximum necessary power consumed by drone, otherwise it is unable to provide enough power. Nevertheless, at the same time, it can not be too large, because the higher the maximum power of the motor, the greater its volume and weight will be, which increases the weight of the drone reducing the endurance. Thus, to choose the motor, you should first calculate the power of the climb phase.

First, the wing area S_{pf} can thus be calculated in the cruise:

$$S_{pf} = \frac{M_{to} g}{0.5 \rho C_{l(climb)} V_c^2} \quad (3)$$

Calculate climb power with an angle of attack α
The rate of climb can be expressed as a function of other parameters using equation (4):

$$V_{climb} = \left(\frac{M_{to} g \cos\alpha}{0.5 \rho C_{l(climb)} S_{pf}}\right)^{1/2} \quad (4)$$

According to Newton's second law, the climbing power P_{climb} is equal to the traction force T multiplied by the climbing speed:

$$P_{climb} = \left(\frac{M_{to} g \cos\alpha}{f_{(climb)}} + M_{to} g \sin\alpha\right) \times V_{climb} \quad (5)$$

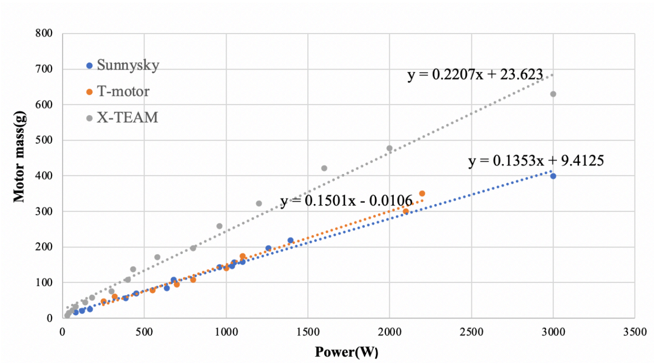

Figure 2. Relation between mass of motor and its power for 3 different manufactures

By comparing data from 40 brushless motors from three manufacturers: T-motor, Sunnysky and X-Team, a linear relationship can be estimated between the power output of a brushless motor and its mass.

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$$M_{motor} = k_{motor} P_{motor} \quad (6)$$

With k_{motor} as a coefficient, its unit is g/W. It is dependent on the manufacturer. In general, the smaller this coefficient, the greater the mass power of an engine. Namely, a small k_{motor} means that this engine can deliver a high power with a low mass. This characteristic is interesting in the aeronautical field. Given that the power of the chosen engine is 2.5 times greater than the power output, the mass of the engine can therefore be expressed as a function of M_{to} using equation (4) (5) (6).

2.4 Modeling of ESC

As a motor needs several different speeds to perform different phases, it is therefore necessary to have an ESC "Electronic Speed Controller", which allows changing the rotation speed of the motor by modifying the intensity. For example, it is often necessary to have an important power for the takeoff phase, and its intensity must also be high.

In order to find the relationship between the maximum current of an ESC and its own weight, a curve should be drawn using the data of 10 ESCs whose maximum current is less than 120 A.

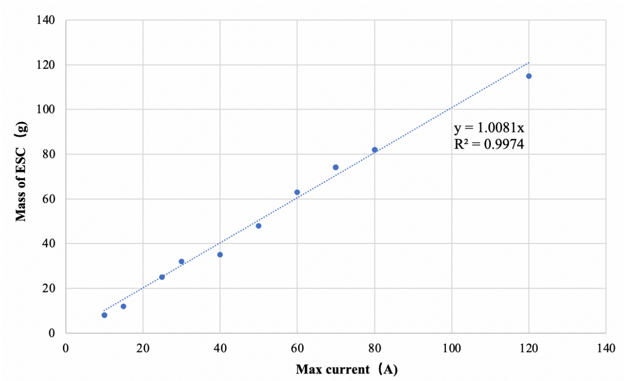

Figure 3. Effect of max current on mass of ESC

The curve in Figure 3 shows that the weight of the ESC increases with the increase of the maximum current. The relationship between its mass and the maximum current can be modeled as a linear function of coefficient 1.
Namely,

$$M_{esc} = k_{esc} I_{max} \quad (7)$$

Where k_{esc}= 1 g/A. However, when the maximum current is higher than 120 A, this rule is no longer valid, because such an ESC is not commonly used, and its weight is very variable depending on the manufacturer.

Due to the fact that the choice of ESC is related to the engine, there is probably also a relationship between the mass of ESC and the engine. Generally speaking, the manufacturer gives a recommended value of ESC for each engine. In order to find the relationship between the two, many different engines and their recommended ESC values can be simply compared.

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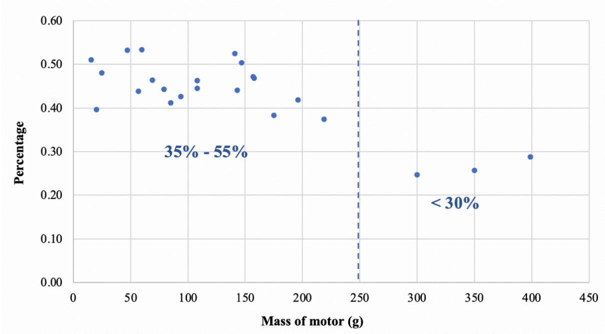

Figure 4. Ratio M_{esc}/M_{motor}

Figure 4 is made using 25 motor groups and its recommended ESC. In general, the ESC weight is 35%-55% of the motor, but there is no exact rule, because a motor can choose different ESC ranges to have different power. For example, a large ESC can deliver a larger current, and thus a higher power. Moreover, when the mass of a motor exceeds 250 g or its maximum power exceeds 2000 W, this percentage can be less than 30%, because generally in the case of a very high power, it is preferable to increase the voltage rather than increasing the current to decrease the loss, whereas the mass of an ESC is related to its maximum current. In the python program, it is considered that the ESC represents 40% of the motor mass.

2.5 Battery modeling

In order to find an ideal battery to increase the flight time of the drone, it is essential to consider at least two criteria: the voltage of the battery and its capacity. The capacity of the battery is dependent on the endurance of the drone, and it can be calculated according to a formula, considering that the descending power and the climb power are the same to maximize the energy:

$$E_{total} = \frac{2P_{climb}\, t_{climb}}{\eta_{motor\_climb}\, \eta_{propeller\_climb}} + \frac{P_{vmax} t_{cruise}}{\eta_{motor\_vmax} \eta_{propeller\_vmax}} \quad (8)$$

η : efficacity

Energy density e is defined as:

$$e = \frac{1.2E_{total}}{M_{battery}} \quad (9)$$

The energy density of a lithium-ion battery is 160 Wh/kg [4] on average. The chosen battery must have a capacity 1.2 times greater than the value found from the calculation for safety reasons [5]. Thus, the mass of the batteries can be expressed as a function of the previous parameters by combining equation (8)(9).

2.6 Structure

In order to save even more mass, the structure is usually hollowed out in a honeycomb pattern or directly hollowed out just a part. After several measurements on the Skywalker X8, it is possible to find a non-linear relationship between the fill rate and the total mass of the drone.

The filling rate r is calculated according to equation (10):

$$r = 1 - \frac{2V_{empty}}{S_{pf} t_{airfoil}} \quad (10)$$

With $t_{airfoil}$: airfoil thickness

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According to the literature, the structural mass is usually about 50-60% of the takeoff weight [6]. It is assumed that the structural mass consists of three parts: wings, fuselage, cables, and that the fuselage has the same mass as the wings of a UAV [7]. The material of the fuselage is Epo foam. Namely,

$$M_{wing} = \rho_{EPO} S_{pf} t_{airfoil} r \tag{11}$$

$$M_{structure} = 2M_{wing} + M_{cable} \tag{12}$$

ρ_{EPO}: Density of EPO

By imposing that the $M_{structure}/M_{to}$ is 55%, a Python program allows finding a relation between the filling rate and the total mass of the drone.

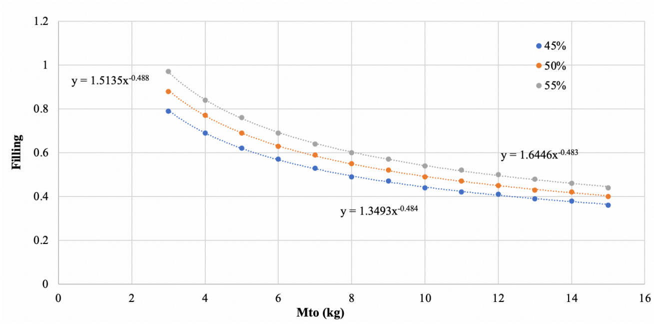

Figure 5. Fill rate according to Takeoff weight for different $M_{structure}/M_{to}$

$$r = 1.65 M_{to}^{0.48} \tag{13}$$

This relationship is only applicable to drones with a mass between 3 and 15 kg, for drones with a mass of less than 3kg, the fill rate is 100%.

2.7 Results

Table 2. Mass balance

Mass balance		
Structure	Wing	469 g
	Fuselage	469 g
	Cables	40 g
Propulsion	Motor	25 g
	ESC	12 g
	Battery	351.6 g
	Propeller	24 g
Payload	Payload	500 g
	Total	1.9 kg

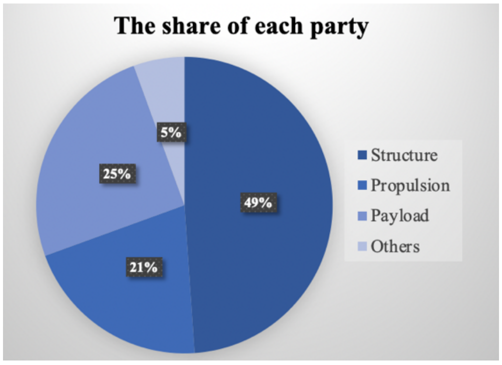

Figure 6. The share of each part

Table 2 lists all the components of the drone chosen according to this method. Figure 6 shows their percentages occupied. The structure represents about 50% of the total mass, and the propulsion part represents about 20% of the total mass.

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2.8 Iterate over the mass to find Payload

This method can be applied to different masses using a Python program. Firstly, the mass of each component must be expressed as a function of the total mass using the formulas found in the previous parts, namely model of each component. With this, once the total mass is imposed, all the masses of each component calculated by this method as well as the power of each phase, the capacity of the batteries, can be displayed. The total mass is the sum of mass of each part, and the equation (14) is given as follows:

$$M_{to} = M_{structure} + M_{payload} + M_{battery} + M_{motor} + M_{esc} + M_{propeller} \tag{14}$$

From equation (15), since each mass can be expressed as a function of M_{to}, then it can have a recursive function, namely:

$$M_{to} = f(M_{to}) \tag{15}$$

It is enough to iterate on the mass. One supposes firstly a mass M_{to1}. With the help of equation (15), one obtains a new mass M_{to2}. Then, one replaces M_{to1} by this new mass M_{to2} in the right-hand side, and one obtains M_{to3}, M_{to4}, etc. This sequence is converged towards a value, and this value is the most appropriate mass for the takeoff.

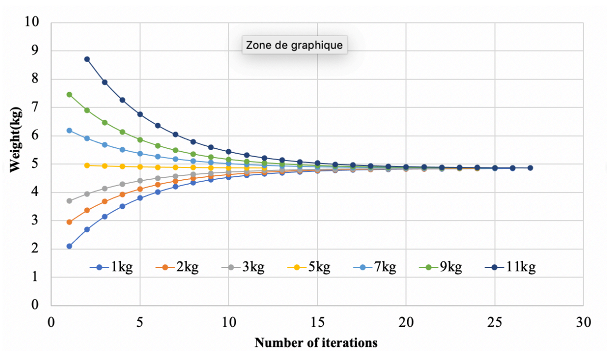

Figure 7. Iteration on the Mass with payload=1kg

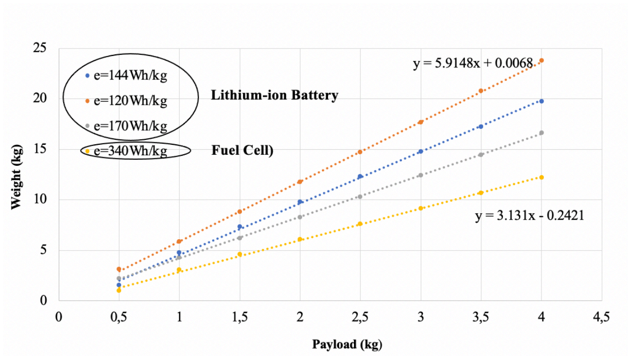

Figure 8. Effect of payload on Takeoff weight for different energy density

The converged value is not dependent on the initial mass, but on the Payload. For the same mission, whatever the imposed mass, the curve converges to the same value, which is 5 kg in Figure 7. To carry 1kg of payload, the best solution proposed by this method is to use a 5 kg drone.

The converged value is dependent not only on the payload, but also on the energy density of the batteries (see the variation in Figure 8). The higher the energy density, the lower the total mass recommended for the same imposed payload. A fuel cell has a higher energy density than a lithium-ion battery, which can reach up to 340 Wh/kg as DP30 Powerpack from Doosan.

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With this program. it is possible to find several relationships between the different parameters.

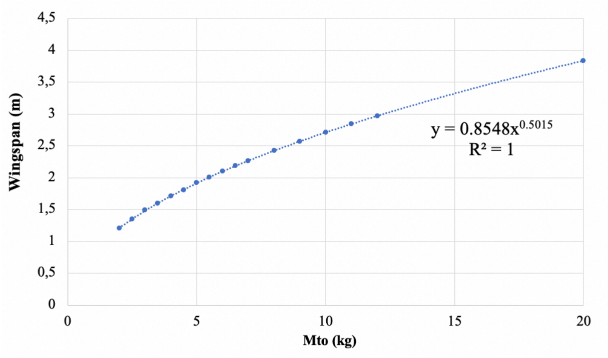

Figure 9. Relation between wingspan and Mass

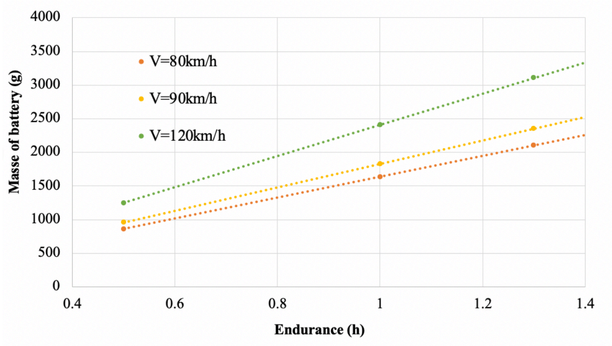

Figure 10. Mass of battery according to Endurance

Figure 9 shows the relationship between span and mass, which is a power trend curve. For Figure 10, the mass of the batteries is proportional to the range, but the coefficient varies with speed. For a high speed, it is more important, because the drone consumes much more energy. In general, the autonomy is rare to exceed 1.5 h with a lithium-ion battery, while it can be possible with a fuel cell with hydrogen.

Verification of the program with existing UAV

To verify that this method is valid for drones with a mass less than 15kg, we compared the parameters of the two existing drones and the parameters calculated by program. The two drones chosen are Mite-2B and kywalkerX7.

Table 3. Comparison between Mite-2B/Skywalker X7 and value calculated by Python

	Mite-2B	**Programme**	**Relative gap**	**Skywalker X7**	**Programme**	**Relative gap**
Mass(kg)	0.21			4		
Wingspan(m)	0.36	0.39	8.3%	50	58	16%
Structure (g)	49	39	20%	1.8	1.72	4%
Power of motor(W)	14	18	28%	500	352	29%
Mass of propeller(g)	7	8.8	26%	60	40	33%
Mass of battery(g)	45	42.9	5%	12	11	8.3%
ESC(g)	6	2	67%	902	812	10%
Payload(g)	79	113	43%	148	118	20%

As shown in Table 3, the relative deviations are acceptable, because not all drones have the same calculation method, and the mission is not the same. The purpose of this comparison is to validate this method, which not only allows quick estimation of the weight of each part and estimation of each parameter of the UAV, but also facilitates the design phase.

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3. Quadcopter

Although the modeling of the quadcopter and the drone plane are quite different, but the order of choice of the component remains the same.

Table 4. Assumptions of the quadcopter

Phase	Symbol	Parameter	Value
Cruise	M_{to}	Takeoff weight	2 kg
	t_{vc}	Endurance	10 min
	V_c	Cruising speed	15 m/s
Hover	t_{hover}	Time of hover	15 min
Horizontal flight in Max speed	V_{max}	Max speed	20 m/s
Climb	h	Altitude	50 m
	V_{climb}	Max velocity of climb	5 m/s
	a_{climb}	Acceleration of climb	0.5 g
Descent	$a_{descent}$	Acceleration of descent	0.5 g
	$V_{descent}$	Max velocity of descent	3 m/s

3.1 Modeling of propeller

The choice of propeller is important because a large propeller can create a lot of lift, but it also requires a high-powered motor, so it is necessary to choose the most appropriate propeller. For this purpose, 16 drones were studied in order to understand the relationship between the mass of the drone and the propeller diameter.

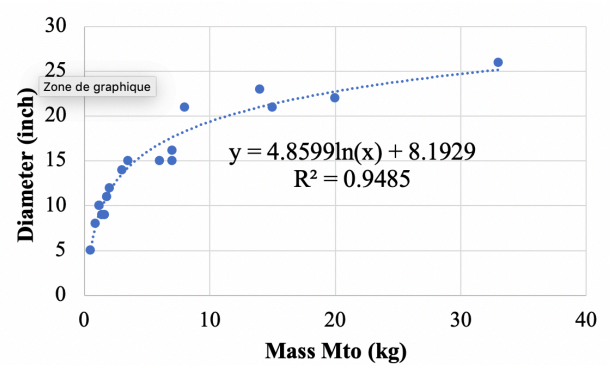

Figure 11. Variation of Propeller diameter according to the total mass

The relationship between diameter D and mass for this type of drone is illustrated in Figure 11, it is a trend curve of logarithmic (eq.16):

$$D = 4.9\ln(M_{to}) + 8.2 \tag{16}$$

3.2 Modeling of Motor Brushless, ESC and Battery

It is quite the same method as an airplane drone, it is necessary to find first the mounted power of a quadcopter.

According to Newton's second law,

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$$\sum_{i=1}^{4} T_i - M_{to}g = M_{to}a \quad (17)$$

$$T_{climb} = \frac{M_{to}(a+g)}{4} \quad (18)$$

$$n_{climb} = \left(\frac{T_{climb}}{\rho C_t D^4}\right)^{1/2} \quad (19)$$

$$P_{climb} = \rho C_p n_{climb}^3 D^5 \quad (20)$$

C_p: Power coefficient.
C_t : Thrust coefficient.
T: Thrust in N.
D: Propeller diameter in m.
ρ: The density of the air in kg/m^3 i.e 1.21 kg/m^3 at 100 m.
a : Acceleration of quadcopter.

However, as the power of the chosen engine is always a few times greater than the maximum power calculated to protect the engine, it would be more rigorous to study directly the relationship between the total mass of the drone and the mass of a single engine. Considering that the recommended mass to lift by manufacturer is a quarter of the total mass:

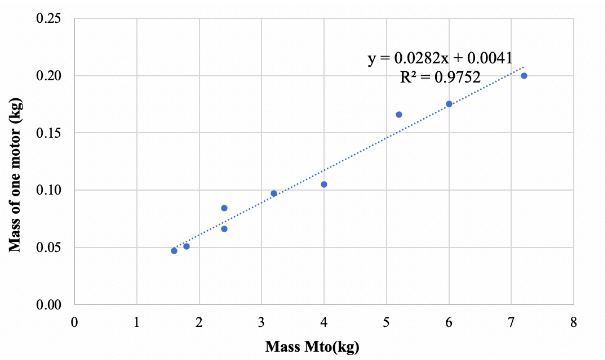

Figure 12. Variation of mass of one motor according to the total mass

$$M_{motor} = 0.028M_{to} + 0.0041 \quad (21)$$

The relationship between the mass of a single brushless motor and the total mass of the UAV can be modeled as a linear line (eq.21). To leave a safety margin, the chosen motor is often heavier than this value. The method of choosing ESC and Battery for an airplane drone is still valid for a quadcopter, it is just necessary to differentiate the power calculation of each phase for two types of drones, because they do not have the same principle.

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3.3 Stucture

In order to estimate the mass of the chassis, simply compare several chassis：

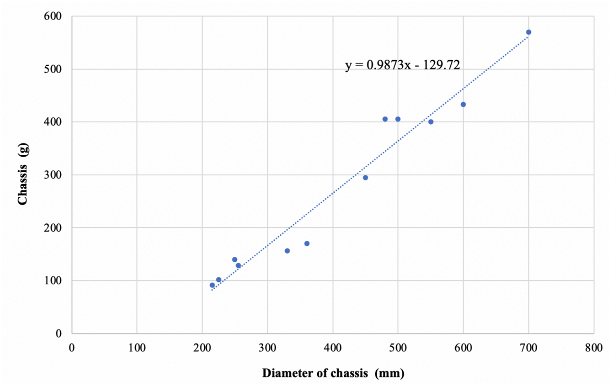

Figure 13. Relationship between the mass of the carbon frame and the diameter of the drone

$$M_{chassis} = k_{chassis} D_{chassis} - 134 \quad (22)$$

Equation (22) shows the relationship between the mass of the chassis and its diameter, with $k_{chassis}$ is 1 g/mm. $D_{chassis}$ is the distance between two motors.

3.1 Results

Table 5. Mass balance of quadcopter

Mass balance		
Structure	Chassis	405 g
	Cable	40 g
Propulsion	Motor (× 4)	336 g
	ESC (× 4)	120 g
	Battery	700 g
	Propeller (× 4)	72 g
Payload	Payload	300 g
	Total	1.95 kg

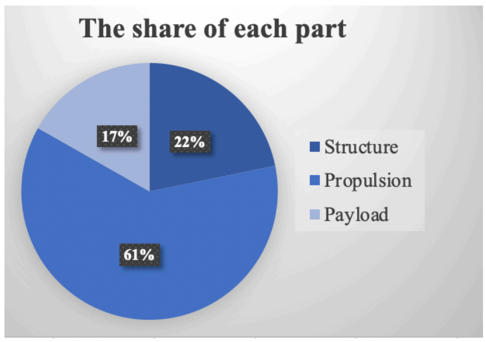

Figure 14. Occupied percentages of each part

Table 5 shows a mass balance, and figure 14 shows the percentages occupied by each part for a quadcopter. For a quadcopter, the propulsion part represents more than half, which is different from aircraft type drones, their structure parts are heavier than the propulsion part.

3.4 Iterate over the mass of find payload

We use exactly the same method as the drone plane described in the part 2.8, it is necessary to express first of all the mass of each part according to M_{to}, i.e. to model each component, then, we put these modeling in a Python program, this program thus makes it possible to display the value of each part as well as the margin of payload by imposing that initial payload is 0. The second use of this programming is to enter a value of payload in the initial parameters, at the end it is going to propose the most adapted mass at the takeoff. The main equation of this method is :

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$$M_{to} = M_{chassis} + M_{battery} + 4(M_{motor} + M_{esc} + M_{propeller}) + M_{payload} + M_{cable} \quad (23)$$

```
#Parameter
M_cable=0.04
M_pay=0       #Payload in kg
e=144         #Energy densities for battery in Wh/kg
h=50          #altitude in m
g=9.81

Vc=15         #Cruising speed in m/s
Vmax=20       #Max speed in m/s
t_vc=600      #Cruising time in s
t_vs=900      #Hover time in s
V_m=5         #Max speed during the climb in m/s
V_d=3         #Velocity during the descent in m/s
a_m=0.5*g     #Acceleration of climb
a_d=0.5*g     #Acceleration of descent
t_acc=5           #Acceleration time in s

M_to=2       #Total mass
```

```
Mass of chassis:303.4831g
Diameter without propeller:440.0mm
Mass of battery:681.3000000000001g
Capacity of battery:98.1144Wh
Capacity of battery:5303.4799mAh
Mass of one motor:72.1g
Mass of one ESC:32.5g
Mass of one propeller:45.8g
Diameter of propeller:11.6inch
Climb power:311.6484W
Descent power:59.9768W
Hover power:169.64W
Cruise power:181.9845W
Total:1.626kg
Payload margin:374.0g
```

Figure 15. Assumptions and results of the program Python with Mto=2 kg, payload=0 g

Finding the necessary mass for an imposed payload

By iterating on the mass with the help of equation (23), one can find the most suitable takeoff weight for an imposed payload, the relation between the two parameters can be drawn in a curve:

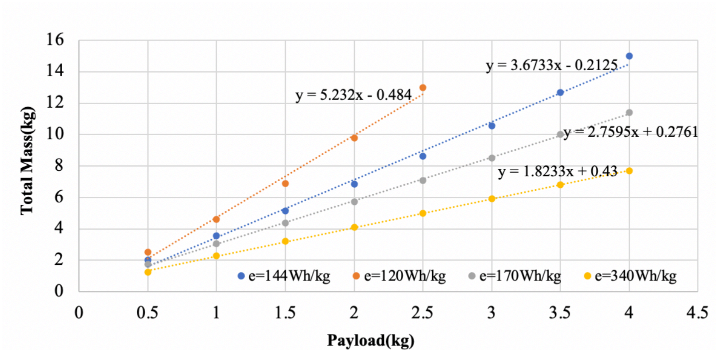

Figure 16. Recommended Takeoff Weights Based on Different Payloads and Batteries

Figure 16 shows a relationship between payload and total mass required for different energy densities, this relationship is linear under this method, and the higher the energy density the lower the total mass required.

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Verification with existing drone

At the end, to verify that this method is valid for drones with a mass is less than 10kg. We compare the parameters of the two existing drones and the parameters calculated by the program. The drones chosen are Phantom 4 pro v2.0 and Mavic 2 pro.

Table 6. Comparison between Phantom4 pro/Mavic2 pro and value calculated by Python

	Phantom4 pro	**Python**	**Relative gap**	**Mavic2 pro**	**Python**	**Relative gap**
Mass(kg)		1,375			0,907	
Endurance (h)		0,5			0,5	
Diameter without propeller(mm)	350	360	3%	354	300	18%
Mass of motor(g)	75	51	32%			
Propeller diameter (inch)	9	9.76	8,4%	8	7.7	4%
Mass of battery(g)	468	461	1.5%	297	312	5%
Battery capacity (Wh)	89	67	25%	60	45	25%

Table 6 shows a comparison between the Phantom4 pro parameters, and the values calculated by Python. The chassis and the propeller have a rather small relative deviation. In addition, the choice of motor and ESC depends on the desired flight mission, the battery depends strongly on the endurance and on its own characteristic, e.g., its energy density, this is the cause of the deviations. All in all, this program is a tool to estimate the mass of each component before assembling them.

Table 6 shows also a comparison between the parameters of the Mavic2 pro and the values calculated by Python. The battery capacity of Mavic2 pro is always about 1.25 times larger than the calculated value, this is due to the different mission of the drone.

Both comparisons show that this method is validated to estimate each parameter of the quadcopter UAV during the design phase.

3.4 Comparison between fixed-wing UAV and quadcopter

The two Python programs also allow to quickly compare the performances of the aircraft and quadcopter drone. For example, the two drones studied all have a mass of 2 kg, even if their principles are totally different, but there are still parameters that are comparable.

Rate of climb

Table 7. Rate of climb comparison between two drones

	Rate of climb
Fixed-wing UAV	1.5 m/s
Quadcopter	5 m/s

Table 7 shows that the rate of climb of a quadcopter is greater than a fixed-wing UAV of the same mass, that's why a fixed-wing UAV needs a wider place to take off, and it is often used to carry the load, but not for aerial photography.

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Payload

By imposing a 30 min endurance for these two drones, we compare the payload margin for these two types of drones at each mass.

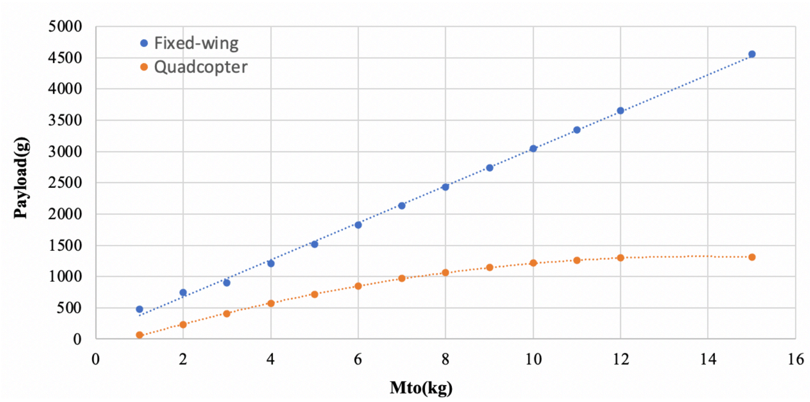

Figure 17. Payload comparison between two types of drone with an endurance 30 min

Figure 17 shows that the payload of a quadcopter hardly exceeds 2 kg, there is a limit. On the other hand, a fixed-wing UAV has a good payload capacity, 2-3 times larger than a quadcopter.

4. Conclusion

At the end of this work, it is good to repeat the main results in the previous parts. Although the modeling of a fixed-wing UAV and a quadcopter is different, their approaches remain the same. Regarding the propeller, there is a power trend relationship between its mass and its diameter. The wooden propeller is lighter than a carbon fiber propeller, but its performance is less than a carbon fiber propeller.

Regarding the ESC, a linear modeling is made between its maximum intensity and its mass. Moreover, the choice of ESC depends only on the power of the motor, in general, the weight of ESC is 35%-55% of the motor. Moreover, when the mass of a motor exceeds 250 g, or its maximum power exceeds 2000 W, this percentage can be less than 30%. As for the engine, the relationship between its mass and power is also almost linear, but the coefficient is not always constant, it depends on the manufacturer.

However, the principle of the two types of drones is totally different. For example, the main mass of the fixed-wing UAV comes from its structure which represents about 55% of its total mass, while for a quadcopter drone, the propulsion part is the heaviest, about 61% of the total mass, because it has 4 engines to support the flight.

In addition, using the Python program, it is possible to draw an infinite number of curves between each parameter to see their influence and to compare these two types of aircraft. The results show that the performance of drones is closely related to the energy density of the battery: the higher the energy density of the battery, the stronger the endurance and the charging capacity. Moreover, with the same weight and flight time, the charging capacity of a fixed-wing UAV is much higher than that of a quadcopter.

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