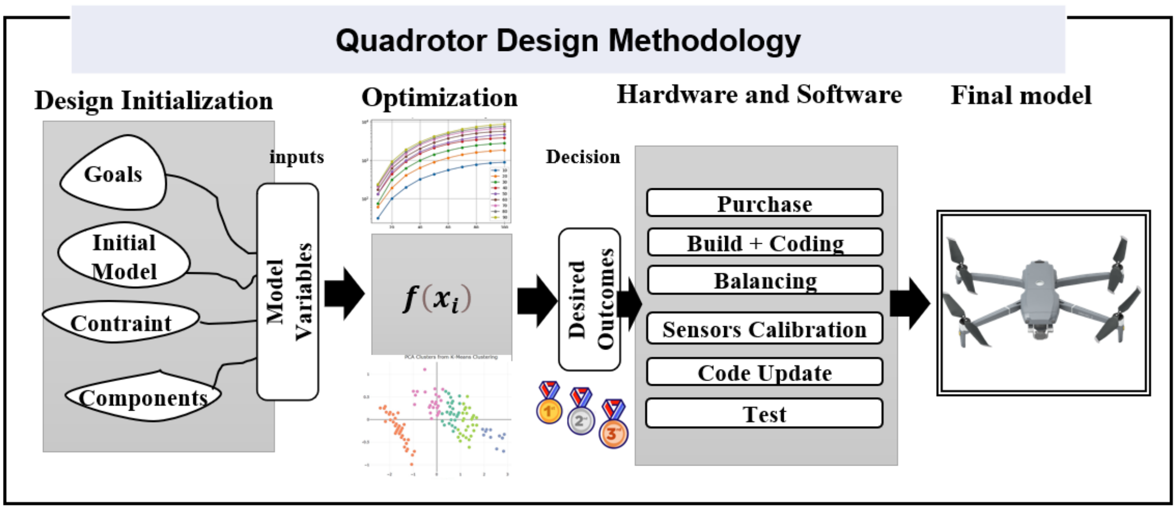
5.1 Quadrotor Sizing Results

The experimental chapter builds upon the theoretical foundation established in the theoretical chapters, where in the first phase of quadrotor design, careful consideration is given to the specific requirements and objectives of the project. This includes identifying the essential features and functionalities that the quadrotor should possess, as well as any limitations or challenges that may arise during the design and construction process. The second phase of quadrotor design follows the determination of sizing requirements. In this phase, sizing and optimization tools such as linear regression and cluster representations are employed. These tools aid in identifying the combination of quadrotor components that meet the predetermined design goals. By leveraging these techniques, the quadrotor's components can be carefully selected and configured to ensure performance and efficiency.



Here we will build upon these theoretical insights, providing a practical implementation of the design process. Through experimentation and data collection, we will demonstrate how the chosen design approach aligns with the theoretical framework. The experimental results will validate the effectiveness of the design choices made in terms of achieving the desired features, meeting the design goals, and overcoming the identified constraints.

5.1.1 Quadrotor Design Initialisation

As mentioned in the theories chapter that the building of quadrotor is begin by, determine the required features and design goals "*xi*". Includes specifying the payload capacity, flight time, maximum flight speed, and wind resistance, among other factors. In addition, based on our methodology design flowcharts for quadrotor in Figure 1.9 and 1.10 we present the following:

Target goals:

- Open-source platform for educational purposes. *x1*
- Support tasks that necessitate high processing (fuzzy logic PDC, etc). *x2*
- Assist with communication, data transfer, and saving. *x3*
- The ability to detect its location, heading, altitude, attitude, etc. *x4*
- Support for future additional devices, such as a flight computer, a camera, a hand, etc. *x4*
- Indoor and Outdoor flighting x*5*
- Non-adaptive morphologies. *x6*
- Good shock resistance. *x7*
- Stability and control of the quadrotor, it can maintain stability in the air and respond to control inputs from the operator. First task is hovering ability Second is trajectory follows, third is obstacle avoiding. *x8*
- Operating conditions, the quadrotor will be flown in, such as wind, temperature, and altitude, which can affect its performance. *x9*
- The ability for remotely controlled and autonomous flight (flight computer) x*10*

Constraints:

- Only components that meet the budget can be used. C1
- Legal requirements, guidelines of governing the use of drones and unmanned aerial vehicles, depending on the location and mission and necessities an authorisation. C2
- Almost of the quadrotor components are not available in Algeria. C3
- Many other constraints. C4

Target components:

- Low-cost. T1

- Those available in Algeria is preferred. T2

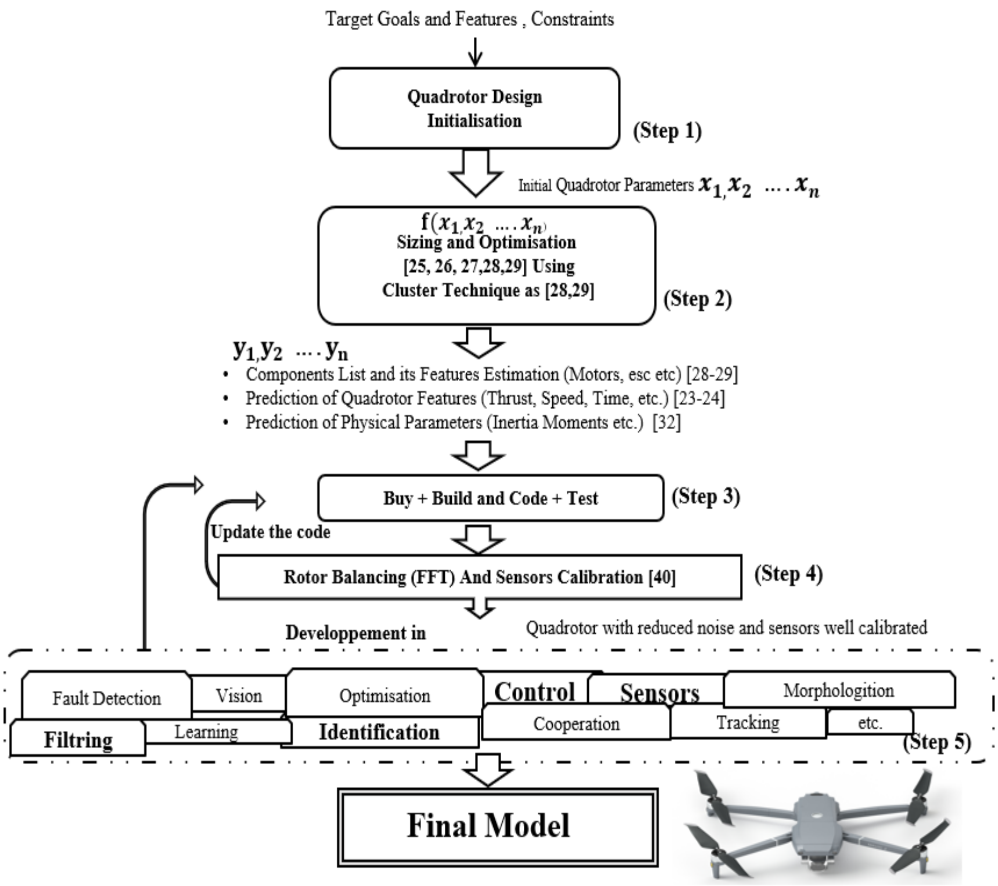
Initial Design:

- Quadrotor with legs and protectors. I1

Target features:

- Payload capacity about: 1.5 kg. *x11*
- Flight time about: 10 minutes. *x12*
- Maximum flight speed about: 20 m/s. *x13*
- Range about: 100 m. *x14*
- Altitude about: 30m. *x15*
- Dimensions about: 50 cm. *x16*

These are just some of the many features that we might consider when sizing a quadrotor, based on these requirements, we can start sizing the quadrotor components beginning by initial estimate for quadrotor components.



5.1.2 Quadrotor Components Sizing Using Cluster Technique

The **first design trend** is determined based on the correlations found in the variables "Propeller Diameter," "Weight," and "Pitch." Figure 1.17 illustrates the relationship between propeller diameter and maximum thrust, representing the maximum thrust achievable by each prop-motor combination.

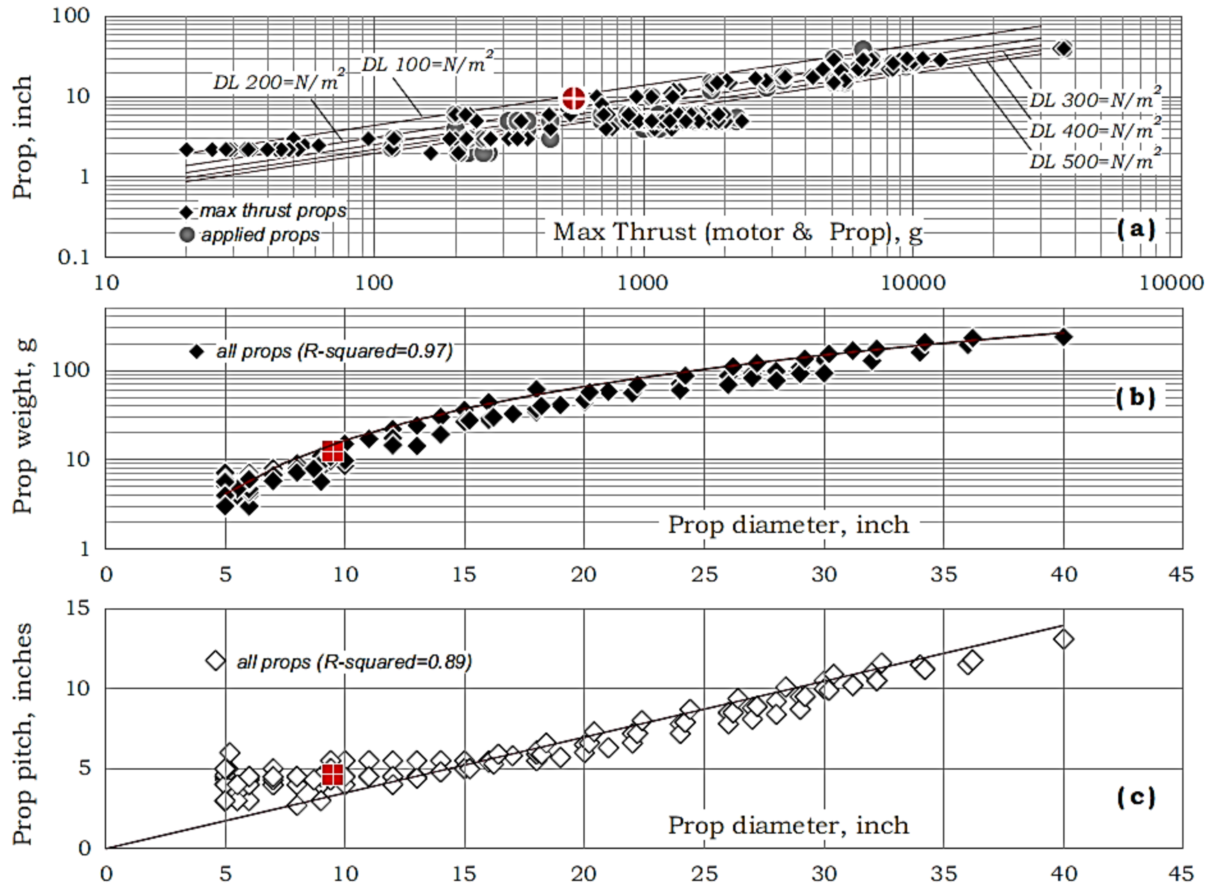


Figure 1.17: Design trends for propeller, diameter, weight, and pitch [32]

When represented using logarithmic scales, the data suggests a consistent linear trend, as anticipated for constant disc loading.

It is worth noting that propeller diameter can be expressed as a function of thrust / disc loading, as defined by the following equation in Table 1.4 as first designe trend:

Table 1.4: First design trend “Propeller Diameter” and “Weight and Pitch” [32]

$D_{[inch]} = \sqrt{T_{Max\ [g]} \frac{4.4}{\sqrt{DL_{[N/m^2]}}}}.$	$W_{Prop\ [g]} \cong 0.156 \cdot D_{\ [inch]}{}^{2}.$

$W_{Prop} \cong \rho_m \cdot (2c) \cdot t \cdot D,$	$W_{Prop} \cong \rho_m \cdot (2c) \cdot t \cdot D,$
$D_{[inch]}$:Propeller diameter. T_{Max}:Thrust. $DL_{[inch]}$ Disc loading. W_{Prop}: Propeller weight. p_m: blade material density. c: average chord t:constant	

The **Second design trend** is determined based on the correlations found in the variables of Motor Table 1.5.

Table 1.5: Second design trend about variables of Motor [32]

$W_{M\,[g]} \cong 0.032 \cdot T_{Max[g]}$	$W_{M\,[g]} \cong 0.512 \cdot D_{[inch]}{}^{2}$	$D_{M[mm]} \cong 1.52 \cdot l_{\,[mm]}{}^{0.46}$
$H_{M[mm]} \cong 0.11 \cdot l_{\,[mm]}{}^{0.76}$	$D_{M[mm]} \cong 1.79 \cdot T_{Max\,[g]}{}^{0.4}$	$D_{M[mm]} \cong 7.09 \cdot W_{M\,[g]}{}^{0.4}$
$KV \cong 241 \cdot 10^3 \cdot T_{Max\,[g]}{}^{-0.8}$	$KV \cong 15.35 \cdot 10^3 \cdot W_{M\,[g]}{}^{-0.8}$	
W_M : Motor weight. T_{Max} :Max-thrust (motor/prop) D_M :Motor diameter. H_M: Motor height. KV: Motor KV value $l_{[mm]}$: Quadrotor Frame size		

This design trend is established by analyzing the correlations among various variables, including motor weight, max-thrust (motor/prop), motor diameter, motor height, motor KV value, and quadrotor frame size as showing in Table 1.4-1.5 and illustrated in Figure 1.17 to Figures 1.19

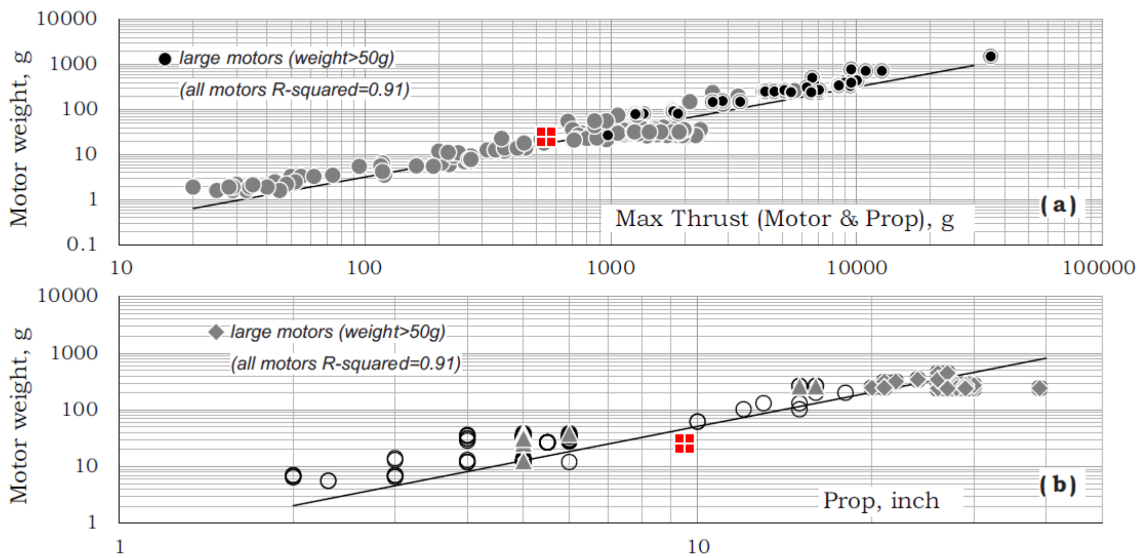


Figure 1.18: Design trends Motor Weight and Max-thrust and Propeller diameter [32]

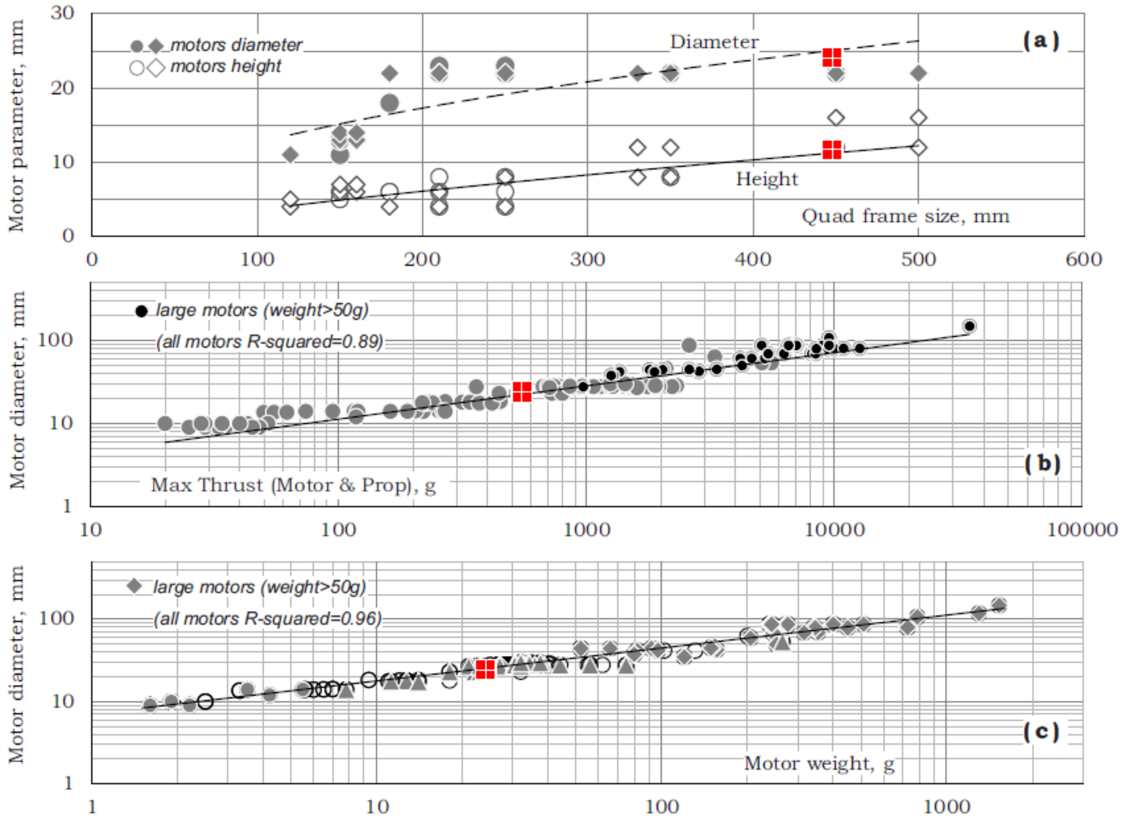


Figure 1.19: Design trends Motor Diameter/Height and Motor weight thrust and quadrotor frame size[32]

Table 1.6: Third design trend "operational parameters of motor & propeller [32]

$I_{max[A]} \cong 0.516 \cdot T_{Max[g]}^{0.528}$	$I_{cont[A]} \cong 6.53 \cdot W_{M[g]}^{0.338}$	$U_{[Volt]} \cong 2.21 \cdot T_{Max\ [g]}^{0.284}$
$U_{[Volt]} \cong 5.65 \cdot W_{M\ [g]}^{0.282}$	$P_{[W]} \cong 1.122 \cdot T_{Max\ [g]}^{0.813}$	
$Q_{\ [Nm]} \cong 2.2 \cdot 10^{-5} \cdot T_{Max\ [g]}^{1.3}$	$P_{[W]} = \Omega_{[rad/\sec]} Q_{\ [Nm]} \cong 0.922 \cdot T_{Max\ [g]}^{0.8}$	

Table 1.7: Fourth design trend "propeller rotational velocity" [32]

$\Omega_{[RPM]} \cong \dfrac{4 \times 10^5}{\sqrt{T_{Max\ [g]}}}$	$\Omega_{[RPM]} \cong \dfrac{1 \times 10^5}{D_{[inch]}}$

Table 1.8: Fiveth design trend “Batteries Characteristics” [32]

$C_{Batt\ [mAh]} \cong 0.129 \cdot l_{\ [mm]}^{\ 1.69}$	$M_{Batt\ [g]} \cong 4.68 \cdot 10^{-2} \cdot C_{Batt\ [mAh]}^{\ 1.10}$
$V_{Batt\ [liter]} \cong 3.1 \cdot 10^{-5} \cdot C_{Batt\ [mAh]}^{\ 1.063}$	$N_c \cong \lfloor 2.25 \cdot \log_{10}\left(M_{Batt\ [g]}\right) - 1.25$
$V_{Batt\ [liter]} \cong 5.98 \times 10^{-4} \cdot M_{Batt\ [g]}^{\ 0.966}$	$E_{Batt\ [Wh]} \cong 9.25 \times 10^{-2} \cdot M_{Batt\ [g]}^{\ 1.072}$
$E_{S\ [Wh/kg]} \cong 74.2 \cdot C_{Batt\ [mAh]}^{\ 0.079}$	$E_{\rho\ [Wh/liter]} \cong 112.017 \cdot C_{Batt\ [mAh]}^{\ 0.116}$
$E_{Batt\ [Wh]} = 3.7 \cdot 10^{-3} \cdot C_{Batt\ [mAh]} \cdot N_c$	

Table 1.9: Sexth design trend “Payload” [32]

$\left.\frac{W_{PL}}{GW}\right\|_{\text{FSHs \& MPCs}} \cong 0.36$	$\left.\frac{W_{PL}}{GW}\right\|_{\text{RWUAVs}} \cong 0.2.$

Table 1.4 to Table 1.9 provide detailed information on the design trends related to "Motor & Propeller Operational Parameters," "Propeller Rotational Velocity," "Batteries Characteristics," and "Payload." These tables present the correlations and findings regarding these specific variables. While the paper [32] provides comprehensive details about the equations and their associated variables.

Based on the stated requirements **target goals** {*x1* … *x10*} and **initial Design** aim {*I1*} and **target features** {*x11*…*x16*}, we can initiate the process of determining the appropriate sizes for the initial quadrotor components. However, it is important to keep in mind that these results are just an “initial estimate” and the final selection of components and their characteristics will be based on other factors such as constraints and specific target goals. Let give some examples of estimation of quadrotor components using cluster technique.

To illustrate the selection of motor variables discussed in the theoretical part, we can examine the second design trend related to motor variables. Specifically, we consider motor weight, max-thrust (motor/prop), motor diameter and height, motor KV value, and quadrotor frame size, as presented in Figure 5.1. Through our analysis, we have discovered a significant correlation between these variables, and we have formulated a relationship model, which is outlined in Table 1.5 in the theoretical section and presented in the flowchart Figure 5.1. The model displays the following insights:

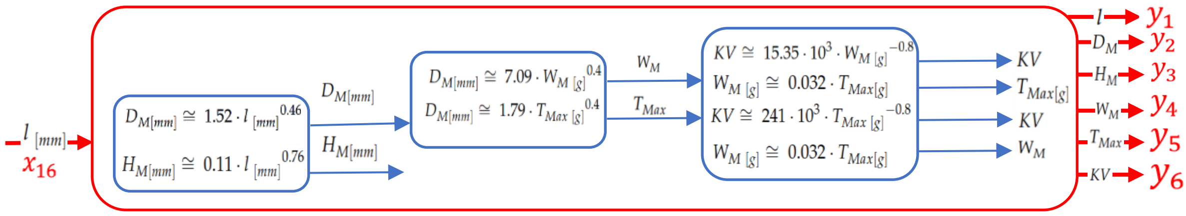


Figure 5.1: Sizing box for second design trend related to motor variables.

Table 5.1: Numerical Solution of Motor Variables second design trend

$x_{16} = y_1(mm)$	$y_2\ (mm)$	$y_3\ (mm)$	$y_3\ (g)$	$y_4 = y_3\ (g)$	$y_5\ (g)$	$y_6\ (kv)$
500	26.50	12.37	27.00	26.98	845.30	1099

In our analysis of target features, our primary focus was on the input variable x_{16}, which represents the dimensions of the quadrotor frame size. Specifically, this dimension is approximately 50 cm, denoted as x_{16}=50 cm and referred to as $l_{[mm]}$ in the equation. We utilized this value as an input for the sizing box depicted in Figure 5.1. This particular box encompasses all the equations associated with the "second design trend," which are directly related to motor variables. The resulting outputs from this box are (y_1...y_6) presented in Table 5.1 represent various other quadrotor features. These outputs are subsequently utilized as inputs for subsequent boxes, such as the third design trend, which deals with the operational parameters of the motor and propeller, as illustrated in Figure 5.2.

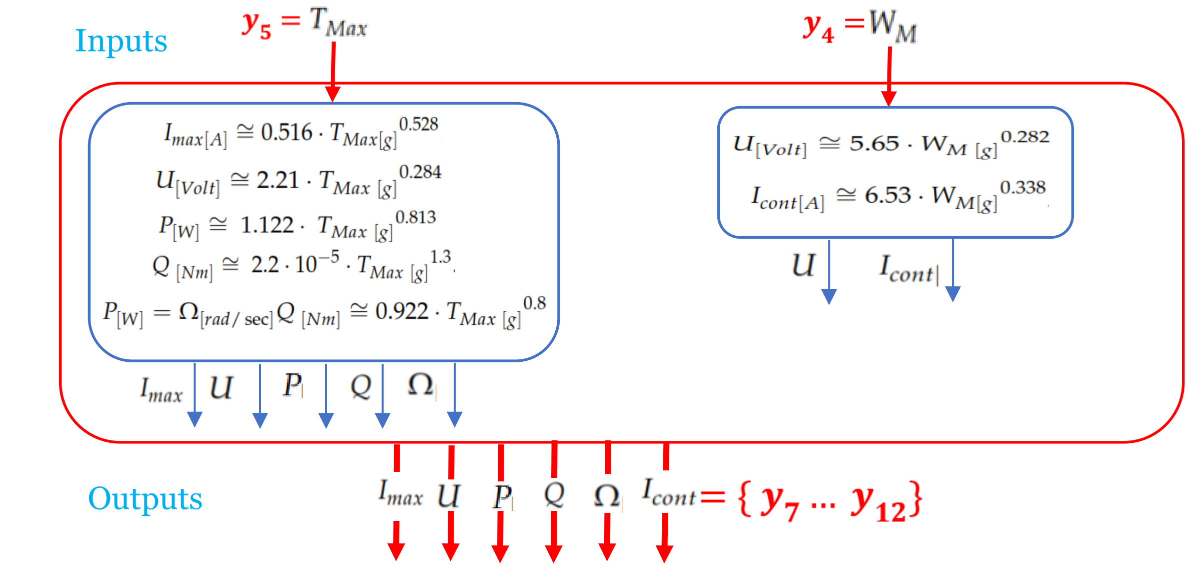
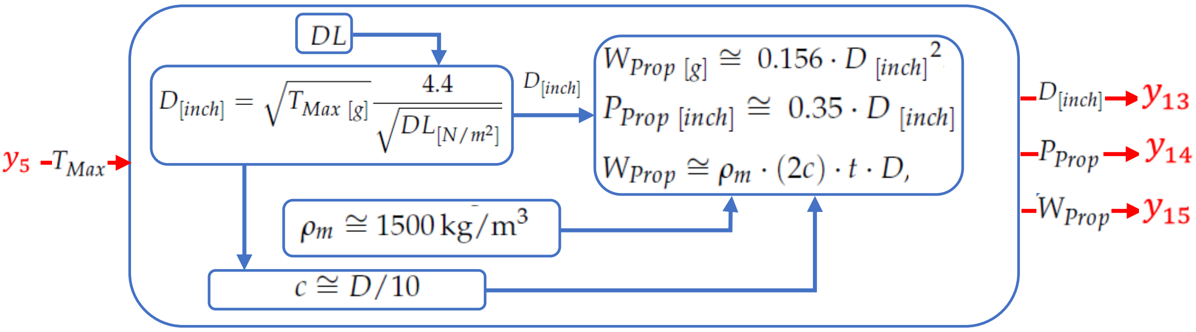


Figure 5.2: Sizing box for third design trend related to motor/prop operational parameters.

Table 5.2: Numerical Solution of motor/prop operational parameters

$y_7 (A)$	$y_8\ (V)$	$y_9\ (W)$	$y_{10}\ (Nzm)$	$y_{11}\ (rad/s)$	$y_{12}\ (A)$
18.09	14.97-14.31	268.42	0.14	1917-1443	19.89

Based on the data presented in Table 5.1 and Table 5.2, we can draw conclusions about the appropriate motors for a quadrotor with a size of 50cm and a weight exceeding 1.5 kg. The ideal motors would have a diameter of approximately 26.5mm, a height of around 15.37mm, and a weight of approximately 27 grams. Their KV value should be around 1099 rotations per volt, enabling them to generate a thrust of 843 grams. Furthermore, based on these motor characteristics, we can estimate the power consumption. At maximum thrust, we anticipate a motor-prop current consumption of about 18A, and the maximum continuous current trend-line for all motors is



expected to be around 19.89A. Additionally, the voltage consumption is projected to be approximately 14V, considering either the motor's maximum thrust or its weight. The expected power output of each motor is around 268W. These estimations provide a general overview of the suitable motor specifications for our quadrotor.

Figure 5.3: Sizing box for design trend “Propeller Diameter” and “Weight and Pitch”

Table 5.3: Solution of first design trend “Propeller Diameter” and “Weight and Pitch”

$y_{13}(inch)$	y_{14} *(inch)*	y_{15} *(g)*	c*(inch)*	DL *(N/m^2)*
11.206	5.922	17.48	1.12	130

Based on the requirements and specifications of the quadrotor, the appropriate propeller would have a diameter of approximately 11.2 inches and a pitch of around 5.9 inches. This propeller should weigh approximately 1.75 grams. These dimensions and weight are selected to achieve the desired thrust, stability, and efficiency for the quadrotor's performance.

The process of selecting other quadrotor parameters, including propeller rotational velocity, battery characteristics, payload, propeller diameter, weight, and pitch, follows a similar methodology. By applying this process, we can envision an appropriately designed quadrotor that aligns with our target features and goals.

5.1.3 Quadrotor Design Final Selection of Components

The final selection of quadrotor components is a result of a comprehensive process that takes into account the characteristics obtained from the previous step, which involved sizing based on clustering or design trends. Additionally, the selection process considers the constraints (*C1…C4*) and the target components (*T1, T2*) outlined earlier. The process involves carefully evaluating the available components that meet the required specifications and align with the quadrotor's target goals and constraints. It takes into consideration factors such as budget limitations, legal requirements governing drone use, component availability in Algeria, and other specific constraints identified during the design process.

The final selection is made by comparing and assessing various component options, weighing their compatibility with the quadrotor's requirements and the constraints imposed. Components are chosen based on their ability to meet the desired payload capacity, flight time, maximum flight speed, range, altitude, and dimensions.

Frame: To accommodate the payload and other components, we would need a rigid frame non-adaptive (*x6*) with dimensions of around 50 cm (*x16-x4*). A quadrotor frame made of carbon fibre or aluminium or adequate plastics would provide the necessary and stability (*x7*). The frame of a quadrotor is indeed an essential component and plays a crucial role in providing structural integrity and stability to the overall system. There are two main options for acquiring a quadrotor frame: building it using available materials such as carbon-fiber or aluminium, or purchasing a commercially available frame.

The commercially available frames have the advantage of being well studied and designed by manufacturers who specialize in quadrotor components. These frames undergo rigorous testing and optimization to ensure their performance and reliability. Commercial frames come in various sizes and designs, catering to different quadrotor configurations and payload capacities.

The following Table 5.4 showcases three well-known commercial quadrotor frames as candidates, highlighting their characteristics such as width, weight, and cost. Additionally, a radar chart in Figure 5.4 illustrates a comparison between these frames based on their performance against target goals.

Table 5.4: Commercial quadrotor frames

F450	**F550**	**Tarot TL65S01 650**
		
• Width: 450mm • Weight: 395g • Super strong & smooth • Price: € 3,86 • **Shipping: € 14.27**	• Width: 550mm • Weight: 630 ±2 g • Full carbon fiber • Price: € 62,80 • Shipping: €10.90	• Width: 600mm • Weight: 1000g • Full carbon fiber • Price: 119,16 • Shipping: €32.96

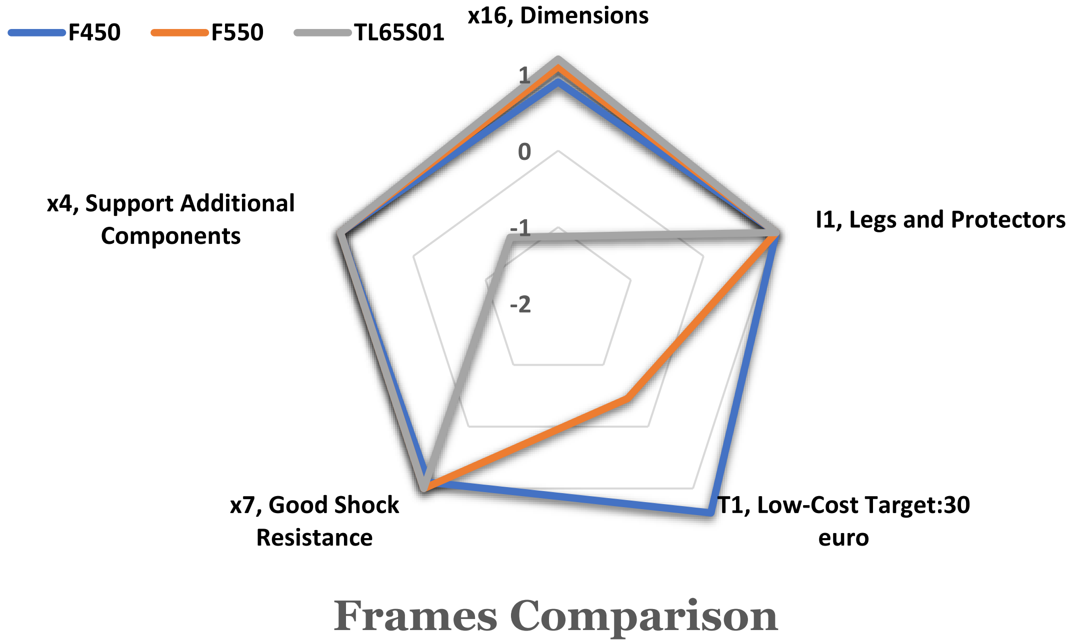


Figure 5.4: Comparison of the commercial quadrotor frames

Based on the comparison of the commercial quadrotor frames, the analysis indicates that the F450 frame emerges as the best choice. This conclusion is drawn from evaluating several factors, including its cost (*T1*), shock resistance (*x7*), dimensions (*x16),* leg and protectors (*I1*), and support for additional components (*x4*). The F450 frame exhibits favourable performance in these areas, making it the optimal selection among the available options.

Motors: Because the payload target capacity is about 1.5 kg (x11). The total thrust of the select motors is preferred to be twist the payload target capacity (3 kg), which make each motor have at minimum thrust of 750 g of each (we found y5=845.30 g). It is important to consider the desired payload capacity. If the payload capacity is high (3 kg), larger and more powerful motors may be required to lift the weight and maintain stability. In this case, a lower KV rating may be necessary to generate the required torque. In addition, this can be achieved by using brushless DC motors with a KV value around 800-1000 KV (we found y6=1099 KV). These motors would have a power rating of around 1000W each.

Propellers: The propeller diameter (y13) calculated using the formula for propeller thrust efficiency. The propellers should be able to generate enough thrust (y5) to carry the payload (x11) and maintain stability during flight (x8). A larger diameter propeller (y13) will typically generate more thrust (y5), which is necessary to carry a heavy payload of 1.5 kg at less. Propellers with a larger diameter tend to be more efficient, which results in longer flight times (x12). In this case, the goal is to achieve a flight time of 10 minutes, so choosing propellers with a larger diameter can help to achieve this goal. In addition, the maximum flight speed (x13) of 20 m/s requires adequate propellers (y13, y14, y15), which can be achieved with larger diameter and adequate pitch (y14) propellers. In general, propellers with an advance ratio of around 0.5 are considered to be the most efficient, as they provide a good balance between thrust and efficiency. The propellers around 11-inch (y13) with 4-inch (y14) of pitch propellers chosen should have a high pitch, which will provide the necessary thrust to maintain stability during flight (x8). The material of the propellers is also important, as lightweight materials (y15) such as carbon fibre or plastic provide better efficiency.

Battery: To achieve the desired flight time of 10 minutes, we would need a battery with a capacity of around 5000mAh. To ensure the safety of the system, we could use a LiPo battery with a C rate of at least 25C. Or battery of 3700 mAh with CC of 80CC.

Electronic Speed Controllers (ESCs): The ESCs should have a continuous current rating of at least 30A and a burst current rating of 40A or higher. They should also have a built-in voltage regulator to ensure stable operation.

Flight Controller: A flight controller should have a fast-processing speed, multiple inputs and outputs, with advanced features such as GPS, altitude hold, and position hold would be suitable for this system. The flight controller should be compatible with the other components and have a sufficient processing power to handle the required calculations.

Radio Control System: A radio control system with a range of at least 100 m would be required to control the quadrotor. We could use a 2.4GHz radio control system with a minimum of 8 channels to provide enough control options. We can choose between a traditional analog radio controller or a digital system such as the FrSky Taranis or the Spektrum DX9.

These are the main components and specifications of a quadrotor system designed to meet the target features outlined previously. Keep in mind that the specific components and specifications may vary depending on the exact requirements or new constraints or specific target goals.

Table 5.5 presents a range of options that are in line with the quadrotor sizing results. These options showcase a selection of commercialized quadrotors, each consisting of a combination of components carefully chosen to meet the required specifications.

Table 5.5: Some commercial quadrotors components combination meets the required specifications

N	Motor	ESC	Propeller	Battery	Frame Size	Hovering Time	Load Weight	Total Weight
1	EMAX XA2212-980KV	EMAX Simonk 20A	APC 10x4.7	LiPo 2S-7.4V-35C-3400mAh	450mm	17.2min.	0.5kg	1kg
2	EMAX MT2208II-2000KV	EMAX BLHeli 20A	HQ 5x4	LiPo 4S-14.8V-40C-	230mm	17.1min.	0.3kg	1kg
3	EMAX MT2206II-1900KV	EMAX BLHeli 20A	HQ 5x4.5	LiPo 4S-14.8V-35C-	230mm	16.8min.	0.3kg	1kg
4	SunnySky X2204-1800KV	Hobbywing XRotor 20A	GWS 8x4	LiPo 3S-11.1V-45C-3900mAh	360mm	17min.	0.4kg	1kg
5	JFRC U2204 KV1800	Hobbywing XRotor 20A	GWS 8x4	LiPo 3S-11.1V-40C-3900mAh	360mm	17.1min.	0.4kg	1kg
1	T-MOTOR F40 KV2300	**T-MOTOR AIR 40A**	4*4.5 DAL	LiPo 4S-14.8V-35C-	180mm	17min.	0kg	1.3kg
2	**EMAX XA2212-980KV**	EMAX Simonk 20A	APC 9x6	LiPo 3S-11.1V-40C-4000mAh	400mm	17min.	0.6kg	1.3kg
3	EMAX MT2208II-2000KV	EMAX Simonk 25A	HQ 6x4.5	LiPo 3S-11.1V-40C-5200mAh	270mm	17min.	0.5kg	1.3kg
4	JFRC U2212 KV750	Hobbywing XRotor 10A	APC 9x4.7	LiPo 4S-14.8V-40C-	400mm	17min.	0.5kg	1.3kg
1	DJI E310-2312 KV960	DJI E310-20A	DJI 9.4x5	LiPo 3S-11.1V-35C-3100mAh	420mm	17.1min.	0.7kg	1.5kg
2	JFRC U2208 KV1100	Hobbywing XRotor 10A	APC 8x5.8	LiPo 4S-14.8V-35C-	360mm	17min.	0.7kg	1.5kg
3	EMAX XA2212-980KV	EMAX Simonk 25A	APC 10x4.7	LiPo 3S-11.1V-45C-4400mAh	450mm	17.1min.	0.7kg	1.5kg
4	JFRC U2216 KV1100	Hobbywing XRotor 20A	APC 9x4.5	LiPo 3S-11.1V-45C-3800mAh	400mm	17min.	0.6kg	1.5kg
5	EMAX XA2212-820KV	EMAX Simonk 20A	APC 11x4.7	LiPo 3S-11.1V-40C-4000mAh	490mm	17.1min.	0.7kg	1.5kg
15	EMAX MT3110-700KV	EMAX Simonk 30A OPTO	Carbon 11x4.7	LiPo 4S-14.8V-55C-4000mAh	490mm	10.3min.	1kg	2.31kg

The selection process for the quadrotor components is completed by identifying a low-cost component (T1) that aligns with the budget constraint (C1), overcomes all other constraints (C4), and preferred available in Algeria (T2). This crucial component will be further discussed in the following section, starting with the quadrotor frame selection.