

**Human Factors in Systems Engineering**

**ENSE 622**

**Project Report**

**Version 1.0**

Delivery Drone Analysis

**By**

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**For**

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# **1.** **Executive Summary and Introduction**

The goal of this analysis is to evaluate the metrics of four designs and help a customer select the best design in accordance with its preferences.

The customer of this analysis is a drone delivery company that wants to develop autonomous drones to transport goods from one place to another. Consequently, it has developed four different drone designs for this purpose and needs help selecting the best design.

The principal metrics are

* **Drone unit cost:** This is the cost per unit of each drone.
* **Rated lifting capacity**: This is the weight of the largest package the drone can transport for a thrust-to-AUW(All-up weight) ratio of 2. The All-up weight is the total weight of the drone plus the weight of any package the drone is lifting.
* **Maximum flight time:** This is the upper limit on the time the drone can spend in flight. It is rated at a constant horizontal speed of 3 m/s.
* **Maximum speed:** this is the maximum speed of the drone at the motor rated voltage.

The principal factors of interest are

* **Drone weight:** This is the total weight of the drone.
* **Component cost:** This is the cost of each component that makes up the drone. The components of the drone are defined in Section 2.
* **Battery capacity:** This is a measure of the charge stored by the battery.
* **Motor design factors:** This includes the following
  + no-load speed (rpm): this is the motor speed when there is no external load.
  + stall torque: this is the torque produced by the motor at zero speed.
  + no-load current: this is the current drawn by the motor when there is no external load.
  + torque constant: this is the change in motor torque/change in current drawn by the motor.
* **Dimension factors:** These are the dimensions of the drone frame.
* **Empirical design factors**: These are factors like the thrust coefficient, torque coefficient and the drag coefficient that are obtained from empirical models.

The Response diagrams for the four metrics are presented in Figures 1- 4

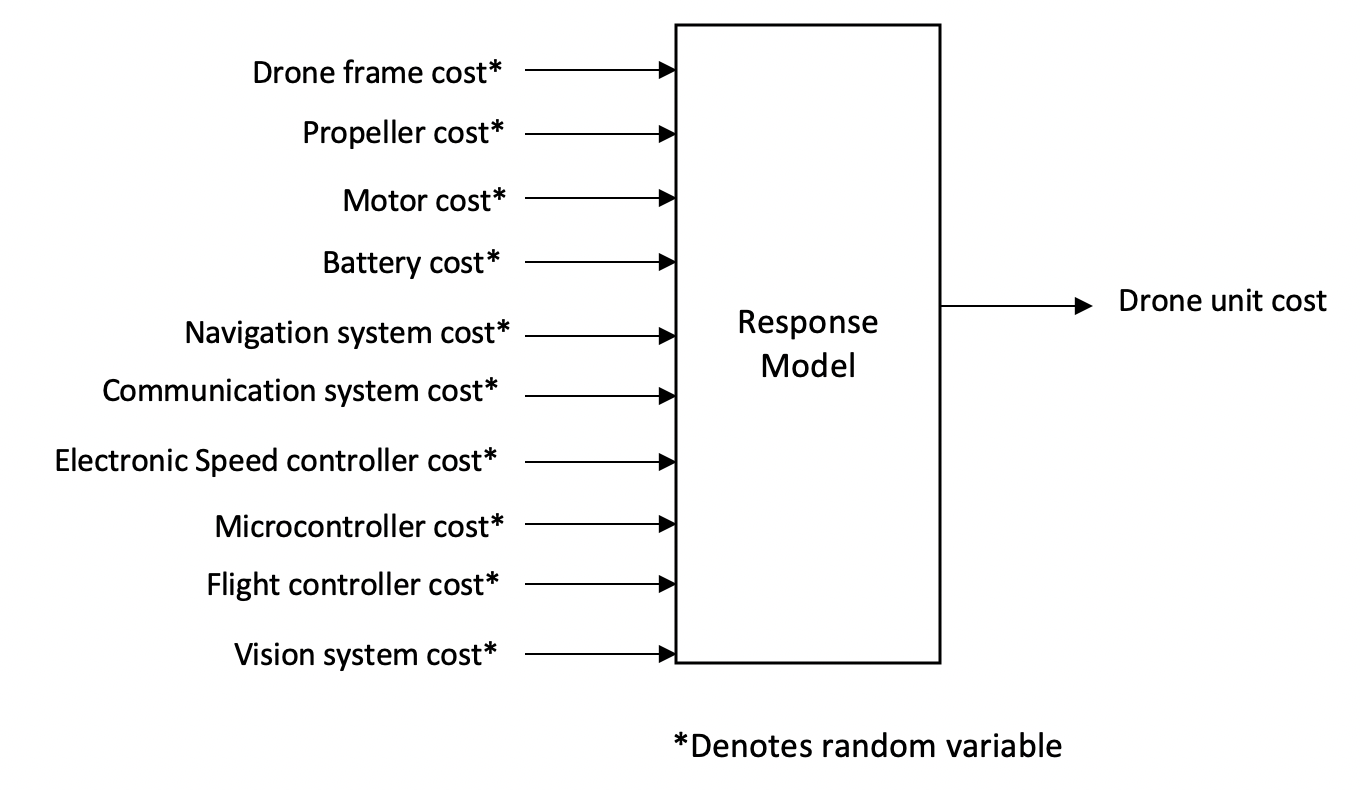
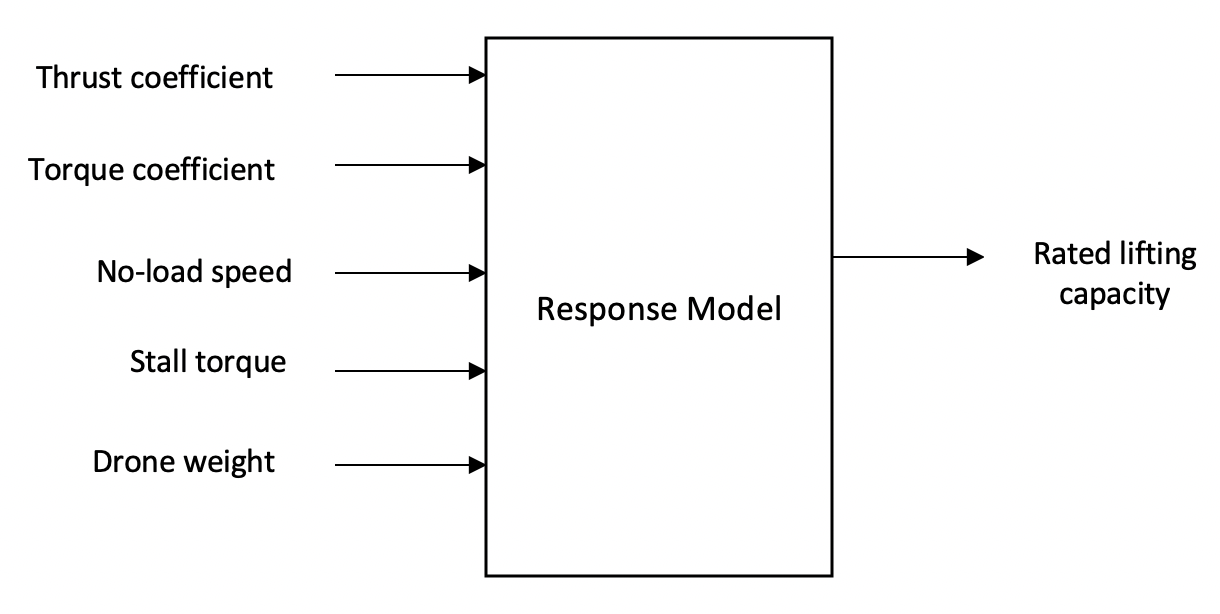


Figure 1: Drone unit cost response model



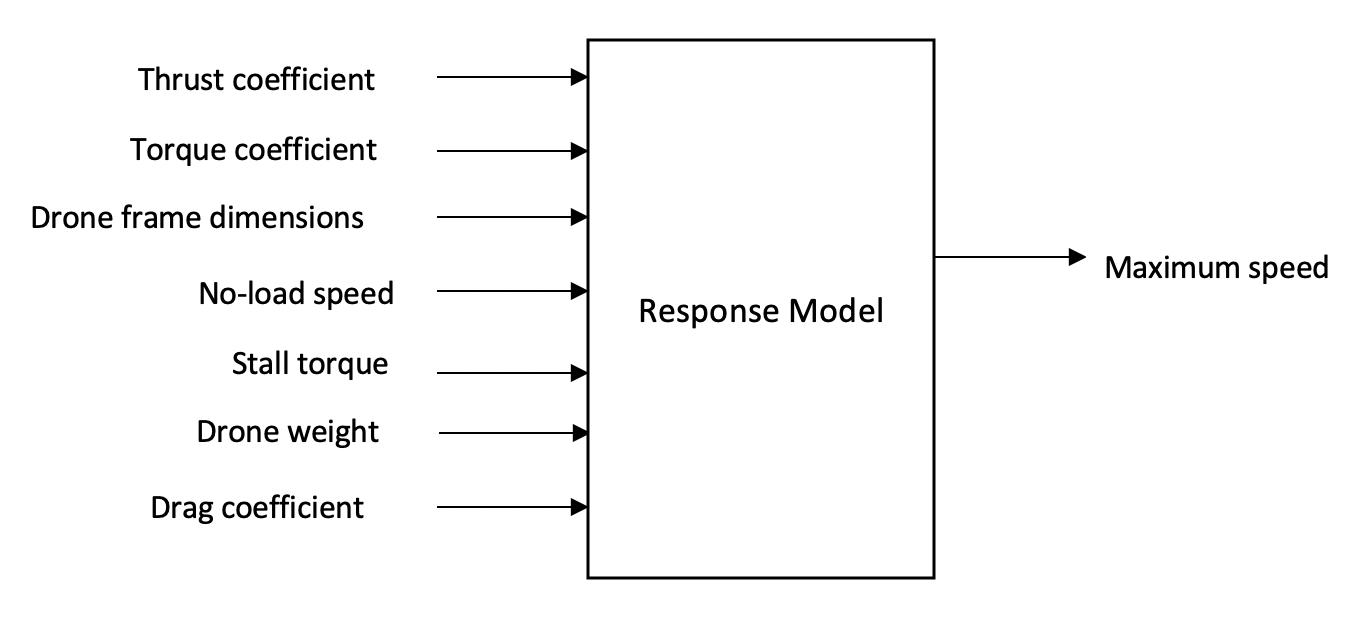
Figure 2: Rated lifting capacity response model

Figure 3: Maximum speed response model

The Response diagram for the Maximum flight time metric is presented in Figure 1

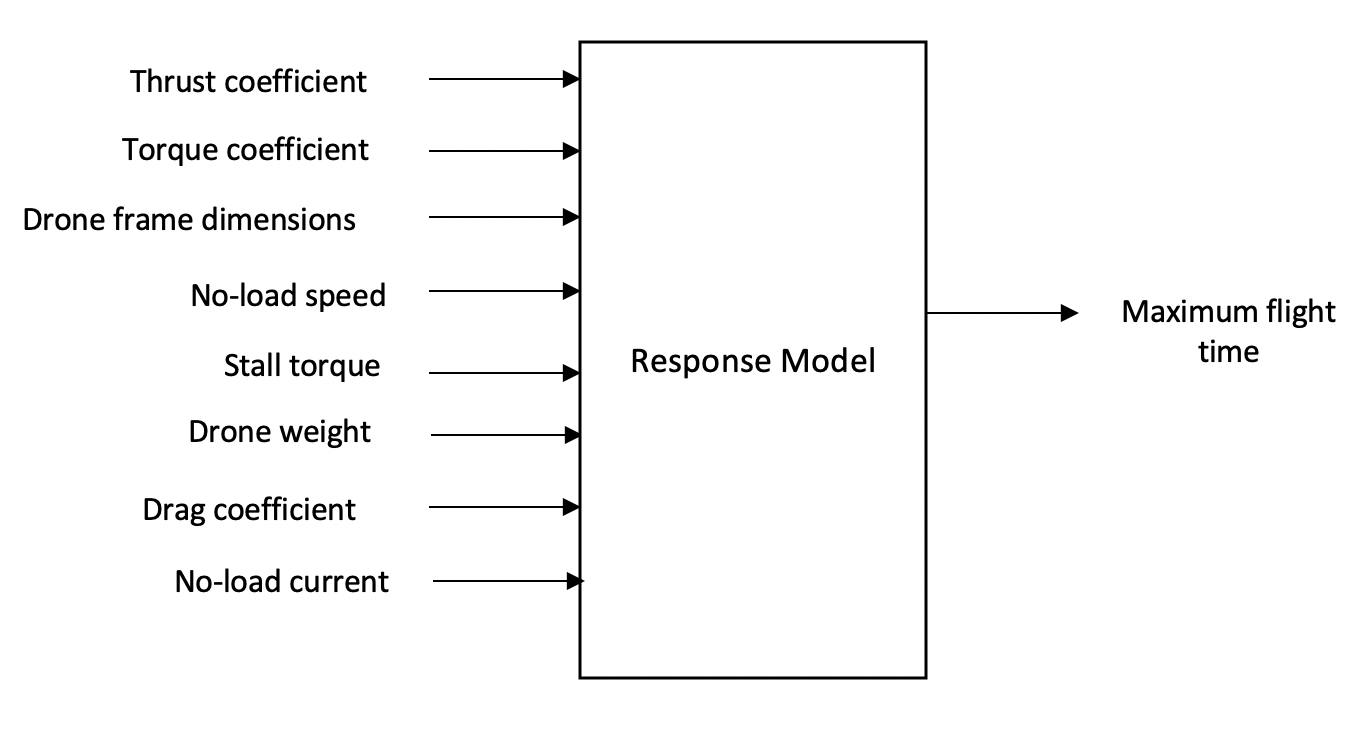


Figure 4: Maximum flight time response model

The Drone weight is a factor for the rated lifting capacity, maximum speed and maximum flight time metrics. Its response model is presented in Figure 5

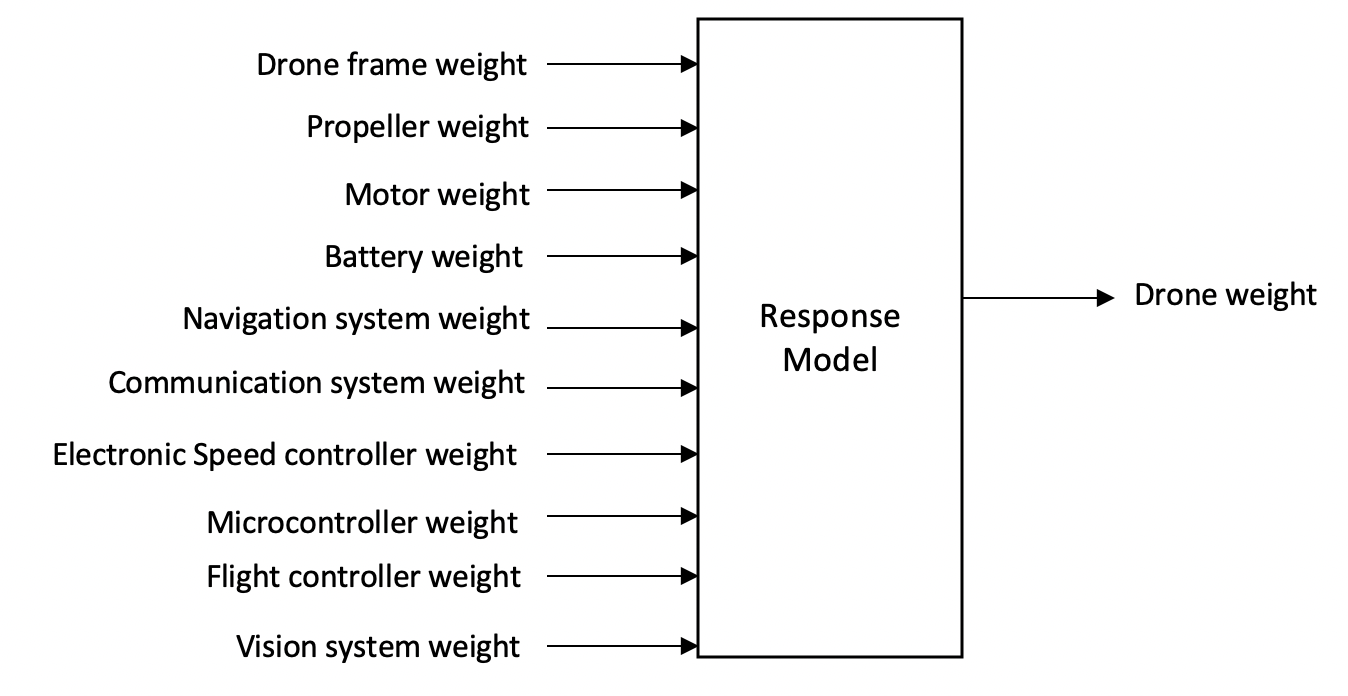


Figure 5: Drone weight response model

The Design options were obtained by searching for different component designs for each drone design. Table 1 presents the specific components that were selected for each design along with the links to the component.

Table 1: Component designs for the four designs.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | Design 1 | Design 2 | Design 3 | Design 4 |
| Battery | [Battery2200mAh](https://www.anaheimautomation.com/products/brush/brush-motor-item.php?sID=616&serID=74&pt=i&tID=101&cID=24) | [Battery3200mAh](https://www.anaheimautomation.com/products/brush/brush-motor-item.php?sID=616&serID=74&pt=i&tID=101&cID=24) | [Battery3200mAh](https://www.anaheimautomation.com/products/brush/brush-motor-item.php?sID=616&serID=74&pt=i&tID=101&cID=24) | [Battery2200mAh](https://www.anaheimautomation.com/products/brush/brush-motor-item.php?sID=616&serID=74&pt=i&tID=101&cID=24) |
| Propeller | [Propeller8in](https://www.getfpv.com/master-airscrew-mr-series-8x4-5-prop-set-x2-black.html) | [Propeller8in](https://www.getfpv.com/master-airscrew-mr-series-8x4-5-prop-set-x2-black.html) | [Propeller8in](https://www.getfpv.com/master-airscrew-mr-series-8x4-5-prop-set-x2-black.html) | [Propeller8in](https://www.getfpv.com/master-airscrew-mr-series-8x4-5-prop-set-x2-black.html) |
| Motor | [Motor12V](https://www.anaheimautomation.com/products/brush/brush-motor-item.php?sID=616&serID=74&pt=i&tID=101&cID) | [Motor12V](https://www.anaheimautomation.com/products/brush/brush-motor-item.php?sID=616&serID=74&pt=i&tID=101&cID) | [Motor12V](https://www.anaheimautomation.com/products/brush/brush-motor-item.php?sID=616&serID=74&pt=i&tID=101&cID) | [Motor12V](https://www.anaheimautomation.com/products/brush/brush-motor-item.php?sID=616&serID=74&pt=i&tID=101&cID) |
| Navigation System | [Holybro](https://www.getfpv.com/holybro-micro-m8n-gps-module.html?utm_source=google&utm_medium=cpc&adpos=&scid=scplp4429&sc_intid=4429&gclid=CjwKCAjwwYP2BRBGEiwAkoBpAtYB8lh-9jfkcy77NonDHcE2FBzjPsp4nWrJ4IsR9BMrHLxHyjhsSRoCaqQQAvD_BwE) | [GPS15136](https://www.digikey.com/product-detail/en/sparkfun-electronics/GPS-15136/1568-1983-ND/9856841?utm_adgroup=Evaluation%20Boards%20-%20Expansion%20Boards%2C%20Daughter%20Cards&utm_source=google&utm_medium=cpc&utm_campaign=Shopping_Development%20Boards%2C%20Kits%2C%20Programmers&utm_term=&utm_content=Evaluation%20Boards%20-%20Expansion%20Boards%2C%20Daughter%20Cards&gclid=CjwKCAjwwYP2BRBGEiwAkoBpArFNkY8FVuMaHaaohp0FeYTzKeteHngifFFs6gLO5LfbSObcBGr8ghoCgzMQAvD_BwE) | [Parallex](https://www.mouser.com/datasheet/2/321/28504-SIM33EAU-GPS-Product-Guide-1.0-1648417.pdf) | [Parallex](https://www.mouser.com/datasheet/2/321/28504-SIM33EAU-GPS-Product-Guide-1.0-1648417.pdf) |
| Drone Frame | [Drone Frame450mm](https://usa.banggood.com/Upgrade-F450-450mm-Wheelbase-Frame-Kit-with-Highten-Landing-Gear-for-RC-Drone-p-1414811.html?rmmds=detail-left-hotproducts__3&cur_warehouse=CN) | [Drone Frame450mm](https://usa.banggood.com/Upgrade-F450-450mm-Wheelbase-Frame-Kit-with-Highten-Landing-Gear-for-RC-Drone-p-1414811.html?rmmds=detail-left-hotproducts__3&cur_warehouse=CN) | [Drone Frame450mm](https://usa.banggood.com/Upgrade-F450-450mm-Wheelbase-Frame-Kit-with-Highten-Landing-Gear-for-RC-Drone-p-1414811.html?rmmds=detail-left-hotproducts__3&cur_warehouse=CN) | [Drone Frame450mm](https://usa.banggood.com/Upgrade-F450-450mm-Wheelbase-Frame-Kit-with-Highten-Landing-Gear-for-RC-Drone-p-1414811.html?rmmds=detail-left-hotproducts__3&cur_warehouse=CN) |
| Electronic Speed Controller | [HK10AX4](https://www.amazon.com/Crazepony-Controller-Oneshot125-Compatible-Multirotor/dp/B07GWF18P2/ref=sr_1_1?dchild=1&keywords=electric%2Bspeed%2Bcontroller%2Bin%2Bdrones&qid=1585420053&s=toys-and-games&sr=1-1&th=1) | [iFlight SucceX-E Mini](https://www.amazon.com/dp/B07R4ZPJNY/ref=psdc_2234132011_t5_B081C1GPSM) | [iFlightSucceX-E](https://www.amazon.com/dp/B07WDRW249/ref=psdc_2234132011_t1_B07GWF18P2?th=1) | [iFlight SucceX](https://www.amazon.com/dp/B081C1GPSM/ref=psdc_2234132011_t2_B07GWF18P2) |
| Microcontroller | [ATMEGA32](https://www.amazon.com/ATMEGA32-16PU-Microcontroller-System-Programmable-ATMEGA/dp/B071VYGJB9/ref=sr_1_fkmr0_1?dchild=1&keywords=Atmega32+avr&qid=1585514649&sr=8-1-fkmr0#detail-bullets) | [ATMEGA32](https://www.amazon.com/ATMEGA32-16PU-Microcontroller-System-Programmable-ATMEGA/dp/B071VYGJB9/ref=sr_1_fkmr0_1?dchild=1&keywords=Atmega32+avr&qid=1585514649&sr=8-1-fkmr0#detail-bullets) | [ATMEGA32](https://www.amazon.com/ATMEGA32-16PU-Microcontroller-System-Programmable-ATMEGA/dp/B071VYGJB9/ref=sr_1_fkmr0_1?dchild=1&keywords=Atmega32+avr&qid=1585514649&sr=8-1-fkmr0#detail-bullets) | [AT32UC3A1512](https://www.microchip.com/wwwproducts/en/AT32UC3A1512) |
| Flight Controller | [F4MPU6000](https://www.amazon.com/dp/B07WFXYH19/ref=sspa_dk_detail_4?pd_rd_i=B07WFXYH19&pd_rd_w=ryk3t&pf_rd_p=48d372c1-f7e1-4b8b-9d02-4bd86f5158c5&pd_rd_wg=fD6UF&pf_rd_r=7Z3EQ5NX7ZVVC1KTY314&pd_rd_r=fe0cc2cc-e476-4aa3-af6f-8e23ae01c78f&spLa=ZW5jcnlwdGVkUXVhbGlmaWVyPUEzODBQREhYRFVINTBWJmVuY3J5cHRlZElkPUEwNzc2MTU5MkpUSUhQU05PV1U5TiZlbmNyeXB0ZWRBZElkPUEwNzkwMDQ1MzE2QkE1QU5KRU83QyZ3aWRnZXROYW1lPXNwX2RldGFpbCZhY3Rpb249Y2xpY2tSZWRpcmVjdCZkb05vdExvZ0NsaWNrPXRydWU&th=1) | [F4MPU6000](https://www.amazon.com/dp/B07WFXYH19/ref=sspa_dk_detail_4?pd_rd_i=B07WFXYH19&pd_rd_w=ryk3t&pf_rd_p=48d372c1-f7e1-4b8b-9d02-4bd86f5158c5&pd_rd_wg=fD6UF&pf_rd_r=7Z3EQ5NX7ZVVC1KTY314&pd_rd_r=fe0cc2cc-e476-4aa3-af6f-8e23ae01c78f&spLa=ZW5jcnlwdGVkUXVhbGlmaWVyPUEzODBQREhYRFVINTBWJmVuY3J5cHRlZElkPUEwNzc2MTU5MkpUSUhQU05PV1U5TiZlbmNyeXB0ZWRBZElkPUEwNzkwMDQ1MzE2QkE1QU5KRU83QyZ3aWRnZXROYW1lPXNwX2RldGFpbCZhY3Rpb249Y2xpY2tSZWRpcmVjdCZkb05vdExvZ0NsaWNrPXRydWU&th=1) | [iFlight SucceX-D](https://www.amazon.com/dp/B081ZS22VR/ref=sspa_dk_detail_0?psc=1&pd_rd_i=B081ZS22VR&pd_rd_w=xofAk&pf_rd_p=48d372c1-f7e1-4b8b-9d02-4bd86f5158c5&pd_rd_wg=8YEAK&pf_rd_r=847D1AH8Z5XGY2VAT442&pd_rd_r=47b16370-45c0-467b-b9b1-309b66c921bf&spLa=ZW5jcnlwdGVkUXVhbGlmaWVyPUEzQTVNTFQyMUxUN0pSJmVuY3J5cHRlZElkPUEwMzU1NjA1MUpJWVNQQUY1SjhKRiZlbmNyeXB0ZWRBZElkPUExMDIzNzYyMzY2Wks3OTI2TzdVRiZ3aWRnZXROYW1lPXNwX2RldGFpbCZhY3Rpb249Y2xpY2tSZWRpcmVjdCZkb05vdExvZ0NsaWNrPXRydWU=) | [iFlight SucceX-D](https://www.amazon.com/dp/B081ZS22VR/ref=sspa_dk_detail_0?psc=1&pd_rd_i=B081ZS22VR&pd_rd_w=xofAk&pf_rd_p=48d372c1-f7e1-4b8b-9d02-4bd86f5158c5&pd_rd_wg=8YEAK&pf_rd_r=847D1AH8Z5XGY2VAT442&pd_rd_r=47b16370-45c0-467b-b9b1-309b66c921bf&spLa=ZW5jcnlwdGVkUXVhbGlmaWVyPUEzQTVNTFQyMUxUN0pSJmVuY3J5cHRlZElkPUEwMzU1NjA1MUpJWVNQQUY1SjhKRiZlbmNyeXB0ZWRBZElkPUExMDIzNzYyMzY2Wks3OTI2TzdVRiZ3aWRnZXROYW1lPXNwX2RldGFpbCZhY3Rpb249Y2xpY2tSZWRpcmVjdCZkb05vdExvZ0NsaWNrPXRydWU=) |
| Communication System | [Artix-7](https://www.mouser.com/datasheet/2/903/ds180_7Series_Overview-1591537.pdf) | [XC7A50T-L1CPG236I](https://www.mouser.com/ProductDetail/Xilinx/XC7A50T-L1CPG236I?qs=rrS6PyfT74fmDj8IL6117g%3D%3D) | [XA7A50T-1CPG236Q](https://www.mouser.com/ProductDetail/Xilinx/XA7A50T-1CPG236Q?qs=rrS6PyfT74dg%2FQs5mJa22g%3D%3D) | [XA7A50T-1CPG236Q](https://www.mouser.com/ProductDetail/Xilinx/XA7A50T-1CPG236Q?qs=rrS6PyfT74dg%2FQs5mJa22g%3D%3D) |
| Vision System | [Mavic 2 Pro](https://myfirstdrone.com/drones-for-sale) | [DJI Mavic 2 Zoom](https://myfirstdrone.com/drones-for-sale) | [DJI Mavic Air](https://myfirstdrone.com/drones-for-sale) | [DJI Mavic Pro](https://myfirstdrone.com/drones-for-sale) |

In the reference case, Design 1 had the highest MAVF value. A single factor sensitivity analysis was conducted for the eight factors (4 metrics and 4 metric ranks) that affect the MAVF and Design 1 had the highest MAVF in 15 out of 16 cases, indicating its dominance over other designs.. The recommendation is that the customer should commission design 1 for production as it is the best design.

The principal techniques used were Monte Carlo simulation, MAVF analysis and sensitivity analysis.

# **2.** **System Description**:

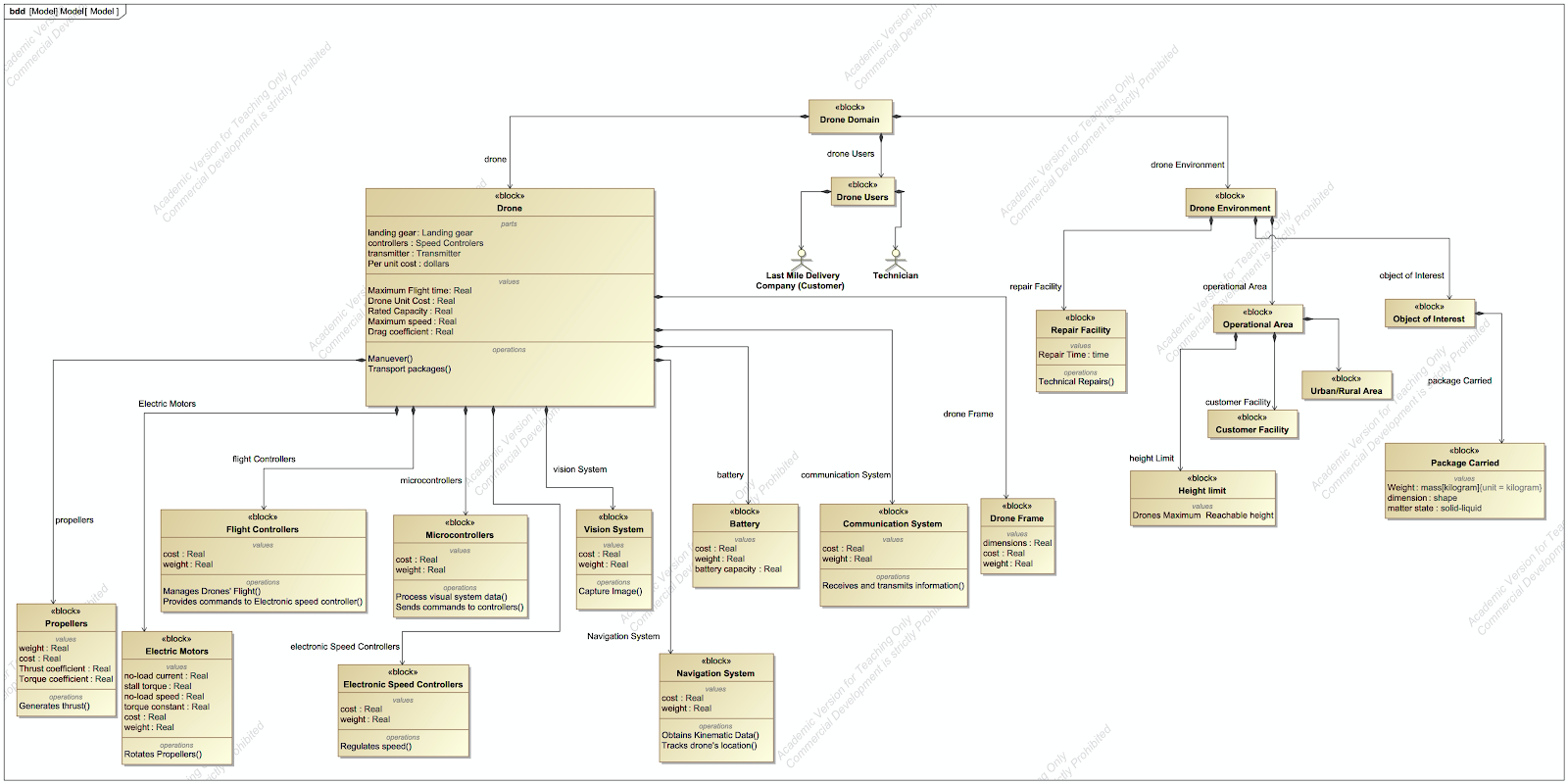


Figure 6: BDD of the drone system

The block definition diagram (BDD) in Figure 1 provides the structural and behavioral features of the drone system and hierarchical relations between different blocks. The structure of an autonomous drone was obtained through extensive research and with the help of online articles on drones [5], [6]. The drone domain is mainly divided into three block namely:

1. Drone
2. Drone Users
3. Drone Environment

**Drone**: This block has value properties which are the metrics used to assess the drone designs.

This block also contains all the components of the drones such as drone frame, batteries, electric motors, speed controllers, propellers, microcontroller, flight controllers, vision system (including gimbals), navigation system and communication system. These elements contain the factors used to obtain the metrics. The factors are represented as value properties in the element blocks.

**Drone Users**: This block defines all the users of the drone. The main user of the drone is the customer. The customers are last mile delivery companies that use drones to deliver goods. The secondary users are the technicians who are needed for maintenance of the drones.

**Drone Environment:** This block defines the environment and object of interest of the drone. It contains the three blocks namely:

1. Repair facility: This block defines the maintenance environment of the drone.
2. Operational Area: This block defines the limit of area of operation of the drones in air.
3. Object of Interest: This block defines the characteristics and state of matter of the package carried by the drones.

# **3.** **Design Options/Course of Action Options**:

Table 1 shows the components that characterize each design. Meanwhile, the properties of these components that are important as factors are shown below in Table 2. These factors are the inputs to the response models used to calculate the system-level metrics.

Table 2: Design factors for the four designs

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Design factors** | **Design 1** | **Design 2** | **Design 3** | **Design 4** |
| Drone frame weight | 460 g | 460 g | 460 g | 460 g |
| Propeller weight (x4) | 7.7 g | 7.7 g | 7.7 g | 7.7 g |
| Motor weight (x4) | 83.63 g | 83.63 g | 83.63 g | 83.63 g |
| Battery weight | 230 g | 330 g | 330 g | 230 g |
| Navigation system weight | 20.6 g | 6.8 g | 16.4 g | 16.4 g |
| Communication system weight | 18.14 g | 16.22 g | 20.68 g | 20.68 g |
| Vision system weight | 379 g | 375 g | 380 g | 390 g |
| Electronic Speed controller weight | 2 g | 6.9 g | 14.4 g | 14.4 g |
| Flight controller weight | 7.6 g | 7.6 g | 7.4 g | 7.4 g |
| Microcontroller weight | 1.541 g | 1.541 g | 1.541 g | 0.657 g |
| Thrust coefficient (N/RPM2) | 8\*10-7N/R | 8\*10-7 | 8\*10-7 | 8\*10-7 |
| Torque coefficient (N-m/RPM2) | 2\*10-9 | 2\*10-9 | 2\*10-9 | 2\*10-9 |
| No-load speed | 3500 rpm | 3500 rpm | 3500 rpm | 3500 rpm |
| No-load current | 3 A | 3 A | 3 A | 3 A |
| Drag coefficient | 0.04 | 0.04 | 0.04 | 0.04 |
| Stall torque | 0.9 N-m | 0.9 N-m | 0.9 N-m | 0.9 N-m |
| Drone frame dimensions | 450 mm frame | 450 mm frame | 450 mm frame | 450 mm frame |

# **4.** **Analysis Approach** :

This project consisted of creating four drone designs, which represent the designs the customer has presented to us. The drone designs are characterized by the designs of its components. These component designs were characterized by different factors, which influence the value of the drone design metrics. These factors are shown above in Table 2. For the motor selection, an analysis was performed to determine if the selected electric motor would provide sufficient thrust and torque needed to power the drone. The equations used to determine this are provided in the next section. Response model equations were also developed for each of the four metrics in order to evaluate each design’s metric value from the drone design factors. These equations were derived by a combination of physics and electrical first principles and empirical models. The empirical models were models that were developed by researchers and the purpose of using the models was to obtain values for factors that were very difficult to calculate theoretically.

The unit drone cost was composed of the cost for each of its components. However, the cost of each component was random and thus, a Monte Carlo simulation had to be performed to determine the drone unit cost. The cost of each component was not characterized by a distribution but by three values: low, medium and high. These values were assigned probabilities based on engineering sense. The low, medium and high values were derived from the cost of different designs of that component and what was assumed to be a reasonable cost for that component from an engineering sense. Appendix A provides the low, median and high values and their corresponding probabilities for each component of each design.

A MAVF analysis was performed to assess the best design. The ranks were chosen by assuming that the customer has stated an order of importance for different metrics. The customer is assumed to weigh the drone unit cost more than the maximum speed and the maximum speed more than the rated lifting capacity and the rated lifting capacity more than the maximum flight time. With this order of preference, rank values were chosen for the four metrics and used to evaluate the weight of each metric.

A sensitivity analysis was performed to characterize the robustness of the results. The 4 metrics were varied from low to high for the best design and the 4 metric ranks were also varied from low to high. The variation in the metric ranks was capped by the level of importance the customer placed on each metric. This resulted in 16 cases and in each case, the MAVF values of all four designs were calculated.

# **5.** **Supporting Models and Simulations**:

5.1.

The response model equations for the rated lifting capacity, maximum speed, maximum flight time are mathematical models that characterize the relationship between the drone design factors and the metrics. They are derived below.

Drone cost = (Drone frame cost + 4\*propeller cost + 4\*motor cost + battery cost + navigation system cost + communication system cost + vision system cost + electronic speed controller cost + microcontroller cost + flight controller cost)

Drone weight = (Drone frame weight + propeller weight + motor weight + battery weight + navigation system weight + communication system weight + vision system weight + electronic speed controller weight + microcontroller weight + flight controller weight)\*1.1

The 1.1 multiplying factor is used to account for other components such as propeller guard, wires, connectors, etc. that were not included in the system definition.

From [1], and

Where At = Thrust coefficient = 8 \* 10-7 N/RPM2

Aq = Torque coefficient = 2 \* 10-9 N.m/RPM2

T = Thrust of a single propeller (in N)

Q = Torque of a single propeller (in N.m)

= Propeller rotational speed (in RPM)

RPM stands for revolutions per minute

From [3] ,

Where Qm = motor torque (N-m)

Q0 = motor stall torque or torque when there the motor is stationary

= motor no-load speed or speed when there is no external load on the motor

= motor speed (RPM)

Propeller torque = motor torque

When the motor operates at its rated voltage,

From [4] , the recommended thrust-to-weight ratio is 2:1.

The free body diagram of the drone in horizontal flight can be represented as follows

T

D

Drone weight



Where is the tilt of the drone or the inclination from the vertical

T is the thrust produced by the drone

D is the drag of the drone

At constant speed, net force is zero.

Thus, Drone weight = T cos and D = T sin

Where D = Drag on the drone (in N)

Cd = Drag coefficient = 0.04 0.0035[2]

= air density = 1.2 kg/m3 at sea level

A = frontal area of the drone i.e. projected area of the drone on a screen orthogonal to the drone direction

V = relative velocity of the drone with respect to the air velocity (in m/s)

Atop

A

Afront



Where Atop is the top area of the drone

Afront is the front area of the drone

Maximum speed is rated for the drone with no package moving continuously in a straight line with the vertical component of its velocity zero. At maximum speed, the drone is producing maximum thrust and is operating at the motor rated voltage.

Drone weight = Tmax cos and

The maximum flight time is rated at 3 m/s for the drone and it is the upper limit on the time the drone can continuously fly in the air.

Where Tmaxft is the drone thrust at maximum flight time conditions

Qmaxft is the propeller torque at maximum flight time conditions

imaxft is the current drawn by the motor at maximum flight time conditions

Qc is the torque constant i.e. change in motor torque/change in current

inl is the no load current i.e. current when there is no external load

BattCap is the battery capacity (in Ah)

ADD RESPONSE MODEL DERIVATIONS

5.2.

The Monte Carlo model accepts the cost probabilities for each component of each design as inputs. These cost probabilities are used to draw from the sample and obtain the average drone cost, the standard deviation of drone cost and the standard error in the mean of the drone cost. This was done for all four designs. The cumulative running mean of the drone cost was also evaluated, to determine when the Monte Carlo simulation results stabilize.

# **6.** **Analysis and Results**:

Analytically determining the mean drone unit cost is required to validate the Monte Carlo simulation results. Hence, the expected value of cost of the drone should be determined. In order to do this, the expected value of each individual drone design component cost is determined, and the expected values are summed to obtain the expected value of the drone design unit cost.

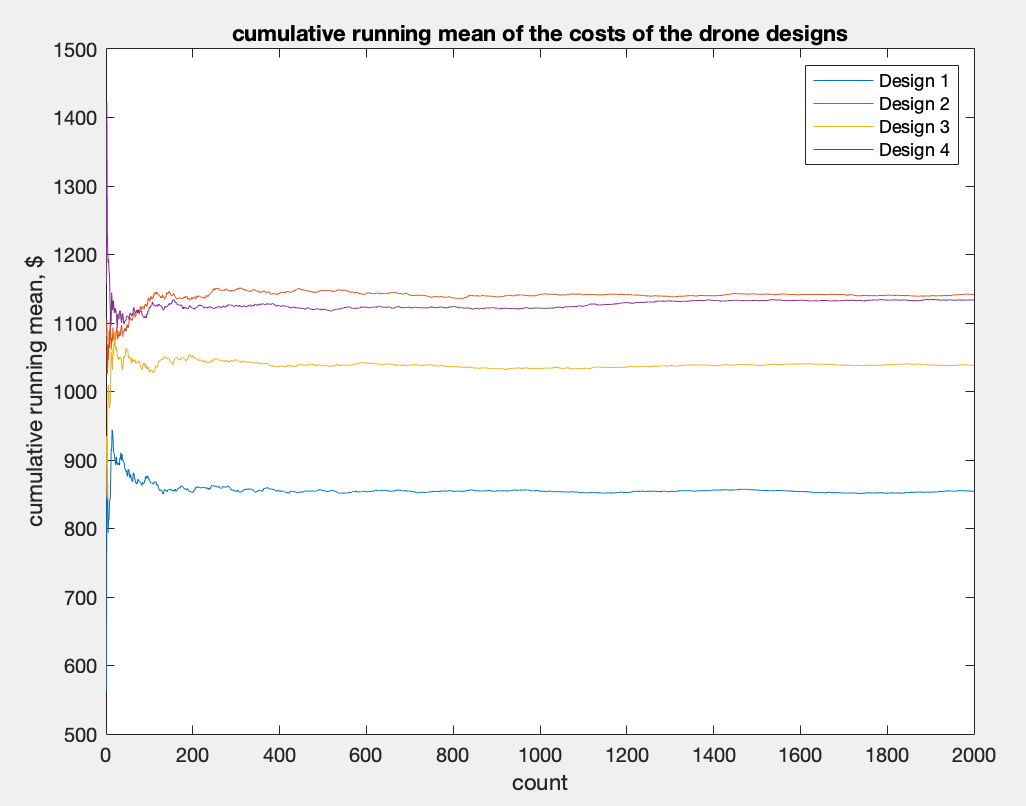
The distribution used in Monte Carlo simulation has mainly 3 values namely: minimum value, maximum value and median value. From market analyses it was determined that the cost of the component will fall under these three values with probabilities P1, P2 and P3 respectively. Now as we know the value and probability of occurrence. we can find the expectation of the cost of the component using the formula:

In this way, the expectation of all the component costs are computed. The total drone cost is computed simply by adding all the individual expectations of the component cost. This can be done because of this property of expectation:

Appendix B provides the results of expectation of each individual component and also the total cost of the drone calculated analytically:

Table 3: Monte Carlo vs Analytical results

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Comparison** | **Design 1** | **Design 2** | **Design 3** | **Design 4** |
| **Expected total drone cost($)** | 857.04 | 1170.33 | 1041.79 | 1136.63 |
| **Monte Carlo average drone cost($)** | 851.98 | 1137.00 | 1044.70 | 1136.60 |
| **% error** | 0.590 | 2.848 | 0.279 | 0.002 |



**Figure 7: Plot of the cumulative running mean of the drone unit cost for all four designs**

Table 3 compares the analytical average drone cost with the Monte Carlo average. It can be seen that the analytical result obtained lies within +/-3% of the Monte Carlo drone cost. Figure 7 shows that stable results are obtained at ~ 1200 iterations. This indicates that the Monte Carlo results are stable at 2000 iterations. Thus, the Monte Carlo simulation results are valid for each drone design.

**Table 4: Metrics and the MAVF values of the four designs**

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Metric** | **Metric rank** | **Design 1** | **Design 2** | **Design 3** | **Design 4** |
| Drone unit cost ($) | 50 | 851.98 | 1137 | 1044.7 | 1136.6 |
| Rated lifting capacity (N) | 35 | 2.58 | 1.67 | 1.38 | 2.36 |
| Maximum speed (m/s) | 25 | 95.25 | 95.01 | 94.94 | 95.19 |
| Maximum flight time (hour) | 40 | 0.677 | 0.980 | 0.979 | 0.676 |
| MAVF |  | 0.833 | 0.285 | 0.274 | 0.408 |

Table 4 summarizes the results of the MAVF analysis and the system-level metrics computed from the element design factors. Design 1 has the highest MAVF, which is more than double the next highest one.

**Table 5: Low, reference and high scenarios for the eight MAVF factors**

|  |  |  |  |
| --- | --- | --- | --- |
| **MAVF Factor** | **Low** | **Reference** | **High** |
| Drone Unit Cost($) | 438.06 | 851.98 | 1274.18 |
| Rated lifting capacity(N) | 1.86 | 2.58 | 3.31 |
| Maximum speed(m/s) | 90.85 | 95.25 | 100.21 |
| Maximum flight time(hr) | 0.675 | 0.677 | 0.679 |
| Drone Unit Cost Rank | 41 | 50 | 70 |
| Rated lifting capacity Rank | 26 | 35 | 39 |
| Maximum flight time Rank | 15 | 25 | 34 |
| Maximum speed rank | 36 | 40 | 49 |

The low and high case of the drone unit cost in Table 4 are 2 standard deviations from the mean drone unit cost obtained from the Monte Carlo simulation. This ensures a 95% confidence that the drone unit cost will fall within this range.

The rated lifting capacity variation comes from the variation in the drone weight. The sum of the weights of all components is multiplied by a factor. This factor accounts for the weight of other components like wires, propeller guards, tools to grip packages etc. The factor is 1.1 in the reference case and is defined to be 1.05 in the low case and 1.15 in the high case.

Since Rated lifting capacity = Max thrust/2 - Drone Weight. Increasing the drone weight reduces the rated lifting capacity and vice versa.

The variation in the maximum speed and the maximum flight time comes from the variation in the drag coefficient and the variation in the drone weight. The drag coefficient is 0.04 +/- 0.0035[2] . Increasing the drag coefficient decreases both the maximum flight time and the maximum speed and vice versa.

Given our customer preference as Cost > Maximum speed > Rated lifting capacity > Maximum flight time. The variation in the metric ranks was designed to follow this preference.

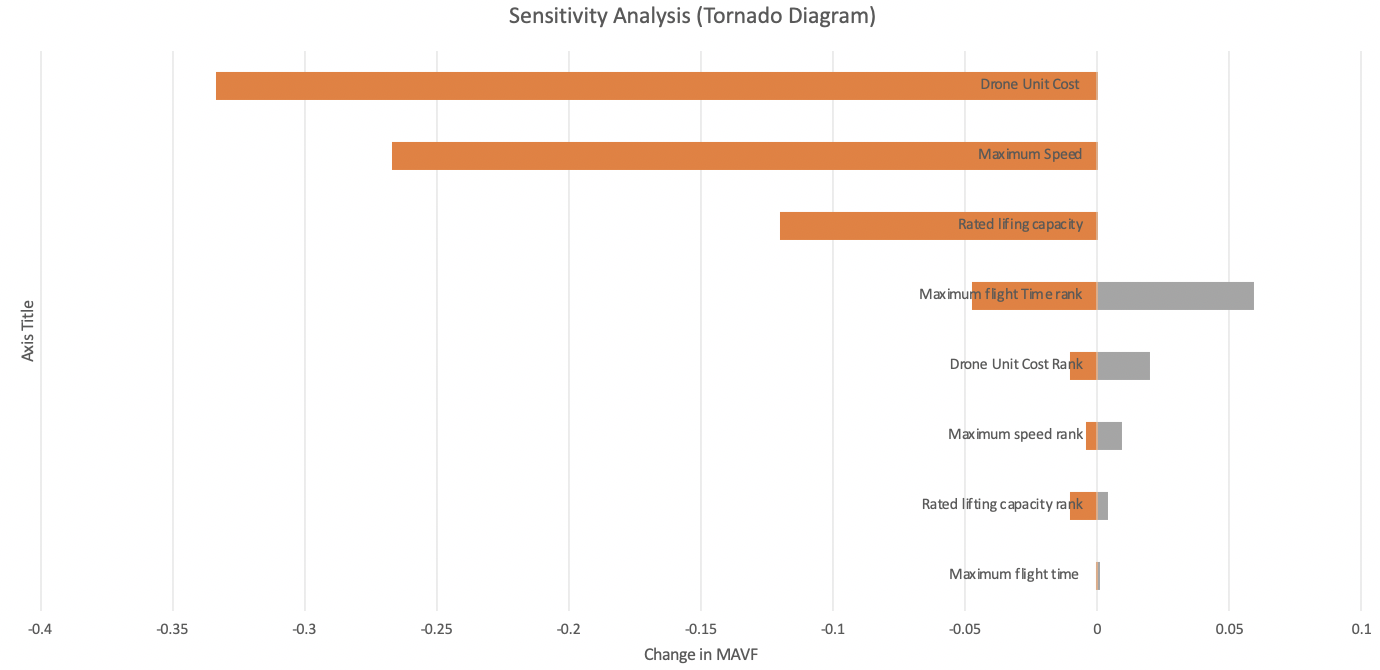
Table 7 characterizes the variation in each MAVF factor and thus provides the inputs to the single factor sensitivity analysis.

Table 8 provides a summary of the results from the single factor sensitivity analysis.

**Table 8: MAVF values of all designs for the different cases**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Case** | **Design 1 MAVF** | **Design 2 MAVF** | **Design 3 MAVF** | **Design 4 MAVF** |
| Reference | **0.83** | 0.28 | 0.27 | 0.40 |
| Low cost rank | **0.82** | 0.30 | 0.27 | 0.43 |
| High cost rank | **0.85** | 0.25 | 0.27 | 0.36 |
| Low rated lifting capacity rank | **0.82** | 0.28 | 0.29 | 0.38 |
| High rated lifting capacity rank | **0.83** | 0.28 | 0.26 | 0.41 |
| Low maximum speed rank | **0.82** | 0.28 | 0.28 | 0.39 |
| High maximum speed rank | **0.84** | 0.28 | 0.25 | 0.43 |
| Low maximum flight time rank | **0.89** | 0.23 | 0.22 | 0.43 |
| High maximum flight time rank | **0.84** | 0.28 | 0.25 | 0.43 |
| Low cost | **0.83** | 0.28 | 0.20 | 0.40 |
| High cost | 0.50 | 0.48 | 0.49 | **0.60** |
| Low rated lifting capacity | **0.71** | 0.29 | 0.27 | 0.45 |
| High rated lifting capacity | **0.83** | 0.26 | 0.27 | 0.33 |
| Low maximum speed | **0.56** | 0.47 | 0.52 | 0.45 |
| High maximum speed | **0.83** | 0.22 | 0.27 | 0.20 |
| Low maximum flight time | **0.83** | 0.28 | 0.27 | 0.40 |
| High maximum flight time | **0.83** | 0.28 | 0.27 | 0.40 |

Table 4 shows that in 15 out of 16 cases, where one of the MAVF factors is changed, Design 1 has the highest MAVF. This indicates that Design 1 is a much superior design to the other designs.



**Figure 8: Tornado diagram of the sensitivity analysis**

Figure 8 shows the tornado diagram of the sensitivity analysis performed on Design 1 for the 8 MAVF factors i.e. metrics and metric ranks. It can be seen that the Drone Unit Cost and the Maximum flight time have the greatest and least impact on the MAVF respectively. It can be noticed that three of the four metrics do not increase the MAVF when the values of these metrics change. The metric ranks have a negligible impact on the MAVF value except for the Maximum flight time rank. Figure 8 also shows that MAVF value is relatively independent of the Maximum flight time variation. The drone unit cost and the maximum speed dominate other MAVF factors in their impact on the MAVF. Thus, more effort should be made to reduce the uncertainty in these factors.

# **7.** **Recommended Course of Action**

Design 1 had the highest MAVF value in the reference case. Despite the changes in the MAVF factors, Design 1 still retained the best design(according to MAVF) 15 out of 16 times. Thus, Design 1 will be recommended to the stakeholders. The metrics used in calculating the MAVF value of Design 1 and other designs were computed from response model equations. These equations required a lot of assumptions that might not hold up in the real world. This could change the values of the metrics significantly, which might affect MAVF results. It would be useful to simulate the designs to get a more accurate estimate of the metrics. Nevertheless, the dominance of Design 1- it has the least cost, best rated lifting capacity and best maximum speed of all the four drones - means that it is the best option for our customers.

# **8.** **Conclusions and Lessons Learned**

One key lesson that was learned is the importance of modeling systems to obtain accurate estimates of a system’s state. Theoretically deriving the equations guiding the dynamics of a system involve complex dependencies of different factors and thus assumptions will be made. There will be a need to conduct a simulation to test the accuracy of our response model equations and the validity of assumptions.

Single-factor sensitivity analysis can be useful for identifying the impact of factor uncertainty on metric uncertainty but it is inadequate in characterizing the interactions of multiple invariant factors. Next time, a multi-factor or stochastic sensitivity analysis will be considered to characterize the impacts of changing multiple factors at a time. In this case, a single-factor sensitivity analysis was adequate because the MAVF values were far apart. However, when the values are close, it fails to account for the nuances of changing multiple factors at a time. Moreover, it might not give an accurate picture as the number of factors in the analysis increases.

Component compatibility was only considered for the motors, batteries and propellers and not for the other electrical components. This could have changed what components were present in what design and swayed the best design to a different design. Thus, it would be more appropriate to analyze an existing drone with all the components operating in tandem efficiently. This would minimize the risk of a design with mismatched components. It would also be possible to obtain an empirical model for an existing drone design that can be used to calculate metrics.

An interesting idea would be to treat the design factors for the maximum flight time, the maximum speed and the rated lifting capacity as stochastic values with their characteristic distribution. This could then be used to obtain a Monte Carlo result for these metrics.

Finally, it might be useful to consider other metrics like reliability that impact what design a customer selects. This project was done with respect to no environment and that is not always tenable for certain locations. One way this project could be advanced is to consider the influence of environmental factors and the environmental state on the design that is selected.

# **9.** **References**

This section provides a list of references. At a minimum you should have an academic reference (i.e., not Wikipedia) for each technique you use.

1. <https://www.researchgate.net/profile/Saiful_Azimi/publication/325580608_Modelling_and_parameters_identification_of_a_quadrotor_using_a_custom_test_rig/links/5b19d21caca272021cf21c1e/Modelling-and-parameters-identification-of-a-quadrotor-using-a-custom-test-rig.pdf>
2. <https://arxiv.org/pdf/1902.01465.pdf>
3. <http://web.mit.edu/drela/Public/web/qprop/motorprop.pdf>
4. <https://www.omnicalculator.com/other/drone-motor>
5. “Autonomous Drone.” *Instructables*, Instructables, 3 Feb. 2019, [www.instructables.com/id/Autonomous-Drone/](http://www.instructables.com/id/Autonomous-Drone/).
6. “Drone Components \_Quick List of It's Parts.” *Grind Drone*, Grind Drone, 27 Dec. 2017, grinddrone.com/drone-features/drone-components.

# **Appendices (as needed):**

The appendices may contain additional figures, tables, derivations, and other supporting material that interrupts the flow of the report.

Material provided that the appendices should be referenced (as “see Appendix X) in the main body where it supports the story.

**Appendix A: Costs and cost probabilities for the components of each design.**

|  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Components** | **Design 1** | | | **Design 2** | | | **Design 3** | | | **Design 4** | | |
| **Range of Probabilities** | **L** | **M** | **H** | **L** | **M** | **H** | **L** | **M** | **H** | **L** | **M** | **H** |
| 1 Propeller cost($) | 3.99 | 5.69 | 14.99 | 3.99 | 5.69 | 14.99 | 3.99 | 5.69 | 14.99 | 3.99 | 5.69 | 14.99 |
| Propeller cost probabilities | 0.35 | 0.45 | 0.2 | 0.35 | 0.45 | 0.2 | 0.35 | 0.45 | 0.2 | 0.35 | 0.45 | 0.2 |
| 1 Motor cost($) | 44.9 | 104 | 199.9 | 44.9 | 104 | 199.9 | 44.99 | 104 | 199.9 | 44.99 | 104 | 199.99 |
| Motor cost probabilities | 0.3 | 0.55 | 0.15 | 0.3 | 0.55 | 0.15 | 0.3 | 0.55 | 0.15 | 0.3 | 0.55 | 0.15 |
| Battery cost($) | 39.9 | 59.9 | 109.9 | 59.9 | 79.9 | 109.9 | 59.9 | 79.9 | 109.9 | 39.9 | 59.9 | 109.9 |
| Battery cost probabilities | 0.3 | 0.5 | 0.2 | 0.3 | 0.5 | 0.2 | 0.3 | 0.5 | 0.2 | 0.3 | 0.5 | 0.2 |
| Electric speed controllers cost($) | 16.9 | 19.9 | 23.9 | 23.6 | 29.6 | 32.9 | 29.6 | 32.9 | 36.9 | 45.9 | 50.9 | 55.9 |
| Electric speed controllers cost probabilities | 0.35 | 0.4 | 0.25 | 0.3 | 0.4 | 0.3 | 0.3 | 0.4 | 0.3 | 0.3 | 0.4 | 0.3 |
| Microcontroller cost($) | 9.9 | 13 | 15 | 9.9 | 13 | 15 | 9.9 | 13 | 15 | 22 | 24.4 | 29.9 |
| Microcontroller cost probabilities | 0.35 | 0.4 | 0.25 | 0.35 | 0.4 | 0.25 | 0.35 | 0.4 | 0.25 | 0.35 | 0.4 | 0.25 |
| Flight controller cost($) | 28.6 | 32.9 | 36.9 | 28.6 | 32.9 | 36.9 | 22 | 24.4 | 29.9 | 22 | 24.4 | 29.9 |
| Flight controller cost probabilities | 0.35 | 0.4 | 0.25 | 0.35 | 0.4 | 0.25 | 0.35 | 0.4 | 0.25 | 0.35 | 0.4 | 0.25 |
| Communication system cost($) | 40.5 | 61.9 | 90.5 | 50.6 | 78.76 | 100.9 | 55.9 | 81.4 | 110.9 | 55.9 | 81.4 | 110.9 |
| Communication system cost probabilities | 0.35 | 0.4 | 0.25 | 0.3 | 0.4 | 0.3 | 0.3 | 0.4 | 0.3 | 0.3 | 0.4 | 0.3 |
| Navigation system cost($) | 20.9 | 36.9 | 50.9 | 148.3 | 185 | 212.6 | 10.4 | 29.9 | 48.9 | 10.4 | 29.9 | 48.9 |
| Navigation system cost probabilities | 0.35 | 0.4 | 0.25 | 0.3 | 0.4 | 0.3 | 0.3 | 0.4 | 0.3 | 0.3 | 0.4 | 0.3 |
| Vision system cost($) | 112.9 | 148 | 186 | 198 | 269 | 346 | 190.2 | 259 | 350 | 244 | 345 | 450 |
| Vision system cost probabilities | 0.35 | 0.4 | 0.25 | 0.3 | 0.4 | 0.3 | 0.3 | 0.4 | 0.3 | 0.3 | 0.4 | 0.3 |

**Appendix B: Expected cost of each design component**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Component** | **Design 1** | **Design 2** | **Design 3** | **Design 4** |
| 4 Propellers Expected cost($) | 27.82 | 27.82 | 27.82 | 27.82 |
| 4 Motors Expected cost($) | 402.78 | 402.78 | 402.78 | 402.78 |
| Battery Expected cost($) | 63.99 | 79.99 | 79.99 | 63.99 |
| Electronic speed controller expected cost ($) | 19.94 | 28.88 | 33.20 | 50.99 |
| Microcontroller expected cost($) | 12.44 | 12.44 | 12.44 | 24.95 |
| Flight controller expected cost ($) | 32.90 | 32.90 | 51.99 | 51.99 |
| Communication system expected cost($) | 61.60 | 77.00 | 82.65 | 82.65 |
| Navigation system expected cost($) | 34.89 | 182.28 | 29.82 | 29.82 |
| Vision system expected system($) | 145.2465 | 270.8 | 265.66 | 346.2 |
| Body Frame expected cost($) | 55.41 | 55.41 | 55.41 | 55.41 |
| **Expected total drone cost($)** | 857.03 | 1170.32 | 1041.78 | 1136.62 |

**MATLAB code for Monte Carlo simulation:**

% ENSE 622 Project

% Calculations

% Author - Oghenetekevwe Akoroda

% Submitted 05/11/2020

clear; clc; close all

% Drone components Weight table

Component = {'Drone frame';'Propeller';'Motor';'Battery';'Navigation System'...

;'Electronic Speed Controller';'Microcontroller';'Flight Controller' ...

;'Communication System';'Vision System'};

Design1\_Weight = [460,7.7\*4,83.63\*4,230,20.6,2,1.541,7.6,18.14,379]'; % Weight in grams

Design2\_Weight = [460,7.7\*4,83.63\*4,330,6.8,6.9,1.541,7.6,16.22,375]';

Design3\_Weight = [460,7.7\*4,83.63\*4,330,16.4,14.4,1.541,7.4,20.68,380]';

Design4\_Weight = [460,7.7\*4,83.63\*4,230,16.4,14.4,0.657,7.4,20.68,390]';

CompWeights = table(Component,Design1\_Weight,Design2\_Weight,Design3\_Weight ...

,Design4\_Weight);

% DroneWeight is in Newton 1.1 accounts for other components like wires,

% package holder, propeller guard that are not included in system description

DroneWeight = 9.81e-3\*[sum(CompWeights.Design1\_Weight),sum(CompWeights.Design2\_Weight) ...

,sum(CompWeights.Design3\_Weight),sum(CompWeights.Design4\_Weight)]\*1.1;

BattCap = [2.2,3.2,3.2,2.2]; % battery capacity(Ah) of designs 1 - 4

% Response Equations

% single motor Torque, Q(N-m) = Aq\*w^2 where w is angular speed(rpm)

Aq = 2e-9;

% drone Thrust, T(N) = At\*w^2 where w is angular speed(rpm)

At = 8e-7\*4; % 4 is for 4 motors

Cd = 0.04; % drag coefficient Drag = 0.5\*Cd\*1.2\*A\*V^2 where v is drone speed

CdLow = 0.04-0.0035;

CdHigh = 0.04 + 0.0035;

Atop = pi\*0.45^2/4; % top area of the drone in meter square

Afront = (0.45/2)\*0.11; % front area of the drone in meter square

Q0 = 0.9; % stall torque (N-m) at rated voltage

w\_nl = 3500; % no load speed (rpm) at rated voltage

i\_nl = 3; % no load current(A)

Qcons = 0.04; % torque constant (change in torque(N-m)/change in current(A))

wmax = (-(Q0/w\_nl)+sqrt((Q0/w\_nl)^2 + 4\*Aq\*Q0))/(2\*Aq); % maximum rotational speed

Tmax = At\*wmax^2; % maximum torque

% DroneWeight is a vector containing the drone weight for the four designs.

% rated lifting capacity, LiftCap (in N)

LiftCap = (Tmax/2) - DroneWeight; %thrust-to-weight ratio of 2

% maximum speed, Vmax (in m/s)

A = (Atop\*sqrt(Tmax^2 - DroneWeight.^2) + Afront\*DroneWeight)/Tmax; % drone frontal area

Vmax = sqrt(2./(Cd\*1.2\*A)) .\* (Tmax^2 - DroneWeight.^2).^0.25;

% maximum flight time (rated at 3 m/s), Ftmax (in hour)

% current drawn by motor at maximum flight time condition

imaxft = (sqrt(DroneWeight.^2 + 0.6\*Cd\*A\*3^2)\*Aq/At)/Qcons + i\_nl;

Ftmax = BattCap./imaxft;

% Monte Carlo simulation

k = 2000; % number of Monte Carlo trials

DroneCost = zeros(1,k); % Monte Carlo drone cost for design 1

CRMCost = zeros(1,k); % Cumulative running mean of the drone cost for design 1

for i = 1:k

frameCost = random3(28.78,46.89,145.99,0.35,0.5); % per unit cost of drone frame

battCost = random3(39.99,59.99,109.99,0.3,0.5); % per unit cost of battery

motorCost = random3(44.99,104.00,199.99,0.3,0.55); % per unit cost of electric motor

escCost = random3(16.99,19.99,23.99,0.35,0.4); % per unit cost of electric speed controller

propCost = random3(3.99,5.69,14.99,0.35,0.45); % per unit cost of propeller

mcCost = random3(9.99,13.00,15.00,0.35,0.4); % per unit cost of microcontroller

flcCost = random3(28.69,32.99,36.99,0.3,0.4); % per unit cost of flight controller

vsCost = random3(112.99,148,186,0.35,0.4); % per unit cost of vision system

navCost = random3(20.99,36.99,50.99,0.35,0.4); % per unit cost of navigation system

commCost = random3(40.55,61.94,90.55,0.35,0.4); % per unit cost of communication system

% calculate unit drone cost

DroneCost(i) = frameCost + battCost + 4\*motorCost + escCost + 4\*propCost + ...

+ mcCost + flcCost + vsCost + navCost + commCost;

if i == 1

CRMCost(i) = DroneCost(i);

else

CRMCost(i) = ((i-1)\*CRMCost(i-1)+DroneCost(i))/i;

end

end

AveDroneCost1 = mean(DroneCost); % Average drone design 1 cost

StdDroneCost1 = std(DroneCost); % Standard deviation of drone design 1 cost

SEDroneCost1 = StdDroneCost1/sqrt(k); % Standard error of the average drone design 1 cost

DroneCost2 = zeros(1,k); % Monte Carlo drone cost for design 2

CRMCost2 = zeros(1,k); % Cumulative running mean of the drone cost for design 2

for i = 1:k

frameCost = random3(28.78,46.89,145.99,0.35,0.5);

battCost = random3(59.99,79.99,109.99,0.3,0.5);

motorCost = random3(44.99,104.00,199.99,0.3,0.55);

escCost = random3(23.69,29.69,32.99,0.3,0.4);

propCost = random3(3.99,5.69,14.99,0.35,0.45);

mcCost = random3(9.99,13.00,15.00,0.35,0.4);

flcCost = random3(28.69,32.99,36.99,0.3,0.4);

vsCost = random3(198,269,346,0.3,0.4);

navCost = random3(48.35,185,212.60,0.3,0.4);

commCost = random3(50.69,78.76,100.99,0.3,0.4);

% calculate unit drone cost

DroneCost2(i) = frameCost + battCost + 4\*motorCost + escCost + 4\*propCost + ...

+ mcCost + flcCost + vsCost + navCost + commCost;

if i == 1

CRMCost2(i) = DroneCost2(i);

else

CRMCost2(i) = ((i-1)\*CRMCost2(i-1)+DroneCost2(i))/i;

end

end

AveDroneCost2 = mean(DroneCost2); % Average drone design 2 cost

StdDroneCost2 = std(DroneCost2); % Standard deviation of drone design 2 cost

SEDroneCost2 = StdDroneCost2/sqrt(k); % Standard error of the average drone design 2 cost

DroneCost3 = zeros(1,k); % Monte Carlo drone cost for design 3

CRMCost3 = zeros(1,k); % Cumulative running mean of the drone cost for design 3

for i = 1:k

frameCost = random3(28.78,46.89,145.99,0.35,0.5);

battCost = random3(59.99,79.99,109.99,0.3,0.5);

motorCost = random3(44.99,104.00,199.99,0.3,0.55);

escCost = random3(29.69,32.99,36.99,0.3,0.4);

propCost = random3(3.99,5.69,14.99,0.35,0.45);

mcCost = random3(9.99,13.00,15.00,0.35,0.4);

flcCost = random3(47.99,51.99,55.99,0.3,0.4);

vsCost = random3(190.20,259,350,0.3,0.4);

navCost = random3(10.45,29.99,48.99,0.3,0.4);

commCost = random3(55.99,81.40,110.99,0.3,0.4);

% calculate unit drone cost

DroneCost3(i) = frameCost + battCost + 4\*motorCost + escCost + 4\*propCost + ...

+ mcCost + flcCost + vsCost + navCost + commCost;

if i == 1

CRMCost3(i) = DroneCost3(i);

else

CRMCost3(i) = ((i-1)\*CRMCost3(i-1)+DroneCost3(i))/i;

end

end

AveDroneCost3 = mean(DroneCost3); % Average drone design 3 cost

StdDroneCost3 = std(DroneCost3); % Standard deviation of drone design 3 cost

SEDroneCost3 = StdDroneCost3/sqrt(k); % Standard error of the average drone design 3 cost

DroneCost4 = zeros(1,k); % Monte Carlo drone cost for design 4

CRMCost4 = zeros(1,k); % Cumulative running mean of the drone cost for design 1

for i = 1:k

frameCost = random3(28.78,46.89,145.99,0.35,0.5);

battCost = random3(39.99,59.99,109.99,0.3,0.5);

motorCost = random3(44.99,104.00,199.99,0.3,0.55);

escCost = random3(45.99,50.99,55.99,0.3,0.4);

propCost = random3(3.99,5.69,14.99,0.35,0.45);

mcCost = random3(22.00,24.40,29.99,0.35,0.4);

flcCost = random3(47.99,51.99,55.99,0.3,0.4);

vsCost = random3(244,345,450,0.3,0.4);

navCost = random3(10.45,29.99,48.99,0.3,0.4);

commCost = random3(55.99,81.40,110.99,0.3,0.4);

% calculate unit drone cost

DroneCost4(i) = frameCost + battCost + 4\*motorCost + escCost + 4\*propCost + ...

+ mcCost + flcCost + vsCost + navCost + commCost;

if i == 1

CRMCost4(i) = DroneCost4(i);

else

CRMCost4(i) = ((i-1)\*CRMCost4(i-1)+DroneCost4(i))/i;

end

end

AveDroneCost4 = mean(DroneCost4); % Average drone design 4 cost

StdDroneCost4 = std(DroneCost4); % Standard deviation of drone design 4 cost

SEDroneCost4 = StdDroneCost4/sqrt(k); % Standard error of the average drone design 4 cost

Metric = {'Drone unit cost($)';'Rated lifting capacity(N)';'Maximum speed(m/s)'...

;'Maximum flight time(hour)'};

Design1 = [AveDroneCost1;LiftCap(1);Vmax(1);Ftmax(1)];

Design2 = [AveDroneCost2;LiftCap(2);Vmax(2);Ftmax(2)];

Design3 = [AveDroneCost3;LiftCap(3);Vmax(3);Ftmax(3)];

Design4 = [AveDroneCost4;LiftCap(4);Vmax(4);Ftmax(4)];

% FinTab is a table with the metric values for each design

FinTab = table(Metric,Design1,Design2,Design3,Design4);

Drone1WeightLow = DroneWeight(1)\*1.05/1.1; % low end of design 1 drone weight

Drone1WeightHigh = DroneWeight(1)\*1.15/1.1; % high end of design 1 drone weight

LiftCapHigh = (Tmax/2) - Drone1WeightLow; % low end of design 1 rated lifting capacity

LiftCapLow = (Tmax/2) - Drone1WeightHigh; % high end of design 1 rated lifting capacity

% low end of design 1 maximum speed

VmaxLow = sqrt(2./(CdHigh\*1.2\*A(1))) .\* (Tmax^2 - Drone1WeightHigh.^2).^0.25;

% high end of design 1 maximum speed

VmaxHigh = sqrt(2./(CdLow\*1.2\*A(1))) .\* (Tmax^2 - Drone1WeightLow.^2).^0.25;

imaxftLow = (sqrt(Drone1WeightLow.^2 + 0.6\*CdLow\*A(1)\*3^2)\*Aq/At)/Qcons + i\_nl;

imaxftHigh = (sqrt(Drone1WeightHigh.^2 + 0.6\*CdHigh\*A(1)\*3^2)\*Aq/At)/Qcons + i\_nl;

% low end of design 1 maximum flight time

FtmaxLow = BattCap(1)./imaxftHigh;

% high end of design 1 maximum flight time

FtmaxHigh = BattCap(1)./imaxftLow;

plot(1:k,CRMCost,1:k,CRMCost2,1:k,CRMCost3,1:k,CRMCost4)

legend('Design 1','Design 2','Design 3','Design 4')

xlabel('count')

ylabel('cumulative running mean')

title('cumulative running mean of the costs of the drone designs')

% random3 is a function that substitutes for a probability distribution

% in generating the random cost variables

function randval = random3(Low,Med,High,pLow,pMed)

% Low is the low cost, Med is the medium cost and High is the high cost

% pLow is the probability of getting the low cost

% pMed is the probability of getting the medium cost

% pHigh is the probability of getting the high cost

rand22 = rand;

if rand22 < pLow

randval = Low;

elseif rand22 >= pLow && rand22 < pLow + pMed

randval = Med;

else

randval = High;

end

end