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Multicopter Drone Mass Distribution Impacts on Viability, Performance, and Sustainability

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Multicopter drone mass distribution impacts on viability, performance, and sustainability

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Abstract

This short communication highlights the value of drone mass and its distribution, a topic that despite its importance has received scant attention in the rapidly growing drone literature. In particular, the focus is on the impact of mass distribution on drone viability, performance, and sustainability.

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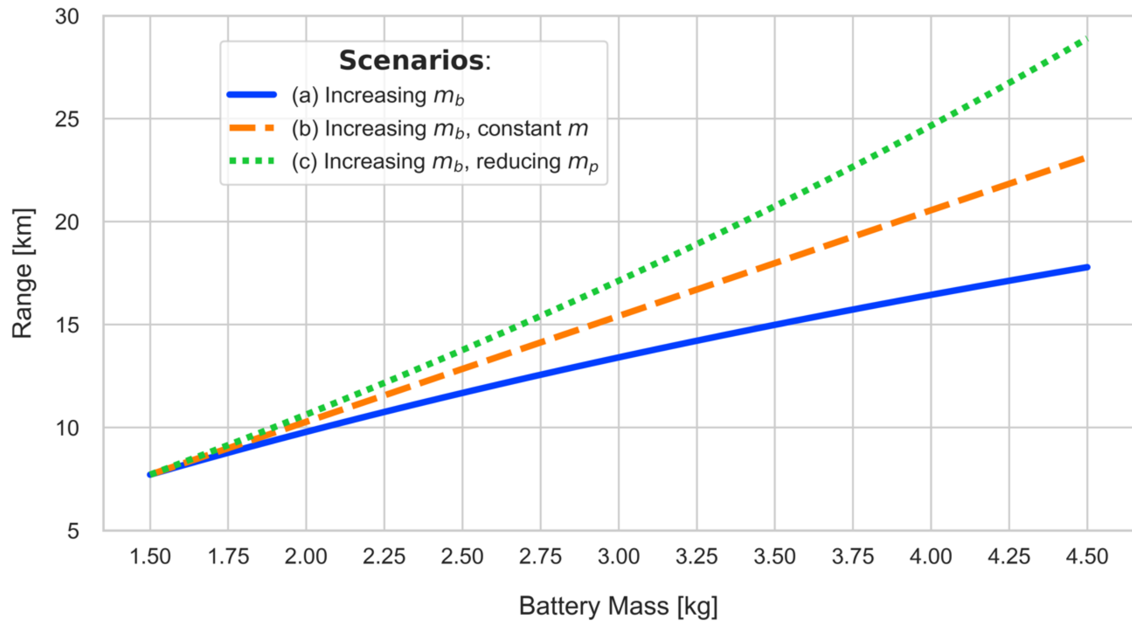
The consequences of drone mass distribution on performance are major and well established. A drone total take-off mass m can be broken down into three components: payload, battery, and tare or empty mass where their sum is the total takeoff mass of the drone. In mathematical notation this can be expressed as $m = m_p + m_b + m_e$ where the subindices refer to payload, battery, and empty mass respectively. These mass components have a key role determining drone range (Hepperle, 2012), the range R of an electric aircraft in steady state forward flight is:

$$R = \frac{E\, m_b\, \eta\, \theta}{g\, (m_p + m_b + m_e)}$$

where the term g is the acceleration of gravity, and E the energy density of the battery. The parameters θ and η are the forward flight and electromechanical efficiencies, the former related to the overall lift/drag aircraft ratio and the later related to the efficiency of converting energy from the battery output to the propellers. Range increases when the battery mass increases and the range increase is significantly larger if the increase in m_b is at the expense of $m_p + m_e$. This is illustrated in **Figure 1**, using three scenarios with an initial $m = 10$ kg, $m_b = 1.5$ kg, $m_p = 2$ kg, $E = 720$ KJ/kg, $\theta = 1.0$ and $\eta = 0.7$. In all scenarios m_b is increased from 1.5 to 4.5 kg while (a) keeping $m_p + m_e$ constant, (b) keeping $m = m_p + m_e + m_b$ constant, and (c) gradually reducing payload from 2.0 kg to zero when $m_b = 4.5$ kg. An increase in drone mass also affects energy consumption which increases nearly linearly as a function of mass. Hence, lifecycle emissions are also affected by drone mass.

Figure 1 The impact of changing battery mass on Range.



In the academic literature, the mass of drones varies widely and therefore analyzing normalized masses is useful. A recent review of drone energy consumption by Zhang et al. (2021) includes drone battery, payload, and empty mass data that is shown in **Table 1** normalized by the drone mass, i.e. $f_e = m_e/m$, $f_b = m_b/m$, and $f_p = m_p/m$ with $f_e + f_b + f_p = 1$. The median values for empty, battery, and payload normalized masses are equal to 0.50, 0.27, and 0.20 respectively and their sum is nearly one and comparable values are obtained estimating the mean values (0.50, 0.28, 0.22).

The interval of observed values for f_b is (0.17, 0.42) and as a reference in **Figure 1** scenario (b) f_b is in the (0.15, 0.45) interval. Other academic publications have reported or discussed drone mass distribution. For example when analyzing the mass distribution of drones for agricultural applications Marinello et al. (2016) found typical f_b ratios ranging between 0.20 to 0.25 and the ratio of mass devoted to the payload, sensors, or other devices ranging from 0.25 to 0.35. A report analyzing the specifications of multicopters found f_b ratios ranging between 0.22 and 0.33

and maximum f_p ratios ranging between 0.25 and 0.30 (Figliozzi, 2018) which implies values of f_e ranging from 0.42 and 0.47. An awareness of realistic drone mass distributions can facilitate the detection of outliers, typos, or highly optimistic assumptions. For example in Zhang et al. (2023) when discussing Kirschstein (2020) drone with a $f_e = 0.14$ (a typo or mistake) instead of the actual value of $f_e = 0.49$.

Table 1 Normalized average mass distributions f and m. Values derived from Table 3.b in Zhang et al. (2021, 2023) and in the same order.

Reference	f_e	f_b	f_p	*Mass m [kg]*
Liu et al. (2017)	0.78	0.22	-	1.46
Stolaroff et al. (2018)	0.42	0.39	0.19	2.57
Dorling et al. (2017)	0.50	0.17	0.33	3.00
Dorling et al. (2017)	0.50	0.17	0.33	3.00
Tsen et al.(2017a)	0.60	0.20	0.20	2.50
Tsen et al.(2017a)	0.65	0.18	0.18	3.40
D'Andrea (2014)	0.33	0.33	0.33	6.00
Figliozzi (2017)	0.40	0.27	0.33	15.10
Kirchstein (2020)	0.49	0.41	0.10	24.50
Stolaroff et al. (2018)	0.29	0.42	0.29	24.00
Xu et al. (2017)	0.56	0.35	0.10	23.90
Statistic				
Min.	**0.29**	0.17	-	1.46
Median	0.50	0.27	0.20	3.40
Average	0.50	0.28	0.22	9.95
Max.	0.78	**0.42**	0.33	24.50

A drone configuration in **Table 1** stands out with the minimum value of $f_e = 0.29$ and the largest value of $f_b = 0.42$. As discussed earlier, these values will likely produce optimistic range results. Assuming that a drone with a median value of $f_b = 0.27$ experiences a redistribution of mass that results in $f_b = 0.42$ (by reducing empty or payload mass), a 0.15 change in f_b results in a range increase of 55%. Regarding $f_e/\ f_b$ values, this drone is also an outlier with a value

$f_e/\ f_b = 0.7$. As a reference in **Figure 1** scenario (b) $f_e/\ f_b$ values are in the (4.33, 0.78) interval for m_b values in the (1.5, 4.5) interval respectively. This result begs the question, is it realistic to assume values of $f_e = 0.29$ and $f_e/\ f_b = 0.7$ (or even lower) when evaluating a drone viability, performance and sustainability?

A drone manufacturer aims to design a drone that is lighter, has more range, or higher payload capacity. To reduce weight, drone chassis are made of lightweight and strong materials such as duralumin or carbon fiber and lowering f_e beyond certain values generates structural problems in terms of reliability and the strength of the frame that supports the battery and payload. A drone has to endure not only static and dynamic stresses but also temperature related stress when operating in hot summer days with direct sunlight and the risk of brittle fractures in cold freezing environments (Stewart and Martin, 2021). In addition, low f_e values can affect drone reliability, durability, and increase vibration and noise (Quan, 2017). In terms of sustainability, high values of f_b increase drone lifecycle emissions given the relatively high value of emissions associated to sourcing battery materials and manufacturing (Figliozzi, 2017).

Some mass data from drone manufacturers can be found on internet websites, but unfortunately the mass data is usually confusing and not presented in a standardized format. In addition, most of the data available online is for drones used mainly for photography or aerial surveying with mass specifications that are likely not directly transferable to the needs and service conditions of a reliable drone delivery service. Unfortunately drone delivery companies are secretive about their drone designs, thus empty and battery masses are typically not (yet) disclosed. Some payload information is available though. Alphabet (Google) Wing drone website declares a takeoff weight of 14 lbs with a payload of 2.6 lbs (Wing, 2023) which results in $f_p \sim 20\%$ and a WSJ article reported a payload of 3.3 lbs and 10 lbs for the drone

(Bhattacharyya, 2022) which translates roughly into a f_p in the 0.20 – 0.25 range. The company Flytrex that is currently participating in deliveries for Walmart report a value of f_p ~ 0.22 by delivering a payload of 3 kg using a drone that weighs 13.6 kg (Gradstein, 2021). These f_p values are close to the median 0.20 value shown in Table 1 and close to the median f_p values reported drone survey literature. However, actual f_p values may be lower for delivery drones if reliability and durability are prioritized. Summarizing, considering the median and average values of Table 1 and the f_p values obtained for delivery drones, typical values of mass distribution are 0.50 for tare, 0.28 for the battery, and 0.22 for payload.

Drone companies have an incentive to advertise both high range and high payload capacity values, but as shown in the range equation high range and payload are not mutually compatible (Figliozzi, 2023). Hence, manufacturers' figures provide a useful baseline but should be taken with a grain of salt and assumed as obtained with favorable configurations.

The drone with $f_e = 0.29$ and $f_e / f_b = 0.7$ values and range 4.2 km is a Turbo ACE Infinity 9 Drone that was not tested using the design battery mass. Using the design battery, 4.2 kg instead of 10 kg, then more realistic values $f_e = 0.38$ and $f_e / f_b = 1.67$ are obtained but the range is reduced to 2.5 km (from 2.5 to 4.2 the range increases by 68%). Credit is given to the authors of the study (Stolaroff *et al.*, 2018) for including all the mass details and even stating that by increasing battery size even longer ranges (up to 5 km) can be obtained but with a negative side effect: flight control problems. This side effect highlights another problem related to low f_e values: engines, propellers, cables and other accessories must be designed to meet an acceptable power/mass ratio for delivery drones. More power requires more mass for engines and components. A low power/mass ratio creates a performance problem due to the low responsiveness and maneuverability of the drone. Reducing engine mass and power is conceptually similar to driving long-haul truck capable of maximum speeds of 40 miles per hour and maximum uphill grades of 2%. For this low performing truck, the fuel efficiency may be high but the vehicle will not be representative of real-world truck engines or their operating conditions. Researchers can analyze different scenarios for mass distributions and assumptions such as high battery mass and low empty mass, though in this case, ideally, a research paper clearly states that the drone is configured and optimized for range and not for reliability, durability, or maneuverability. Providing enough context facilitates the understanding of figures otherwise may seem outliers or too optimistic.

Drone deliveries continue to grow. For example, in 2022 Walmart made 6000+ drone deliveries from 36 stores scattered across 7 states in the US (Walmart, 2023) and drones will likely become a credible delivery option in many areas. Unlike deliveries using ubiquitous internal combustion and electric commercial trucks, delivery by drone is not a mature industry with well-defined examples of drone performance, size, and mass configuration. The purpose of this short communication is to discuss how drone mass distribution affects range/payload, flight stability, durability, and energy consumption. All these performance measures are important in real-world drone delivery systems and drone mass configuration also has a central role when analyzing the sustainability of drone delivery systems.

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DISCLAIMER
The author's views and opinions expressed in this paper do not necessarily reflect the views or positions of any entity the author may represent o the views of positions of any funding agency.

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