

CRANFIELD UNIVERSITY

QUAN PENG

CONCEPTUAL DESIGN METHODOLOGIES APPROPRIATE TO
ELECTRIC VERTICAL TAKE-OFF AND LANDING AIRCRAFT IN
URBAN AIR MOBILITY

SCHOOL OF AEROSPACE TRANSPORT AND MANUFACTURING
AIRCRAFT DESIGN

PhD

Academic Year: 2019 - 2023

Supervisor: Prof. Howard Smith
Associate Supervisor: Mr Jack Stockford
August 2023

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the degree of Ph.D.

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ABSTRACT

This project aims to investigate the current state of conceptual design issues related to electric Vertical Take-off and Landing aircraft (eVTOL) in Urban Air Mobility (UAM). The thesis seeks to develop design methodologies appropriate for eVTOLs and explore the design space for various configurations, including Vectored Thrust, Lift+Cruise, and Multicopter concepts. This project developed a design model for eVTOL within the multi-disciplinary design analysis and optimization environment - GENUS at Cranfield University. The GENUS framework integrates various aerodynamic analysis tools, efficient geometric parameterization methods, semi-empirical mass breakdown models, and effective boundary layer ingestion analysis models. This enables comprehensive conceptual design and design space exploration for novel aircraft, considering real-world considerations. In this project, optimization and comparison are conducted across more than 200 cases involving different aircraft configurations, passenger capacities, battery capacities, cruising speeds, and ranges. Multicopter configurations are suited for short-range, low-speed flights due to the simpler structure and rotor system, despite limitations in range and speed imposed by disk loading and propeller efficiency. Vectored Thrust configurations are suitable for long-range and high-speed flights due to the high lift-to-drag ratio. The Lift + Cruise configuration is versatile due to the combination of lift rotors and propulsion propellers, resulting in higher efficiency for both cruising and hovering. Battery technology is a crucial factor in eVTOL design. With a battery energy density of 300 Wh/kg, the battery weight accounts for approximately 60% of the total weight for a 2-passenger eVTOL undertaking a 200-mile mission. However, at a battery energy density of 900 Wh/kg, the battery weight for a 20-passenger eVTOL performing a 200-mile mission reduces to around 15-20%.

Keywords:

Aircraft conceptual design, Multidisciplinary design optimization, electric Vertical Take-off and Landing aircraft, Urban Air Mobility

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LIST OF ABBREVIATIONS

AAV	Autonomous Aerial Vehicle
ACS	Airman Certification Standards
AHS	American Helicopter Society
AIAA	American Institute of Aeronautics and Astronautics
AMTs	Aviation Maintenance Technicians
ARC	Abnormal Runway Contact
ATC	Average Total Cost
ATM	Air Traffic Management
BMS	Battery Management System
CFD	Computational Fluid Dynamics
CFIN	Controlled Flight into Terrain
DEP	Distributed Electric Propulsion
DP	Distributed Propulsion
EDF	Electric Powered Ducted Fans
EM	Electric Motor
eVTOL	Electric Vertical Take-off and Landing
FAA	Federal Aviation Administration
HEPS	Hybrid Electric Propulsion System
ICE	Internal Combustion Engine
LCA	Life Cycle Analysis
LCE	Life Cycle Engineering
LOC	Loss of Control In-flight
MTOW	Maximum take-off weight
NAE	National Academy of Engineering
NASA	National Aeronautics and Space Administration
ODM	On-demand Mobility
OEI	One Engine Inoperative
PAV	Passenger Air Vehicle
RE	Runway Excursion
SCF	System/Component Failure or Malfunction
SESAR	Single European Sky ATM Research
UAM	Urban Air Mobility

VFS	Vertical Flight Society
VTK	Visualization Toolkit
VTOL	Vertical Take-off and Landing

A_{keel}	Keel beam area	m^2
A_{bolt}	Bolt area	m^2
B	Number of blades	
C_{Dtotal}	Total drag coefficient	
C_{DLV}	lift induced vortex drag coefficient	
c	Chord of aerofoil	m
C	discharge rate of the battery	C
c_d	local blade profile drag coefficient	
c_l	local blade lift coefficient	
C_{m_a}	moment coefficient curve slope speed	
C_{L_a}	lift coefficient curve slope	
$\bar{c}$	mean aerodynamic chord	m
d_{bolt}	Bolt diameter	m
d	Diameter	m
E	battery specific energy	J/kg
F_{land}	landing impact force	N
F	modified Prandtl's factor	
h_{fus}	Fuselage height	m
I_{land}	landing impact factor	
I	Current	A
i_0	no-load current	A
$K_{Aerofoil}$	Korn factor	
K_V	Speed constant	RPM/V
K_Q	Torque constant	A/(N · m)
L/D	lift to drag ratio	
l_{fus}	Fuselage length	m
L	lift	N
l	Length	m
$m_{battery}$	battery mass	kg
$m_{aircraft}$	aircraft mass	kg
m_{skin}	Skin material mass	kg
m_{canopy}	Canopy mass	kg
m_{bulk}	Bulkhead mass	kg
$m_{keel,\tau}$	Keel beam mass of shear carrier	kg

$m_{keel,\sigma}$	Keel beam mass of tensile stress carrier	kg
m_{fus}	Fuselage mass	kg
m_{copper}	Copper mass	kg
m_{cable}	Cable mass	kg
m_{wiring}	Wiring mass	kg
Ma_{dd}	drag divergence Mach number	
Ma_{crit}	local critical Mach number	
n_{pad}	Number of landing pad	
$P_{battery}$	power out of the battery	W
$P_{aircraft}$	aircraft power	W
P_{max}	Maximum power	W
Q_m	Torque	N · m
r_{copper}	Copper radius	m
R_0	internal resistance	Ω
R	resistance	Ω
r	Radial coordinate	m
R	Tip radius	m
$S_{wet fus}$	Wetted area	m ²
S_{canopy}	Canopy area	m ²
S_{bulk}	Bulkhead area	m ²
t	flight time	s
t_{pad}	landing pad laminate thickness	m
t_{copper}	Copper thickness	m
t	Thickness	m
u_a	local externally induced velocity	m/s
u_t	local externally induced velocity	m/s
V_{pad}	Landing pad volume	m ³
v	Terminal voltage	V
V	freestream velocity	m/s
v_a	local rotor-induced velocity	m/s
v_t	local rotor-induced velocity	m/s
v_∞	flight speed	m/s
w_{fus}	Fuselage width	m
W_W	Wing weight	lb
W_{TO}	Take-off weight	lb
W_a	Axial components of total relative velocity	m/s
W_t	Tangential components of total relative velocity	m/s
W	total relative velocity	m/s
x	state of charge of the battery	
X_{CG}	Centre of gravity position on x axis	m

X_{np}	neutral point on x axis centre	m
Y_{CG}	Centre of gravity position on y axis	m
Z_{CG}	Centre of gravity position on z axis	m
Γ	local blade circulation	
σ_u	ultimate tensile strength	MPa
$\eta_{overall}$	overall aircraft efficiency	
η_m	Efficiency	
θ	maximum landing angle	°
$\Lambda_{0.5}$	midchord sweep angle	°
λ_w	local wake advance ratio	
ρ	Fluid density	kg/m ²
ρ_τ	density of shear carrier	kg/m ²
ρ_σ	density of tensile stress carrier	kg/m ²
ρ_{cable}	Cable density	kg/m ²
ρ_{canopy}	Canopy areal density	kg/m ²
ρ_{copper}	Copper density	kg/m ²
ρ_{skin}	skin areal density	kg/m ²
τ_u	ultimate shear strength	MPa
Ω	Rotation rate	RPM

1 INTRODUCTION

1.1 Background of the Research

With the increase in population and the increase in the number of cars on the road, the capacity of well-established road systems in many countries around the world is exceeded, and the time and energy consumption of ground travel continues to rise. City-to-city transportation and the national economy are seriously affected by traffic congestion and lost productivity. To solve these problems, researchers and companies have performed several studies[1–6] relating to On-demand Mobility (ODM), a multi-modal transportation capability that allows passengers to be safely and efficiently taken from any location to another at a range of approximately 10 to 500 miles at any time [7]. In response to growing interest from communities and organizations, such as NASA and FAA, who co-led ODM Roadmapping Workshops in 2015 and 2016 [8], the concept of Urban Air Mobility (UAM) has emerged. UAM, a subset of ODM, focuses specifically on short-haul traffic within metropolitan areas and offers the potential benefits of short-range vertical take-off and landing capabilities [7]. UAM provides passengers and goods with a faster and more efficient way of moving over intermediate distances with electric-powered aircraft. Kevin R.A et.al [9] studied and evaluated potential take-off and landing areas in the San Francisco bay area and concluded that the door-to-door travel time saved by UAM could be significant for trips greater than 15 miles and could potentially improve door-to-door speeds 3.5 times over city and suburban travel.

According to statistics, nearly 150 companies around the world are engaged in the development of UAM. According to the type of thrust, the VTOL designed by these companies can be roughly divided into four categories: vectored thrust, lift + cruise, wingless (multicopter) and electric helicopters. Vectored Thrust vehicles, eVTOL aircraft using any thruster for lift and cruise, are the most widely used (about 80 eVTOL use this design, such as A³ Vahana [10], Lilium Jet [11]). Lift + Cruise vehicle is an eVTOL aircraft with completely independent propellers for cruise and lift, such as Kitty Hawk Cora [12] and Aurora Pegasus Passenger Air Vehicle (PAV) [13]. Multicopter is an eVTOL aircraft with all the propellers

providing lift and thrust, such as AirCar [167] and DaVinci [168]. Electric Rotorcraft is a type of electric aircraft using helicopter flight control, such as Prades GyroBike [14], Piasecki PA-890 [15] and Vinati F-Helix [16].

1.2 Aim and Objectives of the Research

The aim of this research is to develop a conceptual design methodology to explore the design space associated with the electric vertical take-off and landing aircraft (eVTOL) for urban air mobility (UAM) based on the GENUS framework.

Based on the overall aim of the research, there are four specific objectives identified:

- 1) To find and collect the data of different configuration eVTOLs and finish a literature review.
- 2) To develop suitable design methods for each module, including geometry module, mass estimation, mission, propulsion specification, aerodynamic characteristics, propulsion modelling (including lift and thrust – perhaps with propellers and ducted fans), packaging and C.G., performance modelling and stability module.
- 3) To code the methods of each module into GENUS and debug the codes.
- 4) To explore the design space of the eVTOL aircraft configuration. For example, the effects of batteries and payloads on the performance of different configuration eVTOLs at different speeds and ranges.

1.3 Structure of the Thesis

The thesis is structured into four main parts. The first part, Chapter 2, provides a comprehensive literature review on eVTOL technology. Considering the high demands and constraints of flying within urban environments, an exploration of mission profiles suitable for such vehicles is conducted. By examining the conceptual designs of various eVTOL aircraft available in the market, the classification of eVTOL vehicles is conducted, and their theoretical performance in different missions is analysed. The technical concerns and obstacles linked with this category of aircraft are recognized. Due to the issue of tight integration, a multidisciplinary approach involving design, analysis, and optimization

environments is considered as the fundamental method for designing eVTOL aircraft.

The second part (Chapter 3) outlines the eVTOL design methodology within a multidisciplinary framework for design, analysis, and optimization referred to as GENUS. The GENUS aircraft design environment possesses characteristics such as modularity, scalability, flexibility, independence, sustainability, and executability. This part discusses the development of methodologies applicable to eVTOL within the GENUS environment. Physics-based and empirical formula-based methods are employed to calculate the mass breakdown of the aircraft. Battery modules, considering variations in voltage and internal resistance, are applied to the propulsion module. An extended method based on the classical blade-element/vortex formulation is employed to calculate the aerodynamics of the propellers.

The third part (Chapter 4) presents the application of the GENUS for case study. The design capabilities of GENUS are showcased by comparing the results with the original aircraft data. The effectiveness of the optimizer in exploring the design space is demonstrated by contrasting the data before and after optimization.

The fourth part (Chapter 5, Chapter 6, Chapter 7, Chapter 8, and Chapter 9) presents the results and conclusion of the design space exploration. Chapter 5 to Chapter 7 show the performance of different configurations at different design conditions. Chapter 8 provides a comprehensive analysis and discussion of the optimal solutions for different configurations under varying flight conditions, comparing all the data obtained from Chapter 5 to Chapter 7. Chapter 9 concludes the design recommendations, future work, and prospect of eVTOL.

2 LITERATURE REVIEW

2.1 Historical Background

The AugustaWestland Project Zero (USA), the Volocopter VC1 (Germany) and the Opener BlackFly (USA) proposed the concept of eVTOL in 2011 [17]. Project Zero, shown in Figure 2-1 (a), is an all-electric-powered, hybrid tiltrotor/fan-in-wing technology incubator. During 2011 and 2012, the aircraft completed several test flights in the safe areas of AugustaWestland and Cascina Costa [18]. In 2013, the Vertical Flight Society published an exclusive report on such aircraft [19]. Volocopter VC1, shown in Figure 2-1(b), is an eVTOL prototype aircraft with 16 individual rotors for one passenger. The aircraft completed first flight in 2011, which lasted 90 seconds. According to the Guinness Book of World Records, this is the first manned flight of an electric multicopter [20]. Opener SkyKar, shown in Figure 2-1 (c), is a fixed-wing all-electric VTOL aircraft. Engineer Marcus Leng (now CEO of Opener) achieved the first flight of the aircraft in 2011 [21].



a



b



c

Figure 2-1. (a) Project Zero (Source: [19]), (b) Volocopter VC1.(Source: [20]), (c) Opener SkyKar.(Source: [21]).

In 2014, the American Helicopter Society (AHS) International and the American Institute of Aeronautics and Astronautics (AIAA) officially announced the concept of eVTOL for the first time in the "Transformative Vertical Flight Concepts Joint Workshop on Enabling New Flight Concepts through Novel Propulsion and Energy Architectures" [22]. The purpose of the conference is to lay the foundation for the new electric propulsion system through the developers of emerging and existing VTOL concepts. Project Zero [19] and Sikorsky's Firefly [23] were highlighted in the conference. Sikorsky's Firefly, shown in Figure 2-2, is an all-electric helicopter with 300 battery packs on both sides (150 each). The company's modifications to the aircraft's electric engine include an increase of 40 horsepower, a stable 3,200 RPM, and the use of forced air cooling [23]. Sikorsky estimates that the aircraft can fly with a pilot at 148kmh for 12 to 15 minutes.



Figure 2-2. Sikorsky's Firefly (Source: [23]).

Aircraft manufacturers are increasingly interested in eVTOL aircraft. Ehang 184, shown in Figure 2-3, is one seat, all electric eVTOL aircraft which have 4 arms and 8 propellers. The aircraft completed flight tests in China in 2015-2017, the United States in 2016-2017, and Dubai in 2017 [24]. Ehang 184 is the world's first Autonomous Aerial Vehicle (AAV) capable of carrying passengers.



Figure 2-3. EHang 184 front view (Source: [24]).

2.2 Mission

The main mission of eVTOL includes max take-off weight (MTOW), number of passengers, cruise speed, range, cruising altitude and flight time. The number of passengers is determined by the designer in the initially design. However, the relationship among other parameters, particularly for rotor-configured eVTOLs, requires a distinct approach compared to fixed-wing electric airplanes due to their unique lift and propulsion characteristics. The relationship of other parameters of fixed-wing eVTOL can be expressed in physical expressions.

The range [m] of an aircraft is.

$$Range = v_{\infty} t \quad (2-1)$$

where v_{∞} [m/s] is flight speed, t [s] is flight time.

$$t = \frac{m_{battery} E^*}{P_{battery}} \quad (2-2)$$

where $m_{battery}$ [kg] is battery mass, E^* [J/kg] is battery specific energy, $P_{battery}$ [W] is power out of the battery.

$$P_{battery} = \frac{P_{aircraft}}{\eta_{overall}} \quad (2-3)$$

where $P_{aircraft}$ [W] is aircraft power, $\eta_{overall}$ [-] is overall aircraft efficiency.

$$P_{aircraft} = v_{\infty} T = v_{\infty} D \quad (2-4)$$

where $D = T$ [N] is aircraft drag.

$$D = \frac{m_{aircraft} g}{L/D} \quad (2-5)$$

where $m_{aircraft}$ [kg] is aircraft mass, L/D [-] is lift to drag ratio.

the battery power is.

$$P_{battery} = \frac{v_{\infty} m_{aircraft} g}{\eta_{overall} L/D} \quad (2-6)$$

Rearranging, the flight speed is

$$v_{\infty} = \frac{P_{battery} \eta_{overall} L/D}{m_{aircraft} g} \quad (2-7)$$

the constant-mass aircraft range is.

$$R = \eta_{overall} E^* \frac{L}{D} \frac{1}{g} \frac{m_{battery}}{m_{aircraft}} \quad (2-8)$$

In addition, disc loading is also an important parameter used to measure eVTOL performance. The disc loading is the mass of eVTOL divided by the total area of the main rotors used for hovering. Figure 2-4 is the typical disc loadings and hover lift efficiencies for non-electrified VTOLs image. The trend shows that with the disc loading increasing, the hover lift efficiency decreases. High disc loading also leads to poor performance, such as high downwash speed and high noise [25].

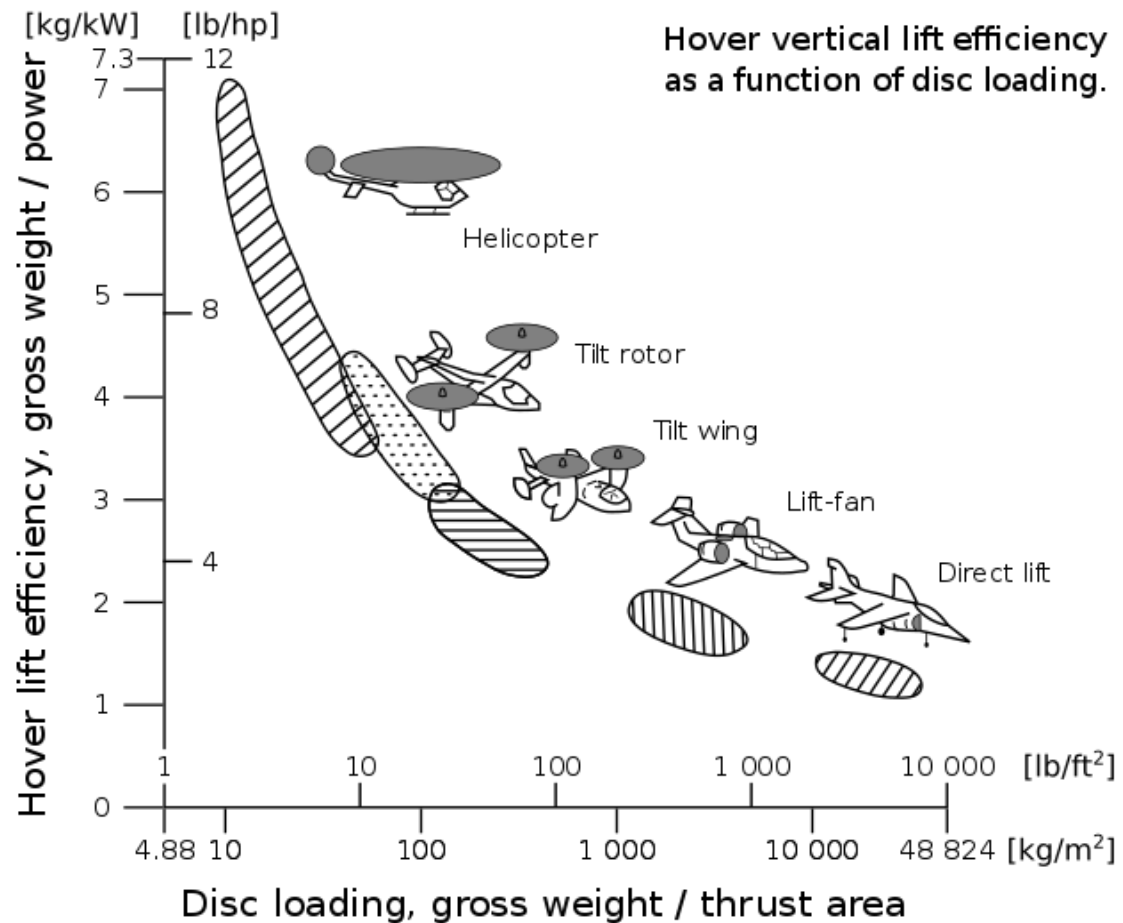


Figure 2-4. Typical disc loadings and hover lift efficiencies for non-electrified VTOLs (Source: [26]).

Figure 2-5 is the disc loadings and hover lift efficiencies for some eVTOLs. The data comes from multiple sources. Compared with Figure 2-4, almost all eVTOLs have lower hover lift efficiency than traditional aircraft under same disc loading. As delineated in [27], the hovering power for eVTOLs is roughly half of the maximum power output. Given that the majority of the eVTOL data I obtained reflects maximum power output and considering the potential for One Engine Inoperative (OEI) scenarios, I have adjusted the data to represent hover power by applying a 50% reduction. When this power is reduced to 50%, Figure 2-6 elucidates a positive correlation, indicating enhanced efficiency for eVTOLs as the disc loading diminishes.

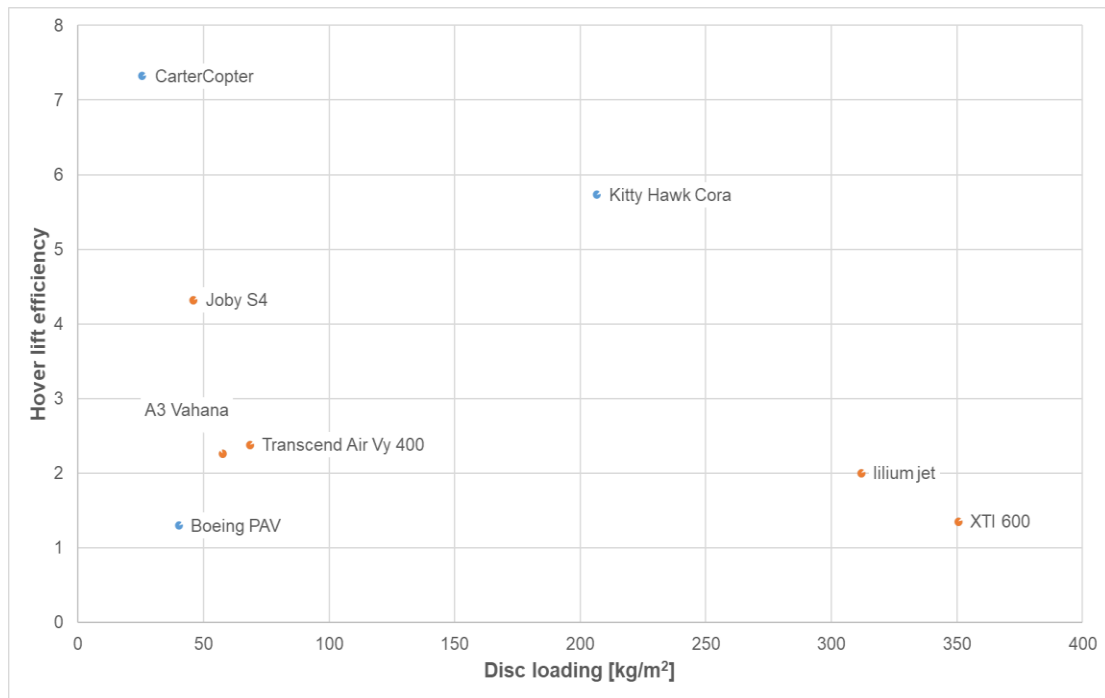


Figure 2-5. Disc loadings and hover lift efficiencies for some eVTOLs.

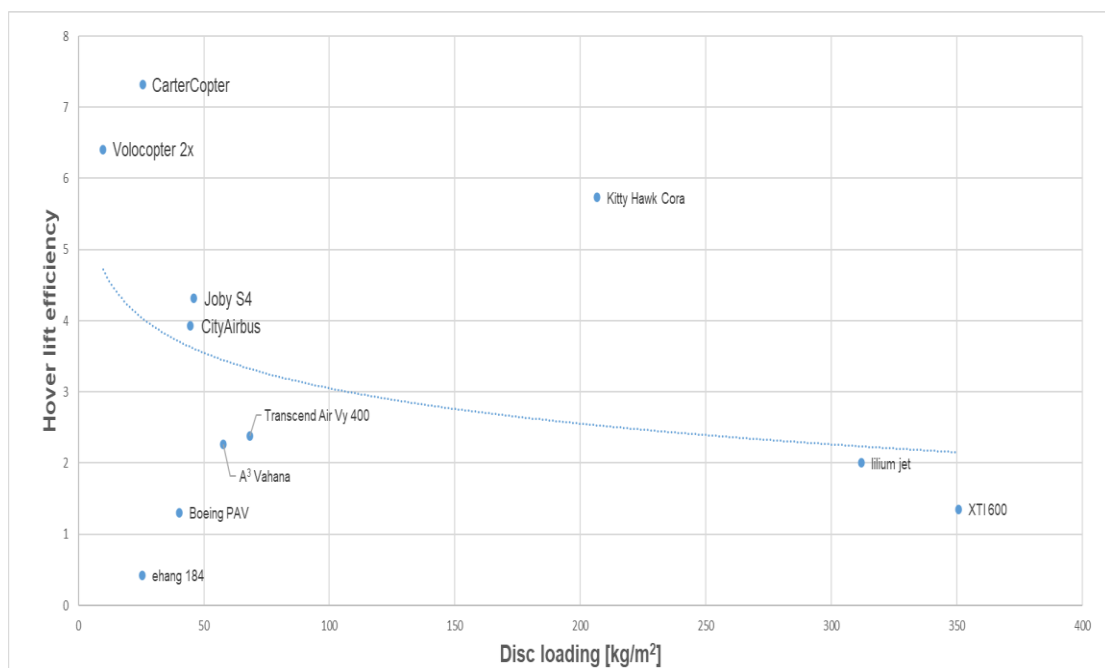


Figure 2-6. Disc loadings and hover lift efficiencies for some eVTOLs after reducing power by 50%.

2.3 Aircraft Configuration

According to the difference of lift and thrust generation, shown in Table 2-1, the eVTOL aircraft for UAM can be divided into: Vectored Thrust, Lift + Cruise,

Multicopter and Electric Rotorcraft. Figure 2-8 shows the VSP models of different configurations.

Table 2-1 Main differences for the four different configurations regarding lift and thrust generation.

	Vectored Thrust	Lift + Cruise	Multicopter	Electric Rotorcraft
Thrust generation in take-off and landing	Rotor/Propeller	Rotor/Propeller	Rotor/Propeller	Articulated rotor
Lift generation in take-off and landing	Rotor/Propeller	Rotor/Propeller	Rotor/Propeller	Articulated rotor
Thrust generation in hover / climb	Rotor/Propeller	Rotor/Propeller	Rotor/Propeller	Articulated rotor
Lift generation in cruise in hover/ climb	Wing, Propeller(option)	Wing, Propeller(option)	Rotor/Propeller	Articulated rotor
Thrust generation in cruise	Tilted rotor/propeller	Pusher or tractor propeller	Rotor/Propeller	Articulated rotor
Lift generation in cruise	Wing	Wing	Rotor/Propeller	Articulated rotor

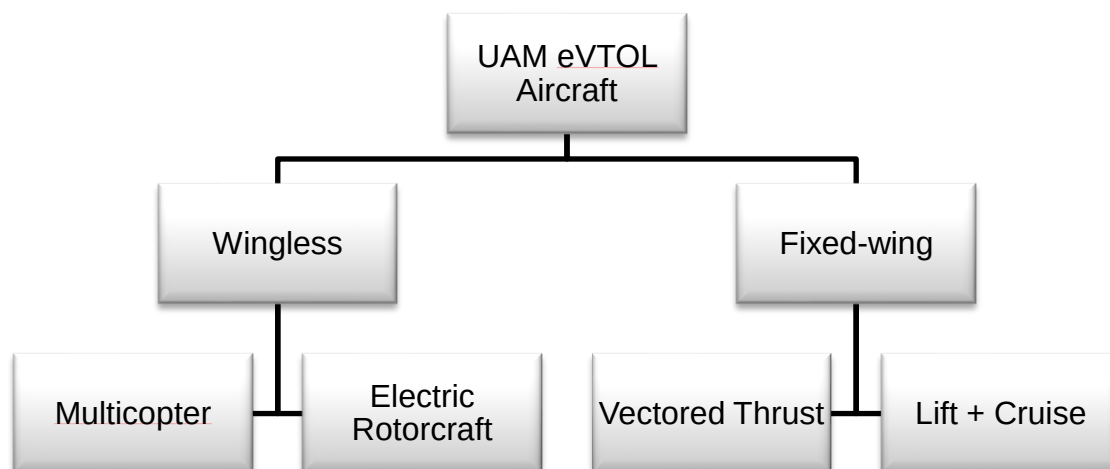


Figure 2-7. Different configurations of eVTOL for UAM application.

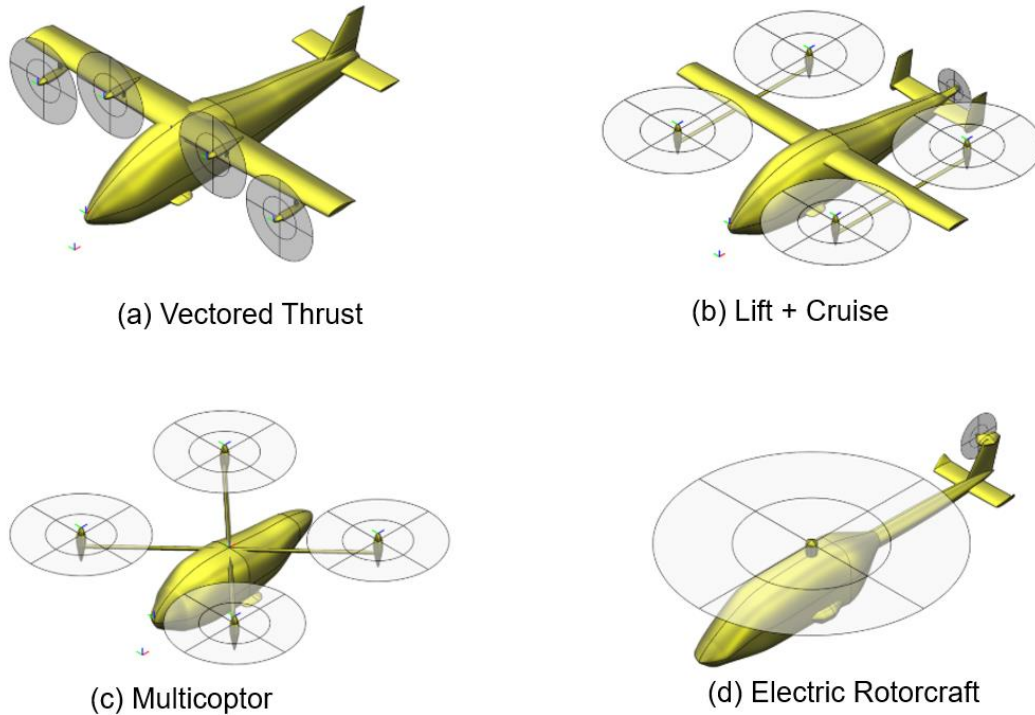


Figure 2-8 VSP models of different configurations (Source: [28])

2.3.1 Vectored Thrust

This section discusses 82 Vectored Thrust eVTOL vehicles that are currently being implemented or are being tested and designed. Figure 2-9 is categorized according to the power system of these aircraft. Table 2-2 shows parameters of the aircraft, including design and configuration, motor and battery specifications, take-off weight and payload capacity and performance.

Table 2-2 Data of Different Vectored Thrust eVTOL for UAM.

1. Electric (E), Hybrid-Electric (H), Other (O)

2. MTOW=Maximum take-off weight

3. Battery Energy Density, Wh/kg

4. Battery Capacity, kWh

Aircraft	Power Train ¹	Number of Passengers	MTOW ¹ (kg)	Empty weight(kg)	Useful payload(kg)	Motor Output ¹ (kW)	Total Output ²	Battery Density ³	Battery Capacity ⁴	Flight Time (min)	Flight Range (km)	Cruise Speed (km/h)	Flying Altitude (m)
A ³ Vahana Alpha	E	1	815	475	90	45	360	200	-	-	60	200	1524
A ³ Vahana Beta	E	2	815	475	200	45	360	200	-	-	100	230	3048
Acs Aviation Z-300	E	2	1000	-	-	35	140	-	-	90	300	222	-
Aerog Aviation Ag-4	H	10	5670	4681	907	1200	4800	-	-	-	-	519	-
Airis Airisone	E	4	-	-	-	-	-	-	-	-	322	282	-
Aston Martin Volante	E	3	-	-	-	-	-	-	-	-	1852	460	9000
Asx Mobi-One	E/H	5	-	-	-	-	-	-	-	-	418	241	-
Aurora Lightningstrike	H	0	5.9 t	5.16 t	737	125(18x),90(6x)	2790	-	-	-	-	555	-
Autonomous Y6s	E	2	-	-	-	-	-	-	-	-	130	113	450
Bartini Flying Car	E	4	1100	-	400	40	320	200	64	30	150	300	1000
Bell Nexus Air Taxi	H	4	2720	-	-	-	-	-	-	-	241	288	-
Delorean Aerospace Dr7	E	2	-	-	-	-	-	-	-	-	193	241	-
Digi Robotics Drofire	E	2	-	-	177	58	348	-	-	150	500	175	6000

Dufour Aero2	H	2	-	-	-	-	-	-	-	-	800 in hybrid	320	-
											120 in electric		
Eco'Trip	E	2	550	350	200	-	535	-	-	60	-	115	-
Eva Valkyr	E	0	-	-	10	-	-	-	-	60	-	-	-
Eva X01	E	2	-	-	250	-	-	-	-	-	250	400	-
Hopflyt Venturi	E	4	815	-	-	-	-	-	-	-	185	220	-
Hoversurf Formula	-	-	-	-	-	-	-	-	-	72	450	250	-
Jetoptera J2000	H	2	-	-	-	-	-	-	-	-	322	322	4500
Joby S2	E	2	-	-	-	-	-	-	-	60	322	322	-
Joby S4	E	4	1815	-	-	-	-	-	-	-	246	322	
Karem Butterfly	E	4	-	-	-	-	-	-	-	-	161	-	-
Kari Pav	-	-	-	-	-	-	-	-	-	15	50	200	-
Kitty Hawk Heaviside	E	1	500	-	-	-	-	-	-	-	160.9	354	-
Kronstadt Air Taxi	H	2 To 4	-	-	-	-	-	-	-	-	150	-	-
Lilium Jet	E	2	640	440	200	-	-	-	320	60	300	300	-
Macchina Volantis Flying Car	H	4 To 5	1650	-	570	-	-	-	-	-	278	-	3048
Moller Skycar S200	O	2	-	598.7	181.4	63.4	126.8	-	-	222	698.4	205	-
Moller Skycar S400	O	4	-	1088	326.5	-	535	-	-	354	1297.1	308	-
Mydraco	E	1 To 2	-	-	-	-	-	-	-	-	300	-	-
Nasa Puffin	E	1	272	136	91	44	88	-	-	19	241	80	9144
Rolls-Royce Evtol	H	4/5	-	-	-	-	500	-	-	-	804.6	250	-

Sabrewing Draco-2	H	-	1157	278	-	24	192			-	8334	-	-
Sabrewing Rhaelgal Rg-1	H	0	1001	373	363	-	447	-	-	-	1850	333	6705
Samad Aerospace Huma	-	-			200	-	-	-	-	-	139.8	201	-
Skyllys Airspeeder	E	3	-	540	-	-	-	-	-	45-50	150	160-240	-
Terrafugia Tf-2 Tiltrotor	E	4	3630	-	500	-	-	-	-	-	445-555	315-333	-
Terrafugia Tf-X	H	4	-	-	-	-	-	-	-	-	800	320	-
Transcend Air Vy 400	H	6	3170	2177	1000	-	-	-	-	-	725	405	4572
Uber Elevate Ecrm-001	E	4	-	-	-	-	-	-	-	180	96	241 ± 24	1524
Verdego Aero Pat 200	H	2	-	-	227	-	-	-	-	-	30-60	150	-
Vickers Wave Evtol	H	4	839	-	297	-	-	-	-	-	2037	222	-
Vimana	H	4	1050	-	400	60	480	-	-	-	900	222	-
Voyzon Aerospace E-Voto	E	2	-	500	-	-	-	-	-	30	-	250	-
Vrco Neoxcraft	E	2	450	-	180	-	-	-	-	60	120	333	-
Xti Trifan	H	6	2404	1588	816	-	750	-	-	-	1060	555	8840
Zeva Zero	E	1	-	-	-	-	-	-	-	-	80	258	-

The design for the vectored thrust aircraft listed in Table 2-2 can be roughly divided into: tiltwing and tiltrotor. A tiltwing aircraft's wings are horizontal for forward flight and rotate up for vertical take-off and landing. The tiltwing aircraft easy and fast to switch between VTOL and horizontal flight modes, which makes it very suitable for the design of vectored thrust aircraft, such as A³ Vahana [10], ACS Aviation [29], Dufour aEro 2 [30] and so on. Figure 2-10 is the side view of Dufour aEro 2. By using proven aerodynamic technology, a tilt-wing design with constant airflow over the wings, Dufour aEro 2 has outstanding stability and controllability even in very slow flight. The large wing surface makes it difficult to be affected by the state of the vortex ring when hovering and at the same time, the efficient tail fan can provide pitch control during hover flight and ensure that the vehicle can resist changes in the centre of gravity and gust conditions. Four motors (two on each side) ensure fully redundant hover capability.



Figure 2-10. The side view of Defour aEro 2 (Source: [30]).

Also, some tiltwing/tiltrotor vehicles use the ducted fans to meet the design requirements. Ducted fan is an air moving arrangement that can reduce the thrust loss from the tips of propeller blades, therefore the ducted fan is more efficient in generating thrust than traditional propellers of similar diameter, especially at low speeds and high static thrust levels. Lilium Jet [11], shown in Figure 2-11, a five-seater, all-electric, vertical take-off and landing aircraft. This vehicle is a pioneering tilt jet aircraft with 36 engines mounted on its flaps. There are two fixed wings on the vehicle, one main wing which have each four flaps

at the rear of the aircraft, another “canard” wing which each have two flaps at the front. Three pioneering all-electric ducted fan engines are mounted on each flap, allowing them to rotate and change the direction of the thrust they create. The Lilium Jet has no tail, no rudder, no oil circuits, no gearboxes, no variable pitch fan blades, and it makes the aircraft simplicity to achieve lower maintenance costs, greater safety, greater affordability, and less weight.



Figure 2-11. Lilium 5 seat eVTOL Jet (Source: [11]).

A tilt-rotor aircraft is an aircraft that generates lift and propulsion through one or more power rotors or propellers. It is a combination of the vertical lift of a helicopter and the speed and range of a conventional fixed-wing aircraft. In the vertical flight, it optimizes the working mode of the ordinary helicopter rotor by tilting the rotor. In the hovering flight, the rotor acts as a propeller to provide thrust, while the fixed wing provides lift for the forward movement of the aircraft. Tilt rotors can achieve higher speeds than helicopters because the wings can be configured for more efficient propulsion and the problem of stalling the helicopter's backward blades can be avoided. SBX eVTOL flying vehicle, shown in Figure 2-12, is a 5 seat, tilting rotors, full electric aircraft [31]. Four Tilting Electric Powered Ducted Fans (EDF) in the corners provide power for the aircraft, each EDF has two counter-rotating multi-blade propellers and a motor with two stators. Only one motor with a two-stator configuration is sufficient to power two counter-rotating propellers, which causes each stator to work independently, and the EDF can keep running if one of the stator fails.

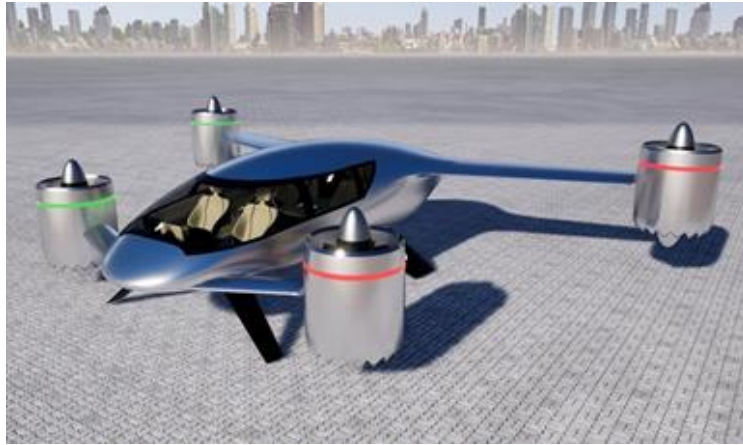


Figure 2-12. SBX 5 seat eVTOL (Source: [31]).

2.3.2 Lift + Cruise

This section discusses Lift + Cruise eVTOL vehicles that are currently being implemented or are being tested and designed. Figure 2-13 is categorized according to the power system of these aircraft. Table 2-3 shows parameters of the aircraft, including design and configuration, motor and battery specifications, takeoff weight and payload capacity and performance.

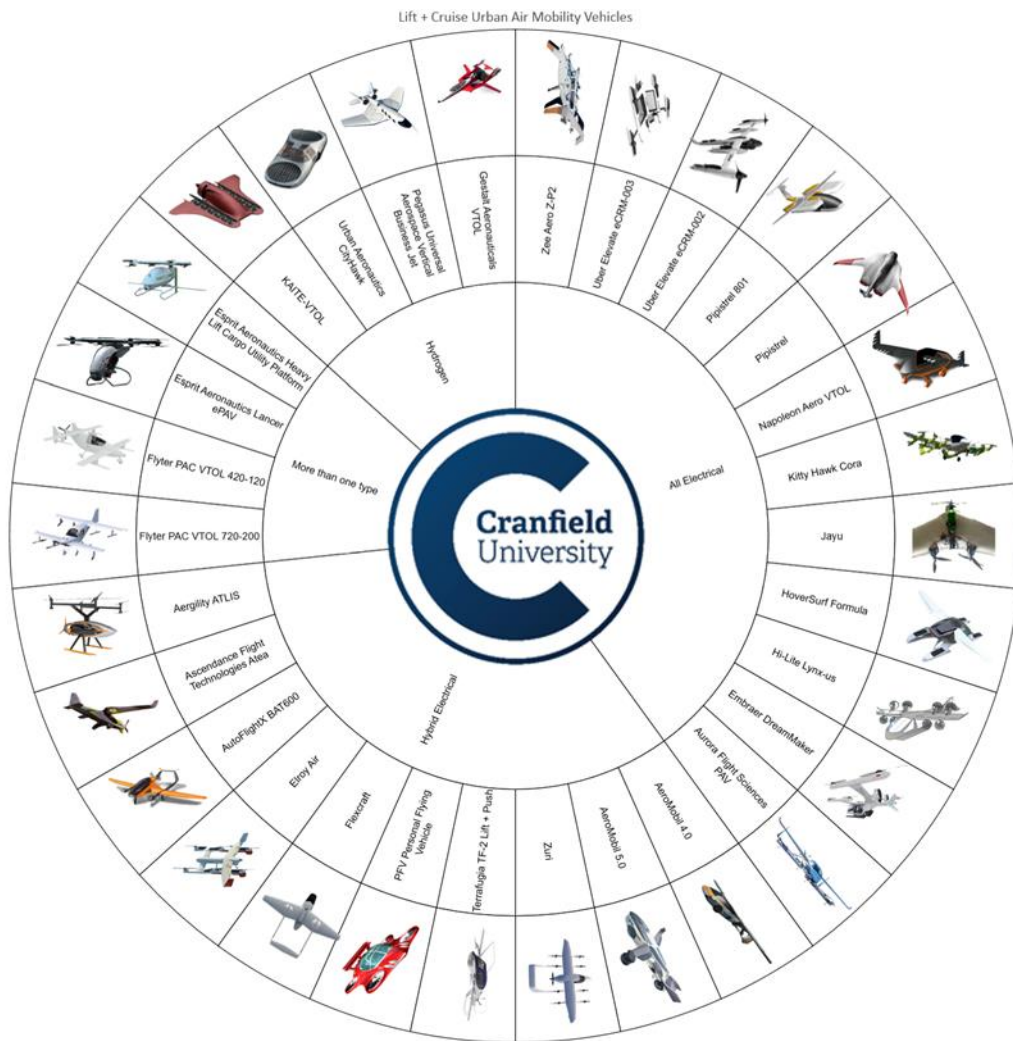


Figure 2-13. the Wheel of Lift + Cruise eVTOL for UAM.

Table 2-3 Data of Different Lift + Cruise eVTOL for UAM.

1. Electric (E), Hybrid-Electric (H), Other (O)

2. MTOW=Maximum take-off weight

3. Battery Energy Density, Wh/kg

4. Battery Capacity, kWh

Aircraft	Power Train ¹	Number of Passengers	MTOW ¹ (kg)	Empty weight(kg)	Useful payload(kg)	Motor Output ¹ (kW)	Total Output ²	Battery Density ³	Battery Capacity ⁴	Flight Time (min)	Flight Range (km)	Cruise Speed (km/h)	Flying Altitude (m)
Aeromobil 4.0 Stol	O	2	960	-	240	-	224	-	-	-	700	259	-
Aeromobil 5.0	H	4	-	-	-	-	-	-	-	-	700	-	-
Ascendance Flight Technologies Atea	H	4	2000	-	450	-	-	-	-	-	150	200	-
Aurora Evtol	E	2	800	565	225	75	600	-	-	-	-	180	-
Autoflightx Bat600	E/H	2	600	-	-	-	-	-	-	120/E 300/H	-	-	-
Elroy Air Chapparral	H	0	-	-	100-225	-	-	-	-	-	500	-	-
Embraerx	E	4	1000	-	-	-	-	-	-	-	-	-	1000
Esprit Aeronautics Lancer Epav	E/H	1	-	-	120	30	240	-	-	32/E, 100/H	-	-	30
Flexcraft	H	9	3239	1814	1000	-	-	-	-	-	926	-	-
Flyter 120-420	H	1	-	-	120	-	-	-	-	-	900	241	9144

Flyter 720-200	O/H/E	2	-	-	-	-	-	-	-	-	150/E 900/H, O	250	3000
Kitty Hawk Cora	E	2	-	-	181	-	-	-	-	19	100	180	900
Pegasus One Vertical Business Jet Vbj®	H	6 to 8	5700	-	-	-	-	-	-	180	2124	-	10668
Pfv Personal Flying Vehicle #1	H	2	-	-	-	-	-	-	-	-	560	-	-
Pipistrel 801 Evtol	E	4	-	-	-	-	-	-	-	-	97	-	-
Terrafugia Tf-2 Lift + Push	E	4	4082	-	500	-	-	-	-	-	400	240	-
Urban Aeronautics Cityhawk	O	2	1930	1170	760	-	-	-	-	-	150	270	-
Zuri	H	4	-	-	-	-	-	-	-	180	700	-	3700

The concept of Lift + Cruise is not a helicopter or an airplane, but an aircraft that combines two designs. This hybrid design features independent systems for lifting and cruising, enhancing the aircraft's versatility and safety. In this configuration, the 'lift' system enables vertical take-off and landing (VTOL) capabilities, like a helicopter, while the 'cruise' system provides efficient forward flight, akin to an airplane. The independence of these systems offers a unique safety advantage: should the 'cruise' component (the wings for forward flight) experience a failure, the aircraft can still perform a vertical landing using its 'lift' system. Conversely, if there's a failure in the 'lift' system, the 'cruise' component can facilitate a controlled landing, minimizing the risk during emergencies. This dual-system approach ensures that the aircraft can maintain flight and safely land under a broader range of scenarios, compared to traditional helicopters or airplanes. Therefore, the safety of the aircraft is greatly improved. The design for the Lift +Cruise aircraft shown in Fig 5 can be roughly divided into two categories, multi-propeller, and ducted fans. This multi-propeller design is used in most of the 30 aircraft types in Figure 2-13, such as Uber Elevate eCRM-003 [32], Kitty Hawk Cora [12], Zuri [33] and so on. The Kitty Hawk Cora is shown in Figure 2-14. It is an autonomous eVTOL aircraft with two passengers. Twelve independent electric lifting propellers are installed on the 11-meter-long wing to provide lift for vertical take-off and landing of the aircraft, and a three-blade propeller provided propulsion for the aircraft to fly forward. The flight test of Kitty Hawk Cora showed that the flight path did not change significantly in the event of a rotor failure [12].



Figure 2-14. Kitty Hawk Cora (Source: [12]).

The design of some Lift + Cruise vehicles uses the ducted fans, such as Hoversurf Formula [34], Urban Aeronautics CityHawk [35], Pipistrel 801 eVTOL [36] and so on. The Hoversurf Formula, shown in Figure 2-15, is an eVTOL aircraft with 52 fans and folding wings. There are twin rows of six fans on the front side and rear side of the passenger compartment to provide 48 fans for lift. The four larger fans at the rear of the aircraft are used to provide the thrust required in cruise mode. Folding wings can provide lift in flight and fold up to save space when the aircraft is parked. The aircraft is also equipped with advanced ballistic parachutes.



Figure 2-15. Hoversurf Formula (Source: [34]).

2.3.3 Multicopter

This section discusses Wingless eVTOL vehicles that are currently being implemented or are being tested and designed. Figure 2-16 is categorized according to the power system of these aircraft. Table 2-4 shows parameters of the aircraft, including design and configuration, motor and battery specifications, take-off weight and payload capacity and performance.

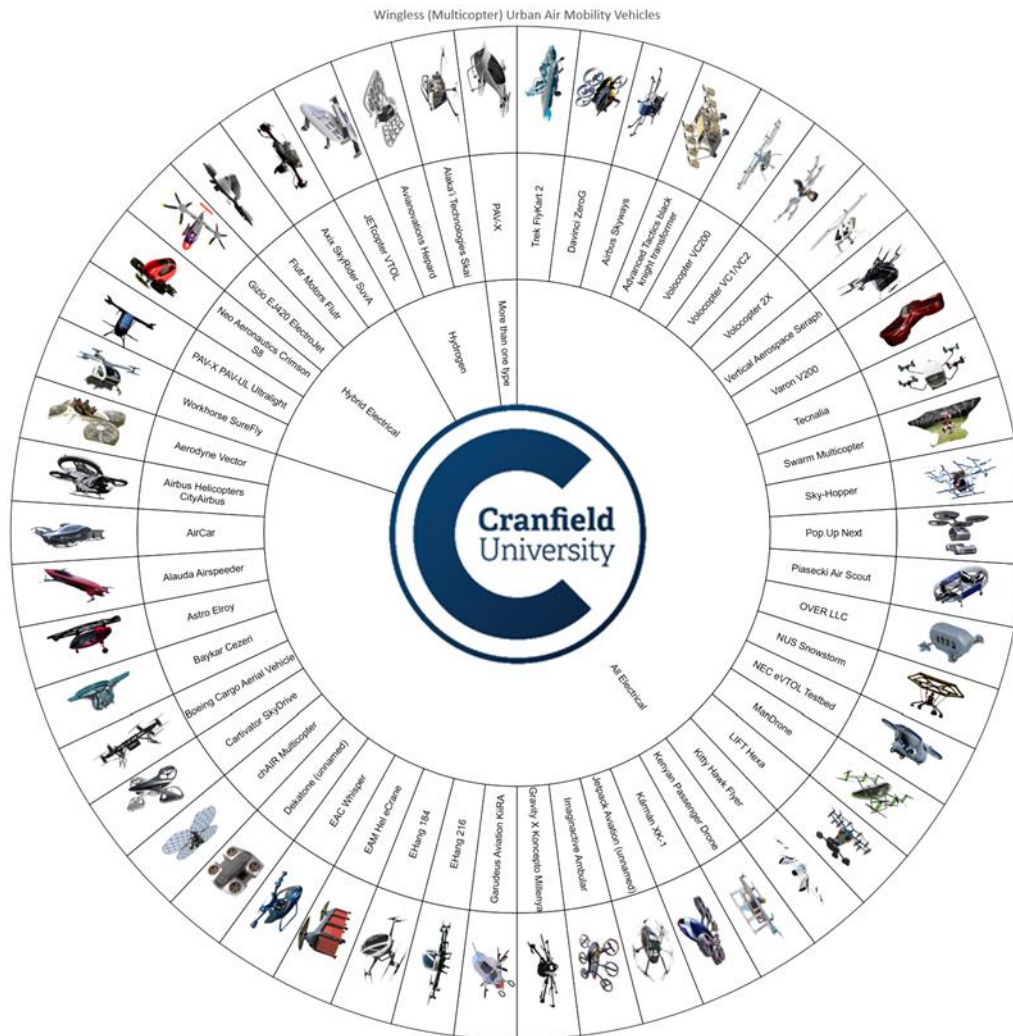


Table 2-4 Data of Different Wingless eVTOL for UAM

1. Electric (E), Hybrid-Electric (H), Other (O)

2. MTOW=Maximum take-off weight

3. Battery Energy Density, Wh/kg

4. Battery Capacity, kWh

Aircraft	Power Train ¹	Number of Passengers	MTOW ¹ (kg)	Empty weight(kg)	Useful payload(kg)	Motor Output ¹ (kW)	Total Output ²	Battery Density ³	Battery Capacity ⁴	Flight Time (min)	Flight Range (km)	Cruise Speed (km/h)	Flying Altitude (m)
Aerodyne Vector	E	2	600	-	150-200	-	-	-	-	30-90	-	60	50
Airbus Cityairbus	E	4	2.2 t	-	-	100	800	-	110	15	-	150	-
Aircar	E	2	-	500	-	-	-	-	-	-	72	120	-
Alauda Airspeeder	E	1	-	120	-	-	-	-	-	10	-	-	-
Astro Elroy	E	2	360	240	120	-	-	-	-	20-25	-	-	-
Avianovations Hepar	O	2	-	510	240	-	-	-	-	30	400 in H 75 in E	150	1000
Baykar Cezeri	E	1	-	-	-	-	-	-	-	60	-	-	-
Boeing Cargo Air Vehicle	E	0	-	320	225	-	-	-	-	-	-	-	-
Davinci Zerog	E	-	-	90	150	-	-	-	52.8	25	70	-	-
Eac Whisper	E	2	-	-	-	-	-	-	-	30	-	-	-
Ehang 184	E	1	360	260	100	19	152	140	17	25	38	60	500
Flutr Motors Flutr	H	2	-	-	-	-	-	-	-	45	200	250	457

Jetcopter Vtol	H	5	2000	-	-	-	-	-	-	1000	300	-
Kármán Xk-1	E	2 to 8	-	450	200	30	240	-	-	-	450	2500
Kitty Hawk Flyer	E	1	-	113	-	-	-	-	-	12-20	-	-
Lift Hexa	E	1	-	115	113	-	-	-	-	10-15	-	152.4
Mandrone	-	1	-	-	100	-	-	-	-	15	-	-
Nec Evtol Testbed	E	-	-	148	-	-	-	-	-	-	-	-
Neo Aeronautics Crimson S8	H	1	-	-	100	-	1	-	100	20	-	15
Nus Snowstorm	E	1	-	-	75	2.2	52.8	-	-	-	-	-
Over Llc	E	3	-	500	500	-	-	-	-	180	-	-
Pavx	E/H	1	380	168	-	-	-	-	-	15 in E 75 in H	-	-
Pav-X Pav-UI Ultralight	-	1	330	135	-	-	-	-	-	-	-	-
Pop.Up Next	E	2	-	-	-	20	160	-	70	31	50	150
Seraph	E	0	-	-	250	-	-	-	-	-	-	100
Tecnalia Air Taxi	-	1	-	-	-	-	-	-	-	15	15	-
Trek Flykart 2	E	1	-	-	-	-	-	-	9.6	-	-	-
Varon Vehicles V200	E	2	-	-	-	-	-	-	-	30	-	83
Volocopter 2x	E	2	450	290	160	2	32	-	-	27	27	100
Volocopter Vc200	E	2	450	300	150	3.9	70.2	-	-	-	-	100
Workhorse Surefly	O	2	680	500	181	-	150	-	15	60	113	113

Wingless (Multicopter) aircraft is a rotorcraft with more than two rotors that can produce lift. Rotor mechanics required for multicopter aircraft flight control are simpler. Multicopter aircraft usually use blades with a fixed pitch, and it can control the movement of the vehicle by changing the relative speed of each rotor to change the thrust and torque generated by each rotor. Multicopter aircraft are usually divided into tricopter, quadcopter (Airbus CityAirbus [37]), hexacopter (Davinci ZeroG [38]), and octocopter (Ehang 216 [39]) are frequently used to refer to 3-, 4-, 6- and 8-rotor rotorcraft. CityAirbus, shown in Figure 2-17, is an all-electric, four-seat, autonomously piloted electric vertical take-off and landing (eVTOL) flight. It has a multicopter configuration that features four ducted co-axial high-lift propulsion units. At the same time, the eight propellers driven by the motor at 950 rpm reduced the acoustic footprint.



Figure 2-17. Airbus CityAirbus (Source: [37]).

Davinci ZeroG, shown in Figure 2-18, is a hybrid electric, hexacopter vertical take-off and landing aircraft. ZeroG has six duct fans which are featured above the short fuselage. Due to the 12 electric motors that power the 12 vertical propellers, the complexity of the aircraft's flight control system is also reduced. The aircraft can run up to 2 propeller / motor failures, and the aircraft will automatically land when one propeller / motor fails.



Figure 2-18. Davinci ZeroG (Source: [38]).

2.3.4 Electric Rotorcraft

This section discusses Electric Rotorcraft eVTOL vehicles that are currently being implemented or are being tested and designed. Figure 2-19 is categorized according to the power system of these aircraft. Table 2-5 shows parameters of the aircraft, including design and configuration, motor and battery specifications, take-off weight and payload capacity and performance.

Electric Rotorcraft Urban Air Mobility Vehicles

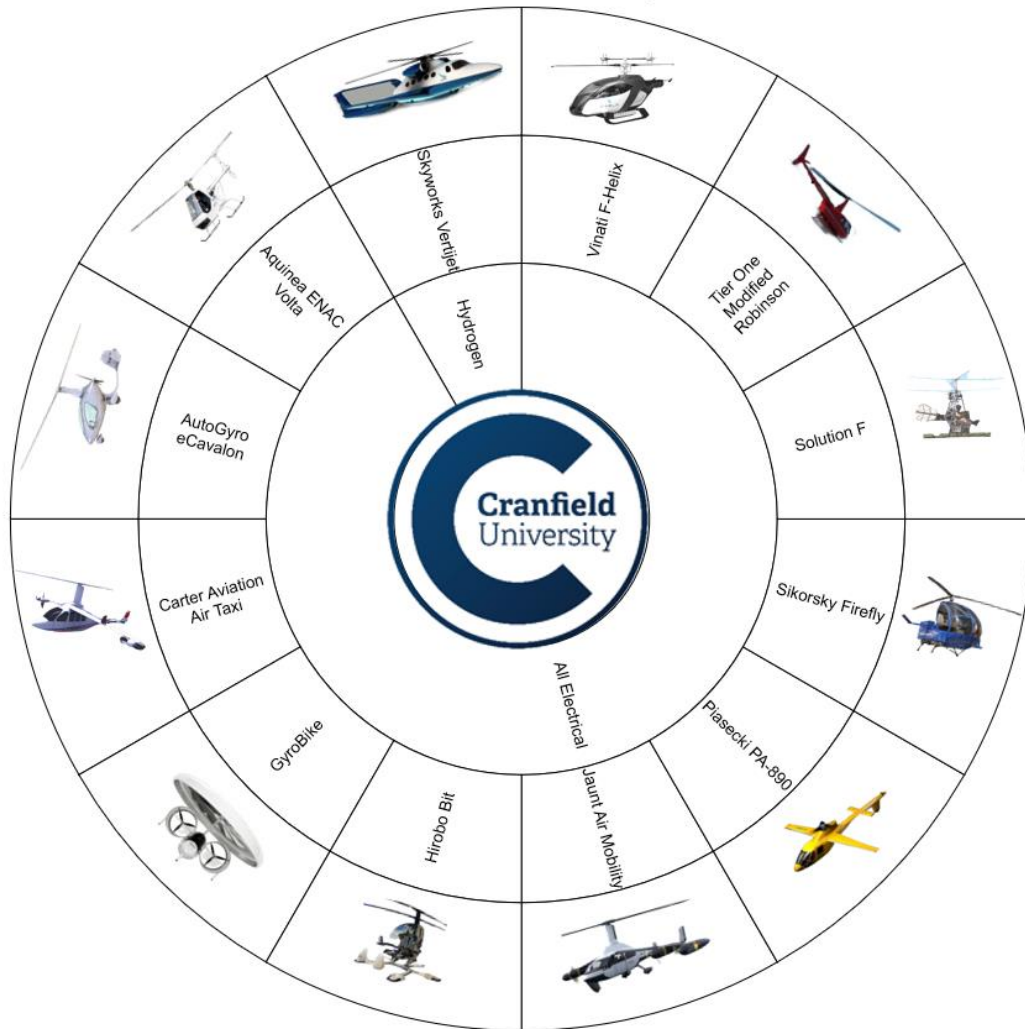


Figure 2-19. The Wheel of Electric Rotorcraft eVTOL for UAM.

Table 2-5 Data of Different Electric Rotorcraft eVTOL for UAM

1. Electric (E), Hybrid-Electric (H), Other (O)

2. MTOW=Maximum take-off weight

3. Battery Energy Density, Wh/kg

4. Battery Capacity, kWh

Aircraft	Power Train ¹	Number of Passengers	MTOW ¹ (kg)	Empty weight(kg)	Useful payload(kg)	Motor Output ¹ (kW)	Total Output ²	Battery Density ³	Battery Capacity ⁴	Flight Time (min)	Flight Range (km)	Cruise Speed (km/h)	Flying Altitude (m)
Aquinea Volta	E	1	520	420	-	-	70	-	22	40	-	-	-
Autogyro Ecavalon	E	1	500	300	-	-	-	-	-	-	-	145	-
Gyrobike	E	1	-	70	-	-	-	-	-	120	-	-	305
Hirobo Bit	-	1	-	-	-	-	-	-	-	38	48	-	-
Jaunt Air Mobility Evtol	E	5	2494	1397	499	-	-	300	-	-	-	281.6	-
Sikorsky Firefly	E	2	929.9	-	-	-	142	-	-	15	-	159.3	-
Skyworks Vertijet	O	-	-	-	454	-	-	-	-	-	1609	-	-
Solution F	E	1	245	170	75	20	40	-	-	10	-	-	-
Tier 1 Robinson R44	E	4	1134	-	-	-	-	-	-	20	55.56	-	-
Vinatix F-Helix	E	1 to 6	862	249	-	-	140	-	-	-	-	140	3397

The number of Electric Rotorcraft is the smallest of the four types of vehicles. There are 12 vehicles shown in the Figure 2-19. Vinati F-Helix [16], shown in Figure 2-20, is one of the representatives of the Electric Rotorcraft. The F-Helix is a 1-6 seat two-bladed fly-by-wire optionally piloted eVTOL with a propeller-driven rotor. A single two-blade rotor with a co-axial counter-rotating mast features an efan pair mounted on each tip. By directly mounting electric propellers onto the main rotor, the exchange of torque between the main rotor and the fuselage is eliminated. This innovative approach addresses the longstanding challenge present in traditional helicopter designs where the torque generated by the main rotor necessitates complex mechanical mechanisms or a tail rotor at the rear to counterbalance the aircraft. In this context, the integration of electric propellers with the main rotor obviates the requirement for torque transmission between the main rotor and the fuselage, effectively resolving this issue. This design alteration likely aims to enhance both the performance and stability of the helicopter.



Figure 2-20. Vinati F-Helix eVTOL (Source: [16]).

2.3.5 Comparison of Different Configurations of All Electric eVTOL

Alessandro Bacchini and Enrico Cestino compared three representative eVTOLs (Vectored Thrust Aircraft: Lilium Jet, Lift + Cruise Aircraft: Kitty Hawk Cora,

Wingless Aircraft: E-Hang 184) on five main parameters (disk loading, total hover time, cruise speed, practical range, and flight time) and three reference missions [40]. By calculating the required time and energy, the performance of eVTOL in urban, suburban, and remote missions was evaluated. The results show that the hovering efficiency of the Wingless aircraft is higher, and the vector thrust aircraft has higher cruise efficiency and longer range. The Lift + Cruise aircraft is a compromise.

Akshay R. Kadhiresan and Michael J. Duff used a weight-based optimization process to evaluate the relative merits of each major configuration class [41]. Choose the best configuration in the two-dimensional domain of mission range and speed, while also considering rotor size, wing load and battery energy density parameters. The results are similar to study of Alessandro Bacchini and Enrico Cestino. Wingless eVTOLs and helicopters are more suitable for short ranges. Tiltwings eVTOLs and Tiltrotor eVTOLs prefer long range and high speed. The Lift + Cruise eVTOL is a compromise.

Because the L/D of each aircraft configuration is different, the optimal range for each aircraft configuration will be quite different. The use of wings can increase the L/D value by nearly 2 times, this value will reach 3 times in horizontal fixed rotor aircraft [42]. According to the range equations in chapter 3, Figure 2-21 shows the range of electric aircraft based on the different battery specific energy.

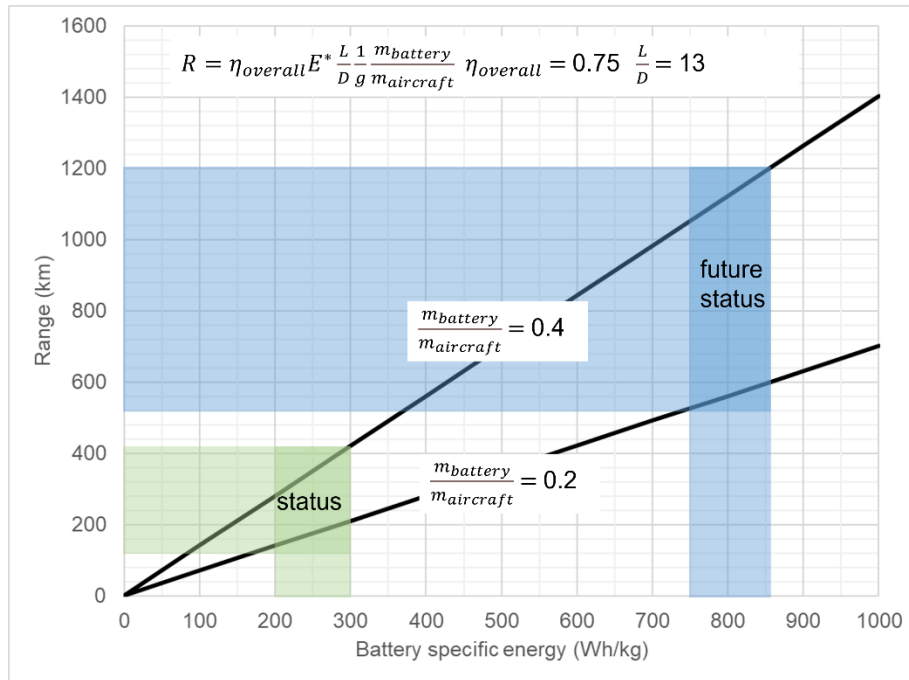


Figure 2-21. Range of electric aircraft.

Table 2-6 qualitatively shows the adaptive range and comparison of different configuration aircraft.

Table 2-6 the adaptive range and comparison of different configuration aircraft

	Advantage/Applicability	Comparative analysis
Multicopter	Best suited for short distances and low-speed flights, considering disk loading and propeller efficiency.	Offers simpler construction and rotor system advantages over electric rotorcraft. Due to smaller rotors, it benefits from reduced motor torque and weight compared to electric rotorcraft.
Helicopter	Ideal for shorter ranges due to inefficiencies during cruise.	Provides faster travel than multirotors owing to the efficiency of a larger articulated rotor.
Lift + Cruise	Serves as a compromise configuration, offering high efficiency in both cruise and hover modes through lift rotors and	At low speeds and ranges, it does not match the multirotor and electric rotorcraft. For

		a pusher propeller.2. high cruise and hover efficiency (lift rotors and pusher propeller)	higher speeds and ranges, it falls short compared to tiltwing and tiltrotor configurations.
Vectored thrust	Tiltwing	1. prefer for long ranges and high speeds (high lift-to-drag ratio, the extra cruise efficiency from the wing and multiple small propellers. 2. performs well for a large	
	Tiltrotor	1. limited to intermediate ranges in optimality. (Does not attain as high of a cruise efficiency)	1. lighter than the tiltwing (the slightly smaller tilting weight penalty)

2.4 Technologies

2.4.1 Safety

Aviation safety refers to the minimum tolerance range and acceptable level of the operation of aircraft and aviation activities [43]. UAM, representing a novel and swiftly evolving sector, diverges significantly from conventional aviation, which primarily operates in less populated, rural settings, often involving flights through largely uninhabited airspace. UAM vehicles will operate in crowded urban environments. It means that UAM needs to face stricter safety challenges—it needs to be able to ensure both the safety of its passengers and anyone on its route. Previous researchers have tried to eliminate or mitigate safety risks from different aspects: regulatory and fiscal measures [44,45], technology [46–48] and flight crew error [49]. Airbus [50] divided the accidents into five main causes: A. Runway Excursion – RE; B. Loss of Control In-flight – LOC-I; C. Controlled Flight into Terrain – CFIN; D. Abnormal Runway Contact – ARC; E. System/Component Failure or Malfunction – SCF. Since most of the aircraft designed for UAM are still in the design stage, this paper pays more attention on the safety technologies to overcome SCF. Redundancy, a commonly employed technique in UAM to enhance aircraft safety performance, is to replicate the key components or functions of the system to improve the reliability of the system. According to the

principle of ultra-redundancy, the Lilium Jet builds 36 independent engines and a triple-redundant flight control computer system. It means that the safety of the aircraft will not be compromised by the failure of any one component. Opener BlackFly widely uses the redundancy technology in the design of aircraft, including redundant propulsion, isolated redundant battery pods and triple-modular redundant controls. Ehang 216 applies redundant smart battery management system in the aircraft design. The Battery Management System (BMS) can monitor status information in real time, including battery voltage, current and temperature, and control it within a safe range, thereby effectively extending the battery life. The system consisting of 12 batteries provides a safe and reliable power supply for the aircraft. It means that in the event of one or several batteries failing or malfunction, the battery system can still operate stably and reliably and provide sufficient power for the aircraft. Given the robust framework established by the BMS for real-time monitoring and controlling critical parameters such as voltage, current, and temperature, the inherent fire risk associated with lithium-ion batteries in eVTOL aircraft is significantly mitigated. The multi-battery configuration, comprising 12 units, further enhances the system's resilience, ensuring a safe and dependable power source. This design redundancy means that, even in scenarios where one or several batteries experience failure or malfunction, the system's overall stability and reliability are maintained, safeguarding against power shortages, and reducing the likelihood of thermal events. Such measures are crucial in addressing the safety concerns related to lithium-ion battery usage in aerial vehicles, providing a solid foundation for managing the potential fire risks effectively. Another technology widely used in safety systems in UAM is distributed electric propulsion (DEP) system [51,52]. The emergence of the distributed electrical propulsion concept of aircraft systems has played a significant role in promoting and innovating the overall efficiency, function, and robustness of future aircraft. The DEP aircraft concept usually involves the use of multiple electric thrusters around the fuselage, as well as one or more independent generators or energy storage devices [53]. This design allows the propulsor to be placed, sized and operated with greater flexibility to take advantage of the synergistic advantages of aero-propulsive coupling and

provide better performance than traditional designs [53]. Airbus CityAirbus uses the DEP theory to feature multiple propellers and motors on an aircraft, so if one or more motors / propellers fail, the other working motors / propellers can safely land the aircraft. Uber is a strong supporter of eVTOL because of the massive benefits of using DEP on Uber Elevate eCRM-003. The aircraft with DEP system has better improved flight ability under normal and severe weather conditions (each engine can run at different speeds to achieve maximum control under wind conditions), higher safety and reliability. Also, the designers thought of other ways to improve the safety of the aircraft. For example, Opener BlackFly is installed with a ballistic parachute in response to emergency of aircraft scenarios. The designers of the Lilium Jet think a simple design will make the aircraft safer – as such the Lilium Jet is a no tail, no rudder, no variable pitch, no folding propellers, no gearboxes, no oil circuits aircraft.

The demands for operational safety could seriously limit the flexibility of eVTOL flights in urban settings, necessitating rigorous safety protocols and systems to mitigate risks. GENUS approaches safety assessment with a comprehensive methodology that integrates advanced simulation and analysis tools. This framework evaluates potential hazards and operational scenarios to identify risks early in the design process. It employs a multi-layered safety analysis that includes failure mode and effects analysis (FMEA), risk assessment, and mitigation strategies, ensuring that safety considerations are embedded in every aspect of the aircraft design and operational planning. By prioritizing safety in its algorithmic assessments, GENUS helps to develop eVTOL concepts that not only meet but exceed the current safety standards, aiming to make urban air mobility a viable and safe mode of transportation.

2.4.2 Noise

Low noise emission is one of the essentials to quickly gain community acceptance for UAM, as aircraft noise has recently played an important role in promoting significant political and legal community action and is the main driving force for the community acceptance [54,55]. The community's poor acceptance

of aircraft operations may lead to various operational restrictions on the UAM system. For example, in 2013, the US Congress instructed the Federal Aviation Administration (FAA) to reduce the noise impact on Los Angeles [56]. In 2017, the New York City Council enacted legislation that mandated a 50% reduction in the number of helicopter tours, effectively cutting annual flights by 30,000 [57]. However, even under low-volume operations, the noise generated by helicopters is still sufficient to force communities such as East Hampton to take legal action to limit the number of flights and when they occur [58]. Through extensively reviewing the latest technology of aircraft noise prediction, the methods to effectively reduce aircraft noise are mainly divided into: engine and airframe technologies, operations, compatible land use and urban development and operational restrictions [59,60]. The noise reduction technology for UAM aircraft mainly adopts several categories:

- Noise reduction by using distributed electric propulsion systems. The advantages of DEP in the noise reduction are [61,62]: a. by reducing exhaust gas velocity to reduce jet noise, b. through simple mechanical arrangement to reduce mechanical noise, c. Multiple smaller fans are easier to install on the aircraft to achieve noise shielding.
- Noise reduction by the low hover tip speed. Aerodynamic noise, which is usually the largest source of wind turbine noise, is generated by air flow on the blades. Reducing the hover tip speed can effectively reduce the aerodynamic noise.
- Noise reduction by optimizing blades of rotors. Rotor noise depends on the rotation frequency of the blades and the number of rotor blades. The rotor noise can be divided into two types of noise: rotor vortex noise and rotor rotational noise. Rotor vortex noise is a high-frequency sound produced by the force on the blade. The random load fluctuation load caused by the tip vortex in the wake of the turbulent rotor appears as vortex noise. Blade shape and spacing can be optimized for low blade-vortex-interaction and high-speed-impulsive noise.

Although researchers have made great progress in reducing aircraft noise, aircraft noise is still the main challenge for the community to accept aviation activities and is also the main factor restricting the development of UAM.

2.4.3 Battery

According to 2.4.5, the performance of the battery (especially the battery energy density and power per unit mass of battery) directly affects the performance of eVTOL aircraft. In fact, the battery mass accounts for a large part of the total mass of eVTOL, about 45 percent [63]. As the battery energy density increases, the area of feasible design for eVTOL aircraft will increase significantly [64,65]. According to current trends, the battery energy density will increase to 250 Wh/kg in 2023 and 300-350 Wh/kg in 2025 [66]. The NAE Committee report predicts that the battery energy density will reach 400-600 Wh/kg by 2035 [67]. The energy density of the battery will reach 400-1000Wh/kg, depending on the time frame [68,69]. Table 2-7 calculates the theoretical energy density of some aviation batteries based on chemical reactions, showing the potential of various batteries. Li-ion batteries are one of the most advanced batteries at present, but its potential is not as great as some other chemical batteries, such as Li-S batteries and Li-air batteries [70].

Table 2-7 Potential Aviation Batteries.

Battery Type	Discharge Reaction	Voltage [V]	Theoretical e_b [Wh/kg]	Ref
Li-ion	$\text{Li}_{1-x}\text{C}_6 + \text{Li}_x\text{MnO}_2 = \text{C}_6 + \text{LiMnO}_2$	3.4-4.1	396-607	[70]
Li-metal	$\text{Li}_{1-x} + \text{Li}_x\text{MnO}_2 = \text{LiMnO}_2$	3.4-4.1	578-1054	[70]
Li-S	$2\text{Li} + \text{S} = \text{Li}_2\text{S}$	2.2	2567	[71]
Li-air	$2\text{Li} + \text{O}_2 = \text{Li}_2\text{O}_2$	3	3505	

				[71]
Li-Se	$2\text{Li}+\text{Se}=\text{Li}_2\text{Se}$	2	1155	[72]
Al-air	$4\text{Al}+6\text{H}_2\text{O}+3\text{O}_2=4\text{Al}(\text{OH})_3$	2.71	2793	[73]
Zn-air	$2\text{Zn}+\text{O}_2=2\text{ZnO}$	1.65	1087	[71]

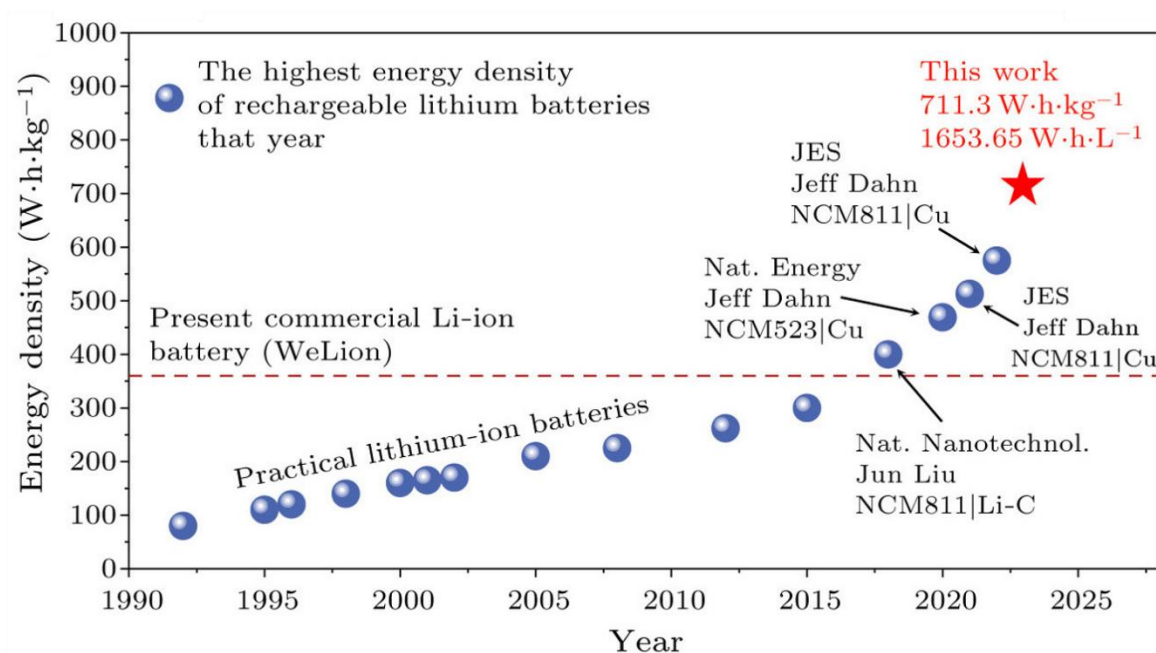


Figure 2-22 Energy Density of Lithium-ion Battery Packs, 1990-2025 (Source:[74])

Li-ion battery is widely used because of its high energy density and environmental friendliness. Figure 2-22 shows the energy density of Li-ion battery packs from 2008 to 2020. However, in recent years, the development of Li-ion battery has encountered obstacles due to the high cost of cathode materials and the electrochemical performance approaching the theoretical limit [75]. The anode intercalation materials of Li-ion batteries are graphite and $\text{Li}_4\text{Ti}_5\text{O}_{12}$ (LTO). Graphite anodes have a higher specific capacity than LTO anodes and researchers are trying to increase the specific capacity of graphite anodes by adding silicon [76,77]. Compared with graphite, LTO material has a faster reaction rate and no passivation phenomenon because of its high redox voltage.

Therefore, the LTO anode has a very fast reaction speed and excellent low temperature performance [78]. In addition, the LTO electrode has a very long cycle life because the standard electrolyte solution does not have a major reduction process [79]. Commonly used cathode materials for lithium-ion batteries include lithium cobalt oxide (LCO, LiCoO_2), lithium iron phosphate (LFP, LiFePO_4), lithium nickel cobalt aluminum oxide (NCA, $\text{Li}[\text{NiCoAl}]\text{O}_2$), lithium nickel manganese cobalt oxide (NMC, $\text{Li}[\text{MnNiCo}]\text{O}_2$), and lithium manganese oxide (LMO, LiMn_2O_4). Due to its high stability, good rate capability and reasonable safety, LCO was selected as the main cathode material for early Li-ion batteries [80]. The unique 3D structure of LMO can realize the multi-directional diffusion of lithium ions so that it has a very fast reaction speed. But LMO also has obvious disadvantages: low capacity, low stability, and Mn-ions dissolution. NMC combines the advantages of high specific energy of nickel and low internal resistance of manganese, while reducing the disadvantages of poor stability of nickel and low specific energy of manganese. But the high price of cobalt limits the development of NMC. NCA is the development product of lithium nickel oxide. NCA has high specific energy, reasonably good specific power, and long service life. But high cost and marginal safety are its disadvantages. LFO (LiFePO_4) has the characteristics of high capacity (very close to the theoretical value), excellent rate capability, high stability, excellent safety, low price, and long service life [81,82]. But its specific energy is moderate, and the self-discharge rate is high.

The Li-S battery has a very high specific energy of 550Wh/kg and a respectable specific power of 2,500W/kg, so it is considered one of the most promising rechargeable batteries. As a redundant by-product in the petroleum industry, sulfur is rich in raw materials and non-toxic, so Li-S batteries will be low-cost and environmentally friendly. However, many problems currently limit the development of Li-S batteries, the most important of which is the limited cycle life. During the battery cycle, sulfur will be lost by leaving the cathode and reacting with the lithium anode. Therefore, Li-S batteries have only 40-50 charge and discharge cycles [83]. The low conductivity of sulfur and excessive volume expansion during discharge are also problems faced by Li-S batteries [84,85].

Li-Air battery has become one of the batteries with great potential in the future due to its excellent specific energy. The usable battery capacity of Li-Air batteries will increase with increasing pressure and the air breathed in cities is not clean enough for lithium air, so Li-Air batteries may eventually have compressors, pump and filter resembling fuel cells [86]. Another serious problem is that lithium and oxygen form a lithium peroxide film that prevents electrons from moving and causes a sudden decrease in the storage capacity of Li-Air batteries.

2.4.4 Hybrid Electric

In recent years, the widespread use of aircraft has had a negative impact on the environment because the emissions of aircraft is directly discharged to the atmosphere [87,88]. Electrification is of interest to the public due to its low pollution characteristics. NASA's research results show that electrification can improve the performance of carbon, noise and NO_x, and can effectively reduce the fuel consumption of the aviation industry and reach their N+3 plan by 2025 [89,90]. However, due to the current limited battery technology, the energy density of batteries is much lower than that of fuel, so the performance of all-electric aircraft is limited [91,92]. Hybrid aircraft have become the choice of many eVTOLs because the use of fuel gives better performance than pure electric aircraft [93,94]. Table 2-8 shows the definition of hybridization with respect to power and energy [95,96].

Table 2-8 Degree of hybridization of different electric propulsion architectures.

	Equation	All-Electric	Hybrid Electric	
			Series Hybrid	Parallel Hybrid
Degree of hybridization of power	$\frac{P_m}{P_{tot}}$	1	1	<1

Degree of hybridization of energy	$\frac{E_b}{E_{tot}}$	1	<1	<1
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Hybrid Electric Propulsion System (HEPS) combines the electric propulsion system with the conventional Internal Combustion Engine (ICE). Usually, electric propulsion systems are used for short trips and fuel is used for extending range. The architecture of HEPS can be divided into series hybrid and parallel hybrid.

The series hybrid design transfers the battery electric energy and the electric energy converted from the fuel energy by the internal combustion engine to the propeller through electrical buses. In this configuration, the electric power can be used to directly power electric motors and the propellers are driven only by electric motors.[97] The series hybrid electric system is easy to extend to the distributed electric propulsion system.[98] The main features of this configuration are high fuel efficiency and an engine that maintains optimal operating conditions. On the other hand, the power loss in the combustion and conversion process and expensive and huge propulsion devices (electric motor, engine, and generator) are the challenges faced by this system.[94]

The parallel hybrid architecture directly mechanically transfers fuel energy to the propeller instead of electrical buses. Unlike the series hybrid system, both ICE and electric motors(EM) are connected to propellers and can provide energy separately or at the same time.[97] The internal combustion engine can charge the battery while working. At the same time, the internal combustion engine can also use electrical energy to reduce fuel flow or disconnect a clutch to achieve full electric flight.[99,100] In a series hybrid system, operating the electric motor at a reduced speed, while independently allowing the ICE to run at a higher speed, enhances overall efficiency. This configuration not only improves fuel consumption but also significantly lowers emissions. By optimizing the operation of both the electric motor and the ICE in this manner, the system effectively balances performance with environmental considerations, albeit with

considerations for increased weight and cost.[101] Compared with a series hybrid system, no energy electrical-mechanical conversion can improve the efficiency and reduce vehicle weight and cost.

2.4.5 DEP and electric motor

Distributed propulsion (DP) is a powered flight propulsion system in which vehicle thrust is generated by an array of propulsors located across the air vehicle. DP aims at improving the system-level efficiency, function, and performance of the aircraft. For example, DP system can reduce induced drag and improve propulsion efficiency by replacing separated trailing edge flow with exhaust jet.[102,103] DP can be used with thrust vectoring to reduce trim drag and reduce the noise of low-speed airframe.[104,105] In addition, DP redistributed the weight of the engine through the fuselage, thereby reducing the passive load and increasing in the wing span to increase the L/D ratio.[106]

Distributed electric propulsion (DEP), based on DP, is a specific method to provide the required electric energy to the aircraft through the power transmission system by multiple propulsion devices. DEP aims to alleviate the limited supply of conventional petroleum fuels and the potential global hazards associated with emissions from conventional aircraft propulsion systems.[53] NASA [107] discussed the feasibility of DEP: 1. The scale-free nature of electric propulsion enables distributed propulsion solutions.[108] 2. New integration strategies provide new degrees of freedom for aircraft design. 3. Battery, motor, controller technology is accelerating development. DEP is characterized using electric drive propulsion that is only electrically connected to energy or power generation equipment. This results in thrusters that can be placed with greater flexibility, adjust size and operation, and provide higher performance than traditional designs.[53]

The advantages of DEP can be summarised as:

- Reduce induced drag by installing propellers at the wingtips.
- Increase wing streamline and provide high-lift effect.

- The power unit is located in the wake of the component (fuselage/wing) to improve the balance of the aircraft.
- Reduce engine cross section to reduce installation resistance.
- The propeller pull can offset (part of) the body weight.

The electric motor, as an important part of the DEP system, has also received great interest from the market. The main function of the electric motor is to convert the electrical energy stored in the aircraft into mechanical power for rotating the propeller. Because the motor has no reciprocating parts and only has rotating parts, it can run with a high efficiency. Improving the efficiency of electric motors is one of the ways to solve the energy storage problem of electric propulsion aircraft. Researchers now mainly focus on the following points to enhance the electric drive:

- Use high-performance and high-frequency magnetic materials to provide high torque density.
- Improve the cooling system to reduce the loss in the electric motor at high temperature.[109]
- Use superconducting materials that can keep higher current densities magnitudes.[110] Therefore, the cross-sectional area of the wire is reduced, and the weight is reduced.
- Reduce the optimal rotational speed of the motor for a direct motor-propeller connection.

2.4.6 Life-cycle analysis

Life cycle analysis (LCA) is a systematic method to analyse the environmental impacts of products, processes and services through different stages of the product life cycle, including design, operation, materials, transportation, construction, energy usage, maintenance and recycling.[111] Khashayar.K and Kare.M.K (2020) used LCA analyse the Airbus' Vahana A³ group eVTOL sizing programs from three aspects, including: energy consumed, environmental

externalities, and operational costs.[112] The results show that the highest average cost per mile for each type of eVTOL and each scheduling method is \$4.15, while the lowest cost is \$1.60, both of which are comparable to the Uber cost (\$2 per mile). Regarding emissions, they suggested choosing larger eVTOL based on different markets, production, and supply costs. For electric vehicles, Cerdas et al., proposed the integrated life cycle engineering (LCE) approach method, which is based on LCA and combines different scenarios and studies the interaction between different designs, product parameters, and spatial differences to provide better support in the design stage.[113] Sofia.P.M et al (2020) presented the main modelling requirements of the LCE framework and discussed the sustainability of eVTOLs.[114] Nicolas André and Manfred Hajek (2019) provided LCA of three eVTOL concept aircraft and quantified the uncertainty in the material composition of the concept. The results show that for UAM, the largest seat utilization, clean power grid, low hovering share, effective travel reduction and low take-off weight can effectively improve the sustainability of eVTOL.[115]

2.4.7 Maintenance

As people's interest in UAM increases, new and special maintenance technologies for eVTOL are required. Compared to internal combustion engines, electric motors generally require less maintenance. For example, the high-speed bearings inside the motor core will need to be monitored and replaced regularly.[116] Thermal damage of insulating components will result in performance loss.[117] Ryan P. N. and Brian J.G. (2018) published a paper about two meetings with aircraft maintenance professionals who held at least an active FAA repairman's certificate with a powerplant rating.[118] These two meetings contain several points:

- In the future, specific information about the safe maintenance of electric propulsion systems can be incorporated into Airman Certification Standards (ACS) for Aviation Maintenance Technicians (AMTs). Or certified AMT can improve their certification level through a separate ACS.

Electric propulsion stakeholders can now begin to organize and develop rules to properly train and certify the labour required to maintain eVTOL.

- The removal, replacement and charging of electric aircraft batteries is a very challenging problem. The problems of electric shock hazard and accidental fouling of connectors are likely to occur during battery replacement. Connector wear and structural fatigue are closely related to the number of battery replacement cycles. The weight of the battery is also a major challenge for battery replacement. So, quickly charged batteries without disassembly may be more suitable for aircraft designed for UAM, or new technical solutions may be needed to improve safety, reduce labour requirements, and minimize maintenance issues with frequent battery removal.
- Modularity and Maintainability are very important attributes for aircraft maintenance.
- Mounting the electric motor on the top of the vertical tail structure can effectively avoid propeller strikes.
- Taking measures to reduce parts costs is the most effective way to reduce aircraft maintenance costs.

2.5 Operation

2.5.1 Application

As a new disruptive mode, UAM aims to alleviate the congestion problem of existing traffic modes. Many studies have shown that the key to the successful introduction of UAM lies in the operational concept and business model.[119–121]

The adaptability of UAM in various traffic is of interest to the market. The UAM system will become an important partner with traditional airlines, which can perfectly expand existing aviation services and provide value-added services to airline customers. In the United States and China, there were 150 million passengers in 2018, assuming only 10% of passengers choose UAM value-added services.[122] UAM system can also be an extended service for high-

speed railways. Especially, it is a good choice for time-sensitive passengers. As a system conceived to mitigate the challenges of urban road congestion, it is anticipated that UAM will eventually command a significant share of the city's transportation infrastructure. For waterways, the UAM system can provide a more comfortable and faster experience through straight-line routes compared to traditional water transportation. The eVTOLs can even take off and land on the deck of some large ships.

The mission is an important factor in determining the application of the eVTOLs. According ref [123], publicly stated missions in the UAM space include: 1. routine trips around a city,[9,124,125] 2. Value-added services at the airport, 3. Door to door city transfer, 4. Connection with other traditional transportation.[126] According to the missions, the application mode of UAM system can be roughly divided into a number of categories:

- Air taxi: Air taxi is a common application in UAM system. Its service model is similar to a taxi, which is an on-demand service. Passengers make reservations based on departure time, departure location and destination.
- Air bus: Airbus is an aircraft that carries passengers on a fixed route on urban air roads with or without fixed schedules.[127]
- PAV: Personal air vehicle (PAV) is a mode that only private individuals can freely use and control without breaking the law. At the same time, the PAV needs a parking space.[120]
- Shared air vehicle: Airlines can designate routes to send passengers to their destinations by using a single vehicle according to their requirements.
- Scheduled air vehicle: It provides on-demand services by providing frequent flights along the same route with regular scheduled services.[2]

2.5.2 ATM

Air traffic management (ATM) includes all systems that assist aircraft in landing from airports, transit airspace and destination airports. ATM is considered an essential part of the air navigation system. The general concept of ATM refers to

all the resources involved required to make compatible different aircraft operations, sharing airspace and airports.

To support the increasing demand for air traffic services, the European Commission launched a legislative package called “Single European Sky Initiative”. Single European Sky ATM Research (SESAR) Program, which was created to achieve the desired goal, will triple air traffic while reducing delays, improving aviation safety, reducing environmental impact and ATC costs.[128] SESAR proposes a concept of transforming from a highly structured and decentralized system to an integrated system based on trajectory collaborative strategic management.[129] The trajectory becomes a key part of a new set of operating procedures called trajectory-based operations in the future European ATM system built under SESAR.[130] In 2017, the goal of SESAR was changed not only to increase the capacity of European airspace, but also to increase performance, improve safety, develop technology, and improve airport capacity.[128] SESAR operations will always be changed according to the ATM master plan.

In the future, the need for UAM will not only increase, but also shift from scheduled operations to other operations described in 5.1. Many researchers have published their solutions to the problem of congested airspace. Through the manoeuvrability, speed and perception capabilities of a single aircraft, a certain airspace safety boundary is defined for the aircraft.[131] Develop technologies for perception and avoidance that either emulate or surpass the skill sets of certified human pilots [132]. Start with a feasible procedure, to increase the level of autonomy, and then to a fully cooperative ATM system.[133] In addition, other technical aspects can be considered to solve problems, such as high-precision positioning systems for low-altitude automatic flight and effective route planning.[134,135] The future airspace will benefit from the integration of multiple technologies, integrating data from the ground and aircraft sensors, using the safe navigation systems of aircraft and ground infrastructure, getting the real-time data information of the airspace through telecommunication technology.[133] In addition, the 5G standard reduces the delay between communications and

provides a building block for future ATM development.[136,137] Flying from point to point in the most economical, safe, and environmentally friendly manner, and by adjusting the airspace boundary according to needs, fair distribution of workload among service providers will be the main development trend of ATM.[138]

Autonomous flight represents a cornerstone of eVTOL operations, promising to revolutionize UAM by enhancing efficiency, safety, and scalability. The integration of sophisticated flight control systems and AI-driven navigation technologies enables eVTOL aircraft to operate with minimal human intervention, potentially reducing the likelihood of human error and optimizing flight paths for energy efficiency and speed. However, the transition to fully autonomous operations poses significant challenges, including regulatory approval, public acceptance, and the development of robust fail-safe mechanisms.

The advent of eVTOL technology introduces new complexities in aircraft operation and maintenance, underscoring the need for specialized training programs for pilots and maintenance engineers. Unlike conventional aircraft, eVTOLs require a unique set of skills and knowledge, particularly in electric propulsion, vertical take-off and landing operations, and advanced avionics systems.

2.5.3 Apps

As people continue to rely on smartphones and tablets to connect with different types of businesses, mobile applications play an increasingly important role in people's lives. With the continuous development of technology, it is an inevitable trend to apply the mobile apps to urban air mobility in the future. Figure 2-23 shows the Lilium app which will be provided in various cities around the world by 2025.[139] The app will enable customers to find the nearest landing point and plan their trip easily. Compared with today's travel, customers can choose a competitive price from a network of landing sites spread across cities and regions.

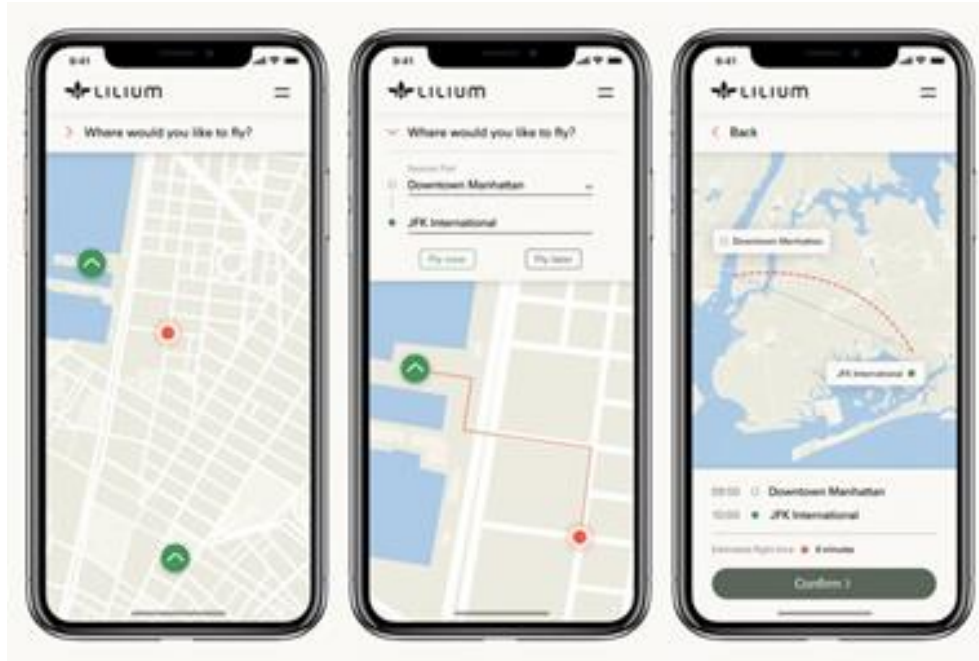


Figure 2-23. Lilium eVTOL Jet app (Source: [139]).

2.6 Relevant Companies and Organizations

2.6.1 A³ Vahana

Vahana is the first project of A³ created by Airbus Ventures in Silicon Valley and is a full-scale prototype electric eight-prop tiltwing VTOL personal aircraft prototype for urban air mobility.[140]

Figure 2-24 is a picture of the A³ Vahana parking on the ground, Figure 2-25 shows the design and dimensions of the tilted wing configuration based on the Vahana Team Prototype Conference held on June 8, 2017 and Table 2-9 shows the specifications of Joby S4. The key features of A³ Vahana are an unconventional tandem tiltwing configuration, DEP system, full automation, and sense-and-avoid technologies.[141] The A³ Vahana is equipped with a tandem tilt-wing configuration with eight fans. Four fans mounted on the front tilting surface, which is called as the canard, the other four fans mounted on the rear tilting surface which is called as the wing. The canard and wing have a pair of counter-rotating fans on each side, with the outer fans mounted on the tips of the

wings. Because of the tiltwing, multi-rotor configuration, the A³ Vahana can take-off and land vertically like a helicopter and cruise as efficiently as a propeller-driven airplane. The hardware on the front of the aircraft is the system it uses to sense and avoid obstacles in the air.[142]



Figure 2-24. Vahana aircraft (Source: [10]).

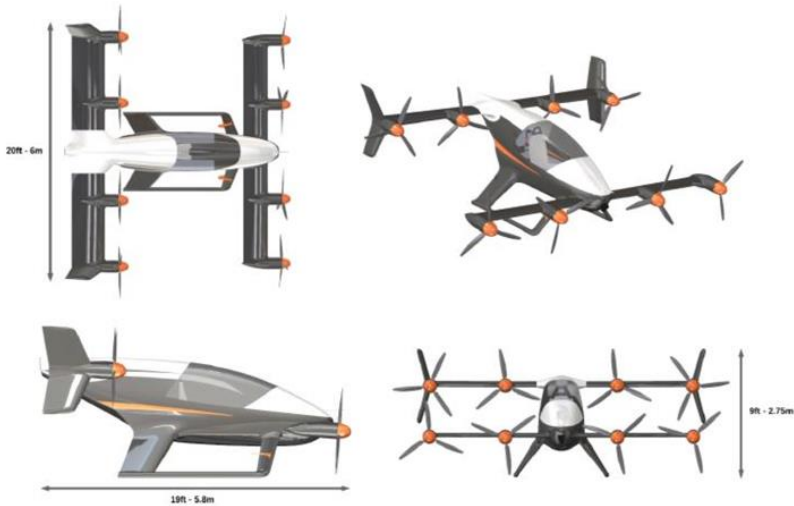


Figure 2-25. Dimensions of the tiltwing Vahana configuration (Source: [10]).

Table 2-9 A³ Vahana specifications.

Passenger capacity	2
Fuselage length	5.85 m
Overall height	2.81 m
Wingspan	6.25 m

Tip-to-tip distance	5.7 m
Empty weight	475 kg
Max gross take-off weight	815 kg
Useful load	200 kg
Range with reserves	100 km
Altitude	3048 m
Cruise speed	230 km/h
Propulsors	8 propellers
Motor output	8 x 45 Kw
Power type	electric
First flight	2018

The first test flight of full sized A³ Vahana (“Alpha One”) took place at the Eastern Oregon Regional Airport on Jan.31, 2018. The vehicle autonomously climbed to a height of five meters and lasted for 53 seconds. As of February 2019, Alpha One, the first unmanned demonstrator, had been tested flight time over 50 hours, and ready to roll out the second, dubbed Alpha Two. As of the latest available update in 2023, the Vahana initiative, while having completed its active flight test phase, laid the groundwork for future urban air mobility solutions. The insights and technological advancements garnered from the Vahana project have been instrumental in shaping Airbus' approach to urban air mobility, contributing to the development of subsequent projects aimed at integrating eVTOL aircraft into urban transportation networks.

2.6.2 Joby S4

Joby S4 is a 5-seater eVTOL (one pilot and four passengers) vector thrust aircraft developed by the Joby Aviation, using six inclined propellers fixed on the wings and V-tail. The company showed a full-size picture of the S4 eVTOL aircraft (see Figure 2-26) on January 15, 2020, as well as information about its aircraft, aircraft usage and other company specifications.[143] Table 2-10 shows the specifications of Joby S4.



Figure 2-26. Joby S4 eVTOL aircraft in flight, Nov. 23, 2020 (Source: [144]).

Table 2-10 Joby S4 specifications.

Aircraft type	eVTOL
Pilot	1
Passengers	4
Cruise speed	200 mph
Range	150 miles

Propellers	6 tiltrotors, 4 propellers tilt vertically including the entire motor nacelle, 2 propellers tilt vertically with a linkage mechanism
Motors	6 high performance electric motors
Power source	Lithium-nickel-cobalt-manganese-oxide batteries with a cutting-edge battery pack design
Wingspan	35 ft
Length	24 ft
Weight	4000 lb
Windows	Large windows for spectacular views for the passengers
Fuselage	Composite
Landing gear	Tricycle wheeled retractable landing gear

Joby S4 uses power and control redundancy to improve aircraft safety. Six distributed electric power units are arranged in an oval shape to evenly distribute the lift and if one distributed electric power unit fails, the control system will automatically reduce the pulling force of the opposing propeller while compensating for the additional torque generated by the other propellers. Its rudder surface design also uses multiple redundancy, which means two outer

ailerons and six independent rudders on the V-tail. Two simple slats are installed inside the aileron. The rudder surface is driven by a small but powerful linear motor mounted on the inner front edge.

In terms of control, Joby S4 uses the unified flight control approach which is how the Lockheed Martin F-35 combat aircraft controls are made. The idea of unified flight control is to reduce the possibility of pilots making mistakes and crashing the aircraft. The argument is not against automation, but against partial automation. The aircraft will take over for a safe landing when needed. The benefits of this design are: 1. Avoid accidents, 2. Simplified vehicle operation, 3. Reduce pilot training costs, 4. Prevent pilots from killing themselves and the passengers.

Joby Aviation announced at the VFS 6th Annual Electric VTOL Annual Symposium held on January 29, 2019 that Joby S4 is 100 times quieter than a helicopter. It mainly achieves such a noise reduction effect through three design techniques. One is that the distributed electric propulsion system can reduce the overall load, thereby reducing the noise of the blade; the second is to reduce the noise by optimizing the design of the five-blade propeller on each distributed electric power unit; the third is to reduce the tip vortex by staggering the propeller position reasonably.

Following the unveiling of the Joby S4 production prototype in June 2023, Joby Aviation continues its journey towards revolutionizing urban air mobility. This milestone, marked by the partnership with Toyota and the achievement of over 30,000 miles flown by its prototypes, underscores Joby's commitment to safety, innovation, and sustainability. As the company advances towards FAA certification and the launch of its on-demand air taxi service, Joby Aviation is poised to redefine urban commuting, offering an efficient, environmentally friendly alternative to traditional transportation methods.

2.6.3 Ehang 216

Ehang 216, shown in Figure 2-27, two seat, 16 coaxial double-blade propellers, all electric vertical take-off and landing flight. The foldable design of 8 arms of Ehang 216 only taking 5 m² parking space. The space and structural components required to install the propeller and motor can be greatly reduced by the design of coaxial dual propellers, which leads to a lighter aircraft. Table 2-11 shows the specifications of Ehang 216.



Figure 2-27. Ehang 216 in flight (Source: [145]).

Table 2-11 Ehang 216 specifications.

Aircraft type	eVTOL
Piloting	Autonomous
Passengers	2
Cruise speed	100 km/h
Maximum speed	130 km/h
Maximum altitude	3000 m
Range	35 km
Flight time	21 minutes

Passenger control panel	30.5 cm screen
Payload	220 kg
Battery recharging time	120 minutes
Propeller	16
Electric motor	16
Windows	Large windows for spectacular views for the passengers
Doors	2 gull-wing doors
Landing gear	Skid type

According to the Ehang white paper,[122] the vehicle has six key factors to ensure the safety of passengers: 1. DEP system, 2. Complete autonomous operations, 3. Backup from repeated flight control, communication, and navigation systems 4. Centralized command-and-control, 5. Intelligent obstacle avoidance capabilities, 6. Intelligent self-detection capabilities.

As of January 2020, EHang 216 aircraft has finished more than 2,000 flight tests with passengers, including flight tests with wind speeds up to 70 km/h and flight tests at an altitude of approximately 50m in fog and low visibility.[146]

Building on the significant advancements and milestones EHang has achieved, the company continues to solidify its position as a leader in the eVTOL industry. With the historic achievement of receiving the world's first airworthiness type certificate for the EH216-S from the CAAC in October 2023, EHang sets a new standard for the industry, underscoring its commitment to safety, innovation, and regulatory compliance. This certification, coupled with over 1,200 overseas pre-orders, highlights the global market's confidence in EHang's technology and its vision for urban air mobility. As EHang paves the way for on-demand air taxis to

become a reality in urban skies, its focus on the Chinese market—recognized as the most rapidly expanding and largest for eVTOL passenger aircraft—positions the company to play a pivotal role in transforming urban transportation in the coming years.

3 INTEGRATED AIRCRAFT DESIGN ENVIRONMENT

3.1 The GENUS Aircraft Conceptual Design Environment

The GENUS environment is an advanced Java-based platform for aircraft design analysis and optimization, developed and refined over several years by the Aircraft Design Group at Cranfield University. This robust tool comprises nine essential modules, illustrated in Figure 3.1, each serving a critical function in the design process. As shown in Figure 3-1, these modules are: 1) Geometry, which forms the basis for the aircraft's shape and structure; 2) Mission, outlining the aircraft's intended operations; 3) Propulsion Specification, detailing the requirements for the propulsion system; 4) Mass Breakdown, providing an analysis of the aircraft's weight distribution; 5) Aerodynamics, examining the aircraft's airflow characteristics; 6) Propulsion, focusing on engine performance; 7) Packaging and C.G., responsible for the aircraft's balance and component placement; 8) Performance, which assesses the aircraft's overall efficiency and effectiveness; and 9) Stability, ensuring the aircraft's safe and stable flight. Moreover, the GENUS environment is modular and extensible, allowing for the integration of specialized modules tailored to the unique requirements of specific aircraft designs.

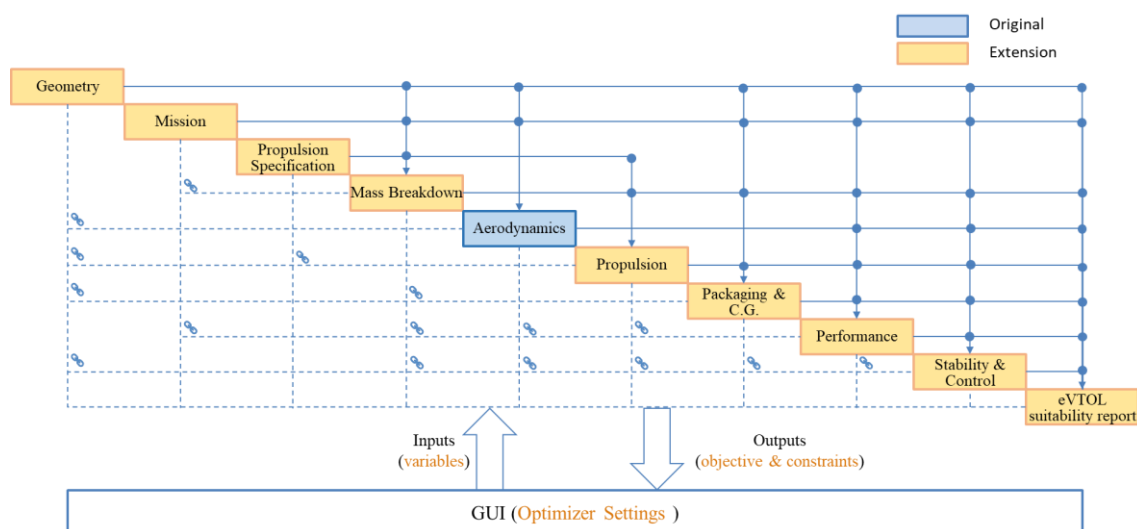


Figure 3-1 Modules and Data Flow of GENUS

The GENUS environment embodies a modular, expandable, flexible, and independent architecture, making it a versatile tool suitable for designing a wide range of aerospace vehicles.

Modularity: GENUS is organized into well-defined modules, each focused on a specific discipline within aircraft design. This allows users to mix and match methods and tools according to the modules available, streamlining the design process.

- **Expandability:** The architecture of GENUS is built to be limitless in terms of software constraints. This enables the addition of an unlimited number of modules or methods, and the potential for an ever-increasing level of detail in each.
- **Flexibility:** The system is designed so that a knowledgeable user can employ any appropriate method to design virtually any type of aerospace vehicle, without being restricted to a predefined set of options.
- **Independence:** Unlike many other design environments, GENUS does not rely on any specific third-party software to operate. Its light-weight design means that it runs efficiently on both laptops and desktops.

By integrating disciplinary models in this modular, expandable, flexible, and independent manner, GENUS provides a comprehensive and customizable solution for aerospace vehicle design.

Modules and optimisers are combined into a GUI, which is developed from Java's native Swing GUI. As shown in Figure 3-2, designers can select different sub-modules/methods for integration studies in the Module Selection tab. As shown in Figure 3-3, the Inputs tab gets inputs from the designer. These inputs can be pre-set in the pre-design module, allowing for less repetitive code. There are three types of inputs: list type (such as engine type, propeller type, etc.), real value type (such as cruise speed, battery energy density, etc.), and int value type (such as electric motor number, propeller kinks, etc.).

GENUS is designed with a focus on user-friendliness, aiming to facilitate a seamless and intuitive design process for eVTOL aircraft. The platform is structured to accommodate users with varying levels of experience in aircraft design, from novices to experts, by providing a comprehensive suite of tools and resources that guide the user through each step of the design and optimization process. The learning curve for new users is significantly mitigated by GENUS's user-centric interface, detailed documentation, and tutorial systems, which together ensure that users can quickly become proficient in utilizing the platform's capabilities.

The duration required to complete an eVTOL design within the GENUS environment is contingent upon the desired level of precision and detail in the design. For projects where the geometric model and mission parameters are predefined, the design and optimization process can be completed within approximately one week. However, for more comprehensive projects that necessitate a full-spectrum design and optimization of the geometric model, mission parameters, and other critical factors, the process can take between one to two months. This timeframe accounts for the iterative nature of design refinement, optimization cycles, and the incorporation of feedback, ensuring a thorough and well-considered final eVTOL design.

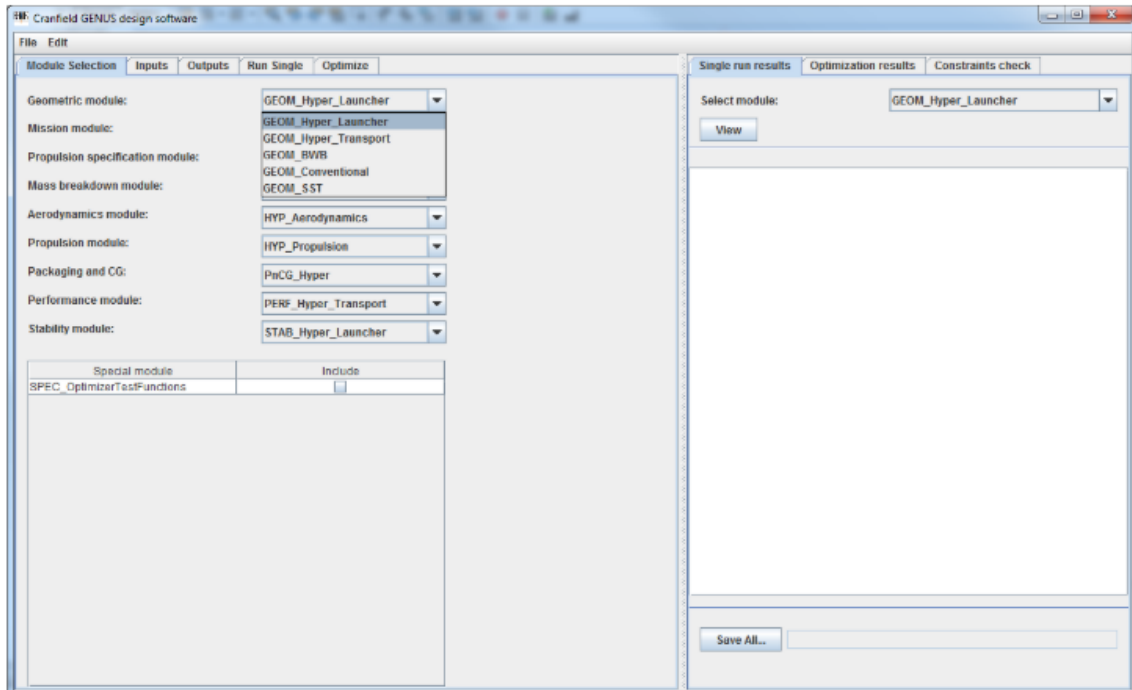


Figure 3-2 GENUS GUI for Module selection

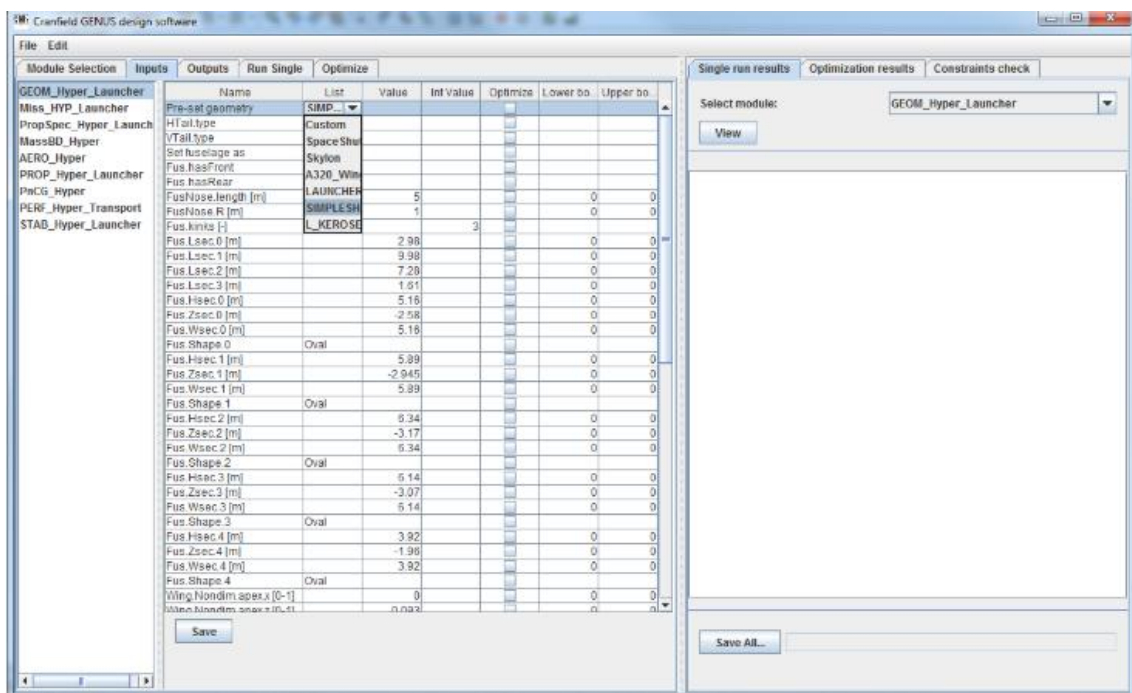


Figure 3-3 GENUS GUI for Inputs

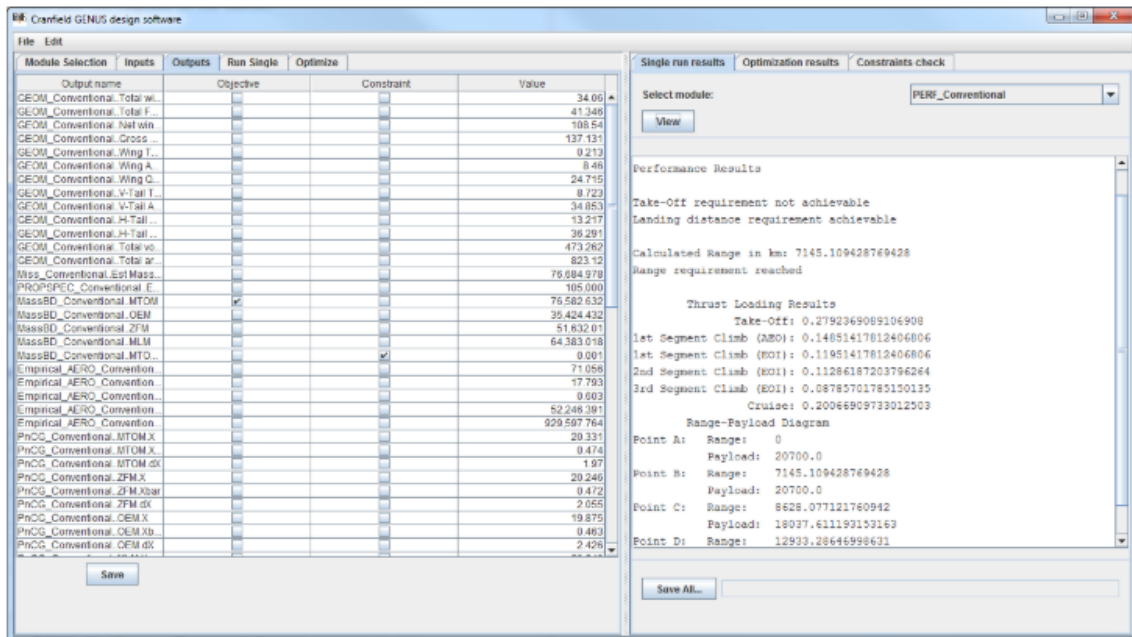


Figure 3-4 GENUS GUI for Outputs

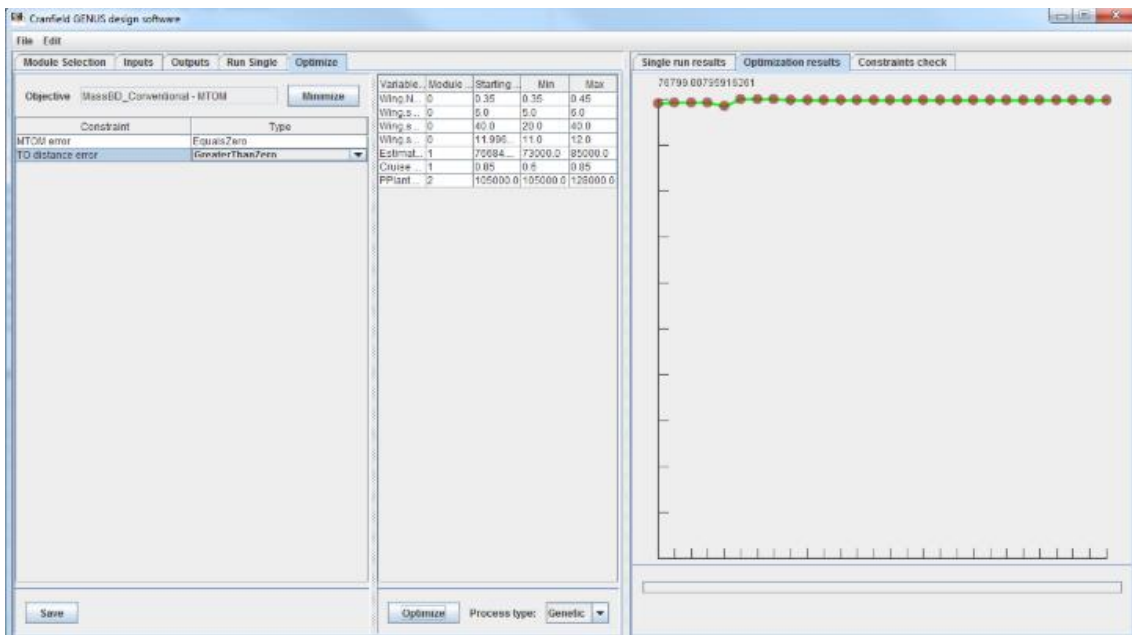


Figure 3-5 GENUS GUI for Optimization

3.2 Geometry Module

3.2.1 Overview

The Geometry module serves as the cornerstone of the aircraft design process in the GENUS environment, playing a pivotal role in informing subsequent

modules such as Aerodynamics, Mass, and Packaging. This module is organized into two primary arrays: LiftingSurfaces and BodyComponents, each catering to different aspects of the aircraft's physical structure.

LiftingSurfaces Array: This array encompasses all elements responsible for generating aerodynamic forces crucial for the vehicle's lift and control. It includes components like the wing, vertical tail, horizontal tail, and propeller.

BodyComponents Array: This array accommodates the remaining structural elements of the aircraft, which do not directly contribute to aerodynamic lift. Items stored here include the fuselage, external fuel tanks, engine pods, and tail booms.

The hierarchical structure of the Geometry module, which dictates the interactions between these arrays and other modules, is outlined in Figure 3-6.

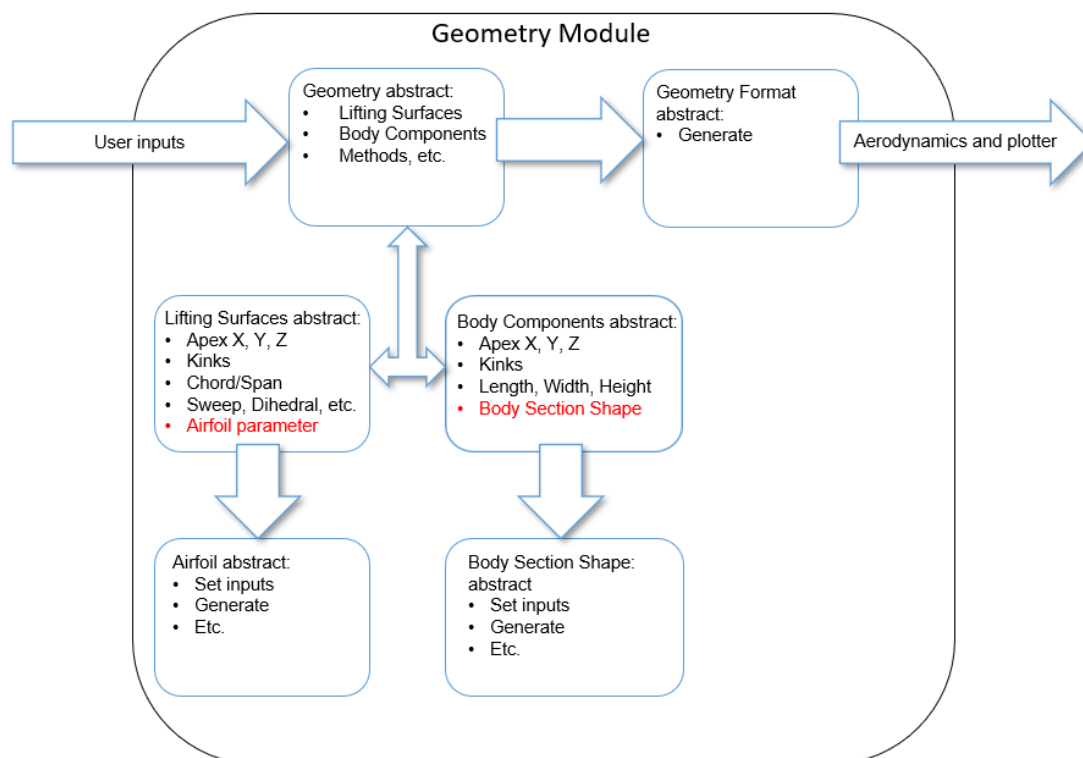


Figure 3-6 Hierarchy and Data Flow of Geometry Module

Table 3-1 lists the inputs to the geometry module and is intended to be intuitive for the user. For convenience, input variables can be preset within the code without entering the same value whenever running the same configuration.

Table 3-1 Geometry Input Variables

Input Variables	Variable Type	Description
Preset geometry	List value	Choose a preset geometry in the list
Body Component number	Integer value	Total number of body components, m
Lifting Surface number	Integer value	Total number of lifting surfaces, n
Repeat the following m times		
Fuselage apex X	Real value	X coordinate of body component apex
Fuselage apex Z	Real value	Z coordinate of body component apex
Fuselage kinks	Integer value	Number of kinks on the fuselage
Fuselage section length [i]	Real value	Length of body component section i
Fuselage section height [i]	Real value	Height of body component section i
Fuselage section Z position [i]	Real value	Bottom X coordinate of body component section i
Fuselage section width [i]	Real value	Width of body component section i

Fuselage section shape [i]	List value	Shape of body component section i
Repeat the following n times		
Wing apex X	Real value	X coordinate of lifting surface apex
Wing apex Z	Real value	Z coordinate of lifting surface apex
Wing kinks	Integer value	Number of kinks of lifting surface
Wing chord [i]	Real value	Chord length of lifting surface section i
Wing airfoil type [i]	List value	Airfoil type of lifting surface section i
Wing airfoil parameters [i]	Real value	Airfoil parameters of lifting surface section i
Wing span [i]	Real value	Span of lifting surface section i
Wing dihedral [i]	Real value	Dihedral of lifting surface section i
Wing incidence [i]	Real value	Incidence of lifting surface section i
Wing sweep [i]	Real value	Sweep of lifting surface section i
Wing control surface ratio [i]	Real value	Control surface ratio of lifting surface section i

By utilizing the defined parameters, the geometry can be generated using VTK (Visualization Toolkit) [147], an open-source software specifically designed for creating 3D computer graphics. The geometry module not only defines the shape of the aircraft but also incorporates utility methods to facilitate shape modification and information extraction from the geometry. These methods are designed to be utilized by other modules within the GENUS.

3.3 Mission Module

3.3.1 Overview

The mission module serves as the main user input module specifying several flight requirements for the aircraft design. Designers can set their own mission variables in subclass modules to meet mission requirements. These variables will affect the calculations in subsequent modules. The module hierarchy is shown in Figure 3-7.

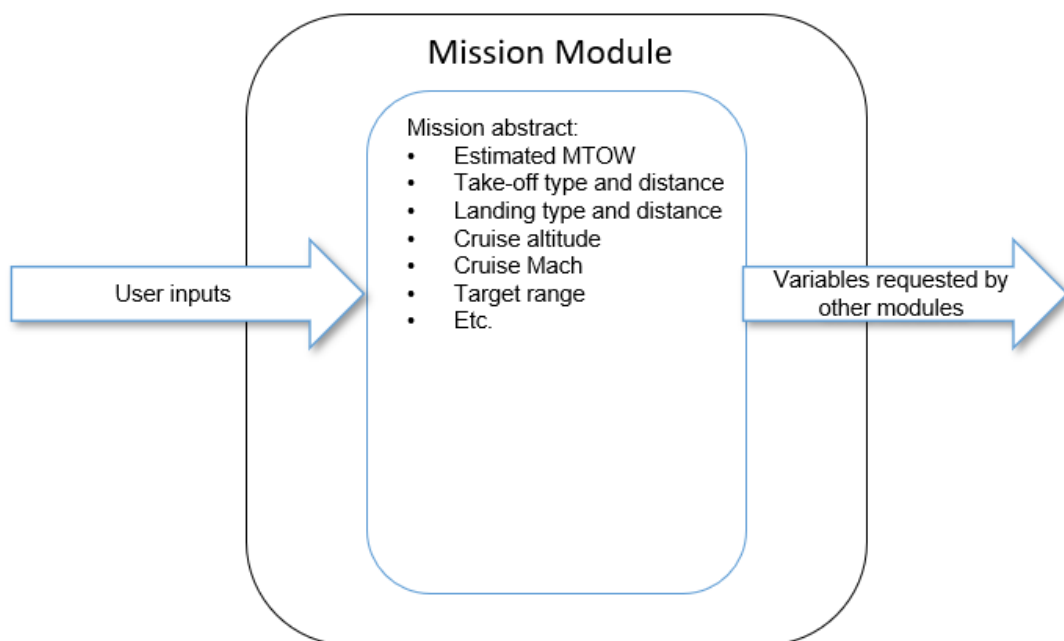


Figure 3-7 Hierarchy and Data Flow of Mission Module

The inputs for mission module are listed in Table 3-2. Designer also can preset the input variables in code.

Table 3-2 Mission Input Variables

Input Variables	Variable Type	Description
Estimated MTOW	Real value	User input maximum take-off weight
Take-off type	List value	User input the take-off type

Take-off distance	Real value	Take-off distance restriction
Landing type	List value	User input the landing type
Landing distance	Real value	Landing distance restriction
Cruise altitude	Real value	Aircraft cruise altitude
Cruise Mach	Real value	Aircraft cruise Mach
Target range	Real value	The target Mach
Manoeuvre load factor	Real value	Aircraft manoeuvre load factor
Passenger number	Integer value	Number of passengers
Crew number	Integer value	Number of crew

3.3.2 Mission Profile of eVTOL

A typical mission profile of an eVTOL is shown in Figure 3-8. The specific parameters of each segment are listed in Table 3-3. These values are an example of eVTOLs' mission. Due to the constraints of battery technology and the various power supply options available (including all-electric, hybrid, and fuel-based systems), these parameters undergo modifications in the design of eVTOL aircraft. The incorporation of reserve energy constitutes an essential facet in the comprehensive design process of eVTOLs. A reserve energy allocation of ten percent is implemented in the design of eVTOLs across Chapters 4 to 7 of this thesis.

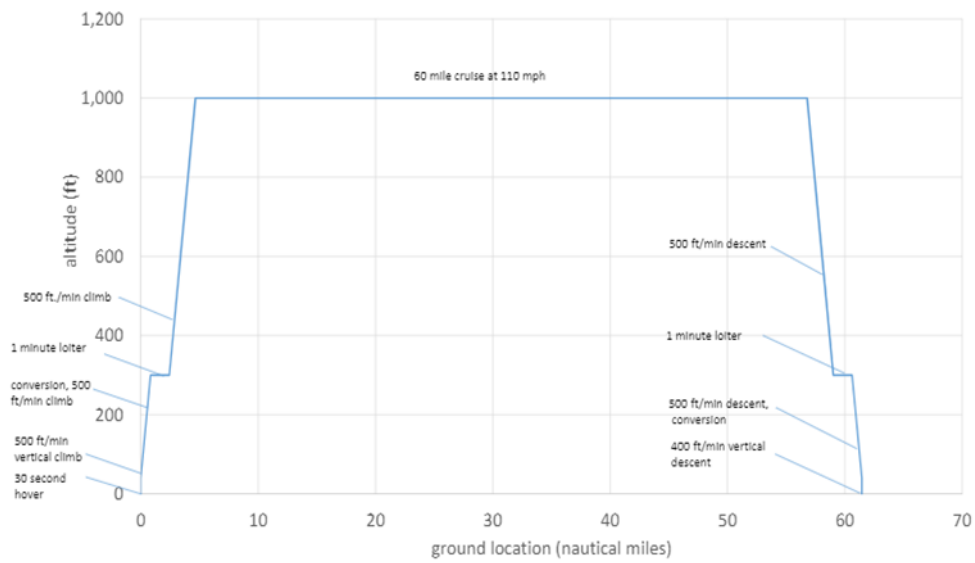


Figure 3-8 Typical Mission Profile of an eVTOL

Table 3-3 Mission Requirements for eVTOLs

Segments	Time	Altitude	Speed
Vertical Climb	30 s	0 to 50 ft	0
Forward Climb (conversion)	30-40 s	300 ft	500 ft/min(1.7 mph)
Hover	1 min	300 ft	0
Forward Climb	1.5 min	300 to 1000 ft	500 ft/min(1.7 mph)
Cruise	30 min	1000 ft	110 mph
Forward Descent	1.5 min	300 ft	500 ft/min(1.7 mph)
Hover	1 min	300 ft	500 ft/min(1.7 mph)
Forward Descent(conversion)	30-40 s	300 ft	500 ft/min(1.7 mph)

Vertical Descent	30 s	50 to 0 ft	100 ft/min (1.136 mph)
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3.4 Propulsion Specification

3.4.1 Overview

The propulsion specification module specifies the engine and fuel to be used, the type of electric motor, the battery's parameters, and the propulsion system's requirements. This provides flexibility for combining the various propulsion systems required for complex vehicles. The module hierarchy is shown in Figure 3-9.

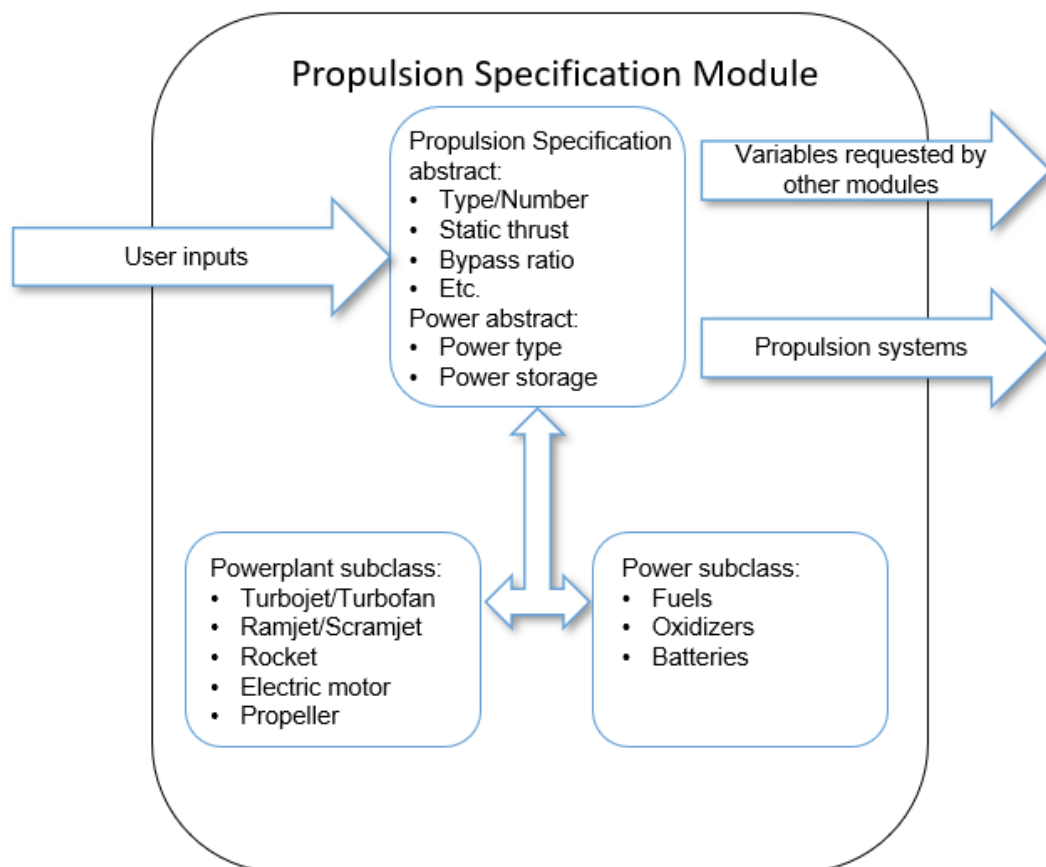


Figure 3-9 Hierarchy and Data Flow of Propulsion Specification Module

The inputs of propulsion specification module are listed in Table 3-4. Each Powerplant subclass represents one type of propulsion system, which can be modelled independently under different requirements.

Table 3-4 Propulsion Specification Input Variables

Input Variables	Variable Type	Description
Fuel fraction	Real value	The total mass fraction of fuel
Powerplant type number	Integer value	Number of powerplant types, m
Repeat the following m times		
Powerplant type	List value	Choose a preset type of powerplant in the list
Powerplant number	Integer value	Number of the chosen powerplant
Sea level thrust	Real value	Sea level static thrust
Wet over dry thrust	Real value	Aircraft burning thrust over non-afterburning thrust
Bypass ratio	Real value	Bypass ratio for chosen powerplant
Design Mach number	Real value	Design condition Mach number
Design altitude	Real value	Design altitude for chosen powerplant
Mach limit	Real value	Mach number limit for chosen powerplant
Fuel type	List value	The type of fuel required by chosen powerplant
Fuel storage	List value	The storage type of the fuel

Number of electric motors	Integer value	Number of the electric motors
Battery specific power	Real value	the maximum power of battery

3.4.2 Propulsion Specification for eVTOL

As with all aspects of conventional aircraft design, the eVTOL's propulsion system is constrained by a multitude of requirements. The high battery energy density can effectively reduce the maximum take-off weight of the aircraft. Higher electrical efficiency is important to increase the payload fraction.

3.5 Mass Breakdown

3.5.1 Overview

The Mass Breakdown module serves a crucial role in providing a comprehensive framework for estimating and representing the weight distribution across various components of an aircraft. This includes structural elements, internal systems, passenger load, fuel, and other essential items. The hierarchical organization of this module, which facilitates a systematic approach to weight estimation and allocation, is detailed in Figure 3-10.

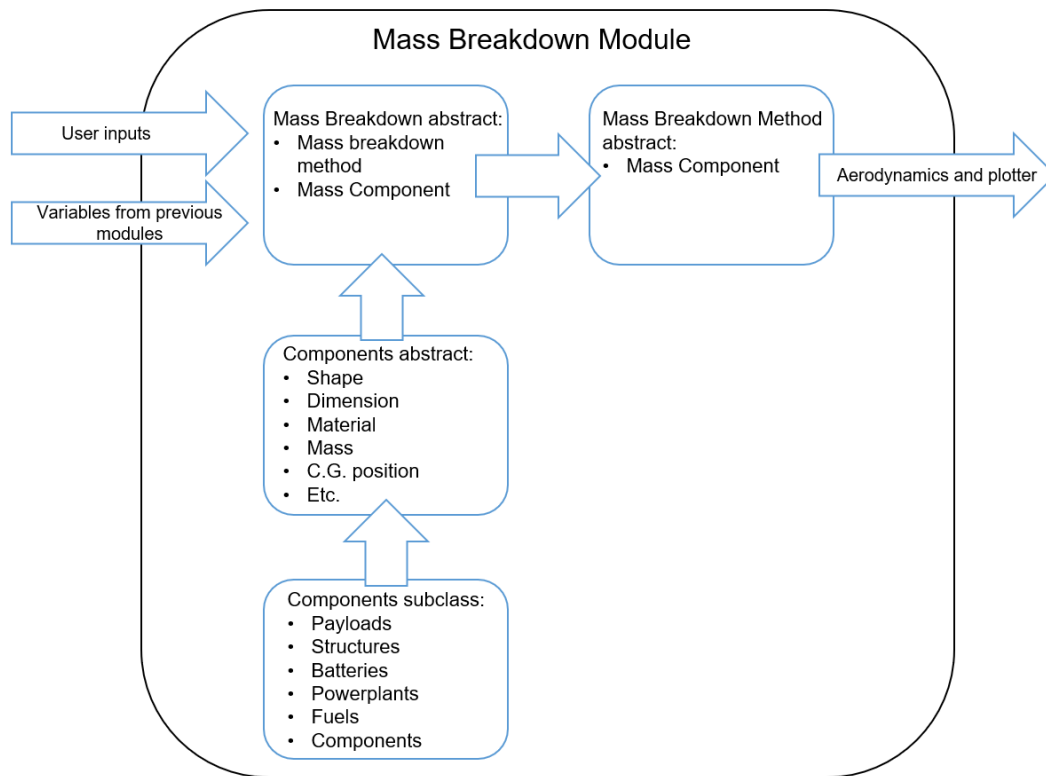


Figure 3-10 Hierarchy and Data Flow of Mass Breakdown Module

3.5.2 Mass Breakdown for eVTOL

During the conceptual aircraft design phase, to estimate component weights, a blend of empirical equations and physically based estimation methods is employed. This approach involves either averaging the results obtained from all applicable mass prediction methods for each component or selectively using values derived from a chosen set of equations from each method, depending on the specific design requirements and accuracy needed. GENUS has implemented a variety of Class II or statistical methods including the Howe's mass prediction method [148], Raymer's mass prediction method [149], Torenbeek's method [150] and the Cranfield in-house mass prediction method.

There are a variety of methods for predicting mass components, depending on the complexity required. Externally run FE simulations could provide accurate and reliable predictions of airframe masses. However, this method is problem specific and requires significant computational resources. Mass prediction

formulas can also be derived through theoretical design methods. This approach relies on experience and is therefore not suitable for new designers. Empirical methods derive formulas from statistical data. This approach is well suited to computational techniques, but it has low fidelity and is problematic for novel configurations. This thesis uses a generally semi-analytical method for estimating the weight of an eVTOL and its various components, shown in Table 3-5.

Table 3-5 the Mass Estimating Method of Each Components

Component Structural	Method
Wing	Semi-empirical formula
Fuselage	Physical-based
Rotors/Propeller	Physical-based
Hub	Empirical formula
Landing gear	Empirical formula
Seats	15-20 kg per seat
Avionics	Empirical formula
Battery	Calculate from total power and specific energy density
Motors	Empirical formula
Servos	Empirical formula
Ballistic Recovery Systems	Estimated based on vendor specifications
Wiring	From fuselage geometry and motor locations

Fuselage

Some parameters of the fuselage, which are used to calculate the mass, are generated by the geometry module based on the inputs. The pertinent materials to be selected are determining to the weight of the fuselage. According to [151], the weight of the vehicle skin and canopy are given as:

$$m_{skin} = S_{wet\ fus} \cdot \rho_{skin} \quad (3-1)$$

$$m_{canopy} = S_{canopy} \cdot \rho_{canopy} \quad (3-2)$$

$$S_{bulk} = \frac{3\pi}{4} (h_{fus} \cdot w_{fus}) \quad (3-3)$$

$$m_{bulk} = S_{bulk} \cdot \rho_{bulk} \quad (3-4)$$

The maximum bending moment can be determined from the MTOW of the aircraft and its geometry. Assuming that the keel is no higher than 1/10 of the height of the fuselage and no wider than 1/3 of the width of the fuselage. The mass of keel is given as:

$$L = g_{max} \cdot MTOW \cdot sf \quad (3-5)$$

$$Mom = L \cdot \frac{l_{fus}}{2} \quad (3-6)$$

$$A_{keel} = \frac{Mom \cdot Height_{beam}}{4 \cdot \sigma_{beam} \left(\frac{Height_{beam}}{2} \right)^2} \quad (3-7)$$

$$m_{keel,\sigma} = A_{keel} \cdot l_{fus} \cdot \rho_{\sigma} \quad (3-8)$$

$$A_{beam,enclosed} = Height_{beam} \cdot Width_{beam} \quad (3-9)$$

$$t_{keel} = \frac{1}{2} \cdot \frac{g_{max} \cdot MTOW \cdot \frac{l_{fus}}{2}}{\tau_u \cdot A_{keel,enclosed}} \quad (3-10)$$

$$m_{keel,\tau} = 2 \cdot (Height_{beam} + Width_{beam}) \cdot t_{keel} \cdot \rho_{\tau} \quad (3-11)$$

Where:

sf is the safety factor,

Mom is the moment.

The maximum landing angle θ to which the size of the landing pad can be adapted is input by the designer. The pad will carry the force through a retaining bolt.

$$F_{land} = sf \cdot MTOW \cdot I_{land} \cdot \sin\theta \quad (3-12)$$

$$A_{bolt} = \frac{F_{landing}}{\sigma_{u,bolt}} \quad (3-13)$$

$$d_{bolt} = 2 \sqrt{\frac{A_{bolt}}{\pi}} \quad (3-14)$$

$$t_{pad} = \frac{F_{land}}{d_{bolt} \cdot \sigma_{u,pad}} \quad (3-15)$$

$$V_{pad} = \left(\pi \cdot (20t_{pad})^2 \right) \cdot \frac{t_{pad}}{3} \quad (3-16)$$

$$m_{keel,pad} = n_{pad} \cdot V_{pad} \cdot \rho_{\sigma} \quad (3-17)$$

The fuselage mass is then:

$$m_{fus} = m_{skin} + m_{canopy} + m_{bulk} + m_{keel} \quad (3-18)$$

Wings

According to [152], Brandon Basgall etc have made improvements and modernizations to weight estimation methods, including the Cessna method[153], USAF method[153], General Dynamics method[153], Torenbeek method [154], and the Vought (Raymer) method [149], in order to make the methods applicable for current and future aircraft. Figure 3-11 is the wing weight trendline for different aircraft. Eq.(3-19) is the equations for the wing weight trendlines.

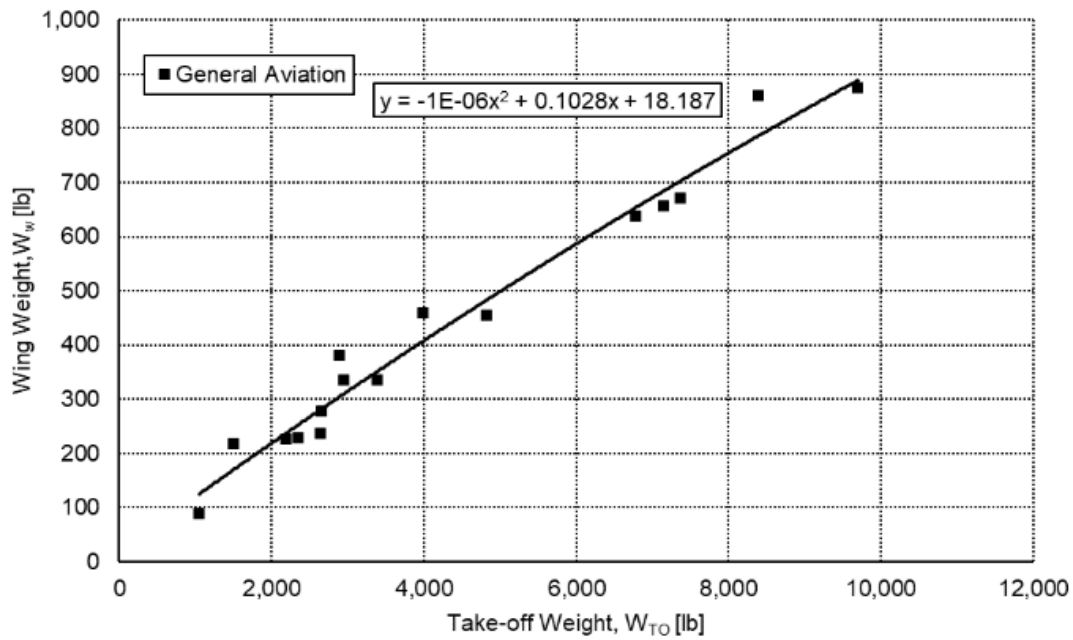


Figure 3-11 General Aviation Wing Weight Trendline (Source: [152])

General Aviation:

$$W_W = -1.35E^{-6} \cdot W_{TO}^2 + 0.103 \cdot W_{TO} + 18.2 \quad (3-19)$$

Where:

- W_W is the weight of wing, lb
- W_{TO} is the max take off weight, lb

Wiring

The weight of the wiring is usually determined by the fuselage size, the motors' position in relation to the distribution system, and the expected maximum power. The length of the wiring can be assumed to be the Euclidean distance from the distribution system. The wiring mass can be determined by summing the wiring lengths required to reach each motor and multiplying the parameters by the maximum power consumption and the specific power density.

$$Volume_{copper} = \frac{P_{max}}{\text{power density of copper wiring}} \quad (3-20)$$

$$m_{copper} = \rho_{copper} \cdot Volume_{copper} \quad (3-21)$$

$$Volume_{copper} = Length \cdot \pi \cdot r_{copper}^2 \quad (3-22)$$

$$Volume_{cable} = 2 \cdot \pi \cdot r_{copper} \cdot Length \cdot t_{cable} \quad (3-23)$$

$$m_{cable} = Volume_{cable} \cdot \rho_{cable} \quad (3-24)$$

$$m_{wiring} = m_{copper} + m_{cable} \quad (3-25)$$

3.5.3 Validation of Methods

The mass breakdown results of Kitty Hawk Cora from GENUS are compared to the NDARC and SUAVE data [155]. The wiring mass, not accounted for by NDARC and SUAVE, has been included in the Systems/Equipment category for this comparison based on GENUS's calculations. Figure 3-13 indicates that the mass breakdown data from GENUS are close to the others (3.57% to SUAVE data, 3.25% to NDARC data), which help to validate the codes.

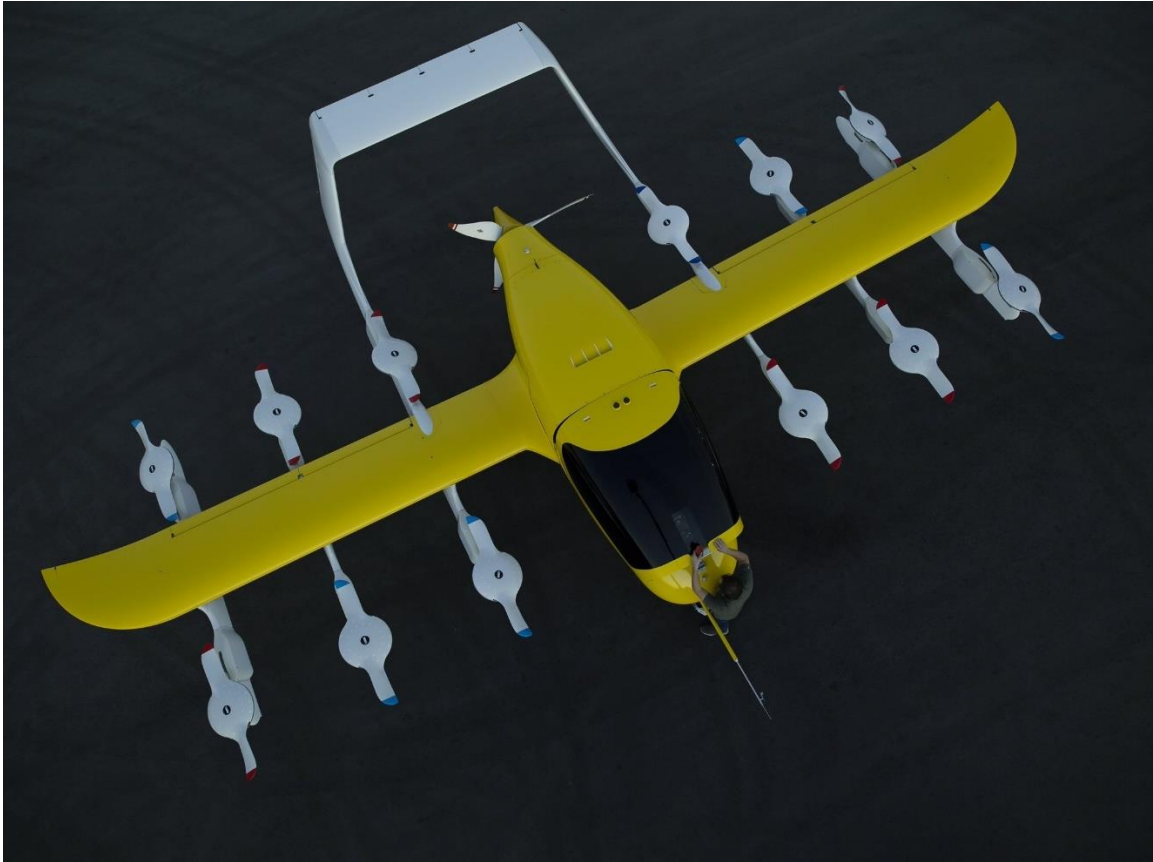


Figure 3-12 Kitty Hawk Cora (Source: [12])

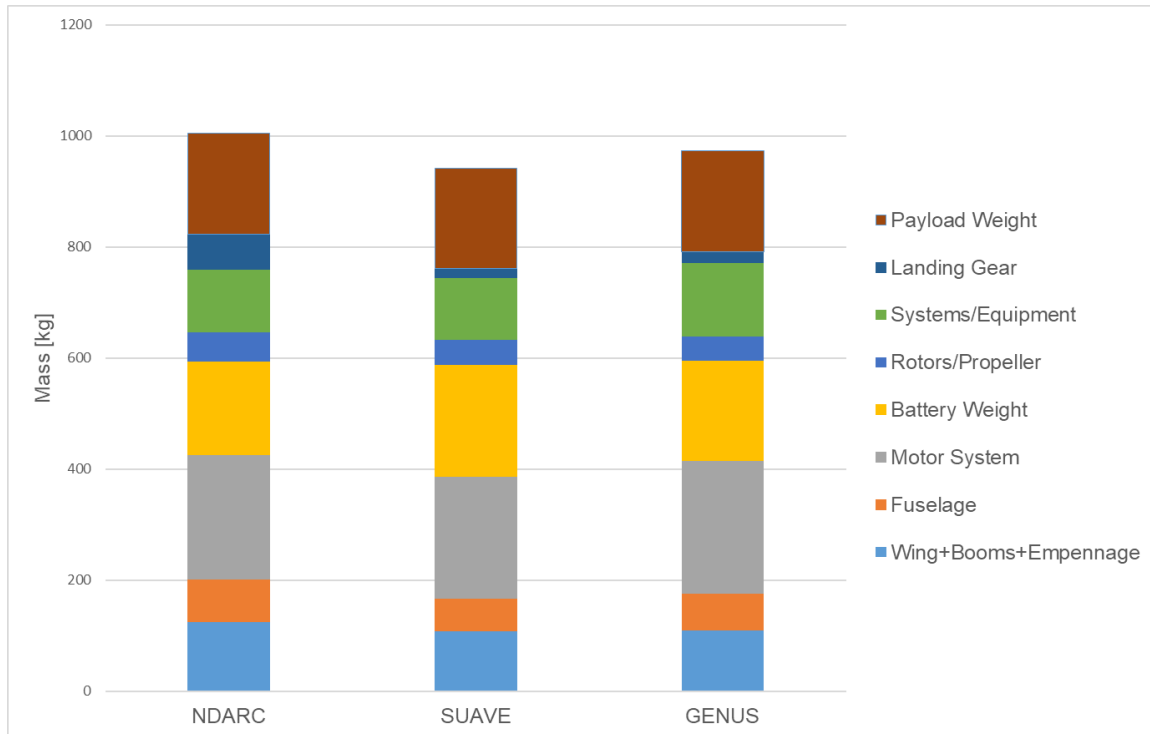


Figure 3-13 mass breakdown comparison of NDARC, SUAVE and GENUS.

3.6 Aerodynamic Analysis

3.6.1 Overview

The Aerodynamic Analysis module is a critical component in the GENUS aircraft concept design process, specializing in the prediction of aerodynamic coefficients. These predictions are based on both the geometry specified in the Geometry module and various flight conditions. The GENUS Aerodynamics module employs a multi-faceted approach, amalgamating multiple analysis methods and levels of fidelity to produce a comprehensive understanding of a vehicle's aerodynamic characteristics.

The outcomes of these analyses are collated into a matrix, storing coefficients that correspond to various Mach numbers and Angles of Attack (AOA). This matrix serves as a shared data object, accessible by other modules within the GENUS environment for integrated, cross-disciplinary studies. The hierarchical structure of the Aerodynamic Analysis module, which delineates the interactions among its various components and other modules, is illustrated in Figure 3-14.

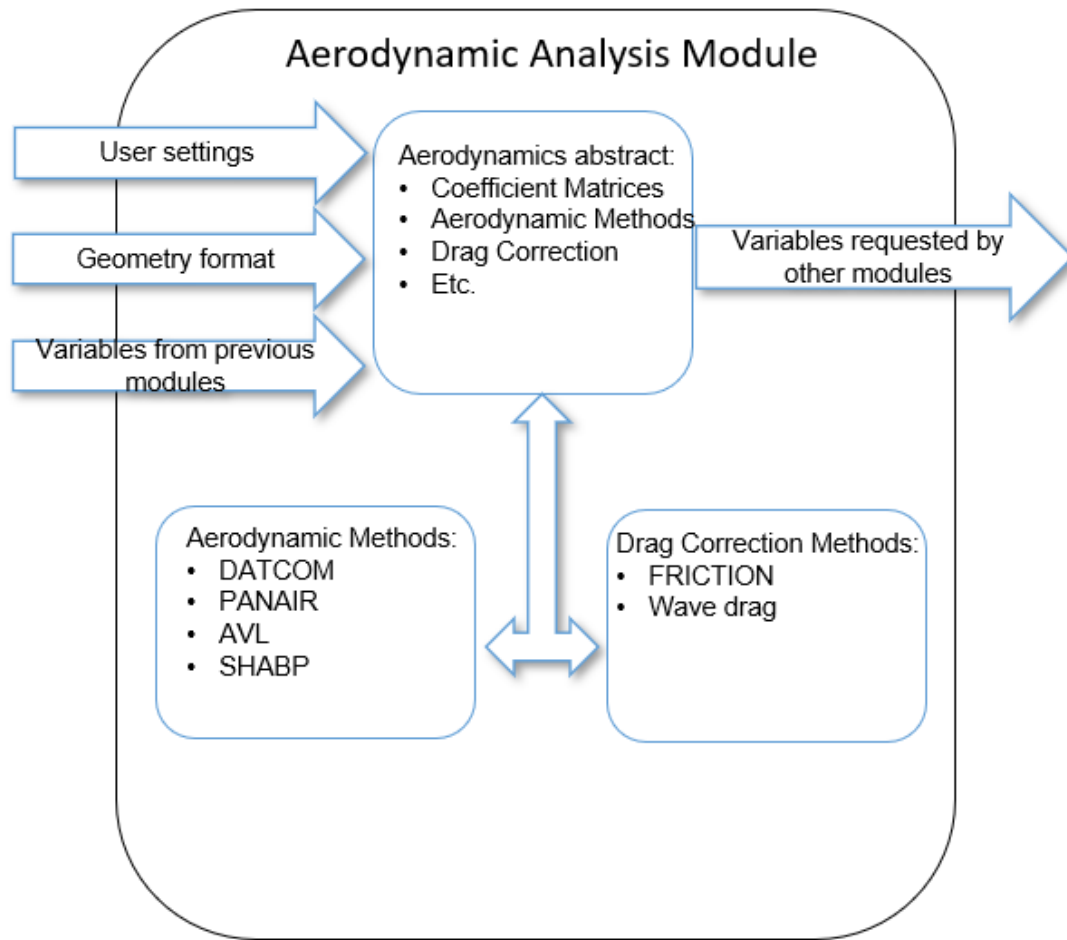


Figure 3-14 Hierarchy and Data Flow of Aerodynamic Analysis Module

3.6.2 Aerodynamic Analysis for eVTOL

There are many different methods of aerodynamic analysis, including 1) empirical methods, 2) vortex lattice methods, 3) panel methods, 4) Euler CFD, and 5) Navier-Stokes CFD. GENUS framework currently includes semi-empirical method digital DATCOM [156], an advanced vortex lattice method AVL [157], panel method PANAIR [158] and Supersonic Hypersonic Arbitrary Body Program SHABP [159]. The capabilities of these aerodynamic analysis codes are listed in Table 3-6.

Table 3-6 Capabilities of the Aerodynamic Codes

	Open Source	Arbitrary Geometry	Mach Range
--	-------------	--------------------	------------

Digital DATCOM	✓	×	No restriction
AVL	✓	×	M<0.6 valid M<0.8 unreliable
SHABP	✓	✓	M>1.5
PANAIR	✓	✓	M<4.0

The total drag C_{Dtotal} components for eVTOL consist of the friction drag C_{Df} , and vortex drag C_{DLV} , as exemplified in Eq. (3-26).

$$C_{Dtotal} = C_{Df} + C_{DLV} \quad (3-26)$$

Friction Drag

The skin friction and form drag calculations have been adapted from the component-based approach proposed by Gur et al [160]. The total friction drag is given by Eq.(3-27). This study estimated the effect of flow turbulence using Schlichting's composition equations [161]. Laminar transition fraction F_{trans} shown in Eq.(3-28). the Eckert reference temperature method [162] is used for laminar flow and the Van Driest II method [163] is used for turbulent flow. Additionally, the analysis integrates the consideration of interference, L&P, and miscellaneous drag components into the overall drag calculation. These components are evaluated through a combination of empirical data and analytical models, specific to the unique aerodynamic interactions present in the aircraft design. While the primary focus of the presented equations and methodologies lies on friction and form drag, the interference and L&P drag components are accounted for using established aerodynamic principles that assess the effects of wing-body interactions, landing gear, and control surface deflections.

$$C_{Df} = \sum_{j=1}^N \frac{FF_j C_{Fj} S_{wetj}}{S_{ref}} \quad (3-27)$$

$$C_{F_j} = C_{F_{turb}} - F_{trans}[C_{F_{turb}} - C_{F_{lam}}] \quad (3-28)$$

From Torenbeek [154], chosen as conservative factors compared to other sources.

$$FF_{BodyComp} = 1 + 1.5\left(\frac{d}{l}\right)^{1.5} + 50\left(\frac{d}{l}\right)^3 \quad (3-29)$$

$$FF_{LiftSurf} = 1 + 2.7\left(\frac{t}{c}\right) + 100\left(\frac{t}{c}\right)^4 \quad (3-30)$$

3.7 Propulsion System

3.7.1 Overview

The propulsion module estimates the thrust required to achieve a specific flight condition in the current configuration and the power consumed. The propulsion module can handle vehicles with any number of propulsion systems in any flight conditions. The hierarchy of this module is shown in Figure 3-15.

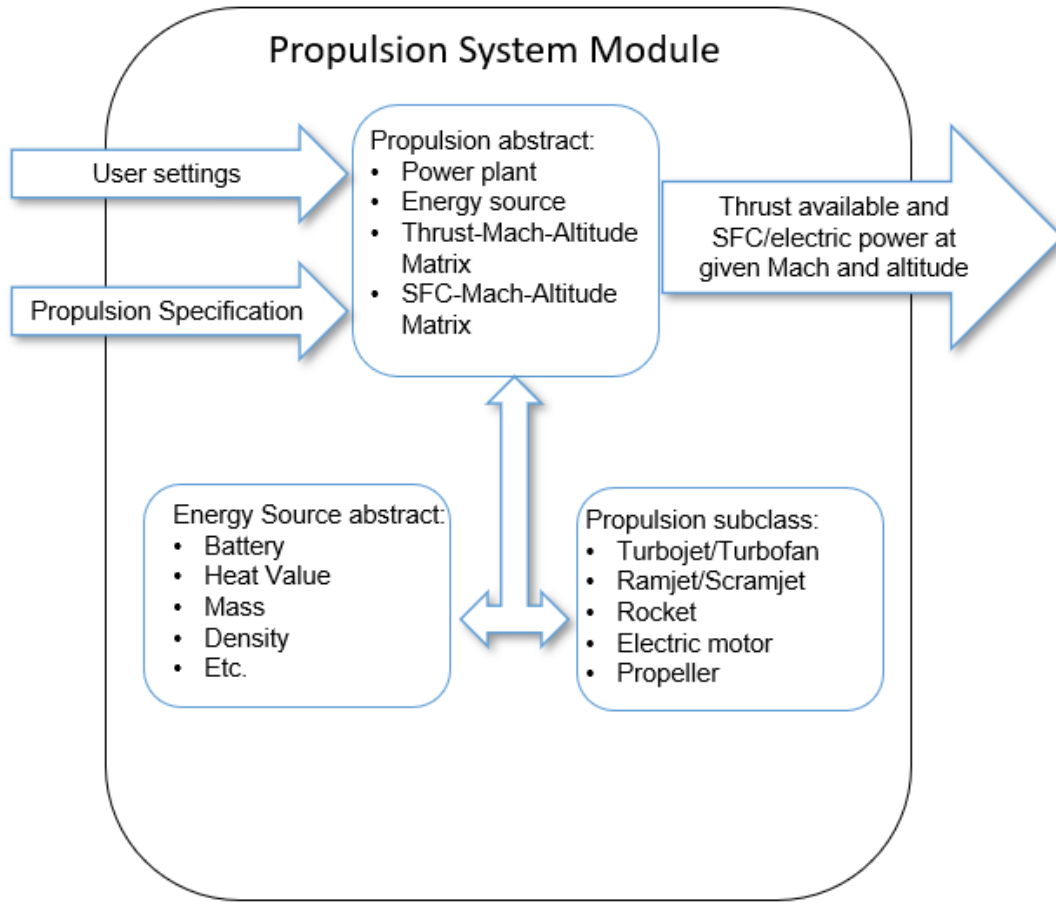


Figure 3-15 Hierarchy and Data Flow of Propulsion System Module

3.7.2 Propulsion System for eVTOL

3.7.2.1 Battery

Considering batteries with significantly different Peukart constants, the following basic empirically based equation approximates the discharge losses [130].

$$f(x) = 1 - \exp(-20x) - \exp(-20(1 - x)) \quad (3-31)$$

$$R = R_0(1 + Cf) \quad (3-32)$$

$$P_{discharge} = I^2 R \quad (3-33)$$

Where:

x is the state of charge of the battery, is the ratio of the battery's current total energy to its maximum energy capacity,

R_0 is a baseline internal resistance,

C is the discharge rate of the battery.

3.7.2.2 Electric Motor

The electric motor model has three fundamental parameters, including the speed constant KV , no-load current i_0 , and resistance R . Figure 3-16 and Figure 3-17 are the functions of the parameters.

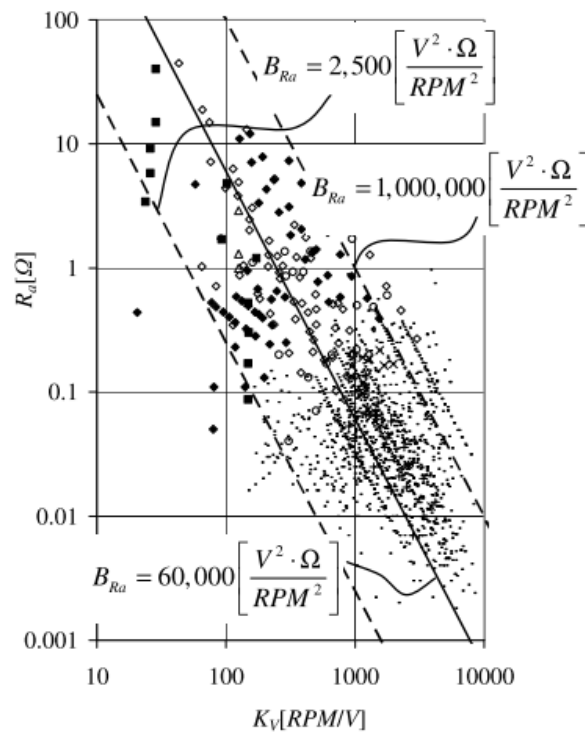


Figure 3-16 Internal resistance as a function of speed coefficient (Source: [164])

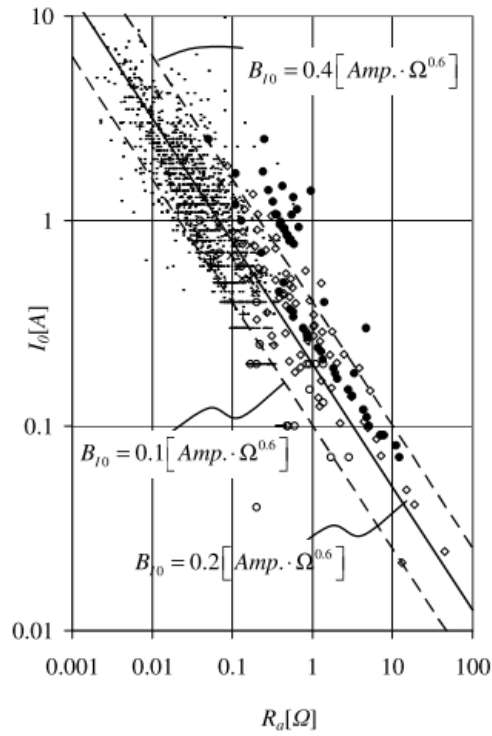


Figure 3-17 No load current as a function of internal resistance (Source: [164])

The resistance and no-load current are given:

$$R = \frac{B_{RA}}{KV^2} \quad (3-34)$$

$$i_0 = \frac{B_{i0}}{R^{0.6}} \quad (3-35)$$

Where B_{RA} and B_{i0} represent the mean of the regressed data.

Figure 3-18 shows the equivalent circuit for a DC electric motor.

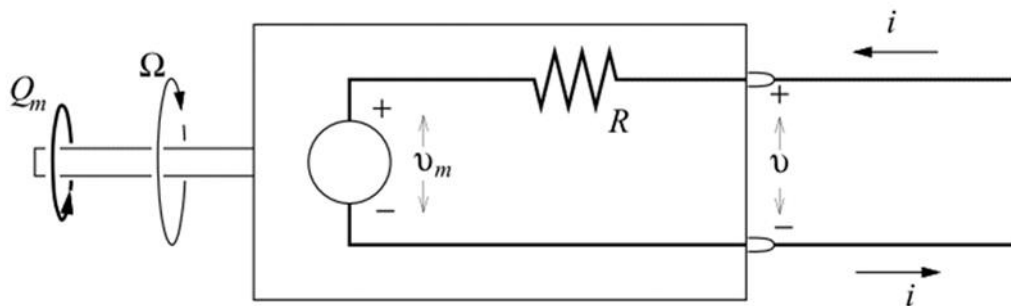


Figure 3-18 Equivalent circuit for a DC electric motor [140]

Assume the resistance is constant. The shaft torque, voltage, efficiency is given:

$$Q_m(i) = \frac{i - i_0}{K_Q} \quad (3-36)$$

$$v(i, \Omega) = v_m(\Omega) + iR = \frac{\Omega}{K_V} + iR \quad (3-37)$$

$$\Omega = (v - iR)/K_V \quad (3-38)$$

$$\eta_m(\Omega, v) = \frac{P_{shaft}}{iv} = \left(1 - \frac{i_0}{i}\right) \cdot \frac{K_V}{K_Q} \cdot \frac{1}{1 + \frac{iRK_V}{\Omega}} = \left(1 - \frac{iR}{v}\right) \cdot \left(1 - \frac{i_0}{i}\right) \quad (3-39)$$

Where:

Q is the torque,

K_Q is the torque constant,

K_V is the speed constant,

Ω is the rotation rate.

3.7.2.3 Propeller

This thesis uses an extension of the classical blade-element/vortex formulation. The theory developed originally by Betz [1], Goldstein [2], and Theodorsen [3], and reformulated somewhat by Larrabee [4].

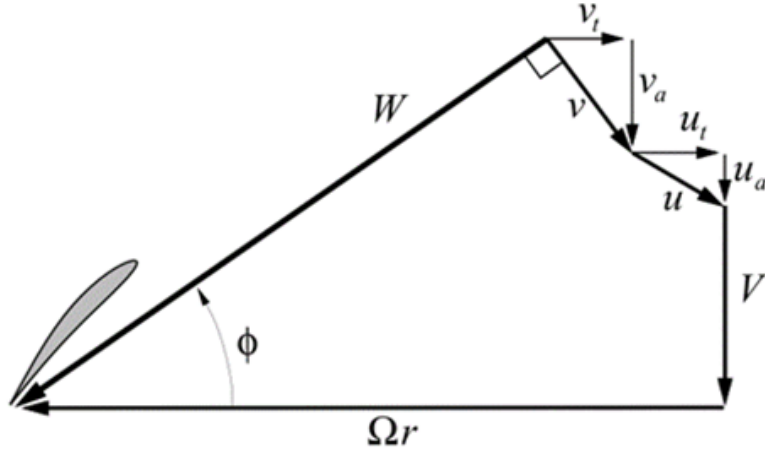


Figure 3-19 Decompositions of total blade-relative velocity W at radial location r (Source:[165]).

Figure 3-19 shows the decomposition of the total blade-relative velocity. The axial and tangential components are given as:

$$W_a = V + u_a + v_a \quad (3-40)$$

$$W_t = \Omega r - u_t - v_t \quad (3-41)$$

$$W = \sqrt{W_a^2 + W_t^2} \quad (3-42)$$

To account for tip losses, the modified Prandtl's factor F is:

$$F = \frac{2}{\pi} \arccos(e^{-f}) \quad (3-43)$$

$$f = \frac{\frac{B}{2} \left(1 - \frac{r}{R}\right)}{\lambda_w} \quad (3-44)$$

$$\lambda_w = \frac{r}{R} \tan \phi = \frac{r}{R} \cdot \frac{W_a}{W_t} \quad (3-45)$$

The total thrust and torque are obtained by Eq.(3-46) and Eq.(3-47)

$$T = \rho B \int_0^R \Gamma \left(W_t - \frac{c_d}{c_l} W_a \right) dr \approx \rho B \sum_r \Gamma \left(W_t - \frac{c_d}{c_l} W_a \right) \Delta r \quad (3-46)$$

$$Q = \rho B \int_0^R \Gamma \left(W_a + \frac{c_d}{c_l} W_t \right) dr \approx \rho B \sum_r \Gamma \left(W_a + \frac{c_d}{c_l} W_t \right) r \Delta r \quad (3-47)$$

Where,

ρ is the fluid density,

B is the number of blades,

Γ is the blade circulation,

3.7.3 Validation of Methods

The lift and power coefficient from GENUS are compared to the UIUC propeller database experimental data [166] for APC 21 x 13 propeller. Figure 3-20 is the picture of APC 21 x 13 propeller. Figure 3-21 shows that the aerodynamic coefficients from GENUS are close to the results of experimental data, which help to validate the codes. Figure 3-22 shows the comparison of energy consumption by flight segments for Kitty Hawk Cora (shown in chapter 3.5.3) between GENUS, SUAVE and NDARC. The substantial differences in cruise energy consumption predictions between methods arise from a combination of factors. Firstly, both GENUS and SUAVE account for the variability in battery performance during flight, which directly impacts energy calculations. Secondly, GENUS adopts an advanced propeller model based on an extended version of blade element theory, incorporating tip loss effects for a more accurate representation of propulsive efficiency. Lastly, the discrepancy is further compounded by GENUS's slightly higher mass estimation compared to SUAVE, affecting the predicted energy consumption. These elements collectively contribute to the variance observed in cruise energy consumption predictions.



Figure 3-20 APC 21 x 13 propeller

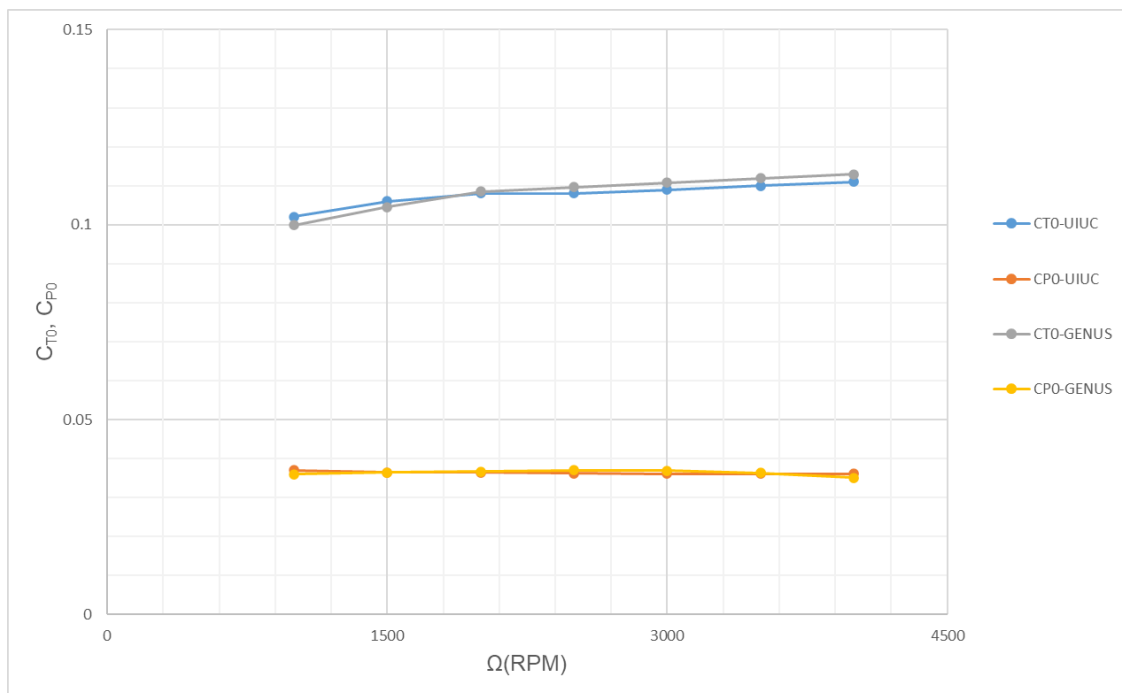


Figure 3-21 Comparison of lift coefficient and power coefficient between GENUS and UIUC database.

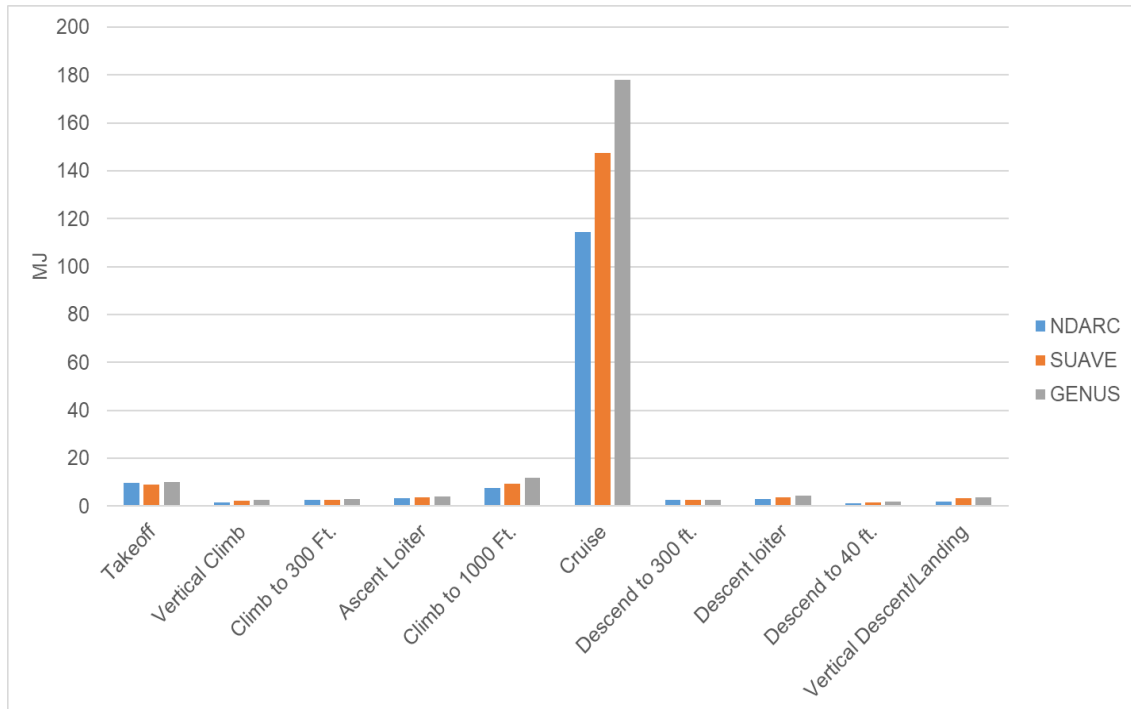


Figure 3-22 Comparison of energy consumption by flight segments between GENUS, SUAVE and NDARC.

3.8 Packaging and Centre of Gravity

3.8.1 Overview

The purpose of Packaging and Centre of Gravity module is twofold: 1. to calculate the centre of gravity for the various configurations (with and without fuel and payload) and 2. to locate the internal components and check that the internal parts fit the structure. The hierarchy of this module is shown in Figure 3-23.

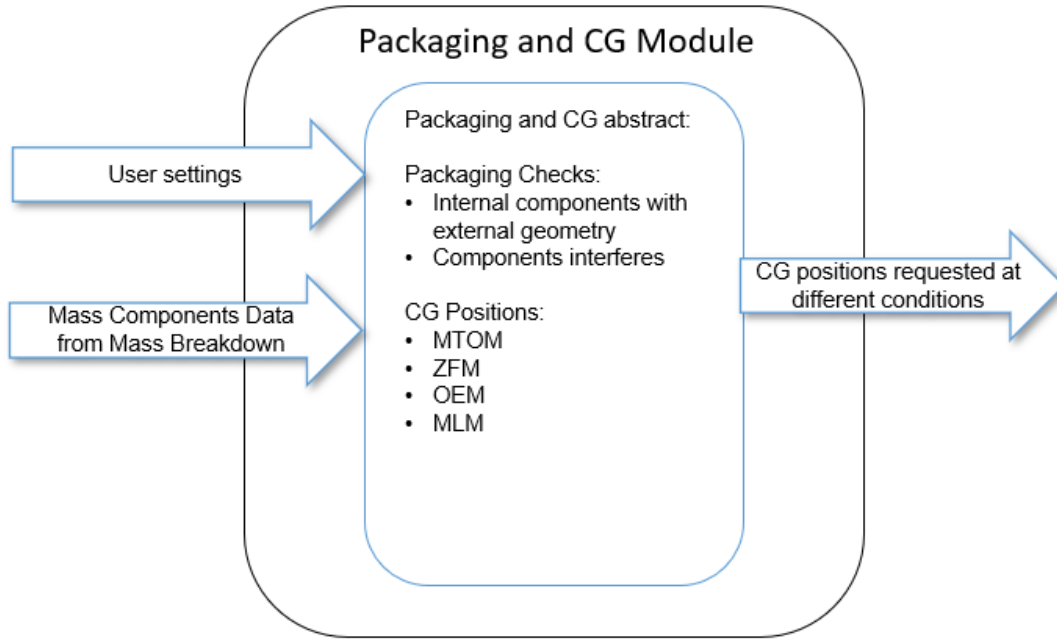


Figure 3-23 Hierarchy and Data Flow of Packaging and Centre of Gravity Module

3.8.2 Packaging and CG for eVTOL

The module dedicated to Packaging and CG Estimation for eVTOL vehicles employs a unique approach. It replaces actual mass components with either calculated or predetermined mass values, dimensions, and shapes. The precise location of the centre of gravity (CG) is subsequently determined through the application of conventional momentum equations.

$$X_{CG} = \frac{\sum m_i x_{cg,i}}{\sum m_i} \quad (3-48)$$

$$Y_{CG} = \frac{\sum m_i y_{cg,i}}{\sum m_i} \quad (3-49)$$

$$Z_{CG} = \frac{\sum m_i z_{cg,i}}{\sum m_i} \quad (3-50)$$

Where:

- $i = 1 \dots N$, representing the number of components,
- X_{CG}, Y_{CG}, Z_{CG} : the X, Y, Z coordinates of the global CG respectively,
- m_i : mass of the different components,

- $x_{cg,i}$, $y_{cg,i}$, $z_{cg,i}$: different components' local CG's x, y z coordinate respectively.

The CG positions play a crucial role in the calculation of longitudinal stability for the aircraft. This is particularly significant during transition segments for tiltwing/tiltrotor configurations, where the aerodynamic centre undergoes rapid movement. The CG module supplies vital information to the stability and control module, enabling it to manage thrust from different propellers effectively to maintain longitudinal stability. In GENUS, the transition for tiltwing/tiltrotor configurations is modelled by dynamically simulating the CG shift's impact on the aircraft's longitudinal stability. This involves calculating the movement of the aerodynamic centre and the corresponding changes in thrust distribution among the propellers throughout the transition phase. The CG module, by providing real-time data on the CG position, enables the stability and control module to adjust thrust outputs effectively, ensuring stable flight during the critical transition from vertical to forward flight and vice versa.

3.9 Performance Analysis

3.9.1 Overview

The Performance module serves as the capstone in the overall concept design process within the GENUS environment. Its primary role is to evaluate if a particular design instance can meet the stipulated mission requirements. The assessment process is bifurcated into two key metrics: Mission Performance and Point Performance.

- **Field Performance:** This focuses on whether the aircraft can achieve specific mission objectives in terms of range or endurance. Essentially, it assesses the aircraft's capability to execute a mission within predefined operational limits.
- **Point Performance:** This evaluates the aircraft's ability to execute specific maneuvers at various points along the mission route, thereby gauging its adaptability and responsiveness in different flight conditions.

In sum, the Performance module acts as the ultimate yardstick, quantitatively and qualitatively evaluating the viability of a given aircraft design in fulfilling its intended mission. The hierarchy and data flow of this module is shown in Figure 3-24.

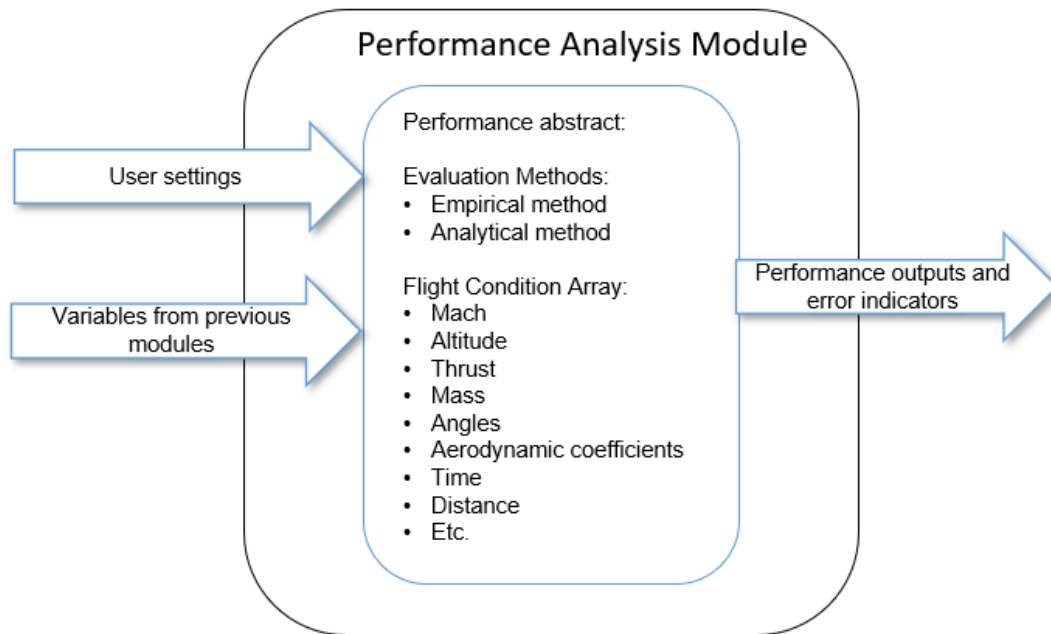


Figure 3-24 Hierarchy and Data Flow of Performance Analysis Module

3.9.2 Performance Analysis for eVTOL

Vertical Take-off

During the vertical take-off segment of an eVTOL aircraft, vertical lift is solely provided by the propellers. Designers have the flexibility to define the objectives of this segment by specifying parameters such as time, final altitude, and final velocity.

Climb

For the Vectored Thrust configuration, during the forward climb segment, the propellers gradually rotate to a vertical orientation. The thrust generated by the propellers gradually increases while the lift diminishes progressively. Concurrently, the lift provided by the wings increases with the augmentation of speed.

In the case of the Lift + Cruise configuration, as the speed increases, the lift generated by the wings escalates while the horizontal propellers' lift diminishes gradually. The fixed vertical propellers provide continuous horizontal thrust throughout the flight.

For the multicopter configuration, multiple propellers adjust their angles to provide both the upward lift and forward thrust required for the aircraft's segment.

Cruise

Due to the current battery models employed by GENUS, which assume constant mass, the overall aircraft mass remains unchanged during the cruise segment. During the cruise segment, the Lift + Cruise configuration generates thrust using limited number of fixed vertical propellers, while the Vectored Thrust configuration achieves propulsion by transitioning multiple propellers into a vertical orientation during the climb segment. Meanwhile, the multicopter configuration necessitates the simultaneous utilization of multiple propellers to provide both the required lift and thrust for the aircraft.

Vertical descent

The dynamics observed during the descent segment exhibit similarities to those encountered during the take-off segment. The salient divergence pertains to the alteration in the direction of acceleration, which becomes antithetical between the two segments.

3.10 Stability and Control

3.10.1 Overview

The Stability and Control module in the GENUS environment is specifically engineered to evaluate the aircraft's stability characteristics and trim capabilities across a wide array of flight conditions. Its primary outputs include calculated metrics that quantify the aircraft's stability features, as well as error indicators that act as diagnostic tools to assess whether the aircraft remains stable or unstable under given flight conditions, speed states, and throughout its entire mission envelope. Essentially, this module serves as a holistic tool for scrutinizing the

aircraft's performance to ensure optimal stability and control across diverse flight scenarios. The hierarchy of this module is shown in Figure 3-25.

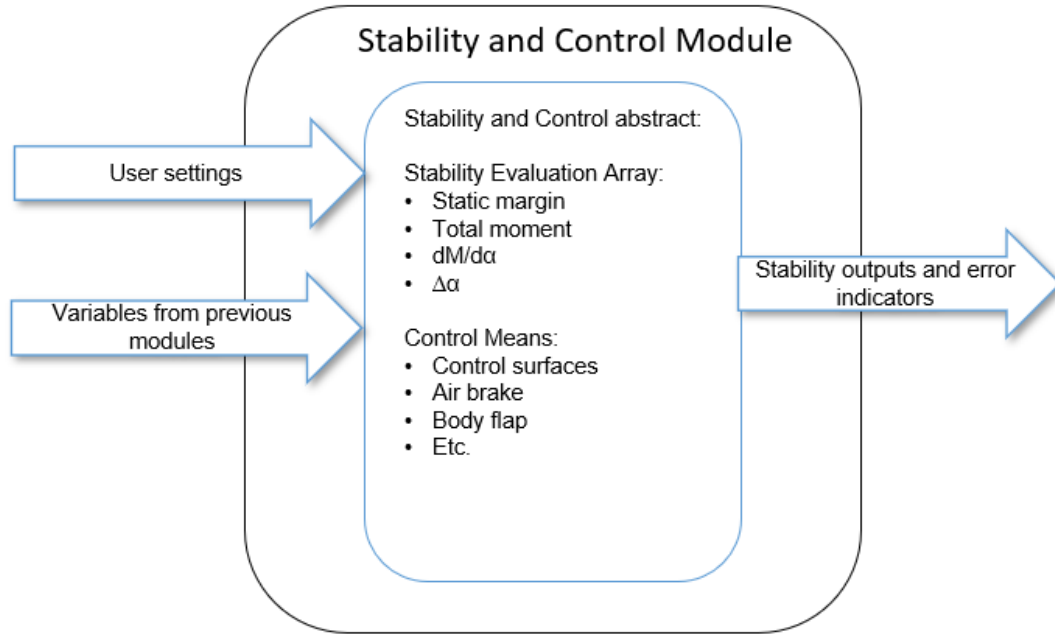


Figure 3-25 Hierarchy and Data Flow of Stability and Control Module

3.10.2 Stability Analysis for eVTOL

The Stability and Control module operates as an integral part of the GENUS environment, designed to rigorously evaluate the aircraft's stability features and trim capabilities under varied flight conditions. One crucial aspect assessed by this module is longitudinal stability, which is determined by comparing the aircraft's CG as calculated by the Packaging and CG module with the aerodynamic centre obtained from the Aerodynamic Analysis module. This comparison is quantified through the static margin equation, which serves as a pivotal metric. Ultimately, the module provides invaluable calculated results and error indicators, which collectively act as diagnostic tools for assessing the aircraft's stability across a wide range of operational scenarios.

The following equation represents the static margin.

$$X_{CG} = \frac{\sum m_i X_{cg,i}}{\sum m_i} \quad (3-51)$$

The neutral point can be estimated:

$$X_{np} = X_{ref} - \bar{c} \frac{C_{m_a}}{C_{L_a}} \quad (3-52)$$

To achieve longitudinal static stability in an aircraft, it is necessary for the static margin to have a positive value.

The GENUS incorporates DATCOM [48] as the stability and control analysis tool, which is applicable for eVTOL aircraft. DATCOM is capable of automatically calculating the impact of symmetrical control effectors on lift and moment coefficients. The longitudinal elevator trim deflection can be computed for different flight conditions. To achieve static stability in the aircraft, Eq. (3-53) should be set to zero. The trim angle at various flight conditions can be determined by considering the deflections of control effectors and the corresponding changes in lift and moment coefficients. The estimation of trim drag involves utilizing the angle of attack and the corresponding trim deflection. The trim drag can be determined by evaluating the derivative of $C_{D_{\delta_e}}$ at a given α . Multiplying the derivative of trim deflection δ_e results in the increase in drag coefficient due to the deflection of the elevator.

$$\sum M_{y_{CG}} = \left(\frac{dC_{M_{ac}}}{d\delta_e} \right) \delta_e - \frac{x_w}{\bar{c}} \left[\left(\frac{dC_L}{d\alpha} \right) \alpha + \left(\frac{dC_L}{d\delta_e} \right) \delta_e \right] = 0 \quad (3-53)$$

GENUS also accounts for the scenario of One Engine Inoperative (OEI). In situations where one or multiple engines experience failures during flight, symmetrical engines are systematically deactivated, concomitantly amplifying the power output of the remaining operational engines. This intricate orchestration is undertaken to guarantee the aircraft sustains the requisite aerodynamic thrust, thus facilitating the seamless continuation of its flight trajectory.

In the study of eVTOL vehicles within the GENUS environment, special attention is paid to the aspect of stability during hovering flight. One critical variable affecting stability during hover is the CG, which can shift due to changes in payload positioning. When the CG moves, it directly impacts the vehicle's trim

characteristics, affecting the control surfaces and propulsion system's ability to maintain a stable hover.

To address this issue, the Stability and Control module incorporates algorithms that adjust control inputs to re-establish the desired trim conditions dynamically. By calculating deviations from the nominal CG position, the module adapts the control surface deflections and motor outputs to counteract any destabilizing tendencies. This ensures that the eVTOL vehicle maintains its stability throughout the hovering phase, even when the CG is altered due to payload shifts. This methodology is validated through the comparison of computational results with empirical data, thereby confirming the robustness and reliability of the Stability and Control module in the GENUS environment for eVTOL applications.

3.11 Optimization

3.11.1 Overview

The Optimisation module contains a variety of optimisers to solve complex aerospace design problems. The output of this module is the optimal objective value and the corresponding variable value. The data flow of the optimization module is shown in Figure 3-26.

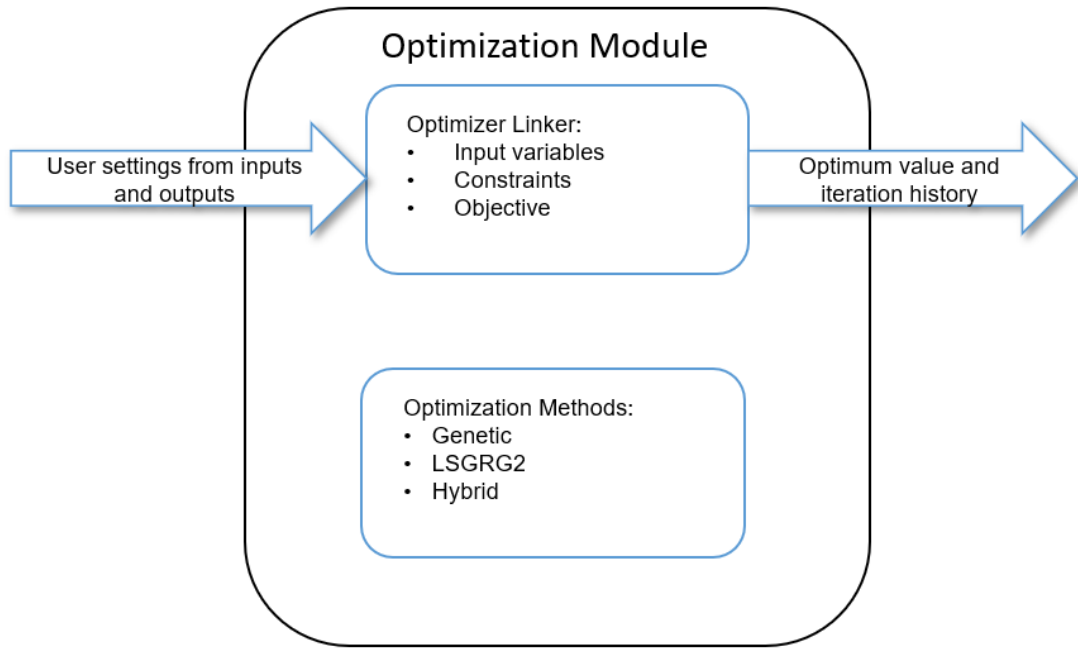


Figure 3-26 Data Flow of Optimization Module

An optimization problem can be described as:

Objective function:

$$\min f(\bar{x}) \quad (3-54)$$

Subject to:

$$g_j(\bar{x}) \leq 0 \text{ for } j = 1, 2, \dots, J \quad (3-55)$$

$$h_k(\bar{x}) = 0 \text{ for } k = 1, 2, \dots, K \quad (3-56)$$

$$x_i^L \leq x_i \leq x_i^U \text{ for } i = 1, 2, \dots, N \quad (3-57)$$

Where:

$\bar{x}$ is the array of optimization input variables, dimension of N,

$f(\bar{x})$ is the objective function, scalar,

$g_j(\bar{x})$ are the inequality constraints, J in total,

$h_k(\bar{x})$ are the equality constraints, in practical terms $h_k(\bar{x}) < \varepsilon$, where ε is a small positive number, K in total,

x_i^L and x_i^U are the respective lower and upper bounds for variables.

3.11.2 Optimization for eVTOL

The GENUS aircraft design environment is equipped with a suite of three optimization algorithms to address different design requirements and computational challenges. These include a gradient-based algorithm, a genetic algorithm, and a hybrid algorithm. The hybrid approach initializes with the genetic algorithm to explore a broad design space and then refines the search using the gradient-based algorithm for local optimization.

The system offers four principal design strategies tailored for eVTOL aircraft:

1. Minimizing MTOW
2. Minimizing Energy Consumption
3. Minimizing Mission Time
4. Maximizing Wingspan

The selection of constraints and bounds on design variables is a critical aspect of the optimization process. These are determined based on current technological capabilities as well as the specific requirements articulated by the designer. For instance, in the strategy aimed at minimizing MTOW, the variables selected for optimization could include estimated MTOW, battery mass, and propeller radius. These constraints are strategically chosen to ensure that the eVTOL aircraft can meet mission requirements without compromising on performance or safety. Further insights and case studies related to optimization can be found in Chapter 4 of this work.

The optimisation objective is formally defined as follows:

$$\min_x f(X) \text{ where } X = [S, AR, b, c \dots] \quad (3-58)$$

The convergence criterion is defined as follows:

$$\frac{|f(x_k) - f(x)|}{|f(x_k)|} < \epsilon \quad (3-59)$$

Where:

ϵ is the minimum criteria that is predefined by the user.

4 V-23 Design Case

This section presents a design of an 8-passenger eVTOL design case to demonstrate the ability of the design model developed in GENUS. This is also the Group Design Project for the Cranfield University Aerospace Vehicle Design MSc students.

MISSION

Maximum Operating Mass	4089.2 kg
Design mission with 800 kg payload(inc. reserves)	120 nm
Minimum cruise ceiling from MOM take-off	20000 ft
Design cruise speed @ 1500m	250mph
Rolling TO/L Field Perf at ISA sea level conditions	TBD
VTOL ceiling at MOM(MCP)	6000 ft

GEOMETRY

Wing:

Gross area	23.2293 m ²
Span	12.752 m
Aspect ratio	7.00
Root chord	1.9872 m
Tip chord	1.6560 m
Leading edge sweep	0°
Dihedral	2°
Mean aerodynamic chord	1.8266 m
Standard mean chord	1.8216 m

Twist	0°
Wing setting angle	1.5°
Zero lift line to horizontal	4.5°
Wing centre line above fuselage datum	1.31 m
Aerofoil section:	
Centreline:	NACA 64A423
Tip:	NACA 64A419
Location of wing centreline apex, aft of nose	3.4047 m
Location of wing mac LE aft of nose apex	3.4047 m

Outboard Flaperons

Type:	Round nose
Control chord/wing chord	25%
Movement	up 40° down 75°
Inboard end from aircraft centreline	3.258 m
Outboard end from aircraft centreline	6.026 m

Inboard Flaperons

Type	Round nose
Control chord/wing chord	25%
Movement	up 20° down 75°
Inboard end from aircraft centreline	1.25 m
Outboard end from aircraft centreline	2.558 m

Tailplane

Gross area	4.0661 m ²
Span	4.2716 m
Aspect ratio	4.4874
Root chord	2.1097 m
Tip chord	1.1706 m
Sweepback of leading edge	16.39°
Aerofoil section	NACA 64A012
Dihedral	0°
Setting angle	8° nose up to 20° nose down
Location of apex line aft of fuselage nose	10.80 m
Vertical location above fuselage datum	3.3550 m

Elevator

Type	Round nose
Elevator chord/tailplane chord	0.3
Movement	+25° to -25°

Fin

Nominal gross area above fuselage datum	4.50m ²
Root chord	2.40 m
Tip chord	1.60 m
Sweepback of leading edge	45°
Sweepback of quarter chord	42°
Aerofoil section	NACA 65A015 root

	NACA 65A009 tip	
Span above fuselage		2.25 m
Location of apex aft of fuselage nose at fuselage		8.6 m
Rudder		
Type		Round nose
Rudder chord/fin chord		20%
Nominal full span rudder		
Movement		$\pm 20^\circ$
Fuselage		
Overall length		11.50 m
Maximum diameter		2.21 m
Internal width of cabin		1.91 m
Aft extent of primary cabin from fuselage apex		4.93 m
Aft extent of secondary cabin from fuselage apex		5.70 m
Rearmost flight deck extent from fuselage apex		2.27 m
Main Undercarriage		
Type:	Twin wheel, sideways retracting	
Location of leg aft of fuselage apex		4.70 m
Track		4.0 m
Nose Undercarriage		
Forward retracting:		Twin
Location of leg aft of fuselage nose		1.25 m
Nose wheel loading to be verified		20.6% to 33.3%

Powerplant

Type: The 8 lift propellers are driven by 8 electric motors which are supported by a thermal management system. The thermal management system is rated for normal operating conditions and will be time limited for emergency conditions.

Ratings (per engine)

Maximum Continuous:	178.453 kw
	7.535 kN
3 min OEI	8.0 kN

NB engines will not all need to run at full power simultaneously – typical continuous thrust will be c. 5.023 kN

Prop-rotor diameter:	3.3 m
Outboard nacelle centre line from fuselage centreline	6.376 m
Inboard nacelle centre line from fuselage centreline	2.908 m

Figure 4-1 to Figure 4-4 show the geometry model of the V-23.

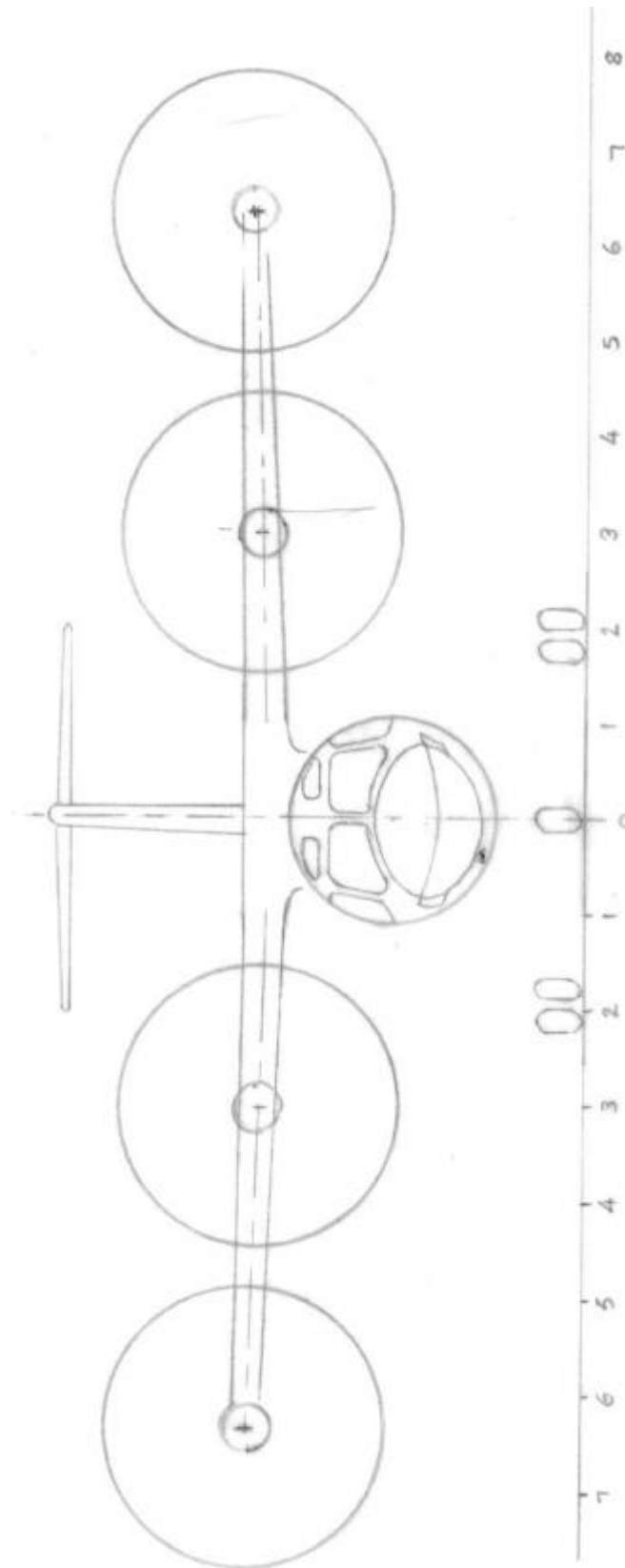


Figure 4-1 V-23 front elevation

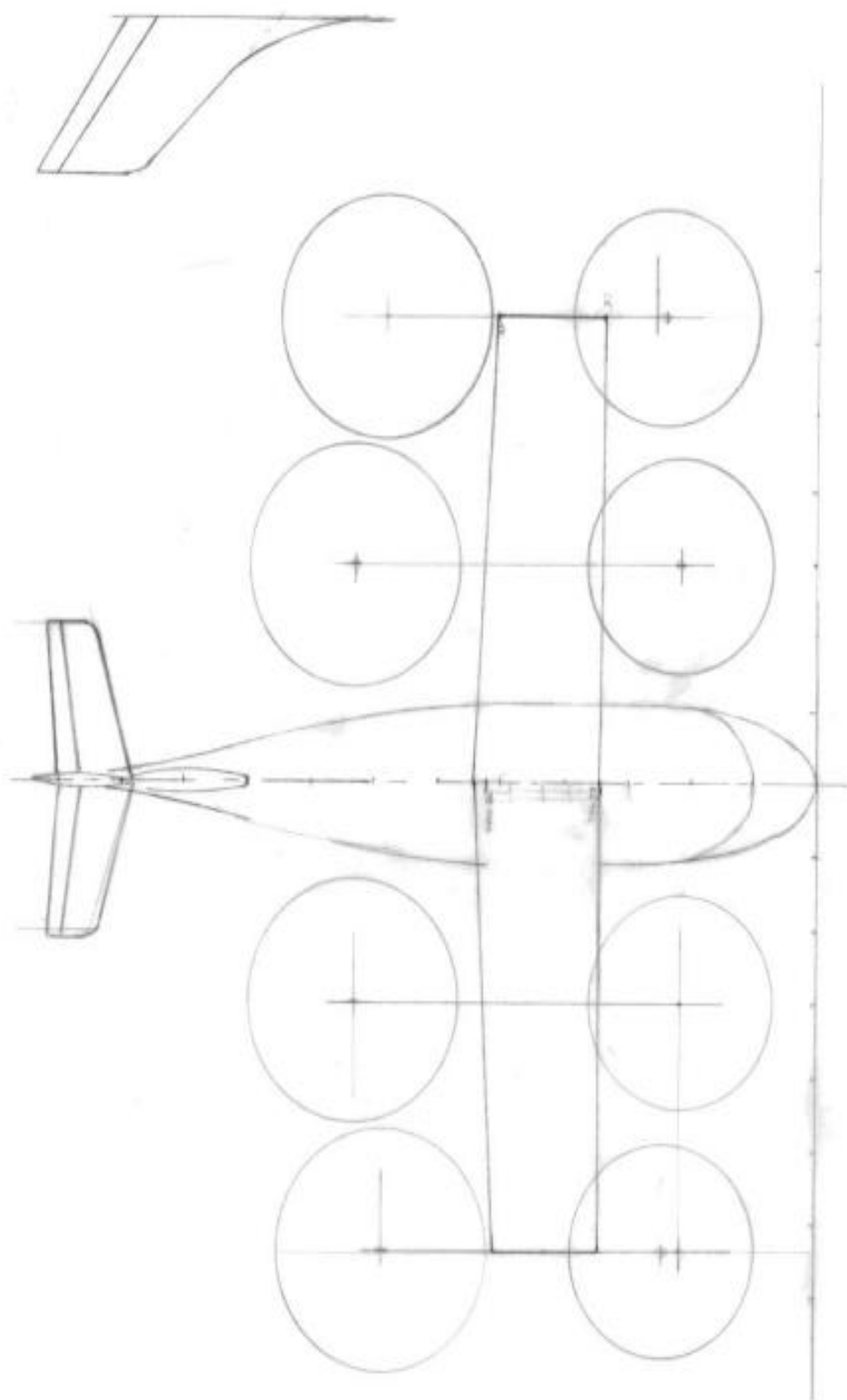


Figure 4-2 V-23 plan view

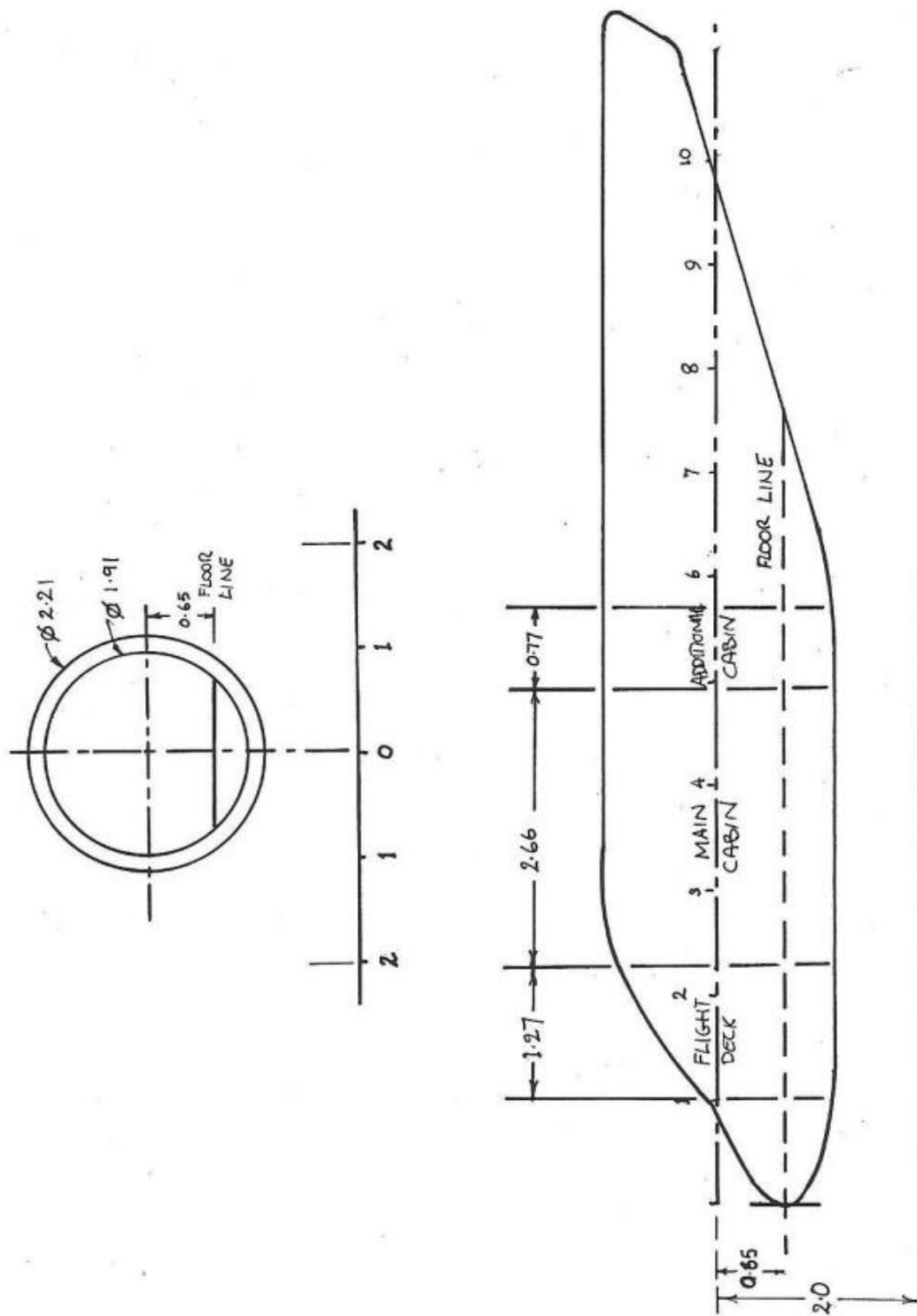


Figure 4-3 V-23 fuselage layout

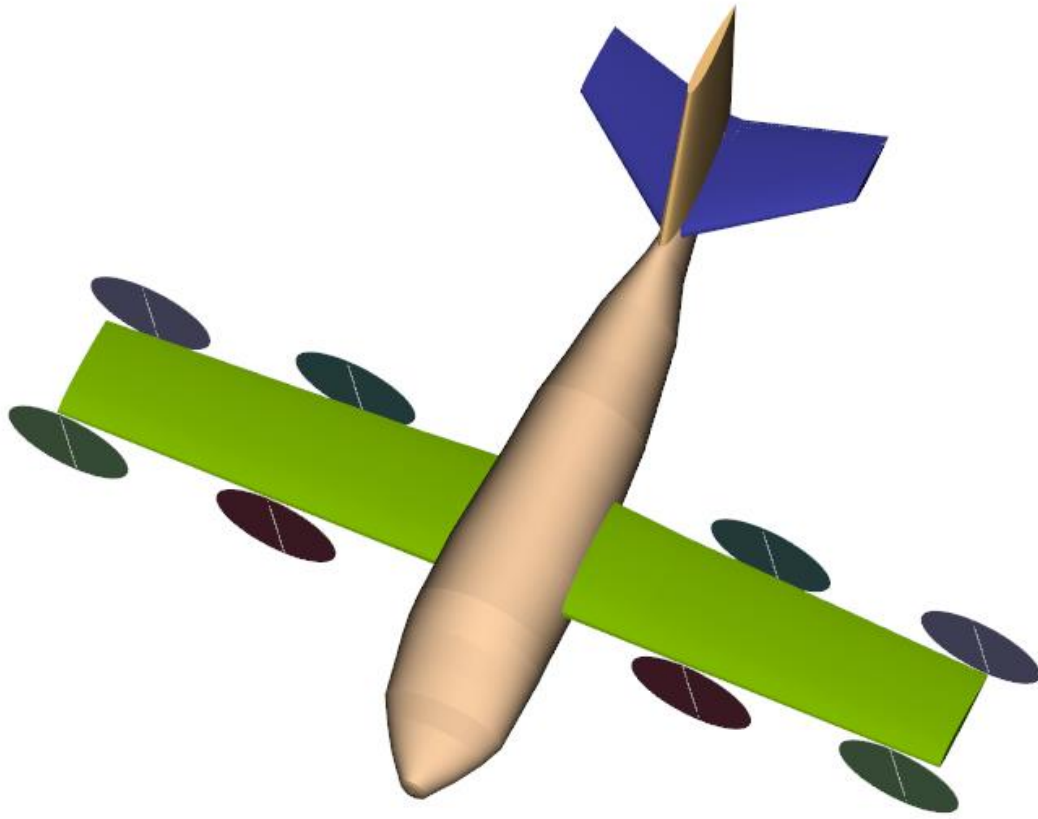


Figure 4-4 V-23 geometry model by GENUS

Different optimization objectives warrant the selection of distinct variables and constraints. For instance, when optimizing the wing model of an eVTOL, geometric variables such as wing dihedral, wing sweep, and wingspan might be chosen for optimization. Constraints are then selected to ensure that the aircraft meets range requirements and that propeller tip speeds remain within prescribed limits. In the case of optimizing the V-23, this study places more emphasis on its MTOM and battery weight. Consequently, the chosen optimization variables include estimated mass and battery mass, while constraints are designed to guarantee the aircraft possesses sufficient energy to fulfil flight requirements. The V-23 optimization setting, and results are listed in Table 4-1.

Where,

$$MTOM\ error = \frac{Estimated\ Mass - MTOM}{MTOM} \quad (4-1)$$

$$\text{Residual Energy} = \text{total energy} * \text{reserve energy ratio} - \text{energy consumption} \quad (4-2)$$

$$\text{Tip speed error} = \begin{cases} 0 & \text{tip speed} < \text{Mach} = 0.9 \\ -1 & \text{tip speed} > \text{Mach} = 0.9 \end{cases} \quad (4-3)$$

Table 4-1 V-23 Optimization Setting and Results

		Initial values	Lower boundary	Upper boundary	Optimization results
Objective	Minimum MTOM	3930.937	-	-	3904.588
Variables	Estimated Mass	4089.2	3000	5000	
	Battery Mass	455.0	300	500	457.573
	Propeller Radius	3.3	2.8	3.8	3.3
Constraints	MTOM error	0.03865	-	-	0
	Residual Energy	-18517.11	-	-	-0.009
	Tip Speed error	0	-	-	0

Table 4-2 shows the mass breakdown data for V-23. Figure 4-5 and Figure 4-6 show the mass data and energy data for V-23.

Table 4-2 Comparison of mass breakdown data for V-23 between V-23, GENUS (before optimization) and GENUS (optimization).

Components	V-23 [kg]	GENUS (before optimization) [kg]	GENUS (optimization) [kg]
Wing	563.8	379.652	365.039
Fuselage	406.5	406.582	397.487
Empennage	69.1	100.287	100.287
Landing gear	262.2	115.138	111.632
FCS	156.6	189.824	189.594
De-ice	37.6	32.726	31.249
ECS	45.4	56	56
Furnishings	99.9	150	150
Avionics	64.3	60	60
Crew	180	180	180
Battery	455	455	457.573
Payload	1107.9	1107.9	1107.9
Powerplant	521.2	595.939	595.939
Electrical system	69.6	37.758	37.758

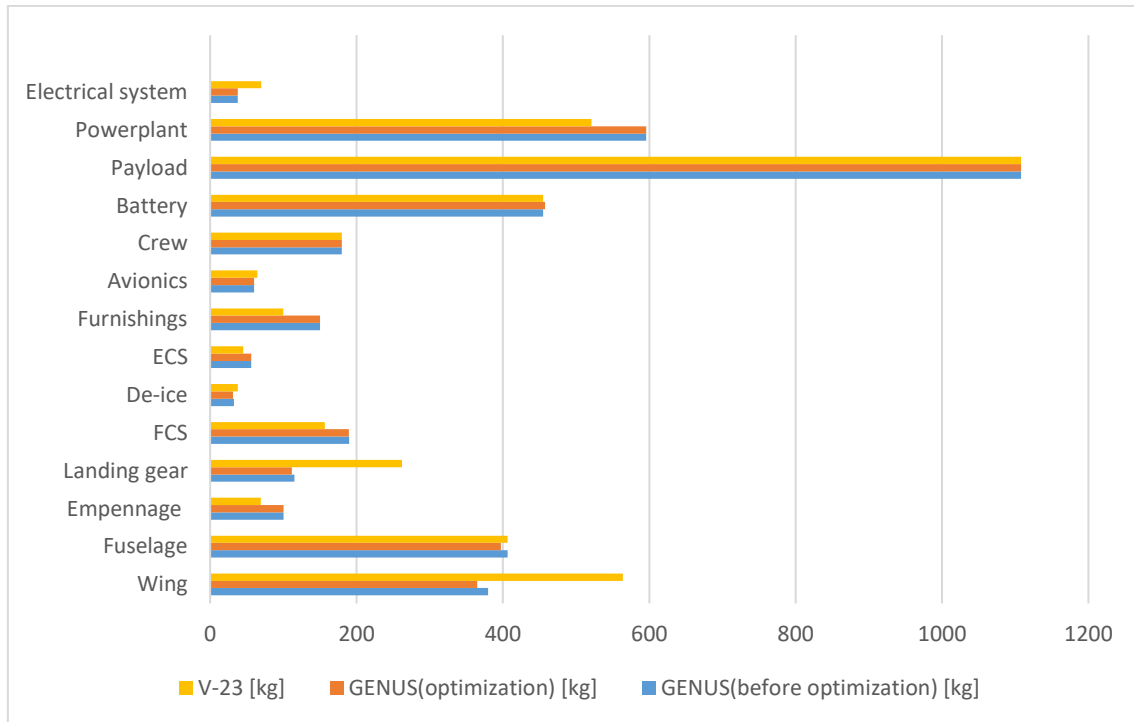


Figure 4-5 Mass breakdown of V-23

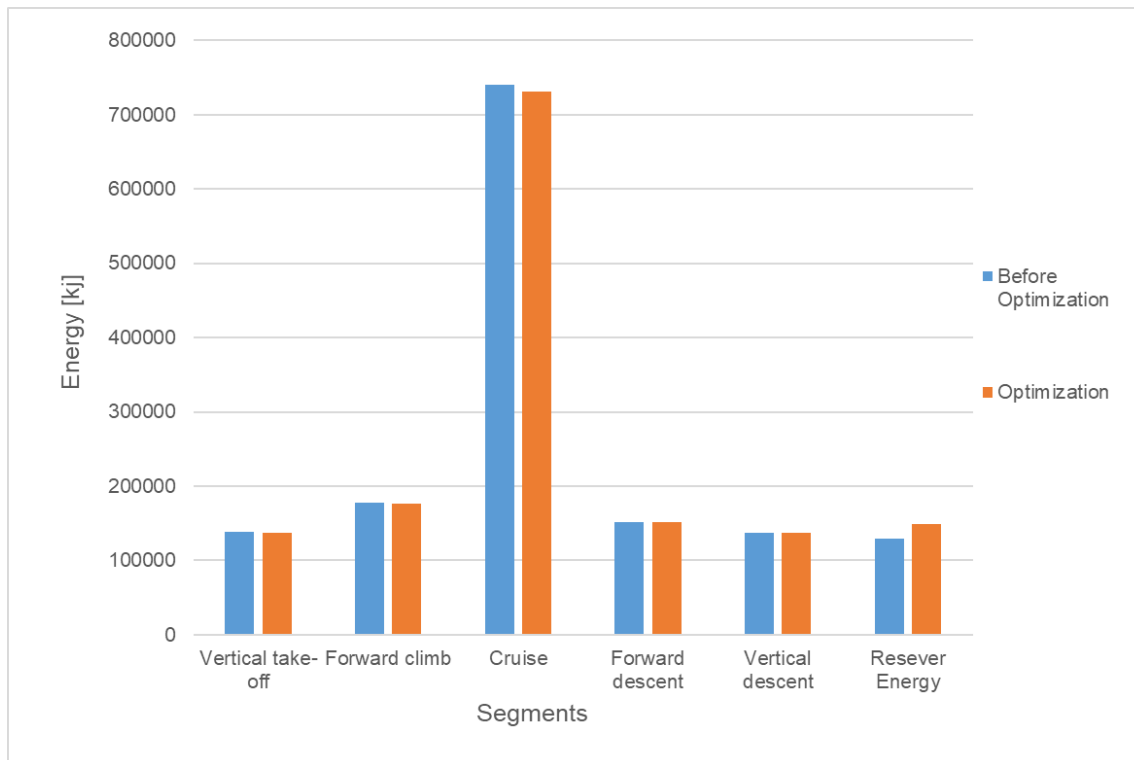


Figure 4-6 Energy consumption by flight regime

5 Vectored Thrust Design Case

Different cruising ranges and cruising speeds are the two most crucial variables in defining the utility of an aircraft as a UAM vehicle. This study also demonstrates design sensitivity to various eVTOL aircraft types, passenger capacities, and battery energy densities. The trade studies conducted are applied to enhance the aircraft's design and performance. The aircraft modelled in this study accommodates passenger capacities ranging from 2 to 20, with a fixed crew of two. Battery energy densities examined vary from 300 Wh/kg to 900 Wh/kg, cruising speeds range from 100 mph to 200 mph, and the aircraft range extends from 50 miles to 200 miles.

In the design case examples presented, each subsequent iteration reflects an increase in passenger capacity, which is comprehensively accounted for across all GENUS modules. This systematic approach ensures that variations in passenger numbers directly influence the associated design parameters, including but not limited to, adjustments in the aircraft's size, weight, and energy requirements. By dynamically incorporating these changes, GENUS enables a detailed analysis of how varying passenger capacities impact the overall design sensitivity, performance metrics, and utility of the aircraft within the UAM context. This holistic integration allows for the exploration of a wide range of design scenarios, from small-scale vehicles carrying 2 passengers to larger configurations accommodating up to 20 passengers, with all related design parameters—such as battery energy density, cruising speed, and range—adjusted accordingly to maintain the aircraft's operational efficacy and efficiency.

5.1.1 Two passengers + Two crew

Gross weight is a critical parameter that must be considered in aircraft design. Figure 5-1 to Figure 5-4 show the gross weight for two-passenger, Vectored Thrust configurations from 300 Wh/kg battery to 900 Wh/kg battery. It is evident that as the battery energy density increases, the aircraft's gross weight significantly decreases. Specifically, when cruising at 200 mph and covering a range of 250 miles, the maximum gross weight drops from 7,544.531 kg at 300

Wh/kg to 4,058.874 kg at 600 Wh/kg, and further declines to 2,947.398 kg at 900 Wh/kg. Similarly, the minimum gross weight decreases from 2,212.642 kg at 300 Wh/kg to 1,857.448 kg at 600 Wh/kg, and then to 1,765.402 kg at 900 Wh/kg.

The aircraft requires substantially less battery weight for shorter ranges and lower speeds compared to longer ranges and higher speeds. Therefore, improvements in battery energy density do not result in proportionately large changes in gross weight for shorter and slower flights. Furthermore, as cruising speed increases, the rate of growth of the gross weight with range also notably escalates. This is due to the increased aerodynamic drag experienced at higher speeds, along with a decline in propeller efficiency as the lift generated by the propeller increases. Consequently, the battery must supply more energy to sustain flight under these conditions.

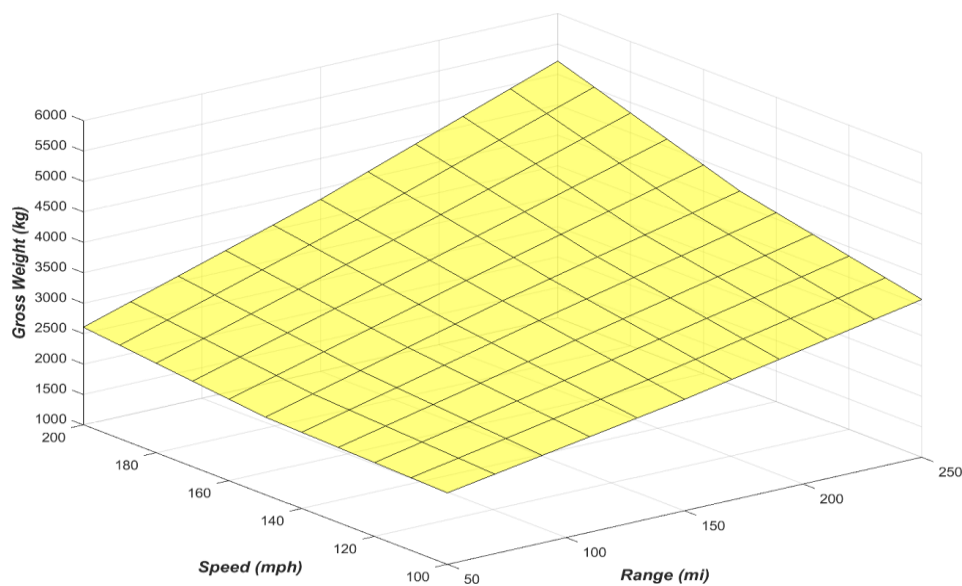


Figure 5-1 Gross weight of Vectored Thrust Configurations: Two-Passenger, 300 Wh/kg Battery

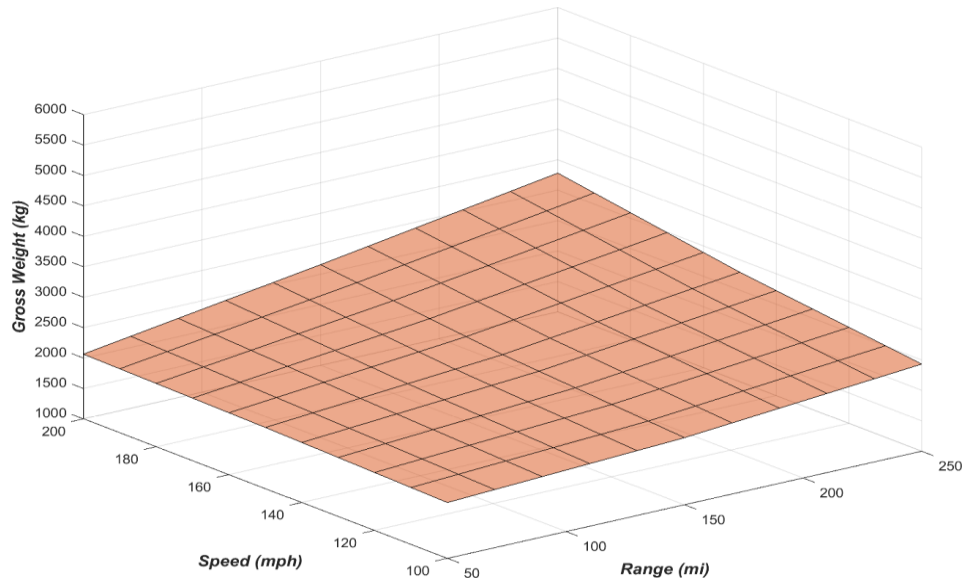


Figure 5-2 Gross weight of Vectored Thrust Configurations: Two-Passenger, 600 Wh/kg Battery

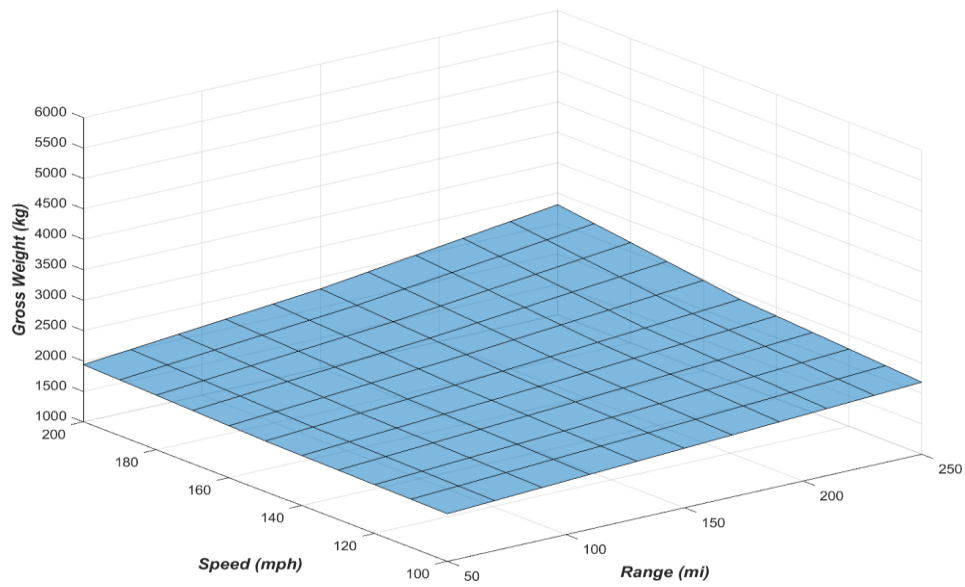


Figure 5-3 Gross weight of Vectored Thrust Configurations: Two-Passenger, 900 Wh/kg Battery

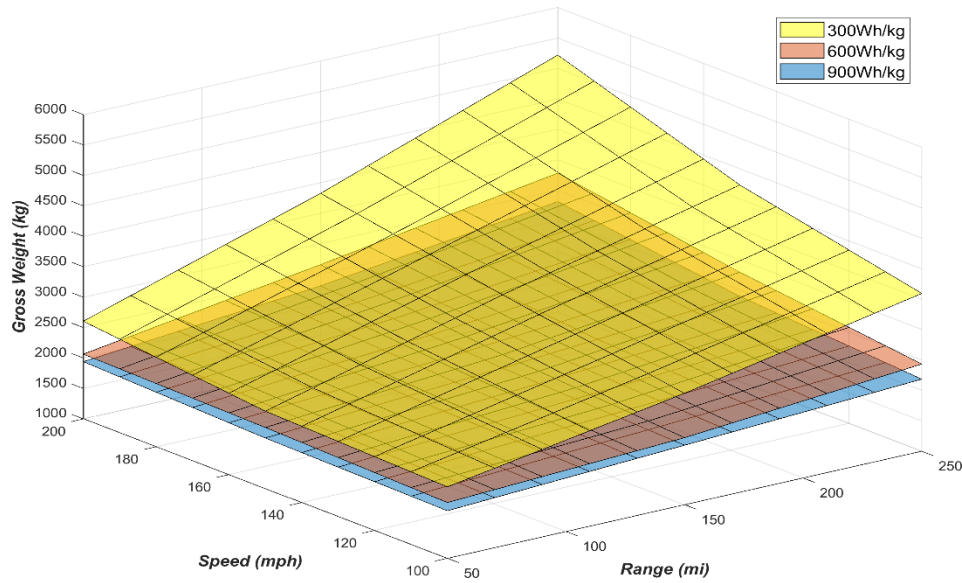


Figure 5-4 Comparison of Gross Weight Across Vectored-Thrust Configurations with 300, 600, and 900 Wh/kg Batteries for Two-Passenger Vehicles

The ratio of battery mass to MTOM is considered a crucial parameter for assessing the feasibility of eVTOL designs. In this study, an upper limit of 50% for this ratio is set, beyond which the eVTOL design is considered unfeasible. Figure 5-5 to Figure 5-7 show the battery mass over MTOM for two-passenger, Vectored Thrust configurations from 300 Wh/kg battery to 900 Wh/kg battery.

As battery energy density increases, a notable reduction in the battery mass over MTOM ratio is observed. At a battery energy density of 300 Wh/kg, the eVTOL remains within the feasible design space for ranges up to 150 miles. However, for ranges extending to 250 miles, the design remains feasible only if the cruising speed is limited to below 135 mph. When the battery energy density is elevated to 600 Wh/kg, all the ranges depicted in the graph fall within the feasible design range, and the maximum battery mass over MTOM ratio is 43.39%. Further, with a battery energy density of 900 Wh/kg, the maximum value for this ratio drops to 32.26%.

This implies that as battery energy density improves, the design space for eVTOL significantly expands, offering greater flexibility and feasibility in design parameters.

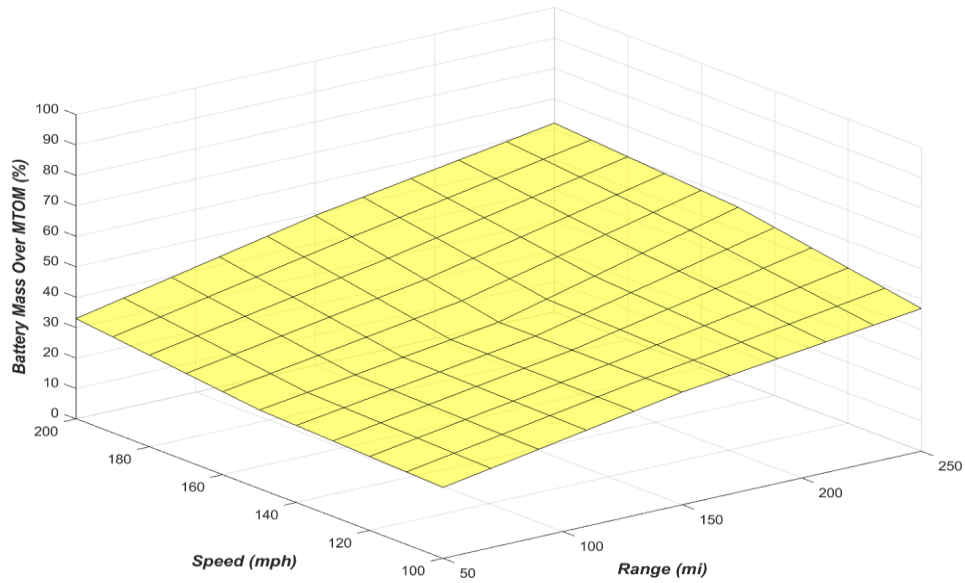


Figure 5-5 Battery mass over MTOM of Vectored Thrust Configurations: Two-Passenger, 300 Wh/kg Battery

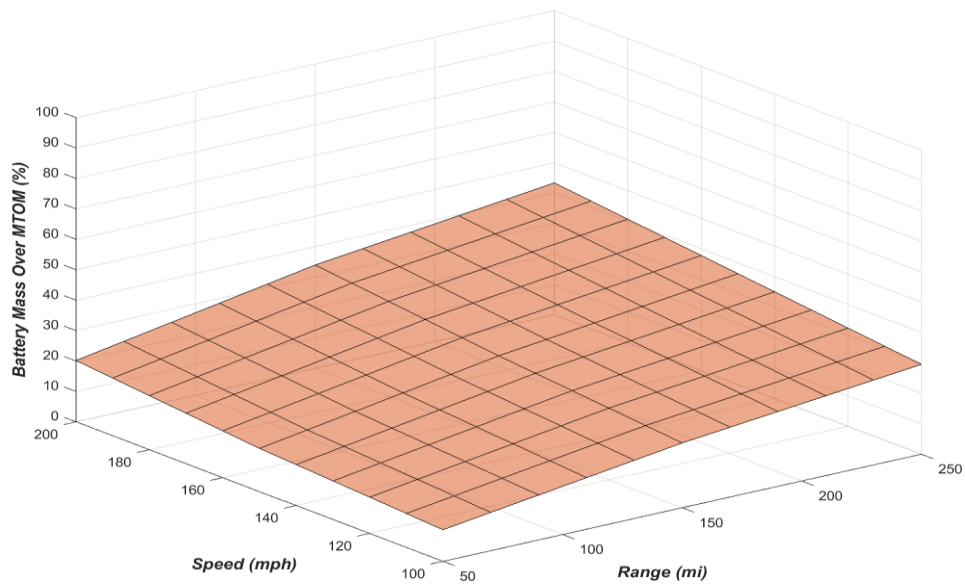


Figure 5-6 Battery mass over MTOM of Vectored Thrust Configurations: Two-Passenger, 600 Wh/kg Battery

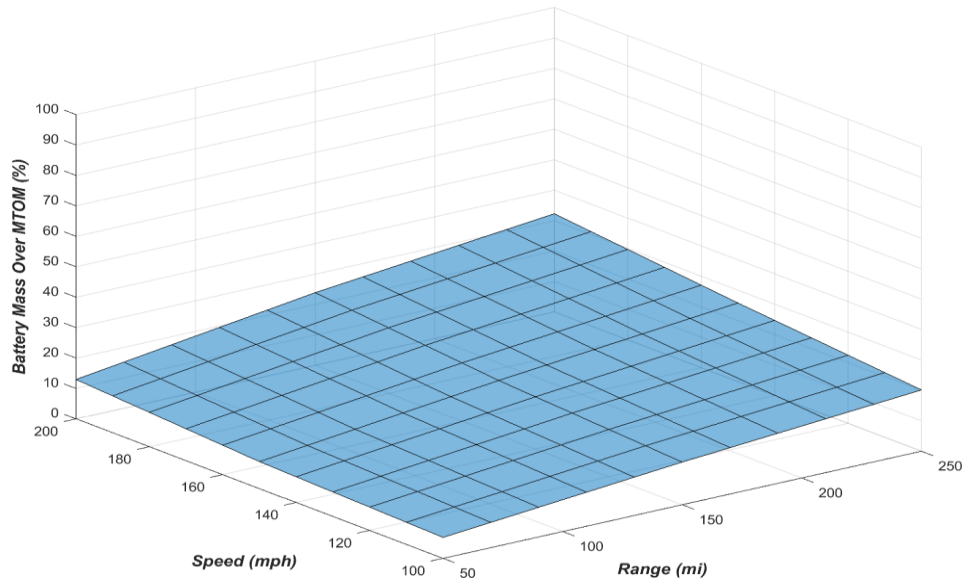


Figure 5-7 Battery mass over MTOM of Vectored Thrust Configurations: Two-Passenger, 900 Wh/kg Battery

Energy consumption is a pivotal metric in the design of eVTOL aircraft. Figure 5-8 to Figure 5-10 show the energy consumption for two-passenger, Vectored Thrust configurations from 300 Wh/kg battery to 900 Wh/kg battery. Since the energy consumption of an aircraft is directly proportional to its gross weight, the observed trends align closely with those for gross weight.

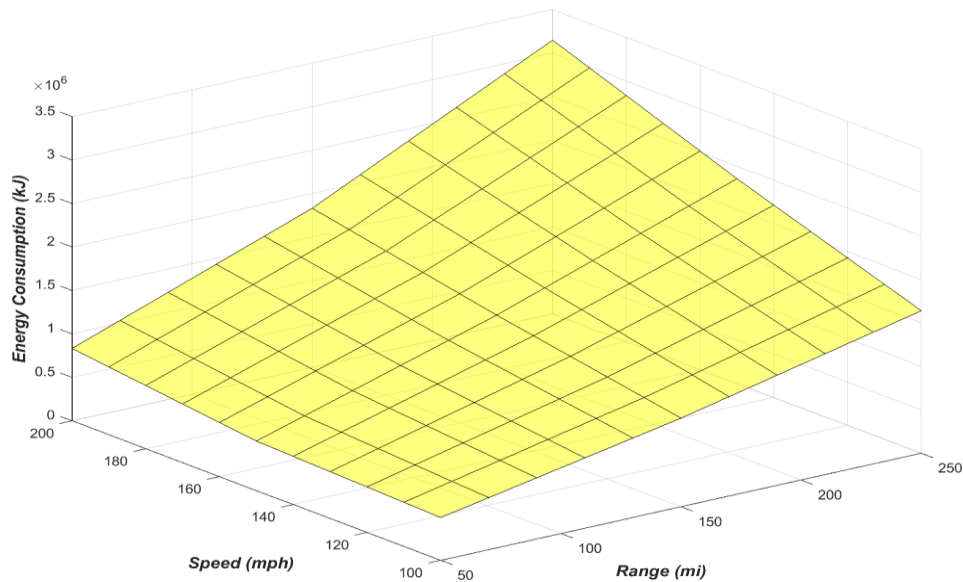


Figure 5-8 Energy consumption of Vectored Thrust Configurations: Two-Passenger, 300 Wh/kg Battery

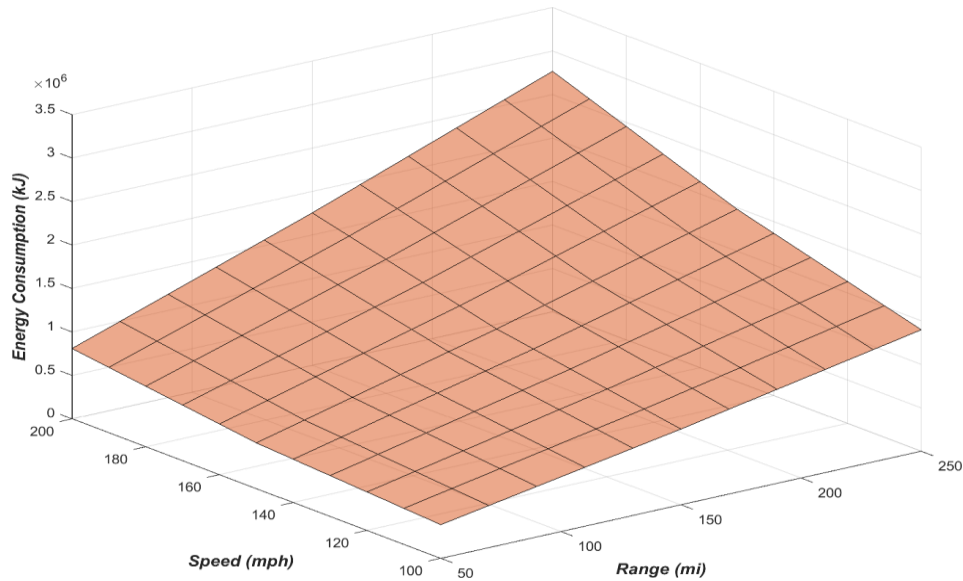


Figure 5-9 Energy consumption of Vectored Thrust Configurations: Two-Passenger, 600 Wh/kg Battery

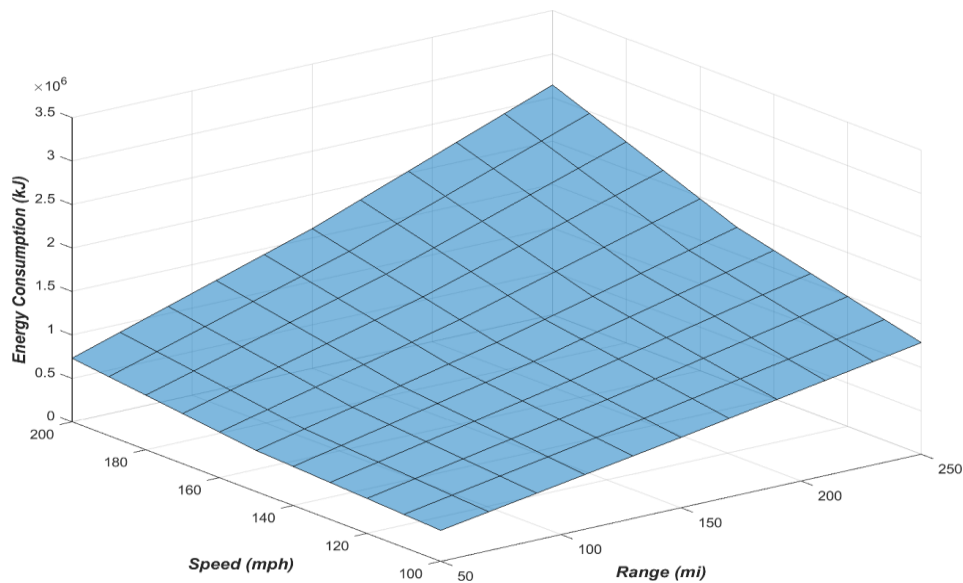


Figure 5-10 Energy consumption of Vectored Thrust Configurations: Two-Passenger, 900 Wh/kg Battery

5.1.2 Eight passengers + Two crew

Given that the design of eVTOL aircraft is targeted for urban air mobility, it is essential to study configurations accommodating varying numbers of passengers. Figure 5-11 to Figure 5-14 show the gross weight for eight-passenger, Vectored Thrust configurations from 300 Wh/kg battery to 900 Wh/kg battery. The overall

trends closely mirror those observed in the two-passenger eVTOL configurations. However, the eight-passenger eVTOL exhibits a substantial increase in gross weight compared to the two-passenger configuration, especially at higher cruising speeds and longer ranges, where the growth rate accelerates. The larger gross weight of the eight-passenger eVTOL contributes to a more pronounced increase in aerodynamic drag and a greater reduction in propeller efficiency as the aircraft's speed increases.

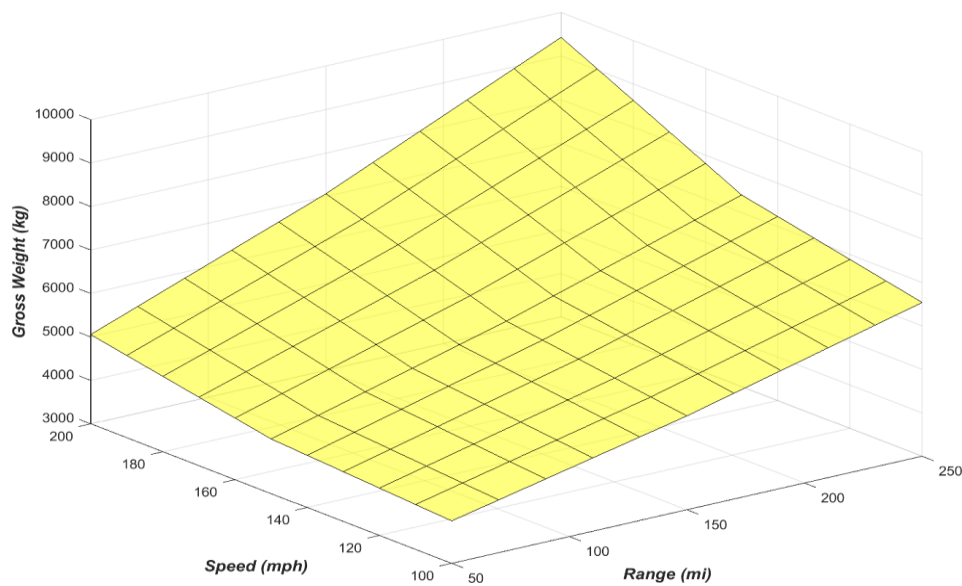


Figure 5-11 Gross weight of Vectored Thrust Configurations: Eight-Passenger, 300 Wh/kg Battery

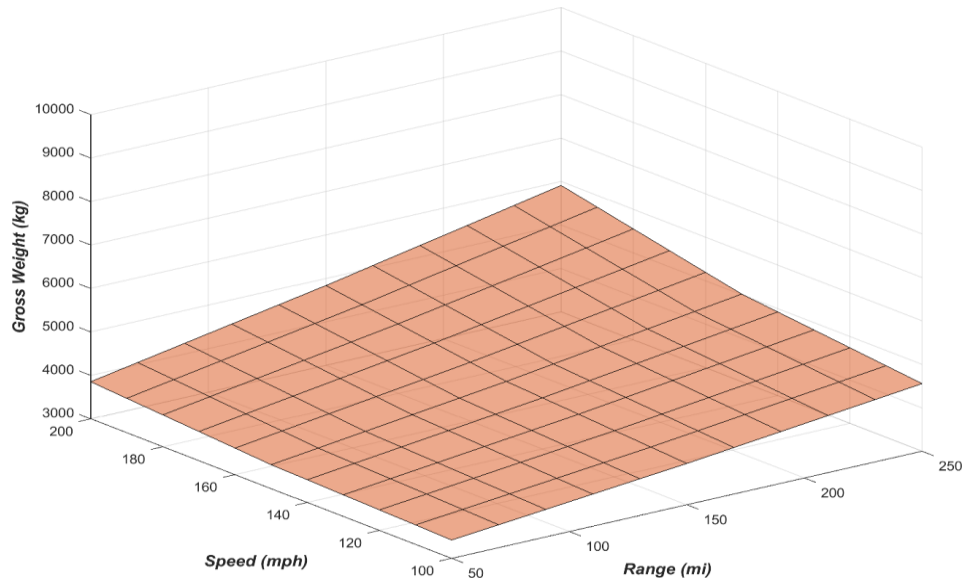


Figure 5-12 Gross weight of Vectored Thrust Configurations: Eight-Passenger, 600 Wh/kg Battery

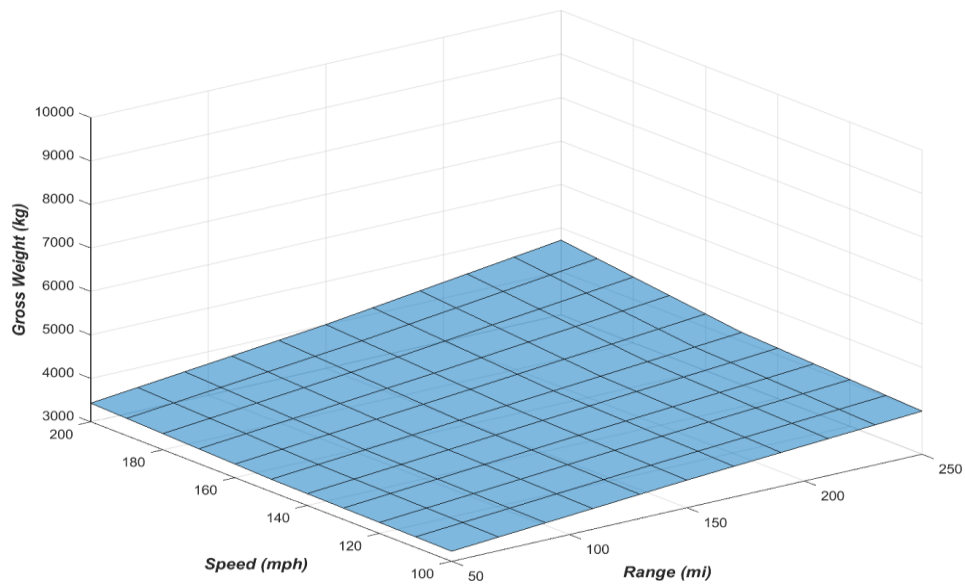


Figure 5-13 Gross weight of Vectored Thrust Configurations: Eight-Passenger, 900 Wh/kg Battery

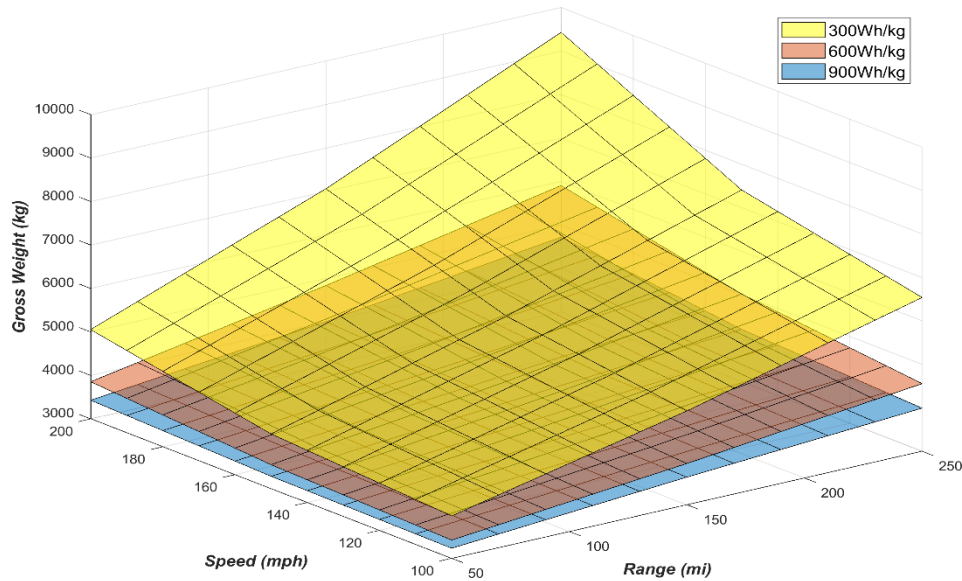


Figure 5-14 Comparison of Gross Weight Across Vectored-Thrust Configurations with 300, 600, and 900 Wh/kg Batteries for Eight-Passenger Vehicles

Figure 5-15 to Figure 5-17 show the battery mass over MTOM for eight-passenger, Vectored Thrust configurations from 300 Wh/kg battery to 900 Wh/kg battery. At a battery energy density of 300 Wh/kg, a range of 150 miles, and a cruising speed of 200 mph, the battery mass over MTOM ratio stands at 49.79%. As the range increases, the flexible cruising speed gradually diminishes; when the range extends to 250 miles, the flexible cruising speed is confined to 120 mph. At a battery energy density of 600 Wh/kg, the maximum value for the battery mass over MTOM ratio is 42.49%. With the battery energy density further increasing to 900 Wh/kg, the maximum value for this ratio drops to 31.54%.

These trends appear to align with those observed in two-passenger aircraft designs. Although the battery mass over MTOM ratio doesn't distinctly differentiate between two-passenger and eight-passenger configurations—given their differing MTOM—it does serve as a valuable metric for assessing the feasibility of aircraft designs and can be used as a reference by designers.

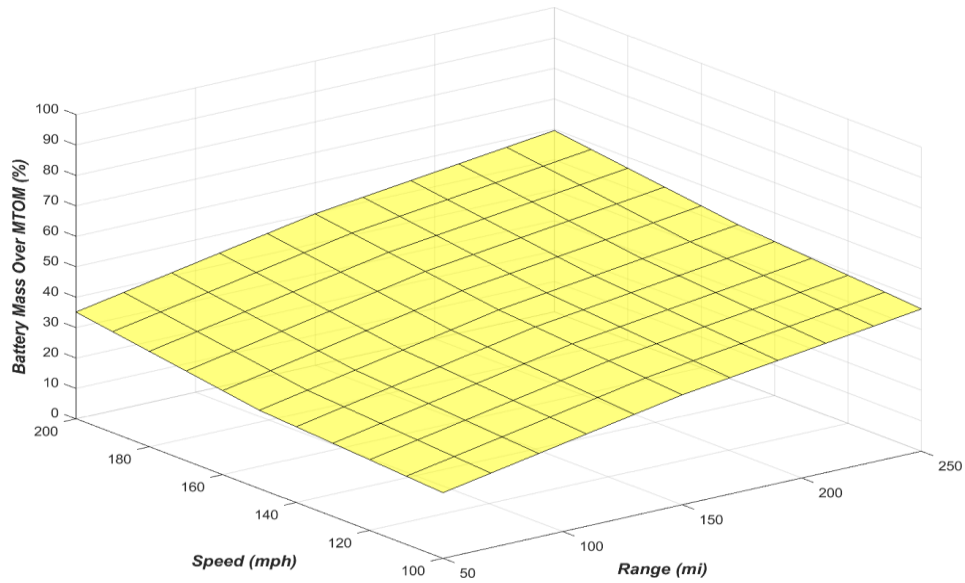


Figure 5-15 Battery mass over MTOM of Vectored Thrust Configurations: Eight-Passenger, 300 Wh/kg Battery

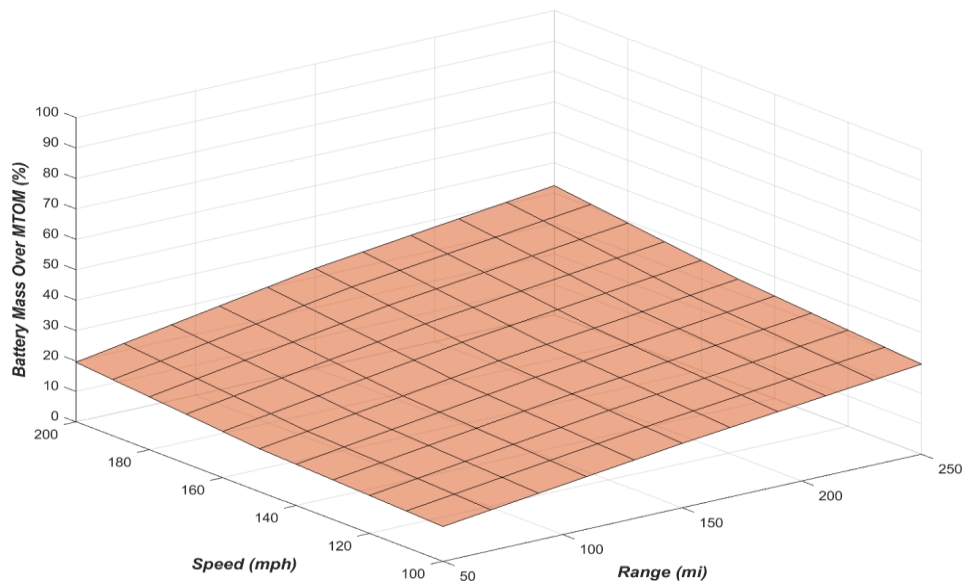


Figure 5-16 Battery mass over MTOM of Vectored Thrust Configurations: Eight-Passenger, 600 Wh/kg Battery

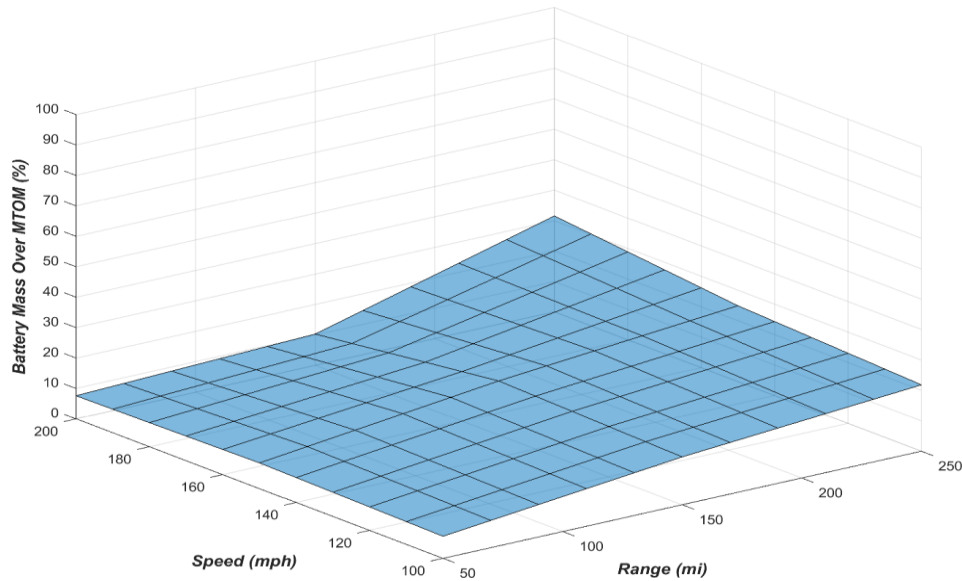


Figure 5-17 Battery mass over MTOM of Vectored Thrust Configurations: Eight-Passenger, 900 Wh/kg Battery

Figure 5-18 to Figure 5-20 show the energy consumption for eight-passenger, Vectored Thrust configurations from 300 Wh/kg battery to 900 Wh/kg battery. While the battery mass over MTOM ratio may not clearly delineate the differences between two-passenger and eight-passenger aircraft configurations, energy consumption does provide a more distinct differentiation between the two. Notably, there is a pronounced uptrend in energy consumption at higher cruising speeds and longer ranges. However, this trend shows signs of mitigation as the battery energy density increases.

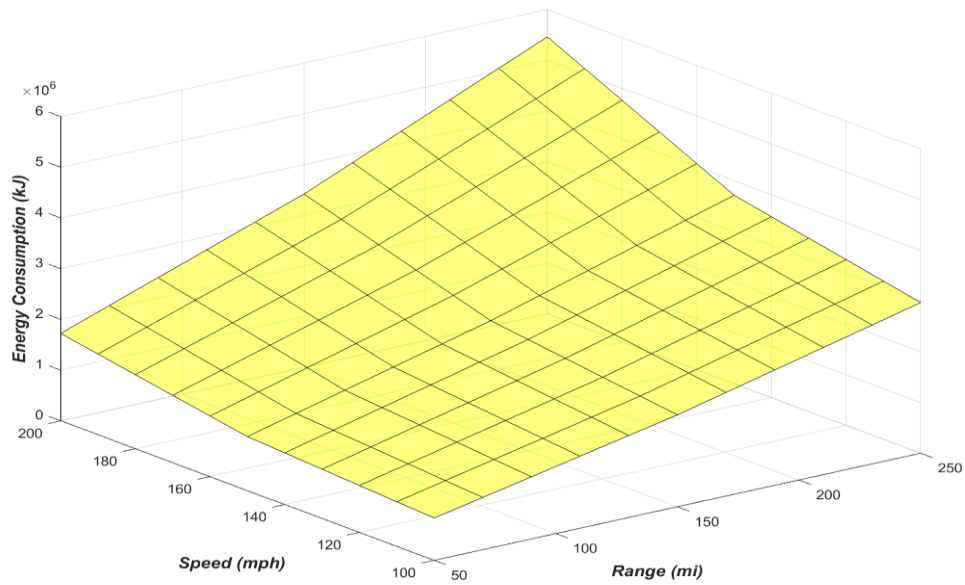


Figure 5-18 Energy consumption of Vectored Thrust Configurations: Eight-Passenger, 300 Wh/kg Battery

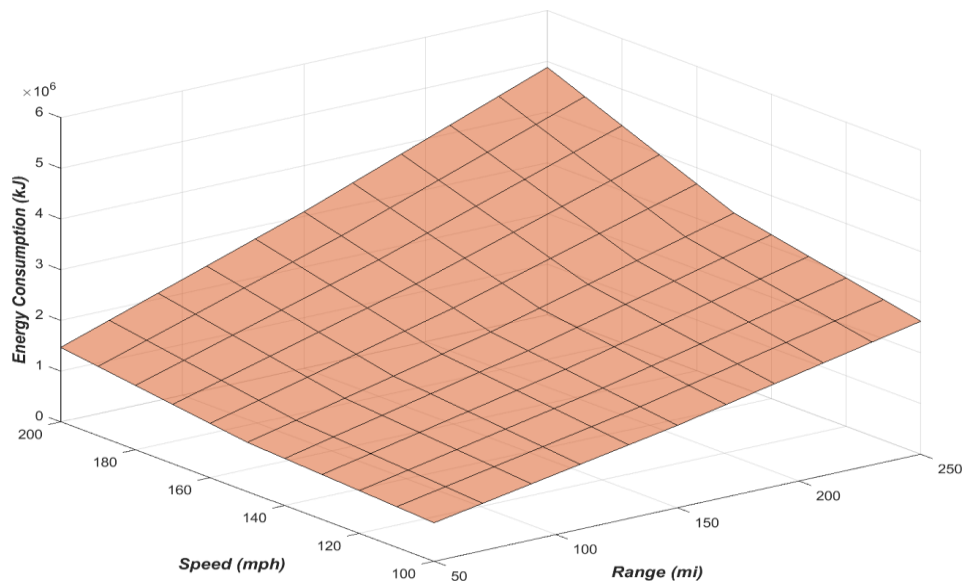


Figure 5-19 Energy consumption of Vectored Thrust Configurations: Eight-Passenger, 600 Wh/kg Battery

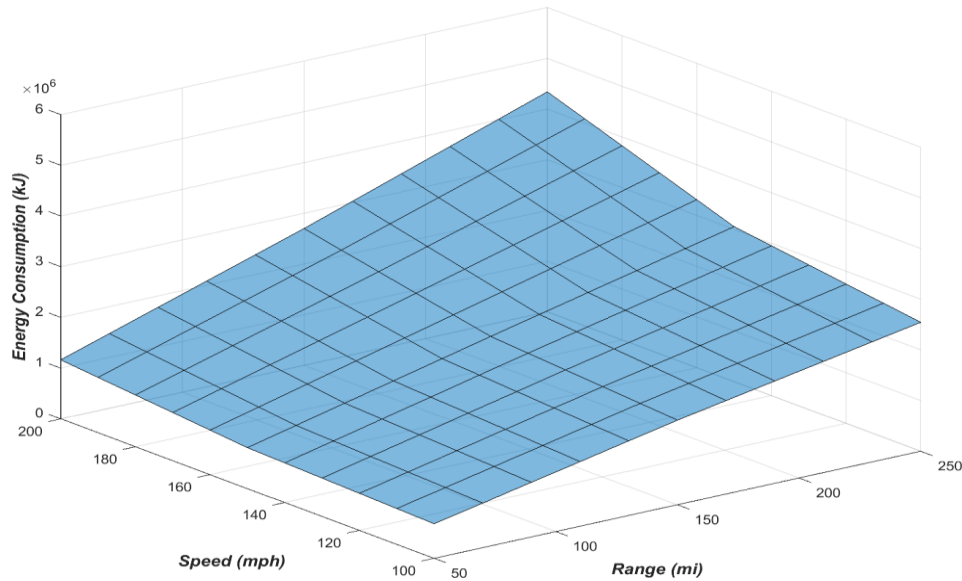


Figure 5-20 Energy consumption of Vectored Thrust Configurations: Eight-Passenger, 900 Wh/kg Battery

5.1.3 Twenty passengers + Two crew

Figure 5-21 to Figure 5-24 show the gross weight for twenty-passenger, Vectored Thrust configurations from 300 Wh/kg battery to 900 Wh/kg battery. The trend in gross weight changes for twenty-passenger configurations is similar to those observed for both two-passenger and eight-passenger configurations. However, the rate of increase in gross weight is more pronounced with higher cruising speeds and longer ranges. This can be attributed to the fact that the twenty-passenger aircraft has a larger gross weight compared to the other two configurations, leading to faster increases in aerodynamic drag and more significant reductions in propeller efficiency as speed increases. Additionally, the gross weight of the twenty-passenger aircraft decreases more rapidly with improvements in battery energy density.

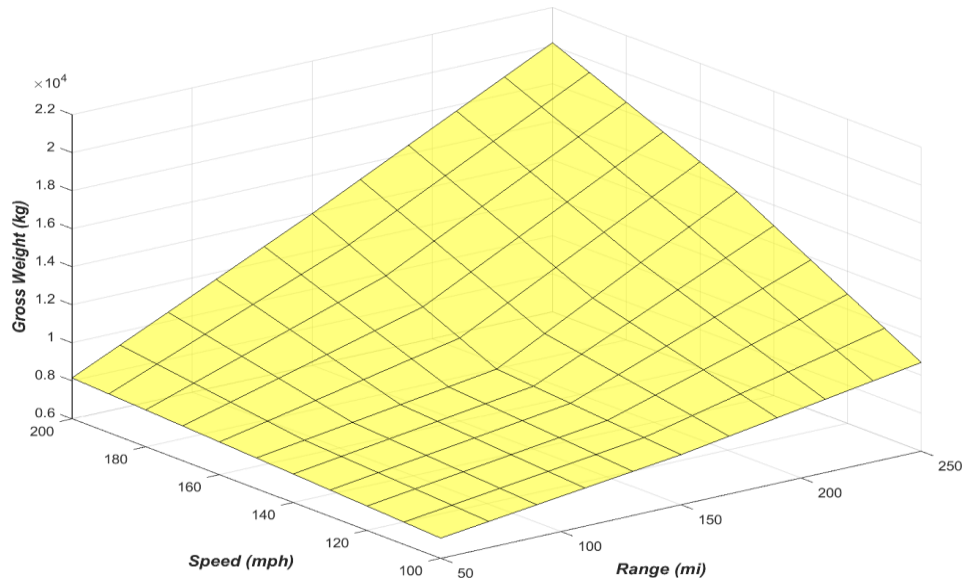


Figure 5-21 Gross weight of Vectored Thrust Configurations: Twenty-Passenger, 300 Wh/kg Battery

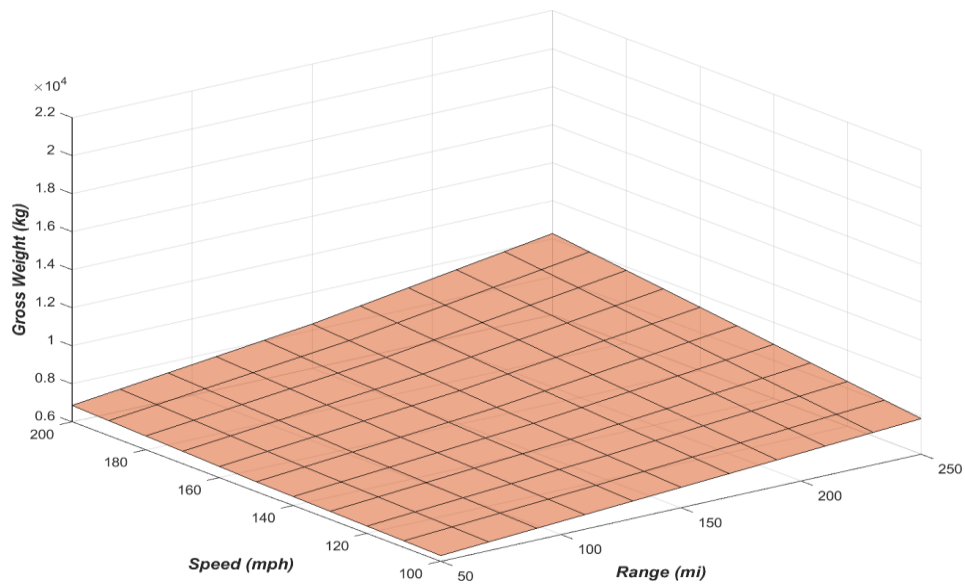


Figure 5-22 Gross weight of Vectored Thrust Configurations: Twenty-Passenger, 600 Wh/kg Battery

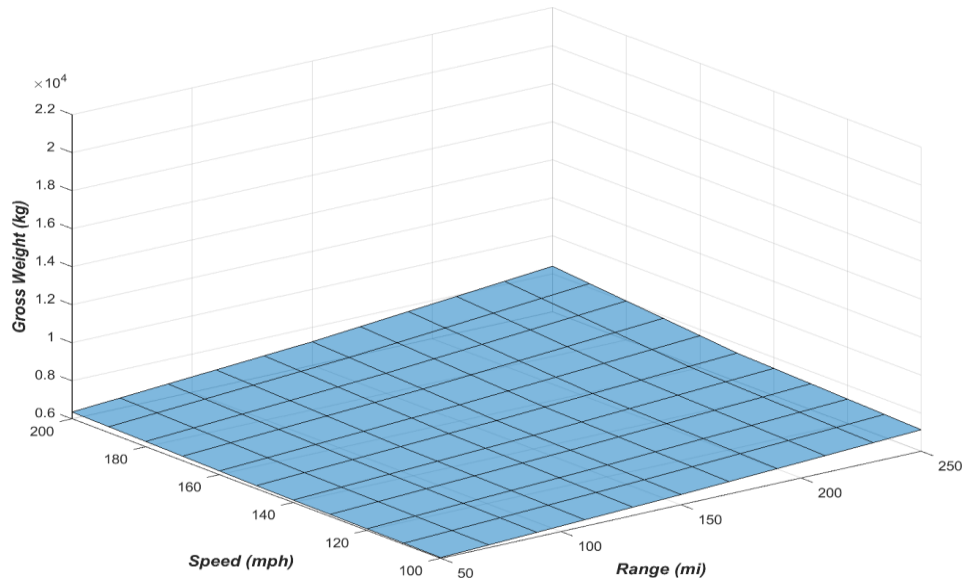


Figure 5-23 Gross weight of Vectored Thrust Configurations: Twenty-Passenger, 900 Wh/kg Battery

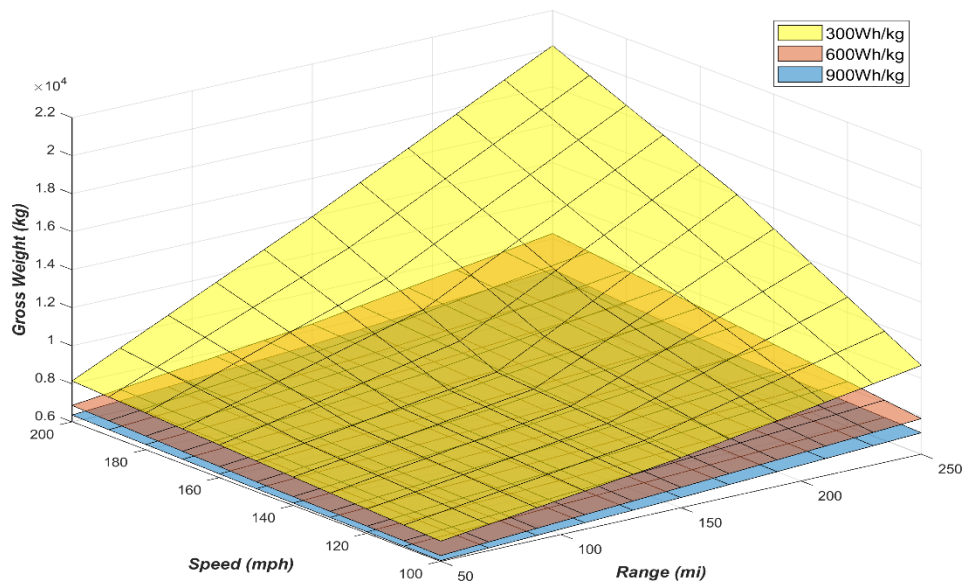


Figure 5-24 Comparison of Gross Weight Across Vectored-Thrust Configurations with 300, 600, and 900 Wh/kg Batteries for Twenty-Passenger Vehicles

Figure 5-25 to Figure 5-27 show the battery mass over MTOM for twenty-passenger, Vectored Thrust configurations from 300 Wh/kg battery to 900 Wh/kg battery. With a battery energy density of 300 Wh/kg, aircraft designs are deemed feasible for a range of up to 50 miles. However, when the range is extended to 150 miles, the cruising speed is capped at 180 mph. At an even greater range of 250 miles, the cruising speed becomes restricted to 125 mph. When the battery

energy density increases to 600 Wh/kg, the maximum value for the battery mass over Maximum Takeoff Mass (MTOM) ratio stands at 39.36%. With further improvement in battery energy density to 900 Wh/kg, this maximum value reduces to 28.46%.

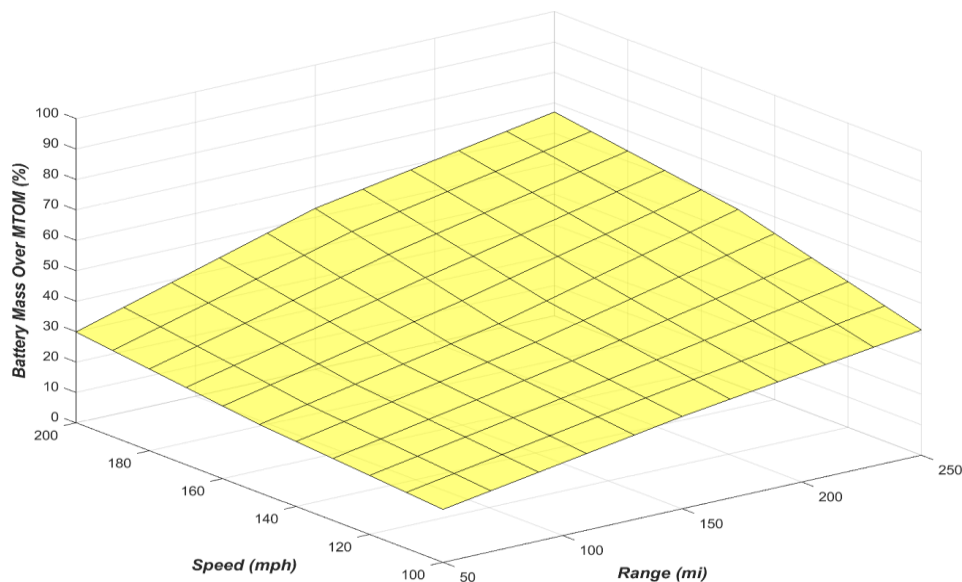


Figure 5-25 Battery mass over MTOM of Vectored Thrust Configurations: Twenty-Passenger, 300 Wh/kg Battery

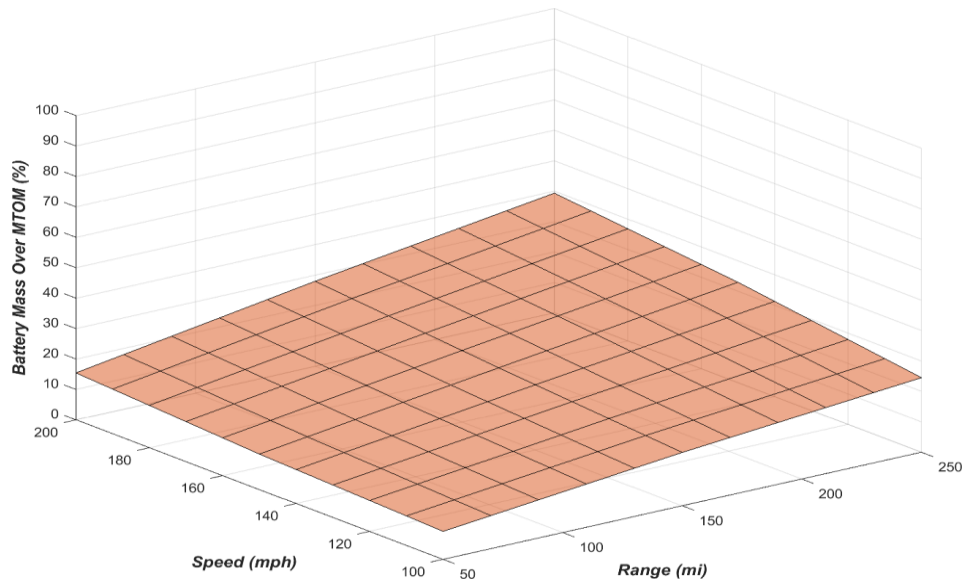


Figure 5-26 Battery mass over MTOM of Vectored Thrust Configurations: Twenty-Passenger, 600 Wh/kg Battery

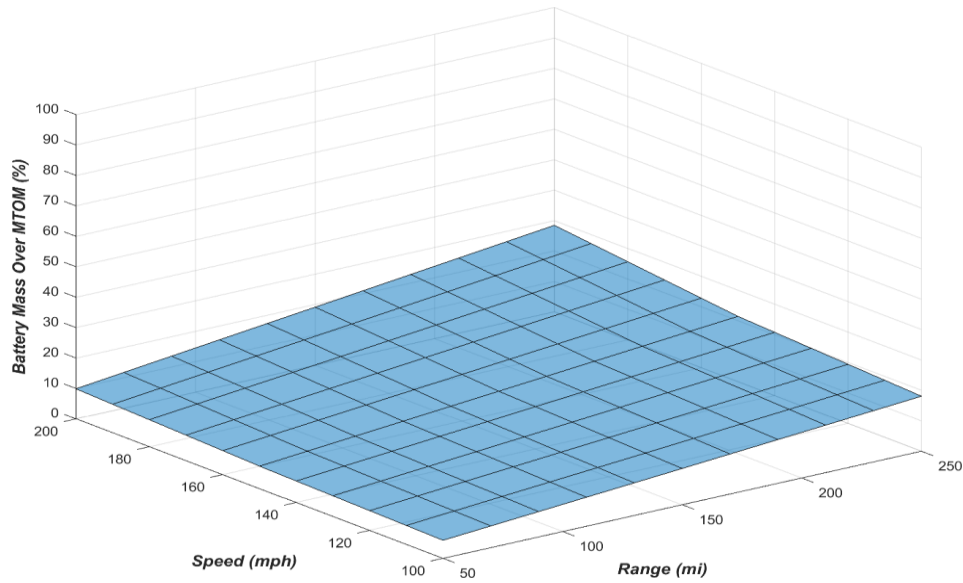


Figure 5-27 Battery mass over MTOM of Vectored Thrust Configurations: Twenty-Passenger, 900 Wh/kg Battery

Figure 5-28 to Figure 5-30 show the energy consumption for twenty-passenger, Vectored Thrust configurations from 300 Wh/kg battery to 900 Wh/kg battery. It is evident that the rate of increase in energy consumption accelerates with higher speeds and longer ranges. However, this accelerating trend in energy consumption is significantly mitigated as battery energy density improves.

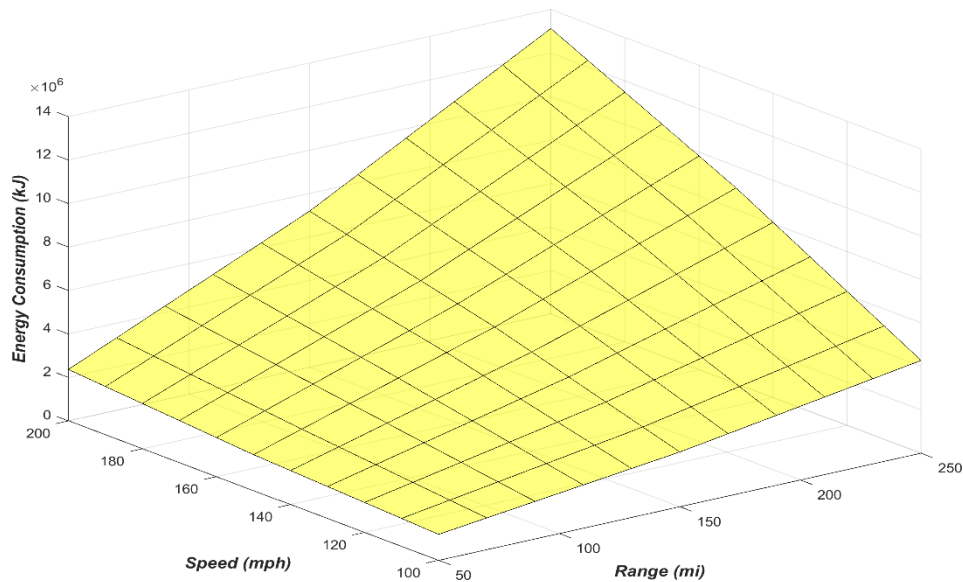


Figure 5-28 Energy consumption of Vectored Thrust Configurations: Twenty-Passenger, 300 Wh/kg Battery

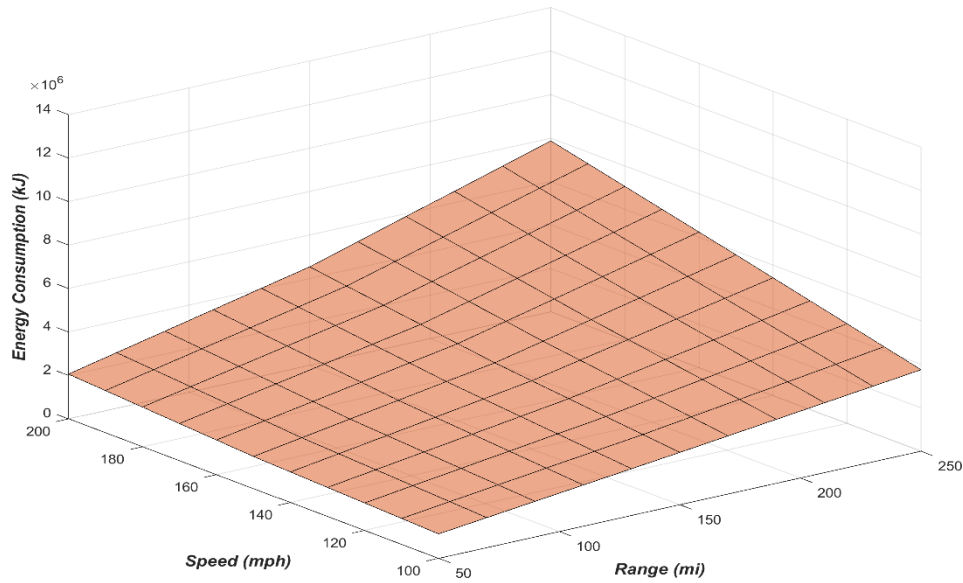


Figure 5-29 Energy consumption of Vectored Thrust Configurations: Twenty-Passenger, 600 Wh/kg Battery

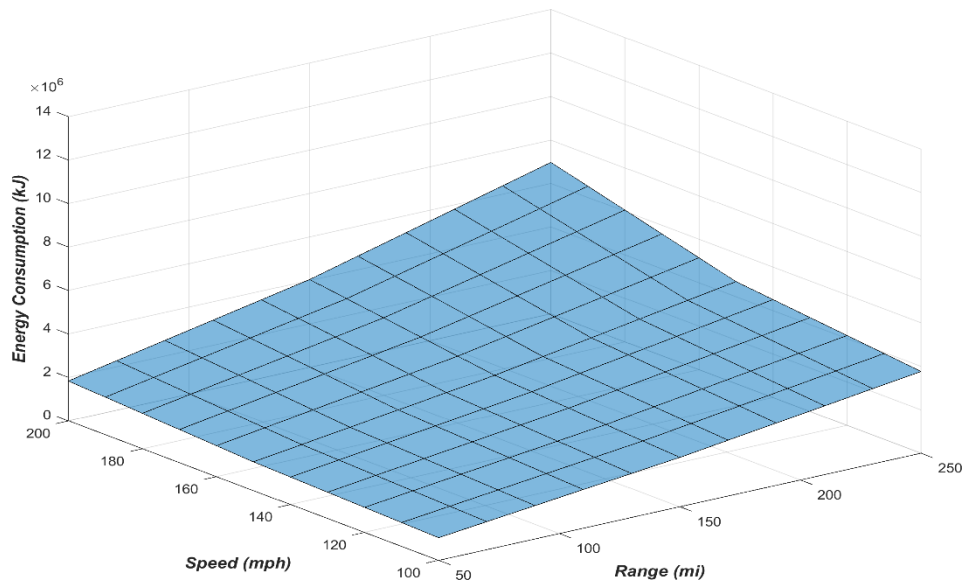


Figure 5-30 Energy consumption of Vectored Thrust Configurations: Twenty-Passenger, 900 Wh/kg Battery

5.1.4 Conclusion

The study illustrates that as speed and range increase, the gross weight of eVTOL configurations shows a noticeable upswing. This rate of increase in gross weight is accentuated with longer ranges, particularly as cruising speeds climb.

Additionally, as the number of passengers rises, the trend of increasing gross weight becomes even more pronounced. However, improvements in battery energy density substantially mitigate this escalating trend in gross weight.

Owing to the direct correlation between gross weight and energy consumption, fluctuations in the former are more lucidly observed in energy consumption metrics. Battery energy density emerges as a pivotal factor influencing the feasible design range and performance parameters across various eVTOL configurations. Higher energy density batteries positively affect the eVTOL design envelope, extending possible flight distances and increasing achievable speeds. Concurrently, boosting battery energy density leads to reductions in the battery mass over MTOM ratio, thereby improving the overall efficiency and payload capacity of eVTOL aircraft.

Distinct eVTOL configurations—namely two-passenger, eight-passenger, and twenty-passenger—exhibit diverging trends in terms of feasibility, heavily influenced by battery energy density and gross weight. This insight can inform future efforts aimed at optimizing eVTOL designs for urban air mobility, considering speed, range, passenger capacity, and energy efficiency.

This conclusion effectively encapsulates the critical takeaways from the study, highlighting the influence of speed, range, and battery energy density on the gross weight and overall feasibility of various eVTOL configurations.

6 Lift + Cruise Design Case

6.1.1 Two passengers + Two crew

Figure 6-1 to Figure 6-4 show the gross weight for two-passenger, Lift + Cruise configurations from 300 Wh/kg battery to 900 Wh/kg battery. The trends observed in the gross weight of Lift + Cruise configurations are largely congruent with those in Vectored Thrust configurations. As both cruising speed and range increase, there is an amplified trend of increasing gross weight. Importantly, advancements in battery energy density have been shown to be highly effective in reducing the gross weight of the aircraft.

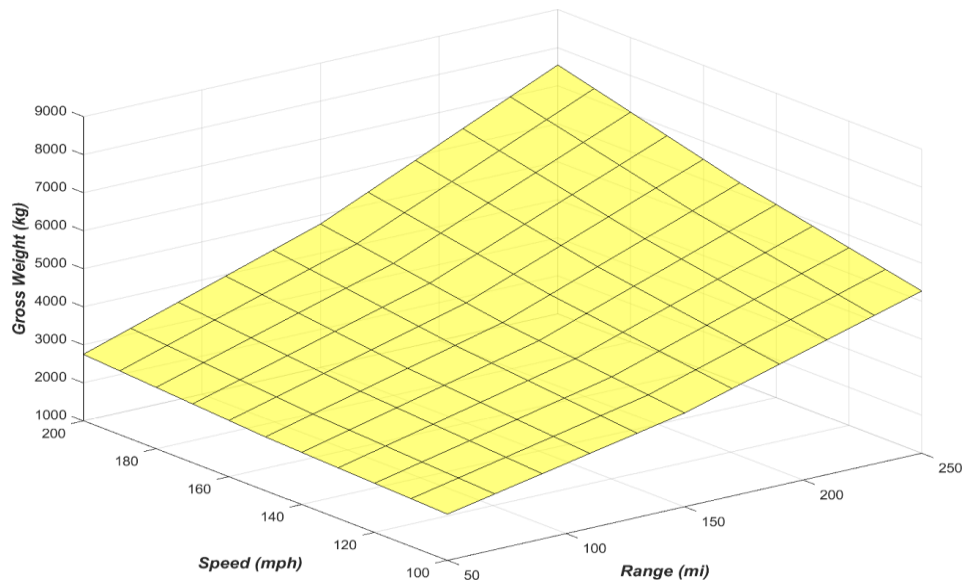


Figure 6-1 Gross weight of Lift + Cruise Configurations: Two-Passenger, 300 Wh/kg Battery

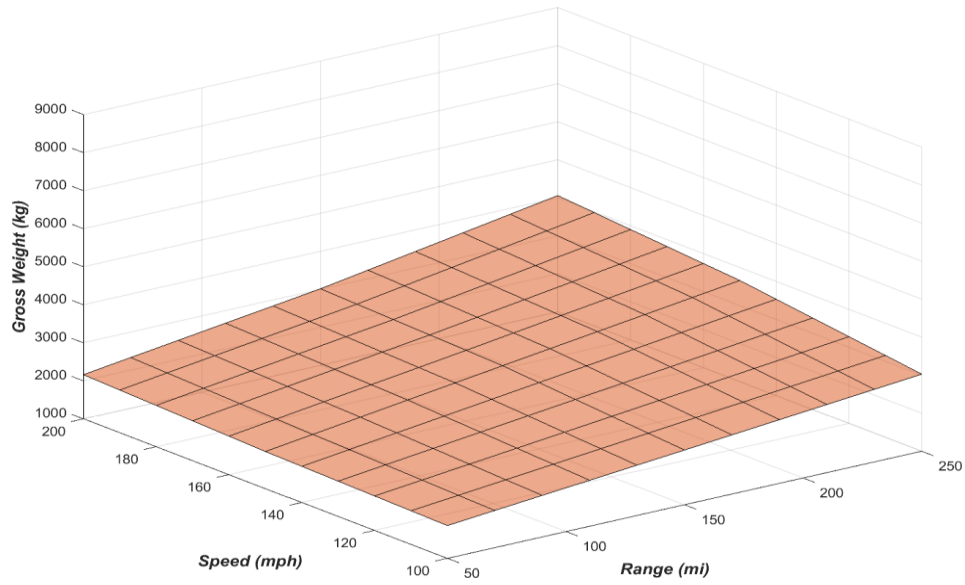


Figure 6-2 Gross weight of Lift + Cruise Configurations: Two-Passenger, 600 Wh/kg Battery

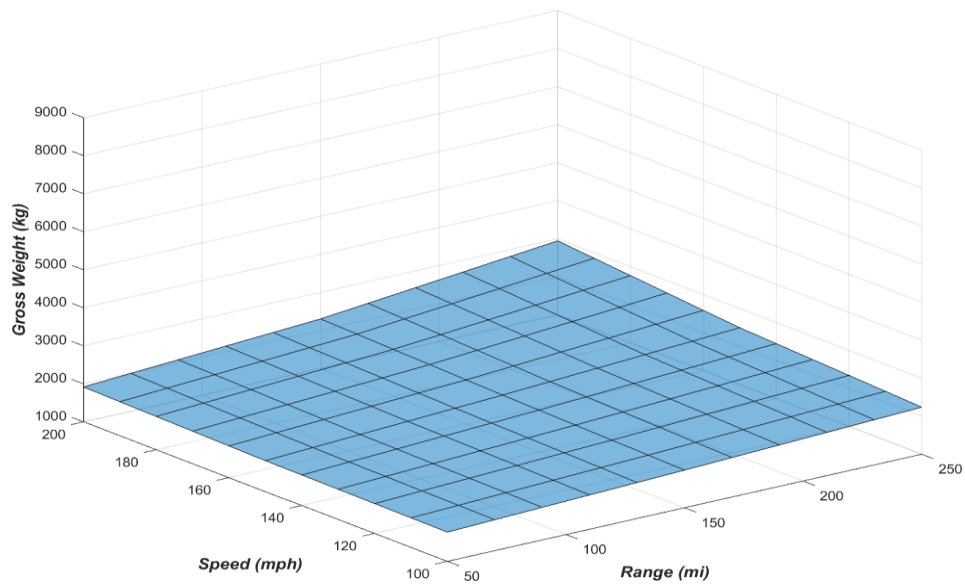


Figure 6-3 Gross weight of Lift + Cruise Configurations: Two-Passenger, 900 Wh/kg Battery

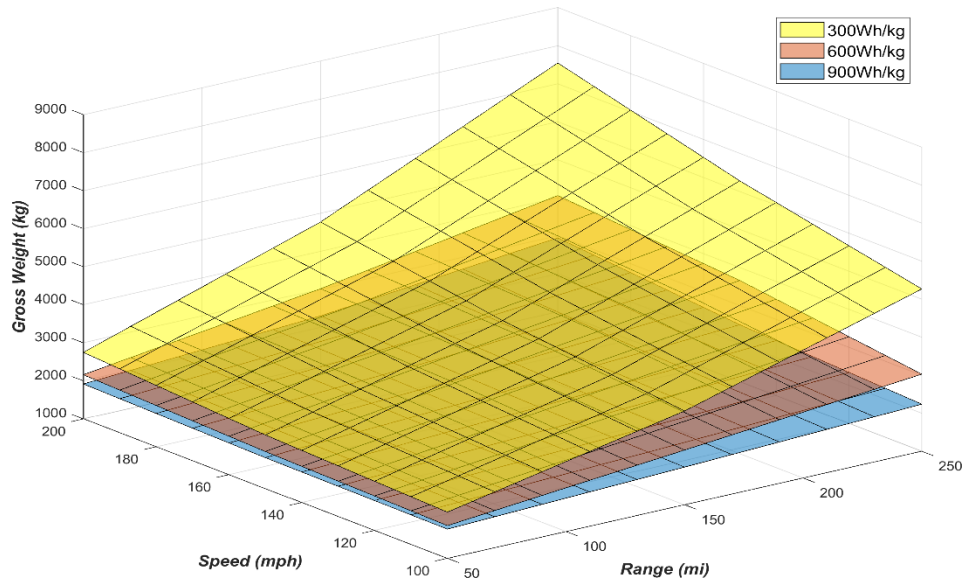


Figure 6-4 Comparison of Gross Weight Across Lift + Cruise Configurations with 300, 600, and 900 Wh/kg Batteries for Two-Passenger Vehicles

Figure 6-1 to Figure 6-3 show the battery mass over MTOM for two-passenger, Lift + Cruise configurations from 300 Wh/kg battery to 900 Wh/kg battery. With a battery energy density of 300 Wh/kg and an operational range of 50 miles at a cruising speed of 200 mph, the battery mass to MTOM ratio is calculated to be 33.28%. However, when the range extends to 130 miles at the same cruising speed, this ratio surpasses the 50% threshold, which is considered to be the limit of feasibility for eVTOL design. As the range further increases, a decline in the allowable cruising speed is observed. Specifically, at a range of 250 miles and a reduced cruising speed of 100 mph, the battery mass to MTOM ratio escalates to 57.31%.

Upon increasing the battery energy density to 600 Wh/kg, the maximum observed battery mass to MTOM ratio is limited to 49.66%. This improves further when the battery energy density is enhanced to 900 Wh/kg, where the maximum value of the battery mass to MTOM ratio is confined to 36.64%.

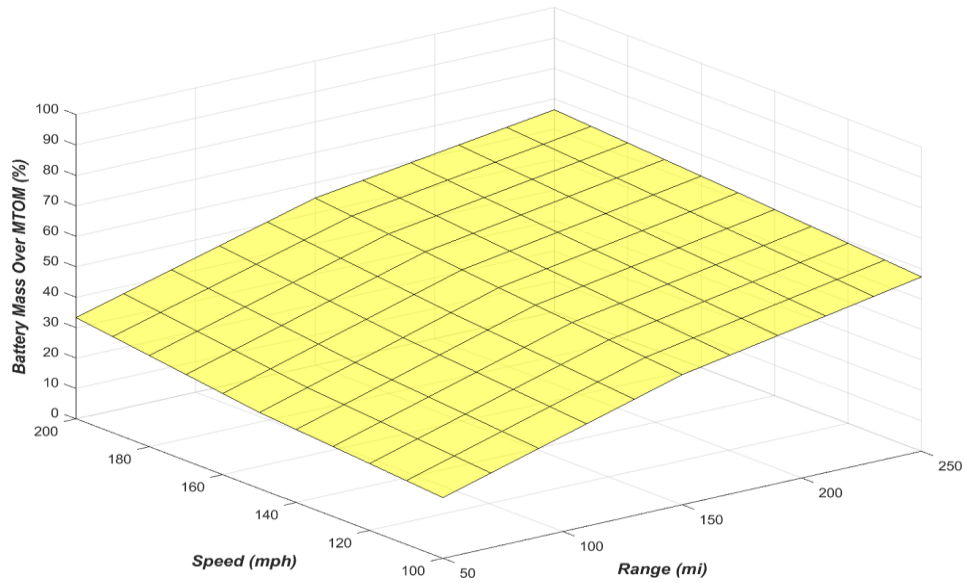


Figure 6-5 Battery mass over MTOM of Lift + Cruise Configurations: Two-Passenger, 300 Wh/kg Battery

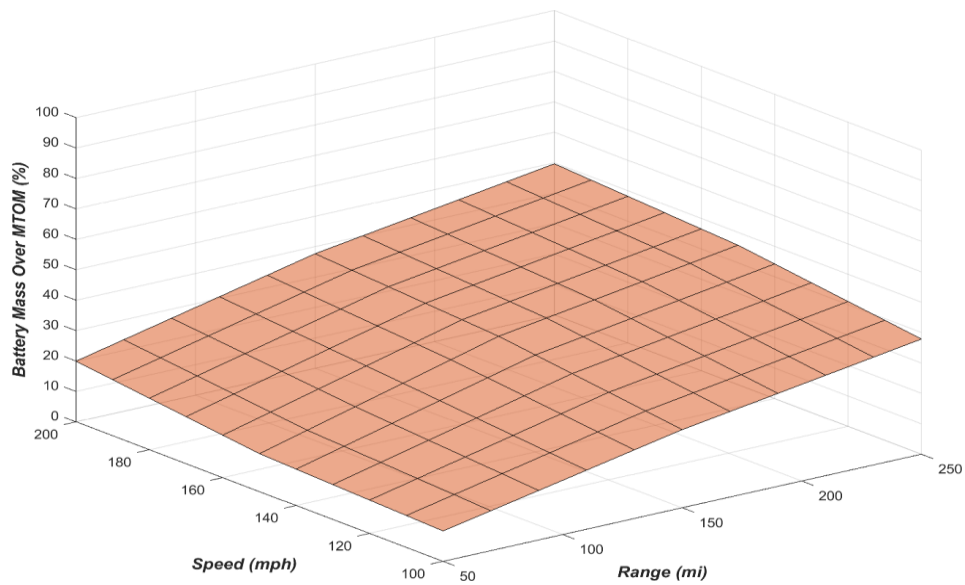


Figure 6-6 Battery mass over MTOM of Lift + Cruise Configurations: Two-Passenger, 600 Wh/kg Battery

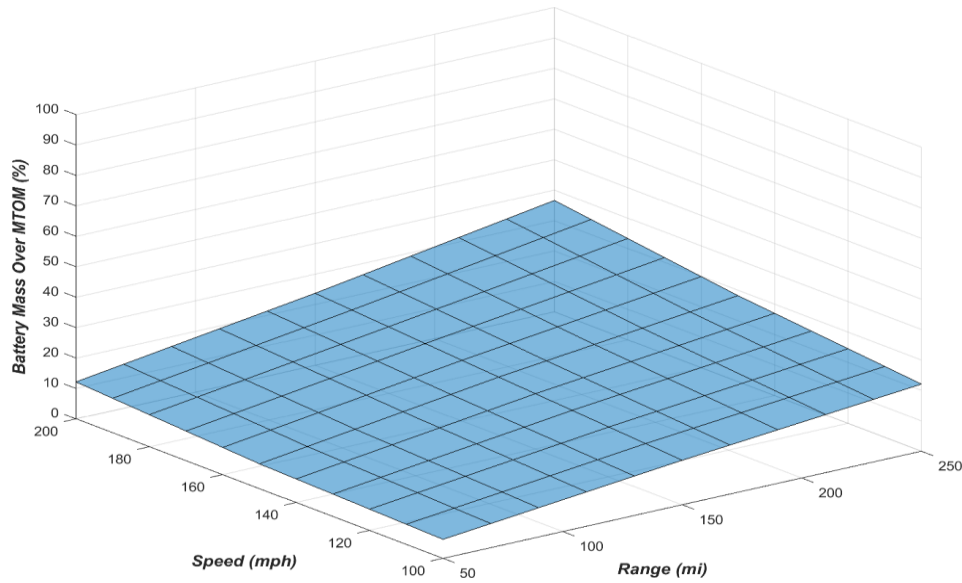


Figure 6-7 Battery mass over MTOM of Lift + Cruise Configurations: Two-Passenger, 900 Wh/kg Battery

Figure 6-8 to Figure 6-10 show the energy consumption for two-passenger, Lift + Cruise configurations from 300 Wh/kg battery to 900 Wh/kg battery. It is observed that with a battery energy density of 300 Wh/kg, there is a significant increase in energy consumption as both speed and range increase. However, this rate of increase in energy consumption becomes less pronounced when the battery energy density is elevated. Specifically, as the battery energy density improves, the magnitude of the escalation in energy consumption diminishes, signifying an improved efficiency in the overall system.

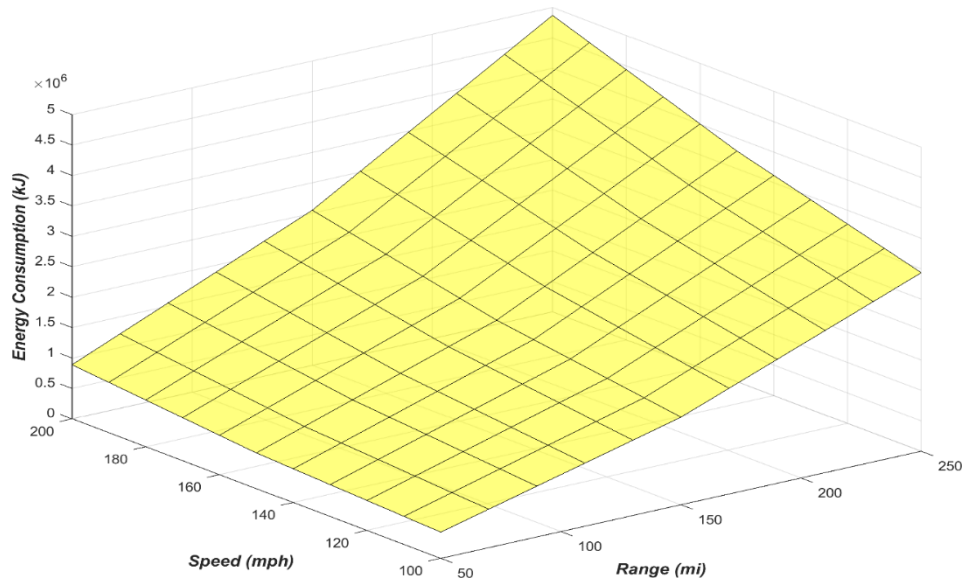


Figure 6-8 Energy consumption of Lift + Cruise Configurations: Two-Passenger, 300 Wh/kg Battery

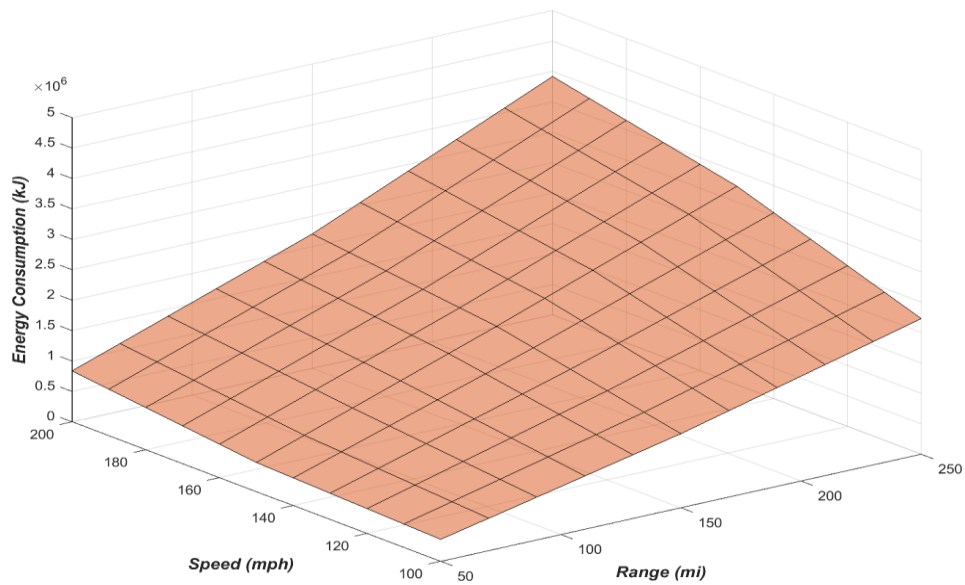


Figure 6-9 Energy consumption of Lift + Cruise Configurations: Two-Passenger, 600 Wh/kg Battery

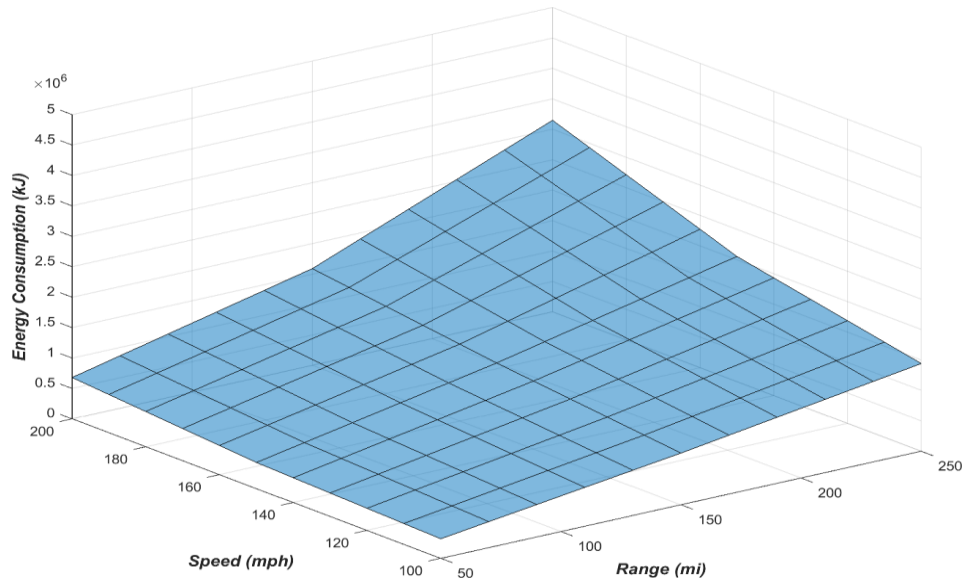


Figure 6-10 Energy consumption of Lift + Cruise Configurations: Two-Passenger, 900 Wh/kg Battery

6.1.2 Eight passengers + Two crew

Figure 6-11 to Figure 6-14 show the gross weight for eight-passenger, Lift + Cruise configurations from 300 Wh/kg battery to 900 Wh/kg battery. A noteworthy observation is the accentuated impact of passenger capacity on the gross weight trends of eVTOL vehicles. As the number of passengers increases, the rate at which the gross weight grows in relation to both range and speed escalates. This suggests that eVTOL designs with higher passenger capacities face more pronounced challenges in terms of weight management, especially when targeting greater ranges and higher speeds.

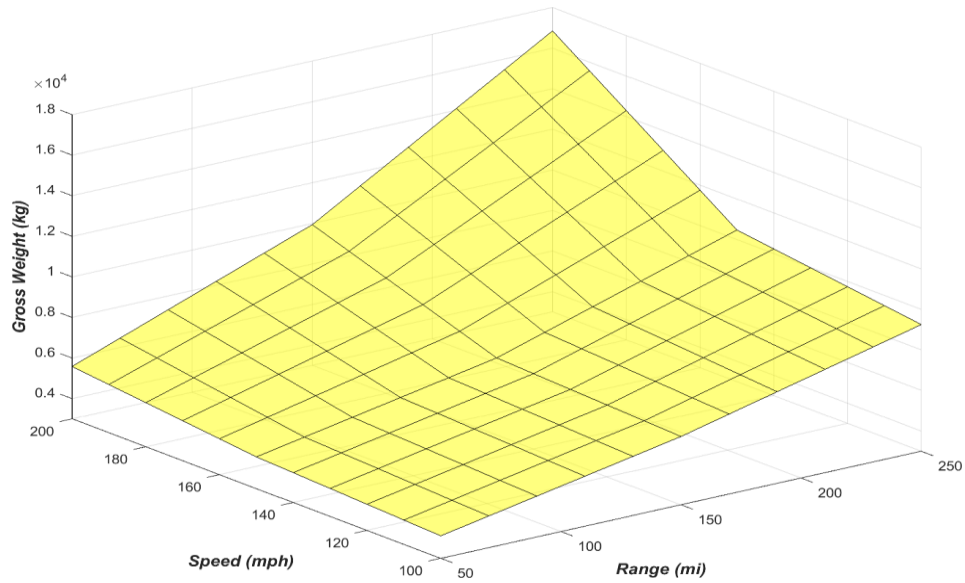


Figure 6-11 Gross weight of Lift + Cruise Configurations: Eight-Passenger, 300 Wh/kg Battery

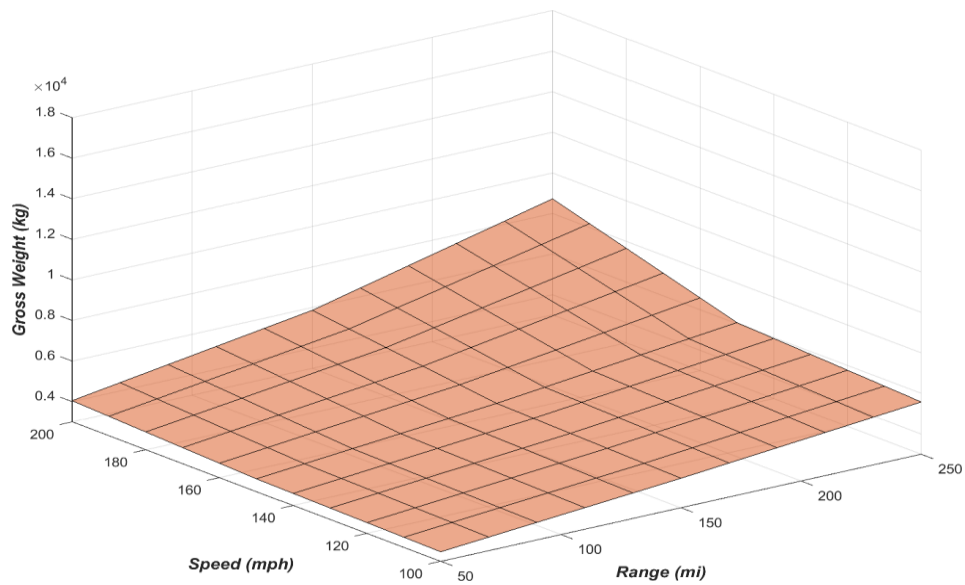


Figure 6-12 Gross weight of Lift + Cruise Configurations: Eight-Passenger, 600 Wh/kg Battery

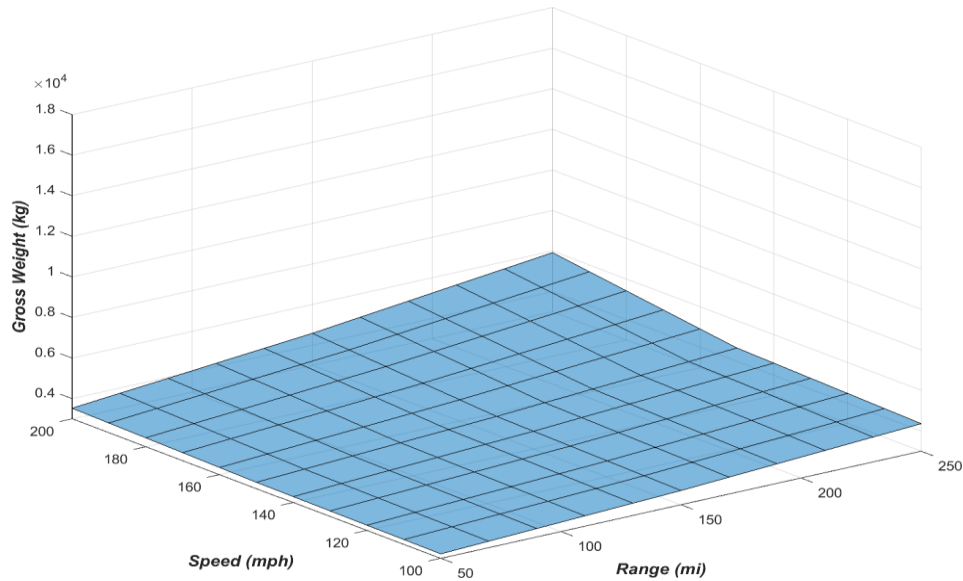


Figure 6-13 Gross weight of Lift + Cruise Configurations: Eight-Passenger, 900 Wh/kg Battery

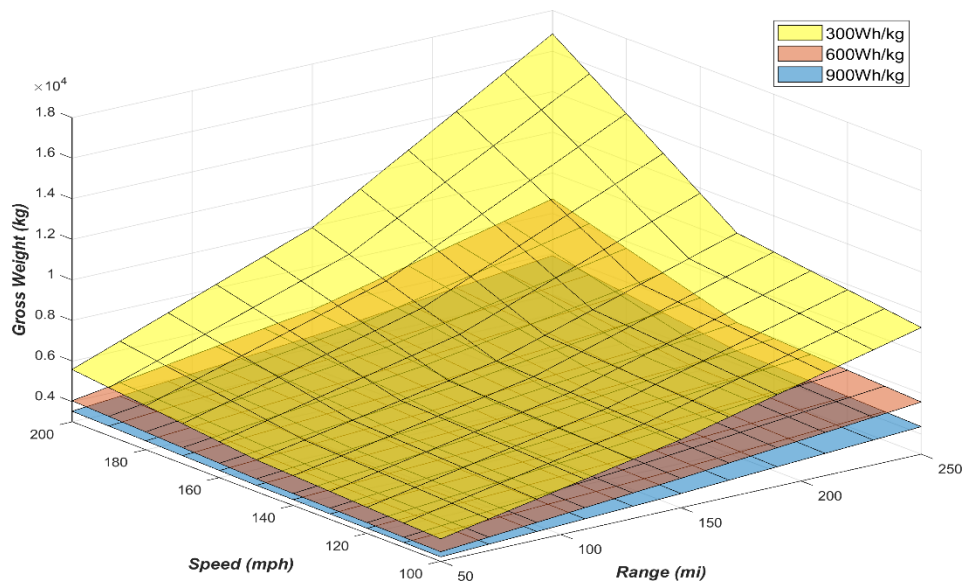


Figure 6-14 Comparison of Gross Weight Across Lift + Cruise Configurations with 300, 600, and 900 Wh/kg Batteries for Eight-Passenger Vehicles

Figure 6-15 to Figure 6-17 show the battery mass over MTOM for eight-passenger, Lift + Cruise configurations from 300 Wh/kg battery to 900 Wh/kg battery. The impact of battery energy density on the viability of eVTOL aircraft manifests conspicuously in several key parameters, notably the battery mass over MTOM ratio. With a battery energy density of 300 Wh/kg, a 50-mile range and a 200 mph cruising speed resulted in a battery mass over MTOM ratio of

39.91%. However, this ratio rapidly exceeded the threshold of 50% as the range increased to 90 miles at the same cruising speed. When the range further extended to 250 miles, even a drastic reduction in the cruising speed to 100 mph led to an unsustainable ratio of 58.99%.

In contrast, advancements in battery technology, elevating the energy density to 600 Wh/kg, did not universally ensure the feasibility of all eVTOL designs; specifically, when targeting a 250-mile range, the flexible cruising speed had to be curtailed to 170 mph. However, a leap to 900 Wh/kg in battery energy density significantly ameliorated this challenge, reducing the highest observed battery mass over MTOM ratio to 42.58%. These findings underline the critical dependency of eVTOL design feasibility on battery energy density, especially as the aircraft aims for higher ranges, speeds, and passenger capacities.

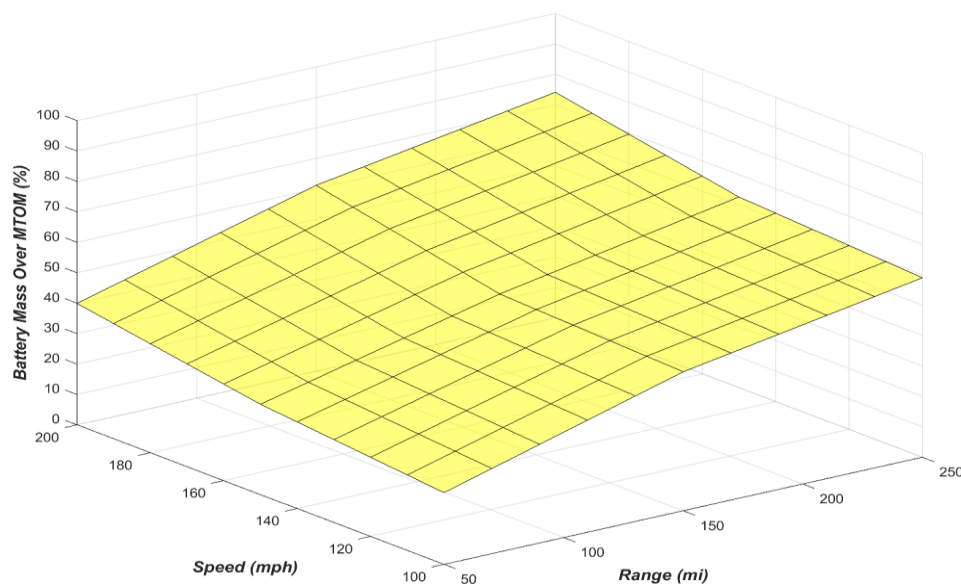


Figure 6-15 Battery mass over MTOM of Lift + Cruise Configurations: Eight-Passenger, 300 Wh/kg Battery

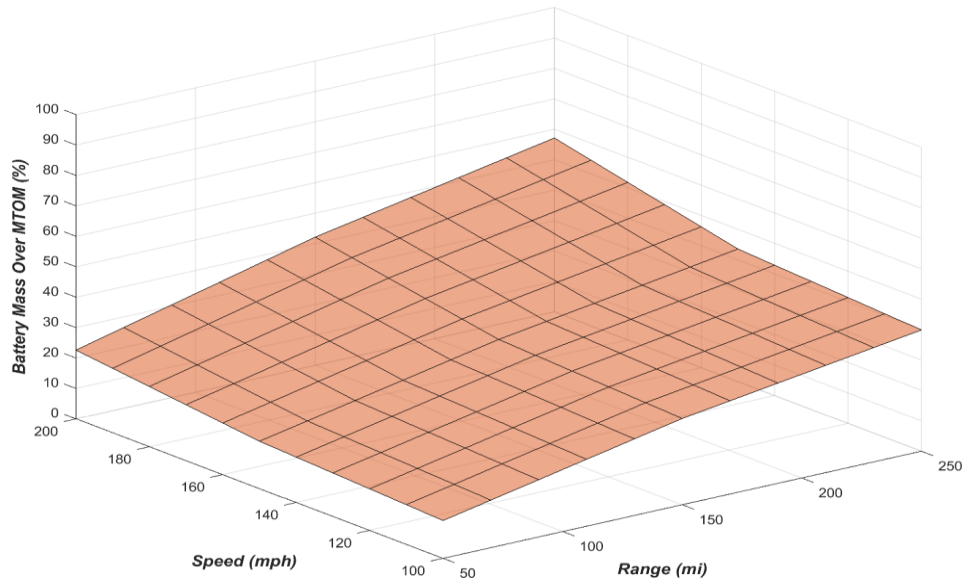


Figure 6-16 Battery mass over MTOM of Lift + Cruise Configurations: Eight-Passenger, 600 Wh/kg Battery

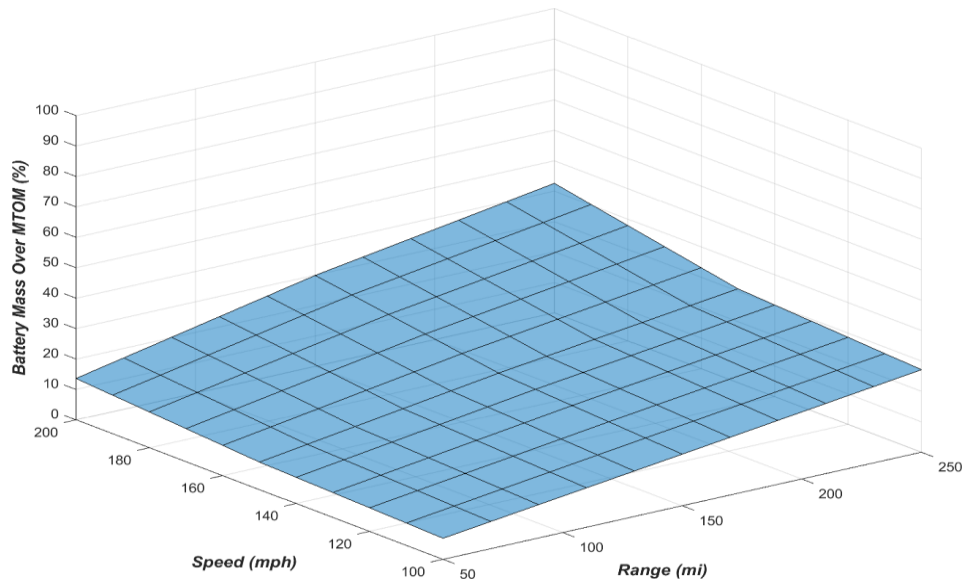


Figure 6-17 Battery mass over MTOM of Lift + Cruise Configurations: Eight-Passenger, 900 Wh/kg Battery

Figure 6-18 to Figure 6-20 show the energy consumption for eight-passenger, Lift + Cruise configurations from 300 Wh/kg battery to 900 Wh/kg battery.

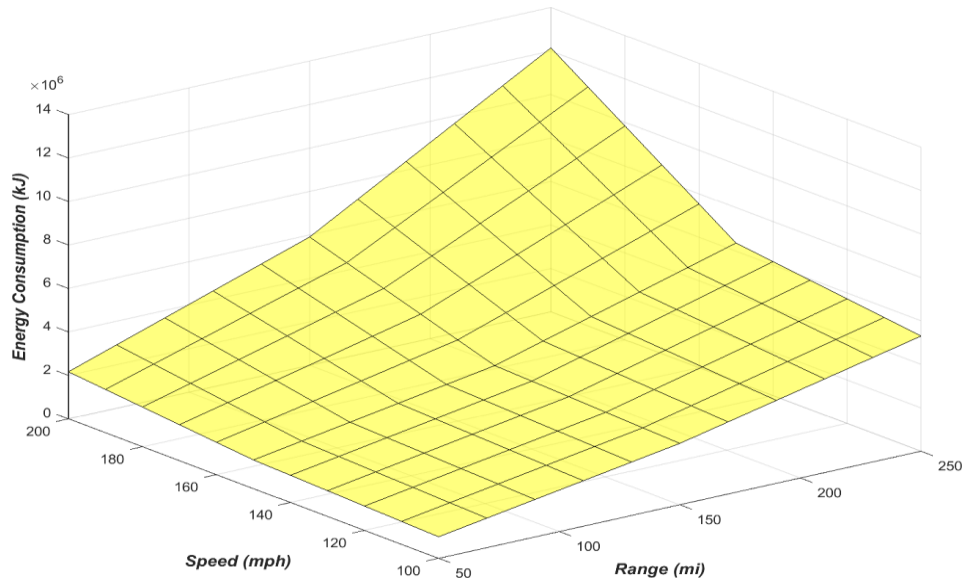


Figure 6-18 Energy consumption of Lift + Cruise Configurations: Eight-Passenger, 300 Wh/kg Battery

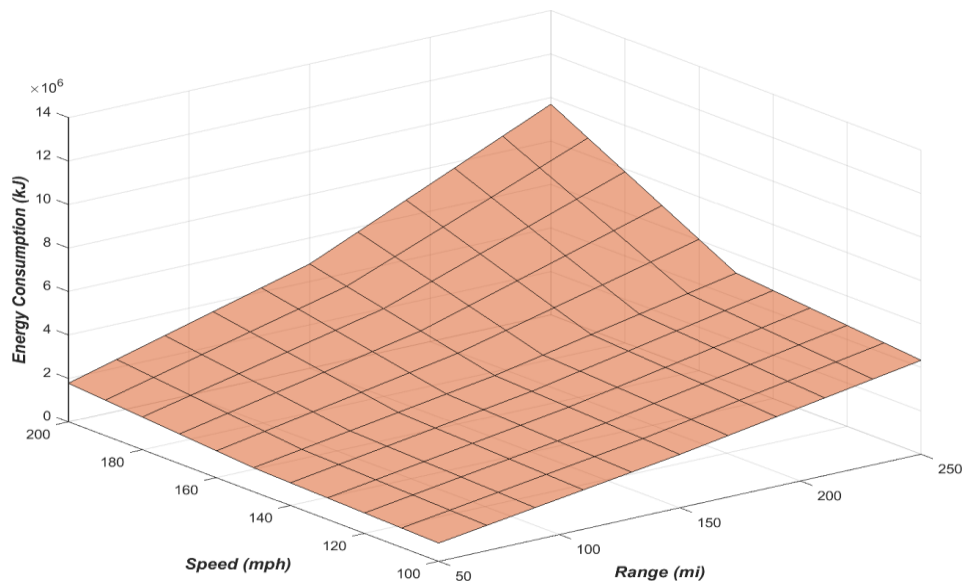


Figure 6-19 Energy consumption of Lift + Cruise Configurations: Eight-Passenger, 600 Wh/kg Battery

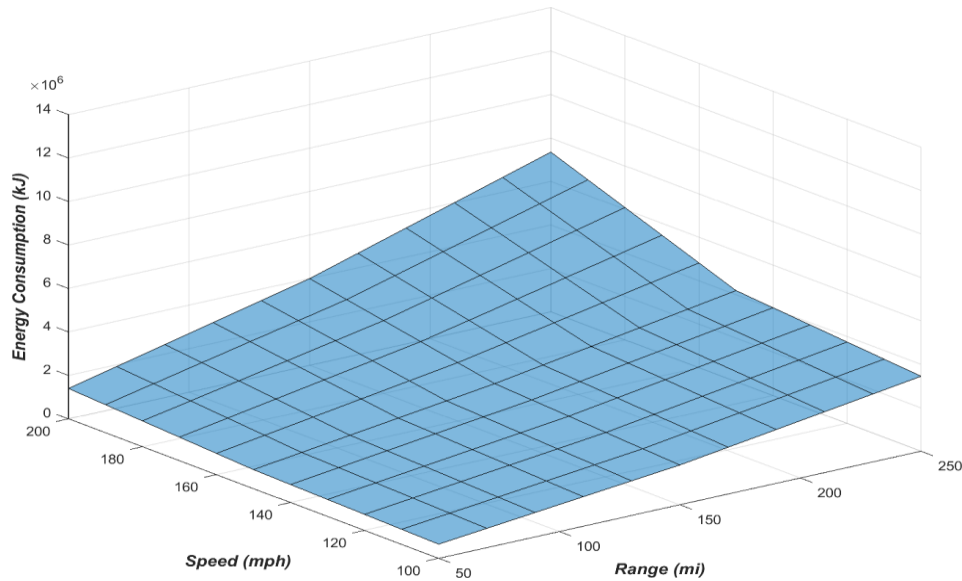


Figure 6-20 Energy consumption of Lift + Cruise Configurations: Eight-Passenger, 900 Wh/kg Battery

6.1.3 Twenty passengers + Two crew

Figure 6-21 to Figure 6-24 show the gross weight for twenty-passenger, Lift + Cruise configurations from 300 Wh/kg battery to 900 Wh/kg battery. The sensitivity of eVTOL aircraft's gross weight to both speed and range intensifies with an increase in passenger capacity. When operating with a battery energy density of 300 Wh/kg, the disparity between the maximum and minimum gross weight values for eVTOL was found to be 19,673.408 kg. However, advancements in battery technology significantly narrowed this gap. Specifically, when the battery energy density was elevated to 600 Wh/kg, the weight differential reduced to 7,867.323 kg, and further decreased to 4,429.453 kg at a density of 900 Wh/kg. These findings highlight the substantial influence of battery energy density on optimizing eVTOL gross weight, particularly as designers aim to accommodate higher passenger loads, speeds, and ranges.

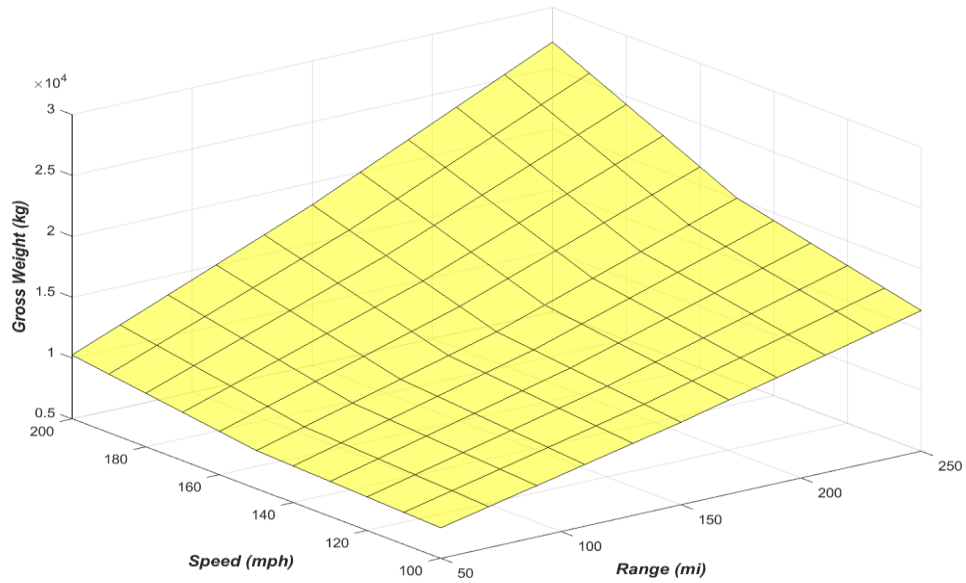


Figure 6-21 Gross weight of Lift + Cruise Configurations: Twenty-Passenger, 300 Wh/kg Battery

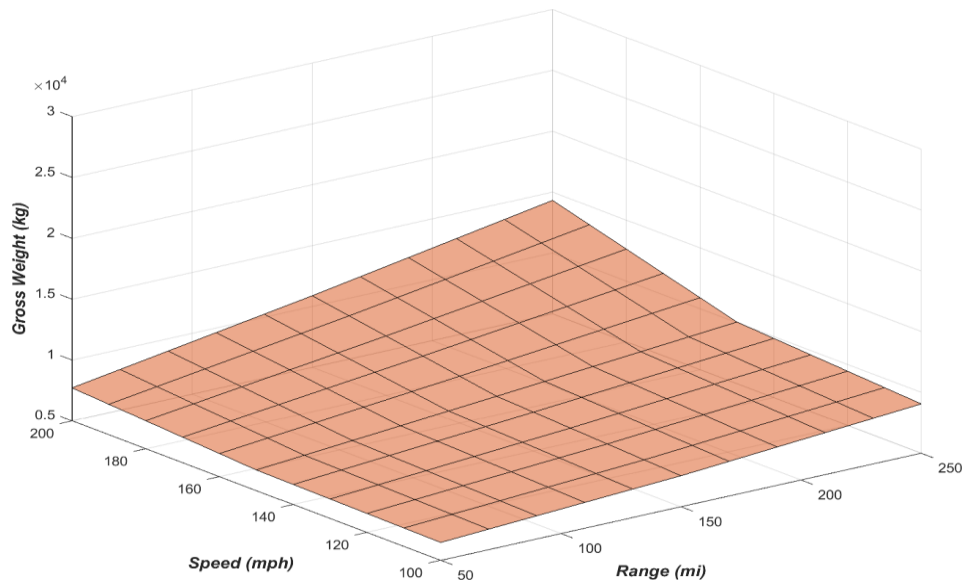


Figure 6-22 Gross weight of Lift + Cruise Configurations: Twenty-Passenger, 600 Wh/kg Battery

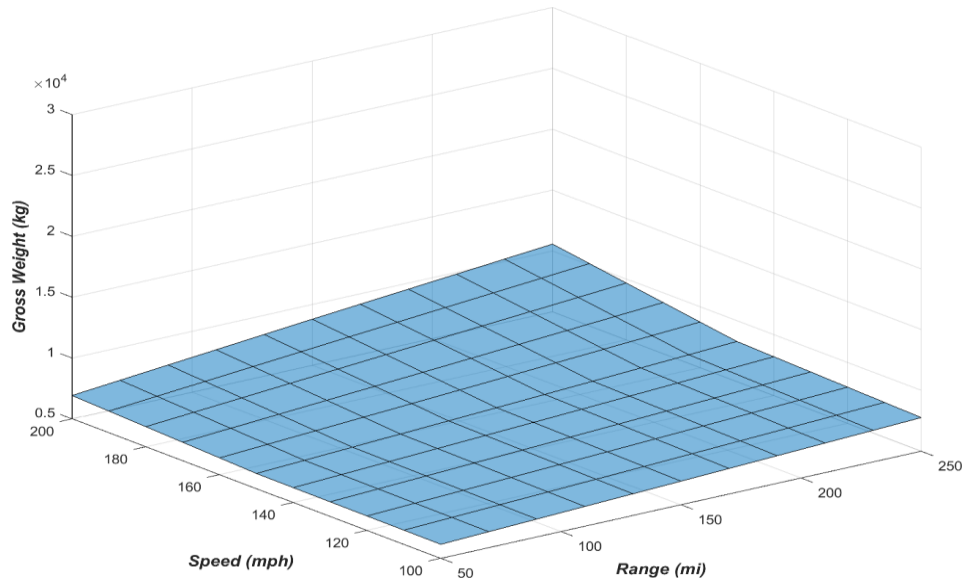


Figure 6-23 Gross weight of Lift + Cruise Configurations: Twenty-Passenger, 900 Wh/kg Battery

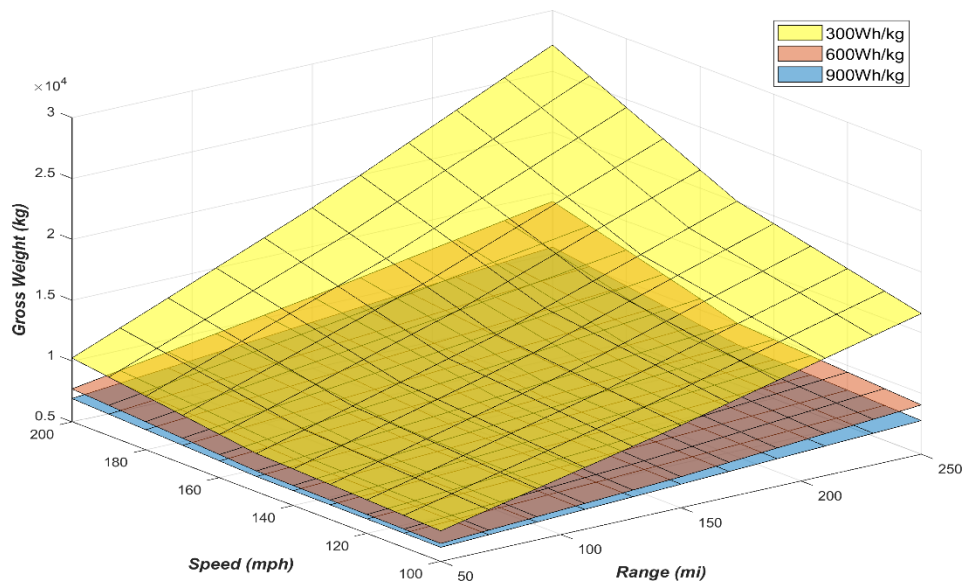


Figure 6-24 Comparison of Gross Weight Across Lift + Cruise Configurations with 300, 600, and 900 Wh/kg Batteries for Twenty-Passenger Vehicles

Figure 6-25 to Figure 6-27 show the battery mass over MTOM for twenty-passenger, Lift + Cruise configurations from 300 Wh/kg battery to 900 Wh/kg battery. At a battery energy density of 300 Wh/kg with a range of 50 miles and a cruising speed of 200 mph, the battery mass over MTOM ratio was measured at 39.19%. When the operational parameters were extended to a range of 150 miles at a speed of 140 mph, the battery mass over MTOM ratio exceeded 50%.

Furthermore, at a range of 250 miles and a speed of 100 mph, the ratio escalated to an unsustainable 59.15%.

However, advancements in battery technology offer some relief to these constraints. When the battery energy density increased to 600 Wh/kg, although a minority of eVTOL designs remained unfeasible, the flexible cruising speed could reach up to 190 mph at a range of 250 miles. Upon further increasing the battery energy density to 900 Wh/kg, the maximum battery mass over MTOM ratio was reduced to 40.74%, making more eVTOL designs viable.

These findings underscore the critical role of battery energy density in the feasibility and performance of eVTOL aircraft, particularly when aiming for higher ranges and speeds.

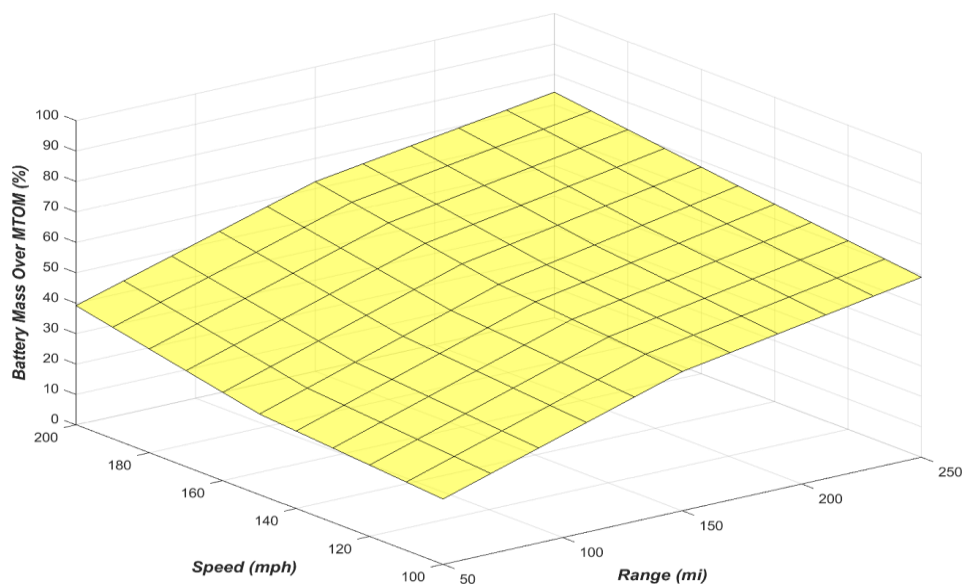


Figure 6-25 Battery mass of MTOM of Lift + Cruise Configurations: Twenty-Passenger, 300 Wh/kg Battery

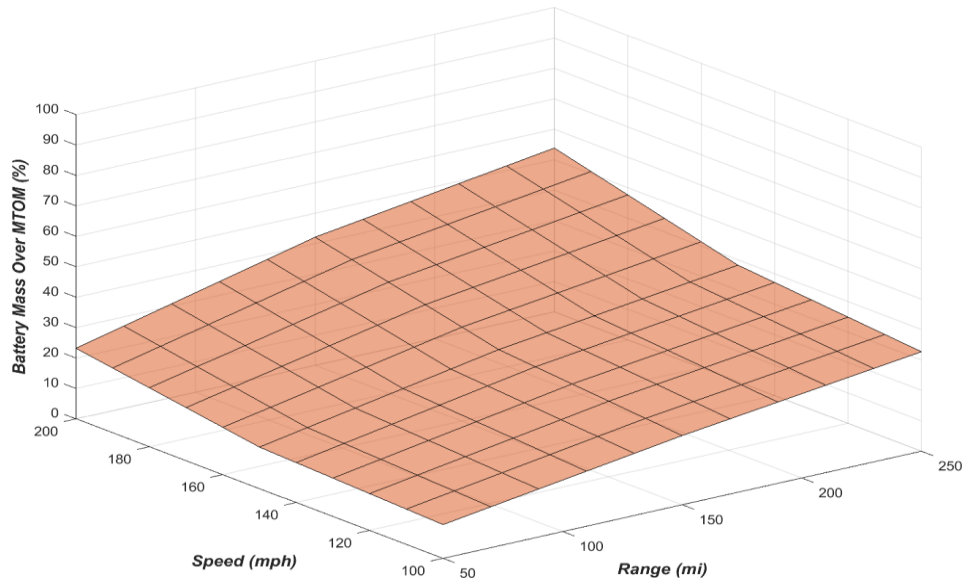


Figure 6-26 Battery mass of MTOM of Lift + Cruise Configurations: Twenty-Passenger, 600 Wh/kg Battery

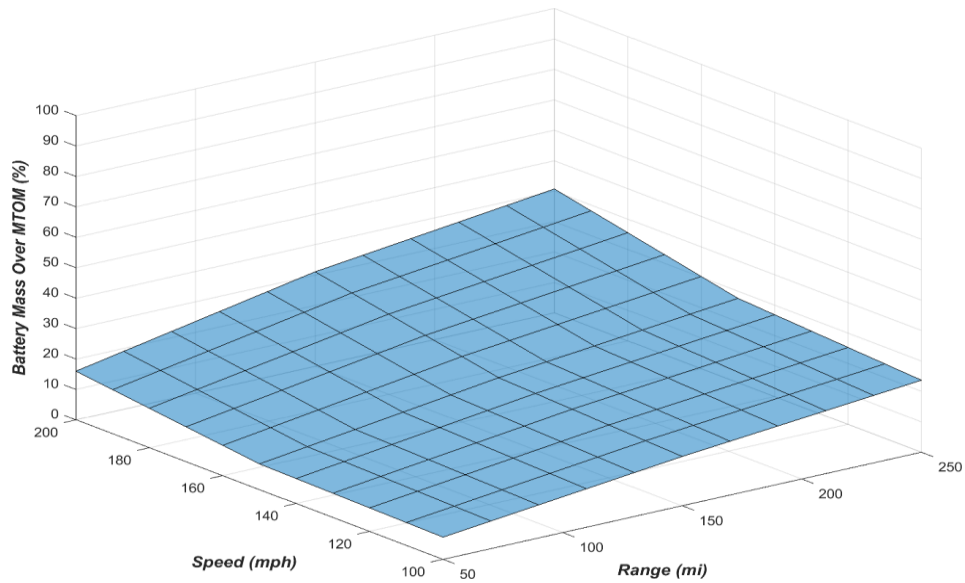


Figure 6-27 Battery mass of MTOM of Lift + Cruise Configurations: Twenty-Passenger, 900 Wh/kg Battery

Figure 6-28 to Figure 6-30 show the energy consumption for twenty-passenger, Lift + Cruise configurations from 300 Wh/kg battery to 900 Wh/kg battery.

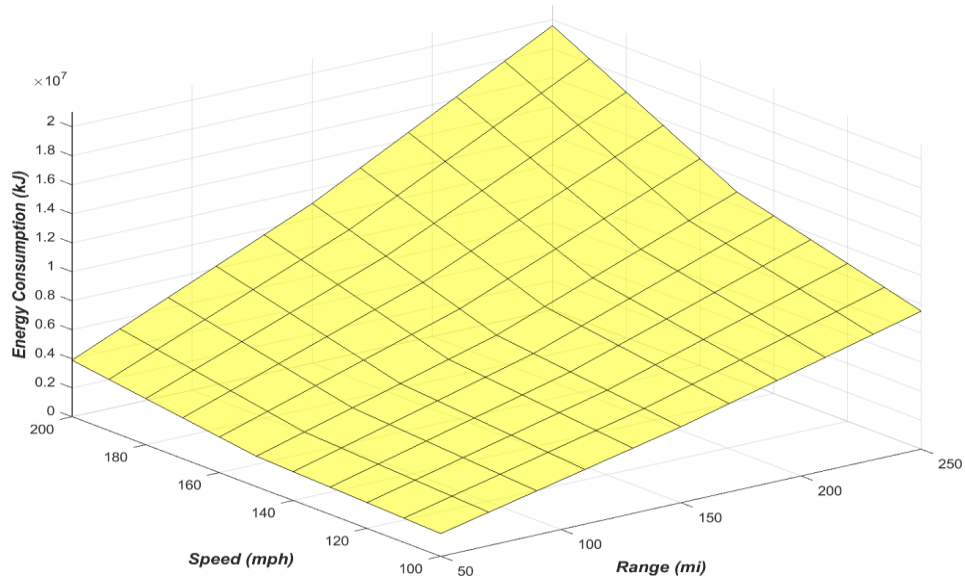


Figure 6-28 Energy consumption of Lift + Cruise Configurations: Twenty-Passenger, 300 Wh/kg Battery

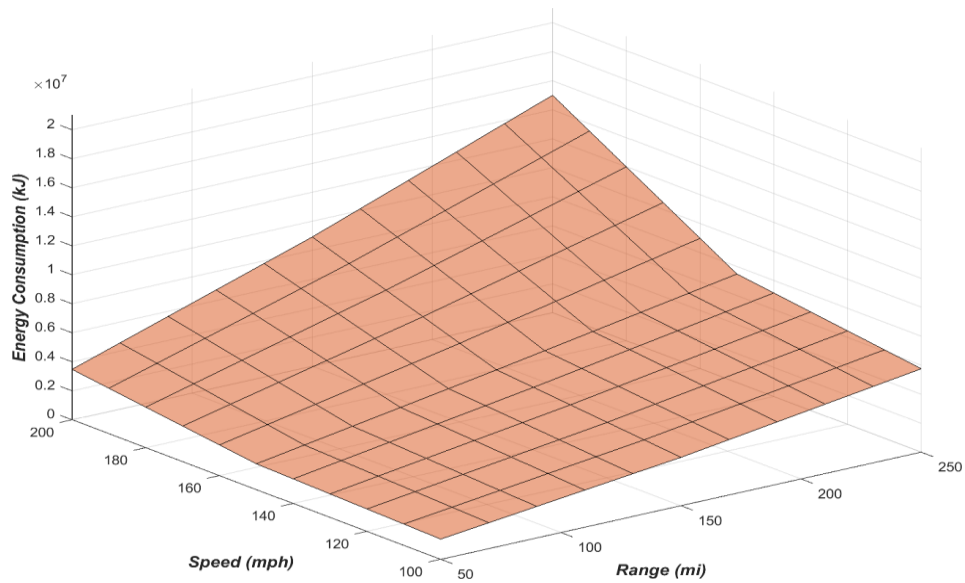


Figure 6-29 Energy consumption of Lift + Cruise Configurations: Twenty-Passenger, 600 Wh/kg Battery

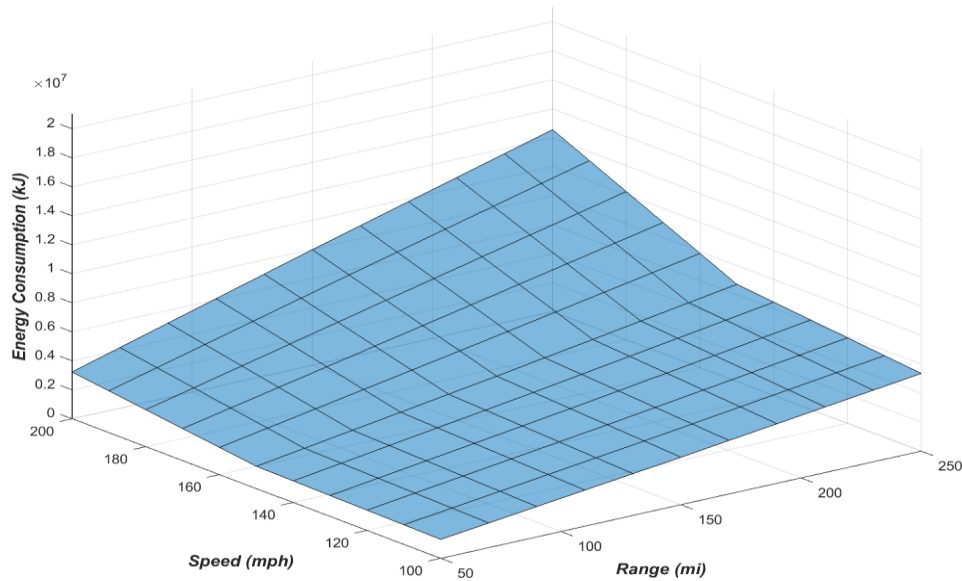


Figure 6-30 Energy consumption of Lift + Cruise Configurations: Twenty-Passenger, 900 Wh/kg Battery

6.1.4 Conclusion

In summary, both Vectored Thrust and Lift + Cruise eVTOL configurations display similar gross weight trends that are sensitive to changes in speed and range. As speed and range increase, the gross weight exhibits a more pronounced growth, a pattern that is particularly emphasized with an increase in passenger capacity. Battery energy density emerges as a pivotal parameter influencing these trends across both configurations.

Increasing the battery energy density leads to a notable reduction in the gross weight and shrinks the variance between the maximum and minimum gross weights for both Vectored Thrust and Lift + Cruise models. This suggests that advances in battery technology could have transformative effects on the feasibility and performance parameters of eVTOL designs across different configurations and capacities.

Moreover, higher energy densities are associated with a decline in the battery mass over the MTOM ratio, enhancing the overall efficiency and effective payload capabilities of the eVTOL aircraft. Therefore, as battery technology improves, the design space for eVTOL configurations, whether Vectored Thrust or Lift + Cruise, is likely to expand, allowing for increased range and speed capabilities.

The nuances differentiating these two types of configurations, while outside the scope of this summary, will be discussed in depth in Chapter 8 of the full thesis.

7 Multicopter Design Case

In the design of the Multicopter configuration, constraints on cruise speed and range have been judiciously set due to limitations imposed by disk loading and propeller efficiency. These factors necessitate a more conservative design approach to ensure optimal performance and energy utilization in this eVTOL configuration.

7.1.1 Two passengers + Two crew

Figure 7-1 to Figure 7-4 show the gross weight for two-passenger, Multicopter configurations from 300 Wh/kg battery to 900 Wh/kg battery. The Multicopter configuration, which relies solely on its propellers for both lift and thrust, displays high sensitivity in its gross weight relative to range and speed. When the battery energy density is at 300Wh/kg, the difference between the maximum and minimum gross weight values varies from 1557.689 kg at a speed of 50 mph to 2629.344 kg at 100 mph. Notably, as battery energy density improves, there is a significant reduction in the aircraft's gross weight. This decline can be attributed to the high battery weight proportion in the Multicopter design; increasing the battery's energy density effectively reduces the weight of the battery and, in turn, the required lifting force from the propellers, thereby improving propeller efficiency.

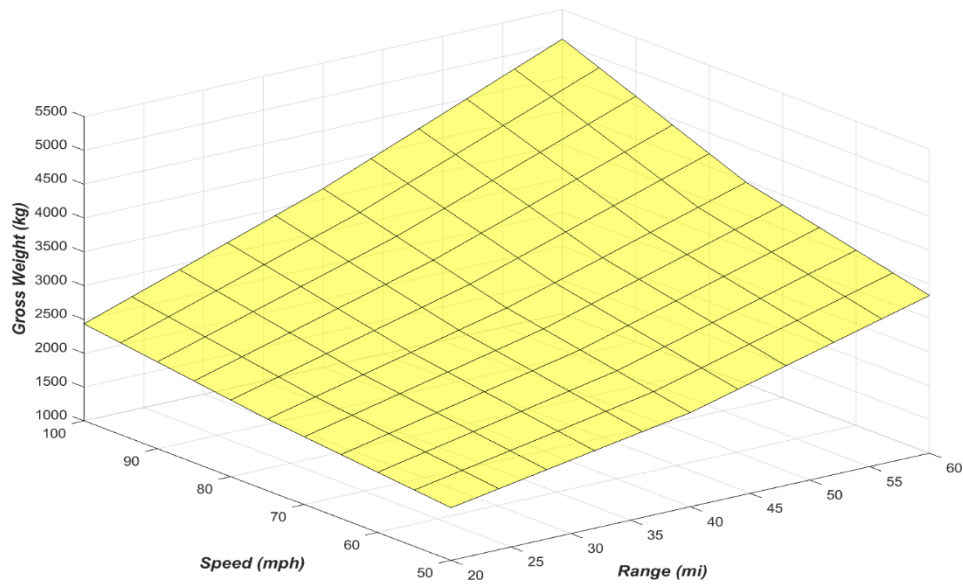


Figure 7-1 Gross weight of Multicopter Configurations: Two-Passenger, 300 Wh/kg Battery

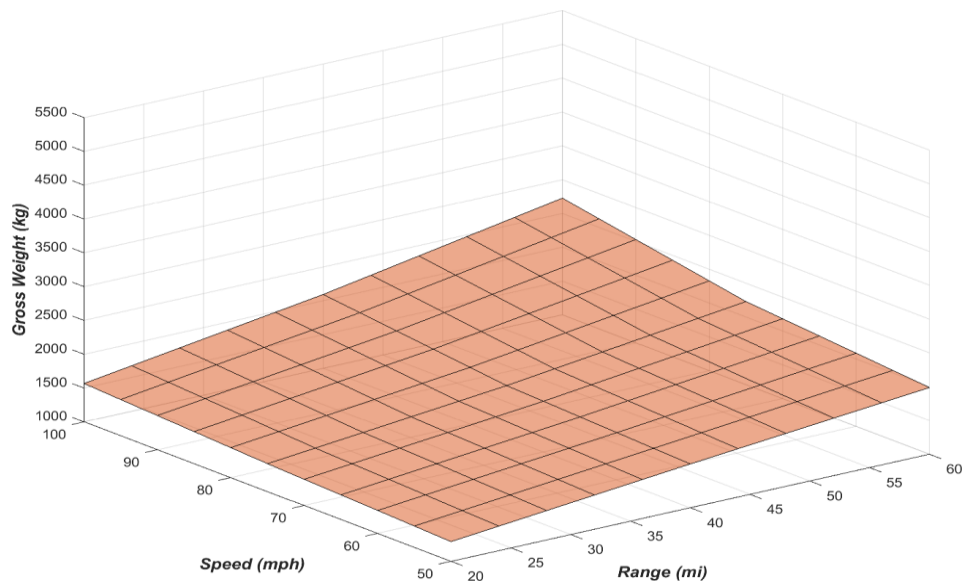


Figure 7-2 Gross weight of Multicopter Configurations: Two-Passenger, 600 Wh/kg Battery

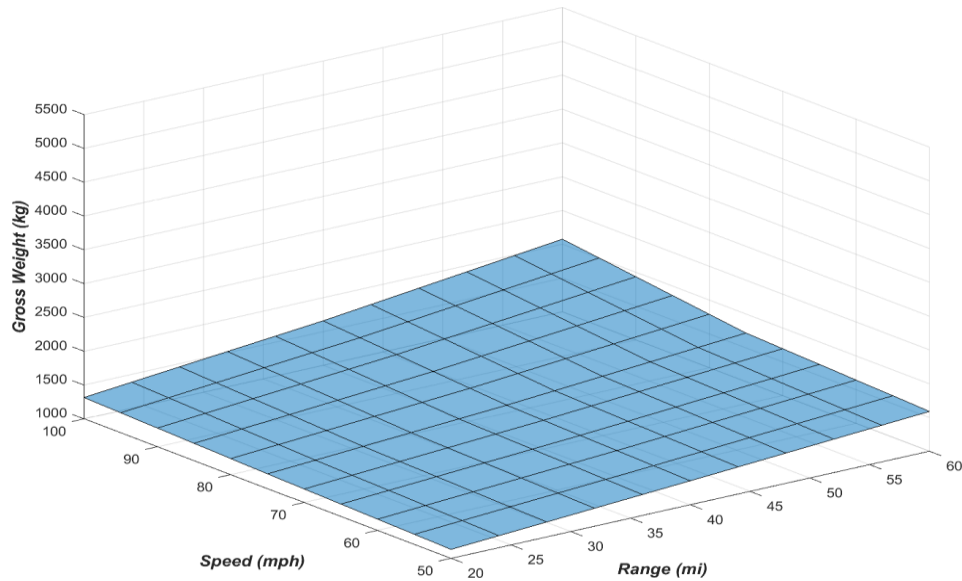


Figure 7-3 Gross weight of Multicopter Configurations: Two-Passenger, 900 Wh/kg Battery

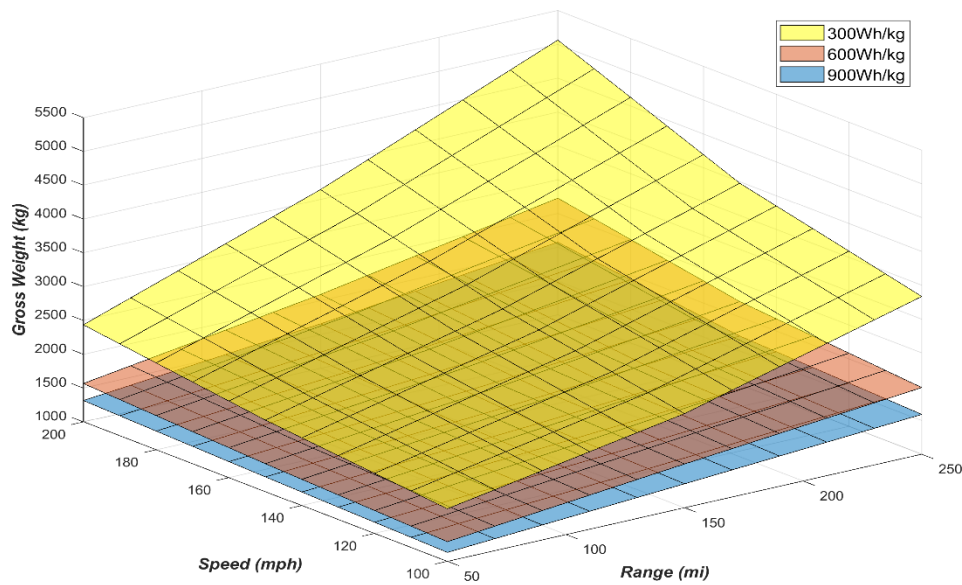


Figure 7-4 Comparison of Gross Weight Across Multicopter Configurations with 300, 600, and 900 Wh/kg Batteries for Two-Passenger Vehicles

Figure 7-5 to Figure 7-7 show the battery mass over MTOM for two-passenger Multicopter configurations from 300 Wh/kg battery to 900 Wh/kg battery. In Multicopter configurations, the battery mass over MTOM ratio generally skews high due to the absence of wings and the reliance solely on propellers for both lift and thrust. At a battery energy density of 300Wh/kg, only a limited number of eVTOL designs are viable. For instance, at a range of 20 miles, the maximum

flexible cruising speed is capped at 70 mph. When the range is extended to 40 miles, the minimum battery mass over MTOM ratio escalates to 56.39%. However, advancements in battery technology yield improvements. When the energy density increases to 600Wh/kg, the flexible cruising speed expands to 90 mph for a 40-mile range and 55 mph for a 60-mile range. Moreover, at an energy density of 900Wh/kg, the maximum battery mass over MTOM ratio is reduced to 51.13%, demonstrating the substantial positive impact of battery advancements on design feasibility.

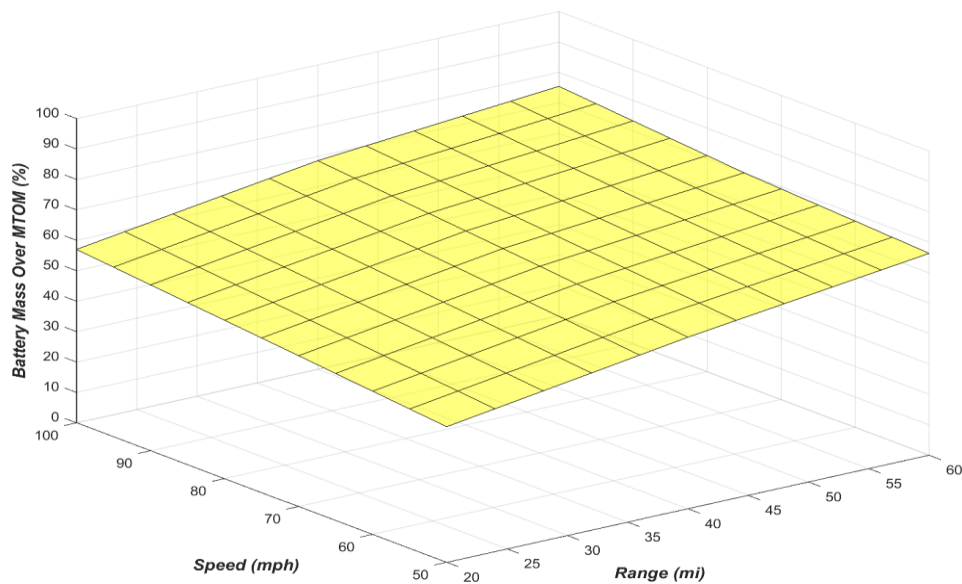


Figure 7-5 Battery mass over MTOM of Multicopter Configurations: Two-Passenger, 300 Wh/kg Battery

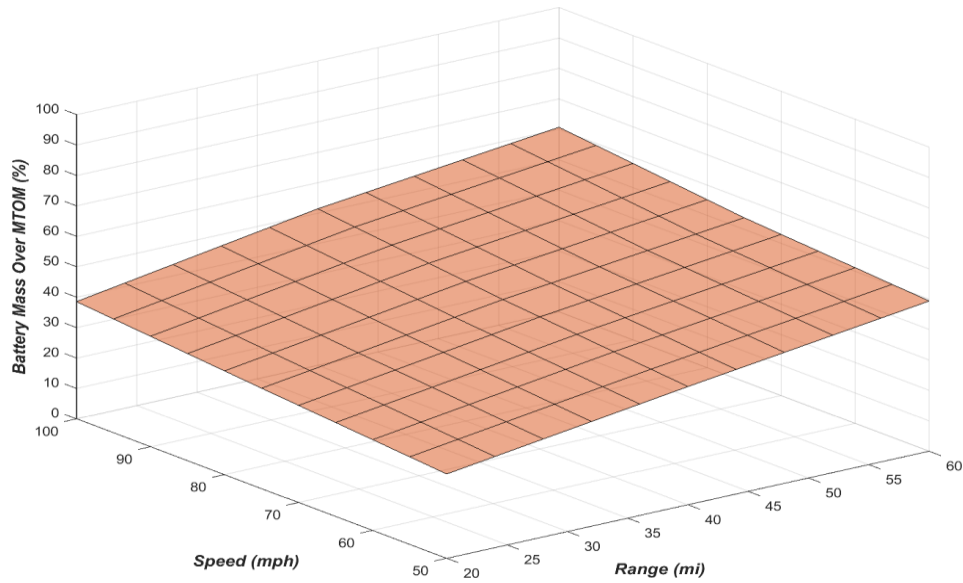


Figure 7-6 Battery mass over MTOM of Multicopter Configurations: Two-Passenger, 600 Wh/kg Battery

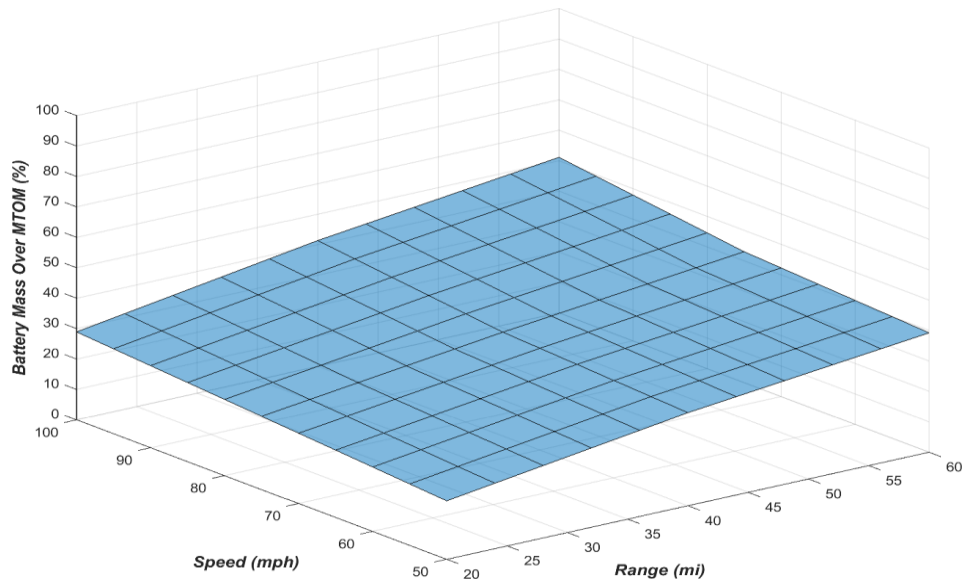


Figure 7-7 Battery mass over MTOM of Multicopter Configurations: Two-Passenger, 900 Wh/kg Battery

Figure 7-8 to Figure 7-10 show the energy consumption for two-passenger, Multicopter configurations from 300 Wh/kg battery to 900 Wh/kg battery.

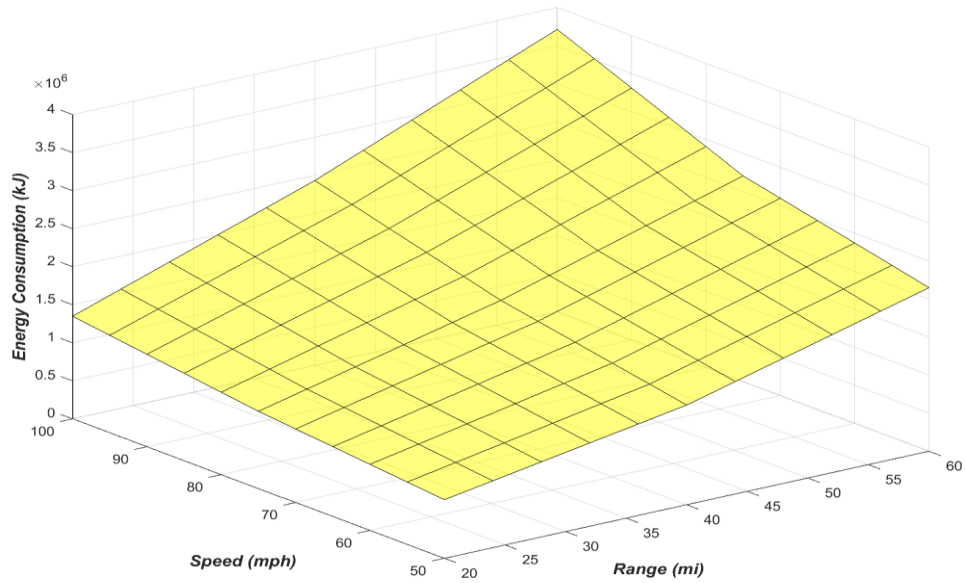


Figure 7-8 Energy consumption of Multicopter Configurations: Two-Passenger, 300 Wh/kg Battery

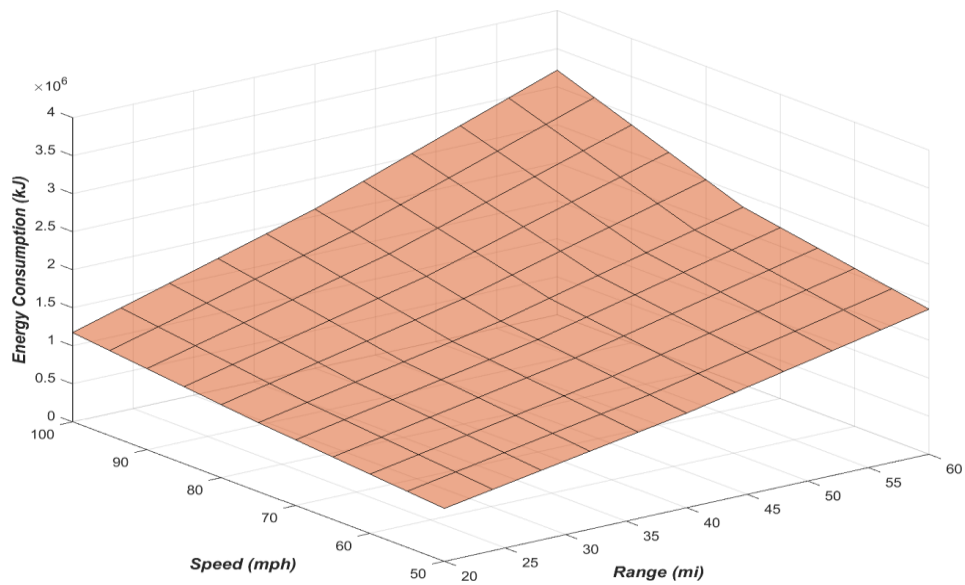


Figure 7-9 Energy consumption of Multicopter Configurations: Two-Passenger, 600 Wh/kg Battery

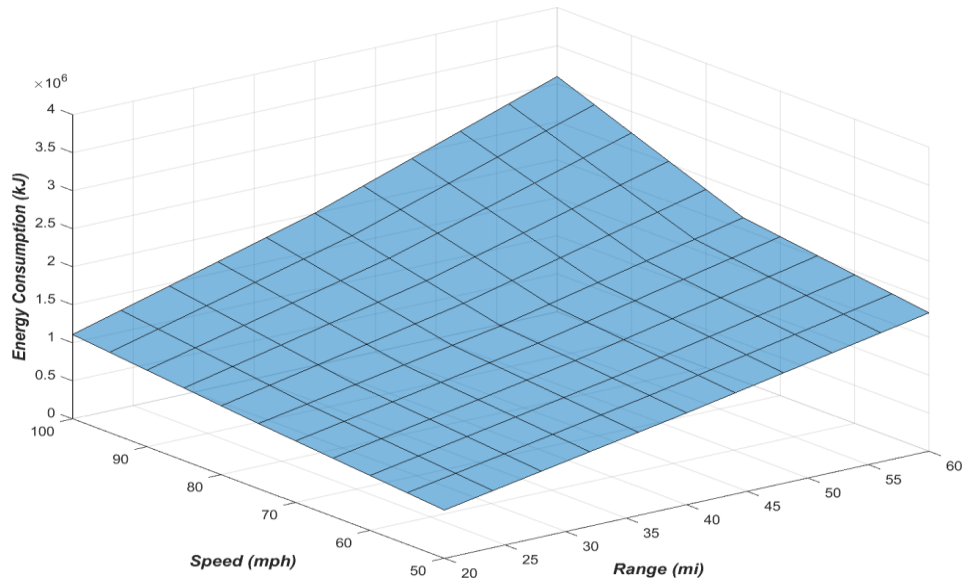


Figure 7-10 Energy consumption of Multicopter Configurations: Two-Passenger, 900 Wh/kg Battery

7.1.2 Four passengers + Two crew

Figure 7-11 to Figure 7-14 show the gross weight for four-passenger, Multicopter configurations from 300 Wh/kg battery to 900 Wh/kg battery. In the case of four-passenger eVTOL designs configured as Multicopters, the general trends observed in the two-passenger models are likewise applicable but magnified. The sensitivity of gross weight to changes in speed and range is even more pronounced. This is particularly noticeable as the higher number of seats increases the overall weight and thus the gross weight, accentuating the interplay between speed, range, and energy requirements. As in the two-passenger configuration, advancements in battery energy density positively affect the feasibility of the four-passenger designs by potentially reducing the battery mass over MTOM ratio.

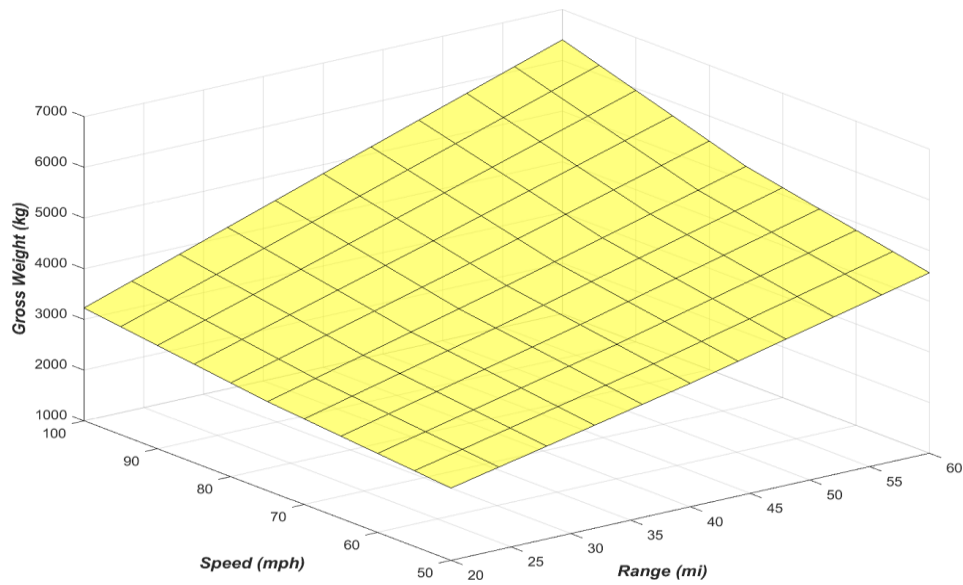


Figure 7-11 Gross weight of Multicopter Configurations: Four-Passenger, 300 Wh/kg Battery

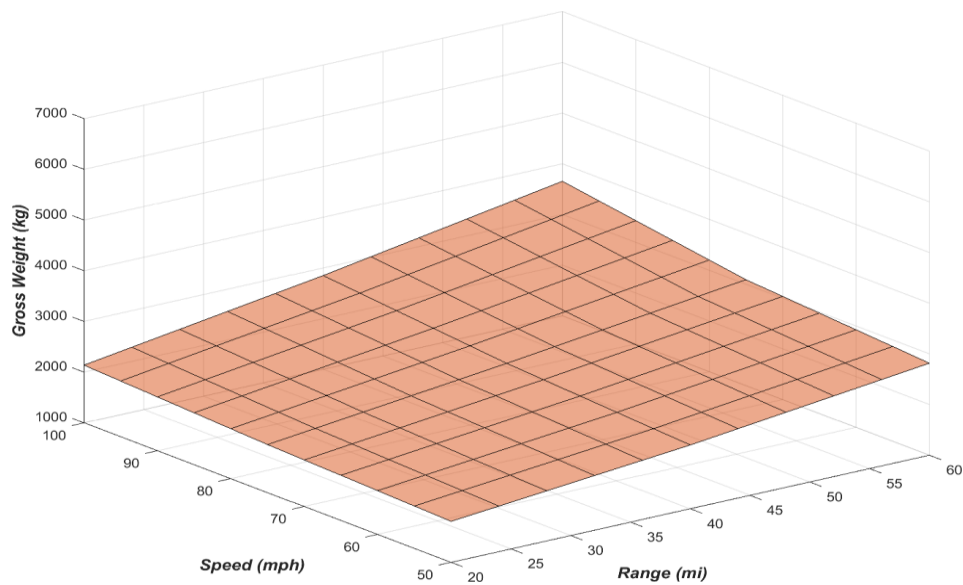


Figure 7-12 Gross weight of Multicopter Configurations: Four-Passenger, 600 Wh/kg Battery

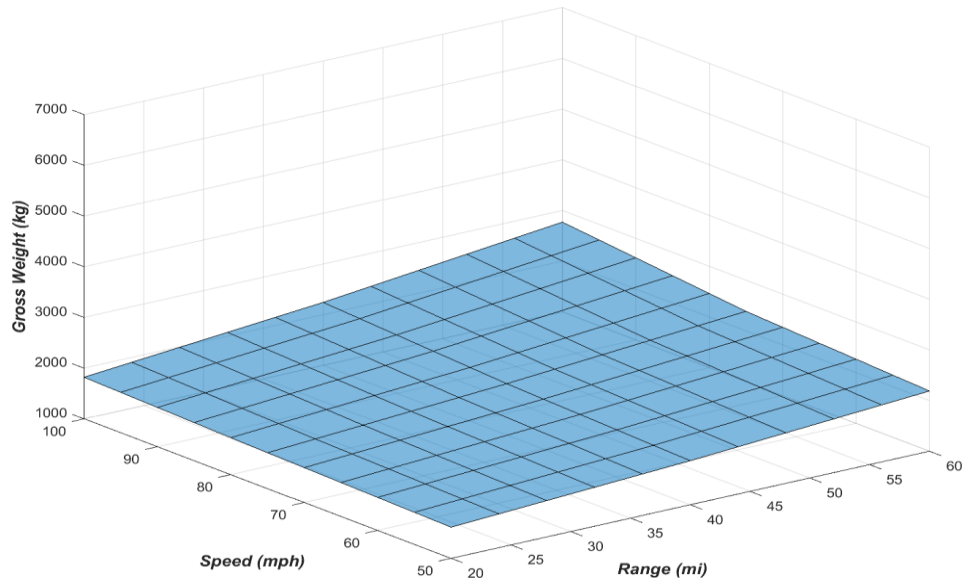


Figure 7-13 Gross weight of Multicopter Configurations: Four-Passenger, 900 Wh/kg Battery

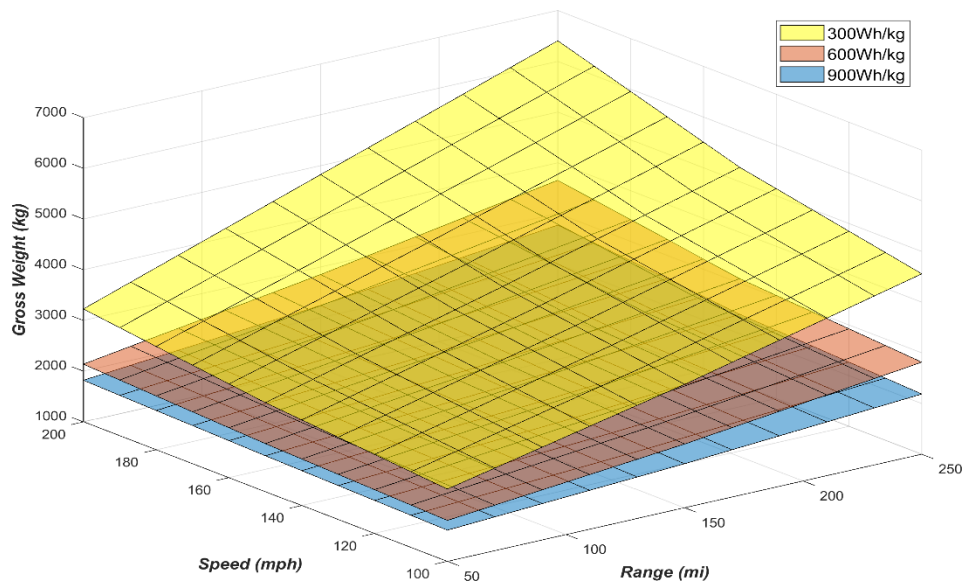


Figure 7-14 Comparison of Gross Weight Across Multicopter Configurations with 300, 600, and 900 Wh/kg Batteries for Four-Passenger Vehicles

Figure 7-15 to Figure 7-17 show the battery mass over MTOM for four-passenger Multicopter configurations from 300 Wh/kg battery to 900 Wh/kg battery. At a battery energy density of 300 Wh/kg, a feasible cruise speed up to 90 mph is achievable for a 20-mile range. As the range extends to 40 miles, the minimum battery over MTOM ratio reaches 56.42%, and further increases to 65.32% for a 60-mile range. These values indicate constraints on the aircraft's design,

particularly in terms of weight and energy efficiency. When the battery energy density escalates to 600 Wh/kg, the design space broadens, rendering all cruise speeds as plausible for 20-mile and 40-mile ranges. Interestingly, for a 60-mile range, the reasonable cruise speed caps at 55 mph, shedding light on the intrinsic trade-offs between range, speed, and energy density. A further enhancement in battery energy density to 900 Wh/kg significantly ameliorates the battery over MTOM ratio, with its peak value capped at 48.05%.

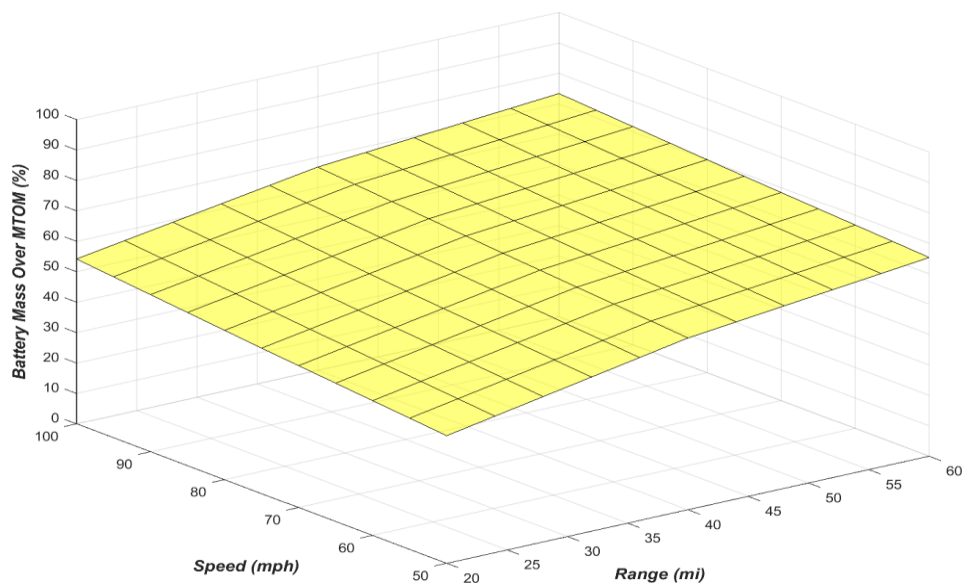


Figure 7-15 Battery mass over MTOM of Multicopter Configurations: Four-Passenger, 300 Wh/kg Battery

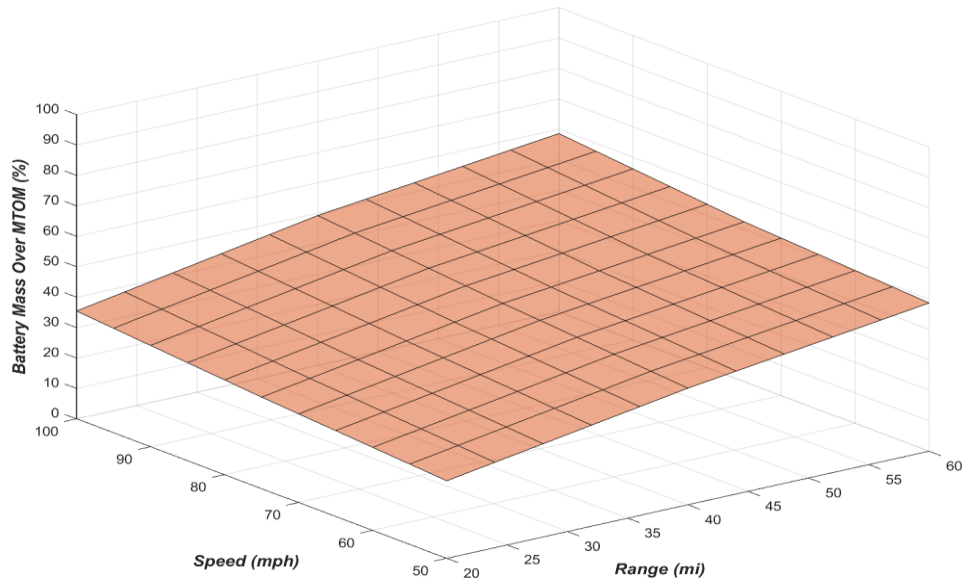


Figure 7-16 Battery mass over MTOM of Multicopter Configurations: Four-Passenger, 600 Wh/kg Battery

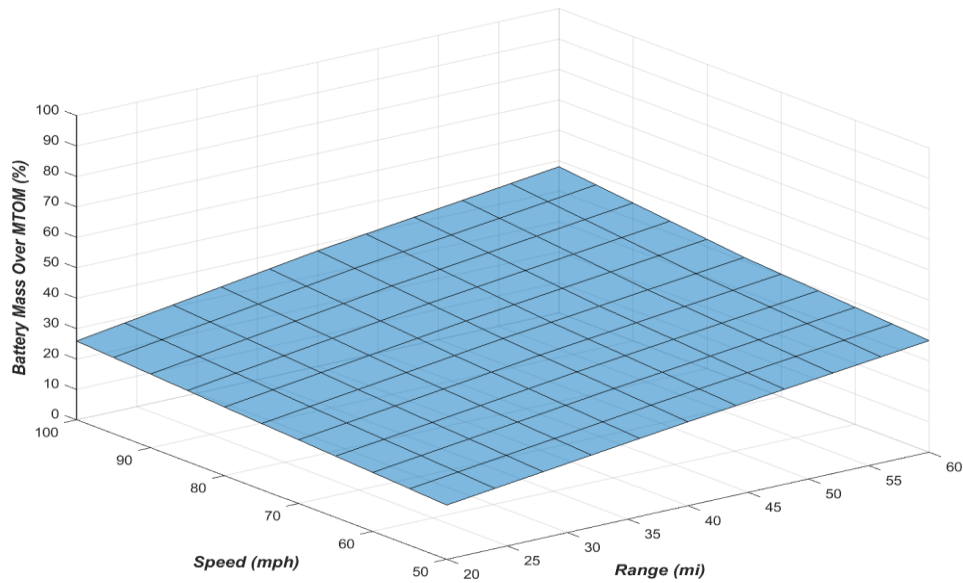


Figure 7-17 Battery mass over MTOM of Multicopter Configurations: Four-Passenger, 900 Wh/kg Battery

Figure 7-18 to Figure 7-20 show the energy consumption for four-passenger, Multicopter configurations from 300 Wh/kg battery to 900 Wh/kg battery.

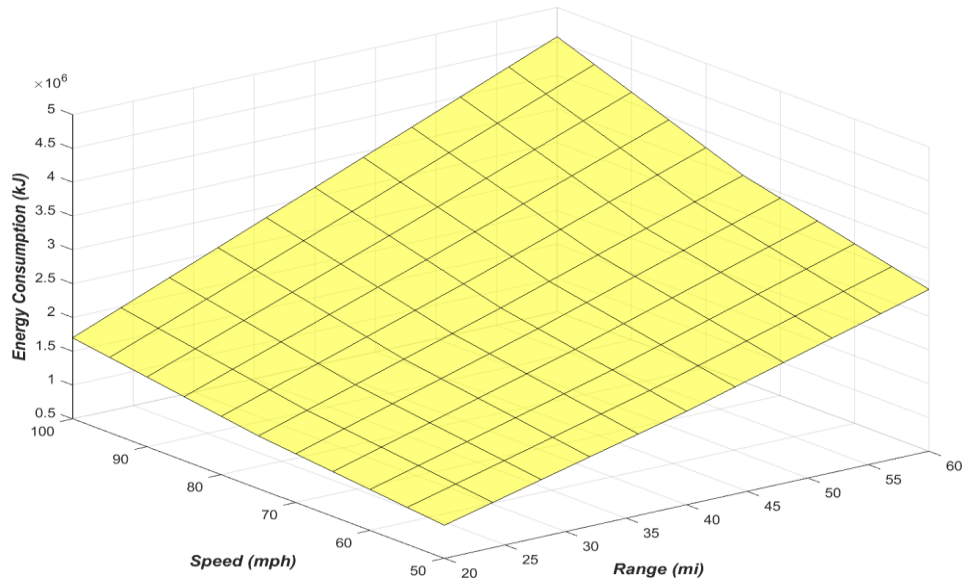


Figure 7-18 Energy consumption of Multicopter Configurations: Four-Passenger, 300 Wh/kg Battery

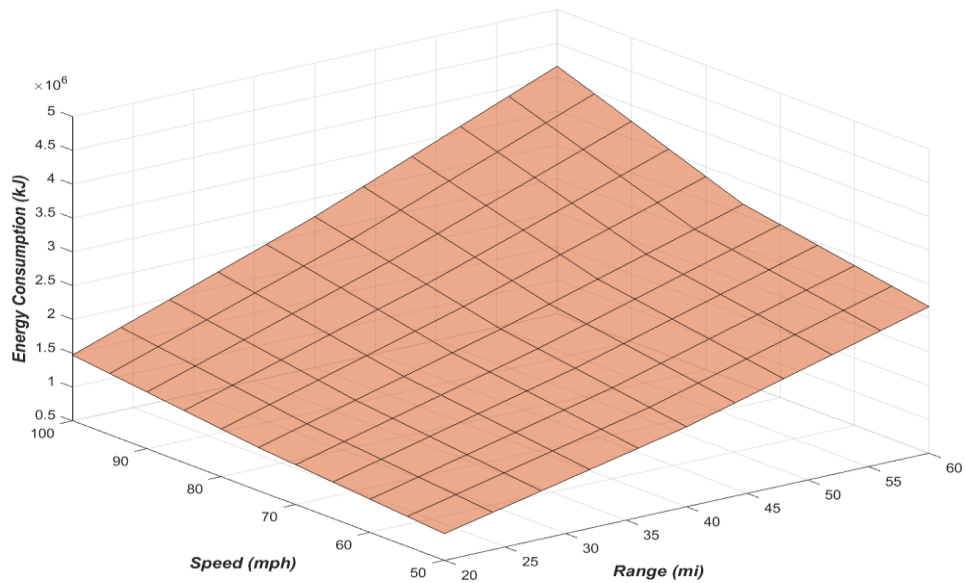


Figure 7-19 Energy consumption of Multicopter Configurations: Four-Passenger, 600 Wh/kg Battery

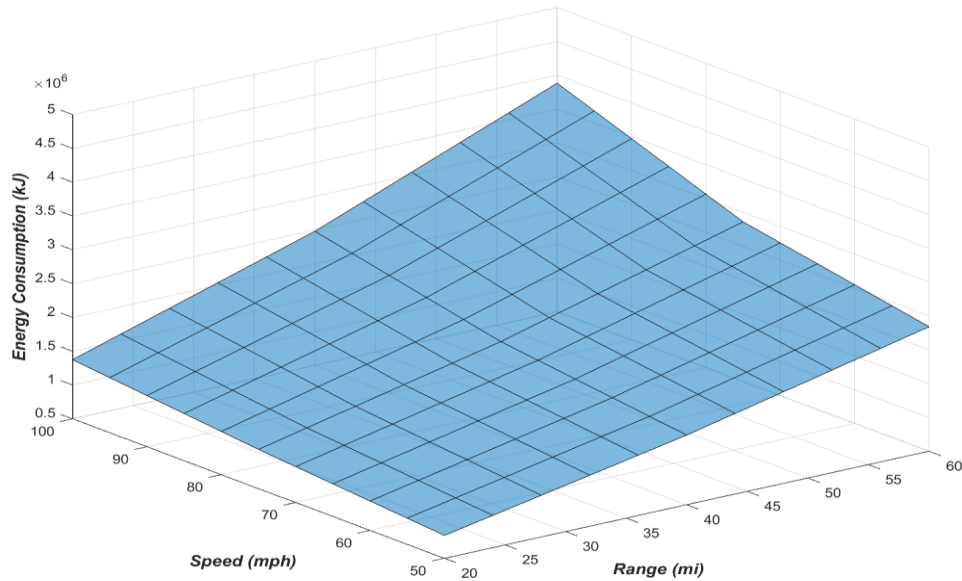


Figure 7-20 Energy consumption of Multicopter Configurations: Four-Passenger, 900 Wh/kg Battery

7.1.3 Six passengers + Two crew

Figure 7-21 to Figure 7-24 show the gross weight for six-passenger, Multicopter configurations from 300 Wh/kg battery to 900 Wh/kg battery. Similarly, the six-passenger Multicopter eVTOL designs exhibit an even greater sensitivity to speed and range fluctuations concerning gross weight. With more passengers, the starting point for gross weight is inevitably higher, exacerbating the already existing sensitivities seen in two-passenger and four-passenger configurations. The trend continues to show that increases in speed and range substantially elevate the gross weight, making advances in battery energy density more critical for rendering such designs viable. A higher energy density enables a more effective reduction in the battery mass over MTOM ratio, hence enhancing the overall feasibility and performance of 6-seat eVTOLs.

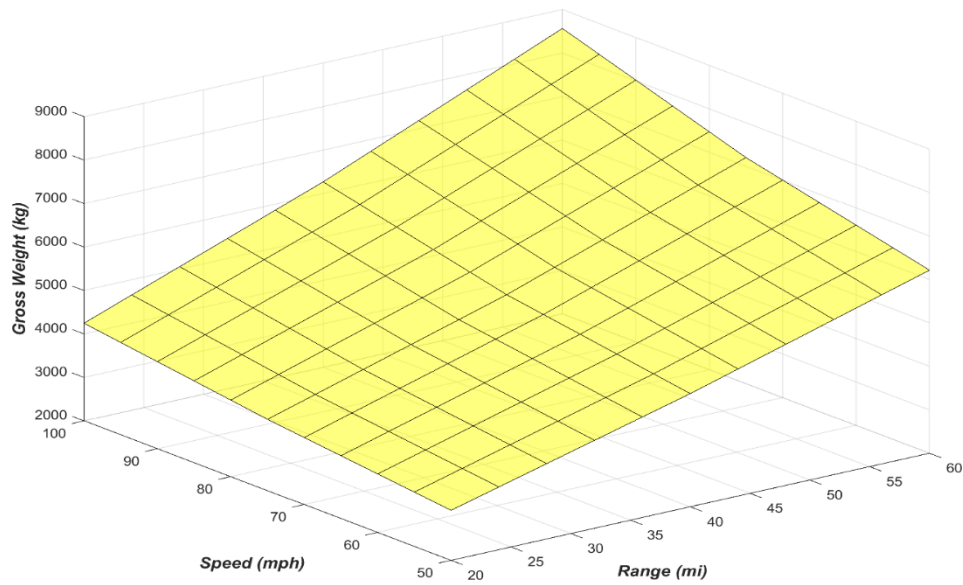


Figure 7-21 Gross weight of Multicopter Configurations: Six-Passenger, 300 Wh/kg Battery

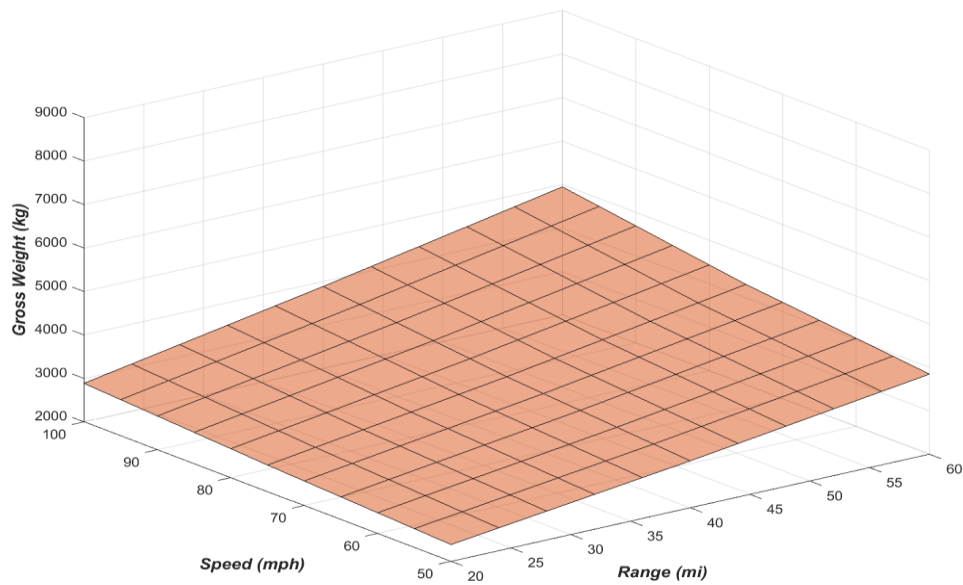


Figure 7-22 Gross weight of Multicopter Configurations: Six-Passenger, 600 Wh/kg Battery

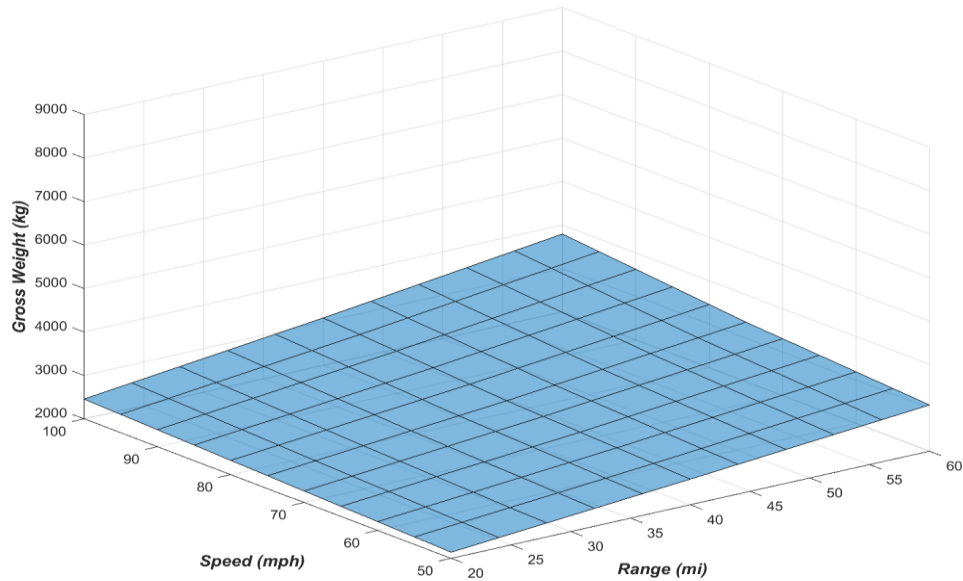


Figure 7-23 Gross weight of Multicopter Configurations: Six-Passenger, 900 Wh/kg Battery

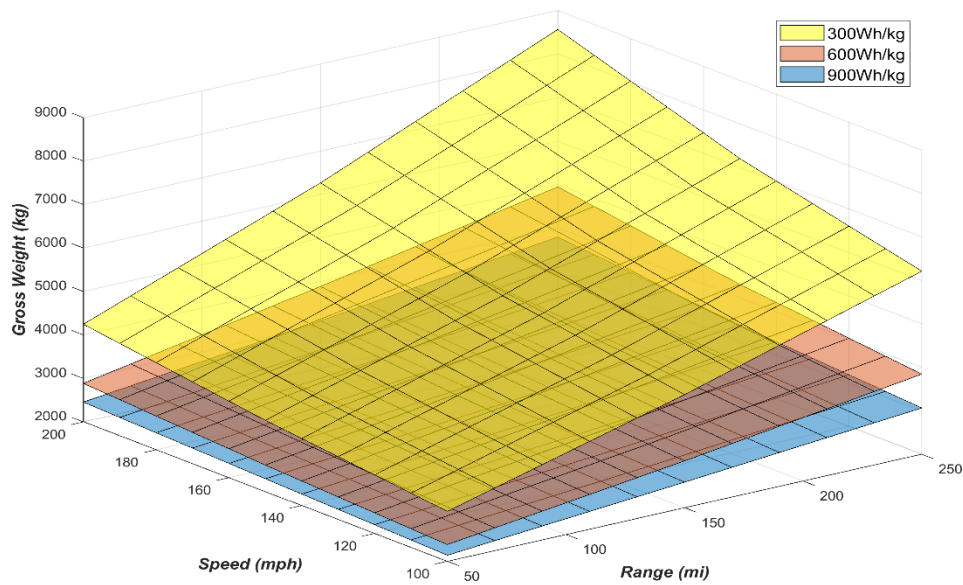


Figure 7-24 Comparison of Gross Weight Across Multicopter Configurations with 300, 600, and 900 Wh/kg Batteries for Six-Passenger Vehicles

Figure 7-25 to Figure 7-27 show the battery mass over MTOM for six-passenger Multicopter configurations from 300 Wh/kg battery to 900 Wh/kg battery. With a battery energy density of 300 Wh/kg, the maximum feasible cruise speed within the design range for a range of 20 miles is 80 mph. At a range of 40 miles, the minimum value of the battery mass over MTOM reaches 57.54%. When the battery energy density is increased to 600 Wh/kg, and the range is set at 60 miles,

the minimum value of the battery mass over MTOM reaches 50.7%. Furthermore, with a battery energy density increase to 900 Wh/kg, the maximum value of the battery mass over MTOM reaches 50.13%.

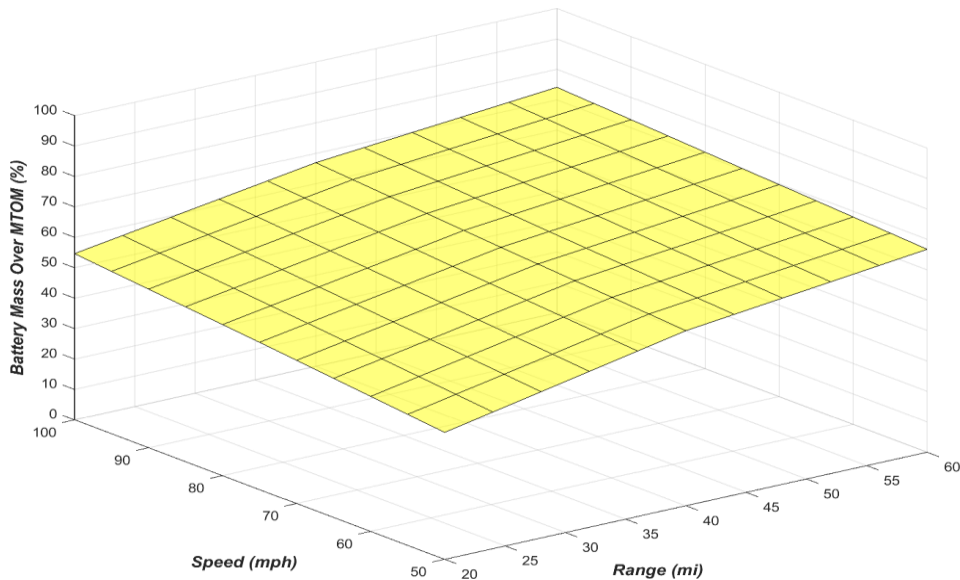


Figure 7-25 Battery mass over MTOM of Multicopter Configurations: Six-Passenger, 300 Wh/kg Battery

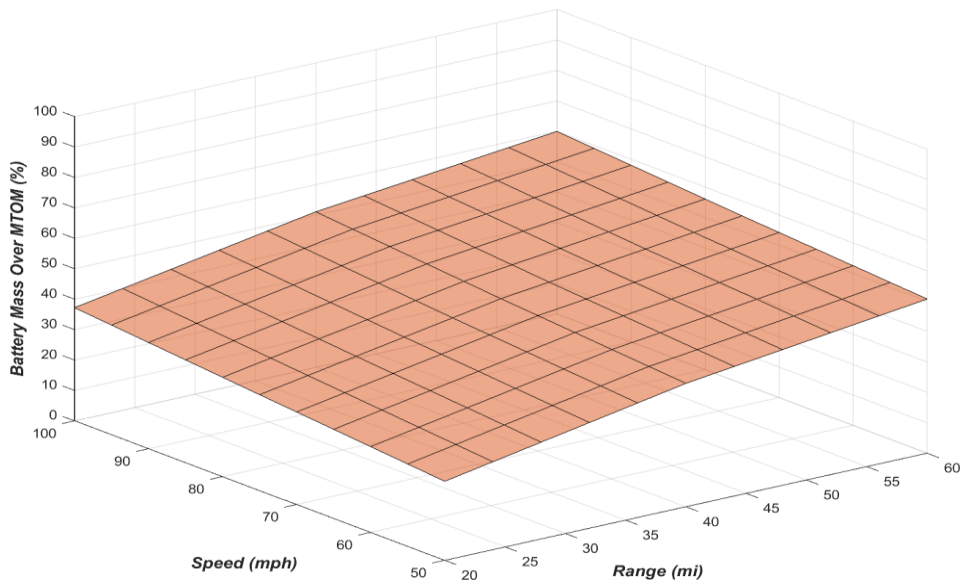


Figure 7-26 Battery mass over MTOM of Multicopter Configurations: Six-Passenger, 600 Wh/kg Battery

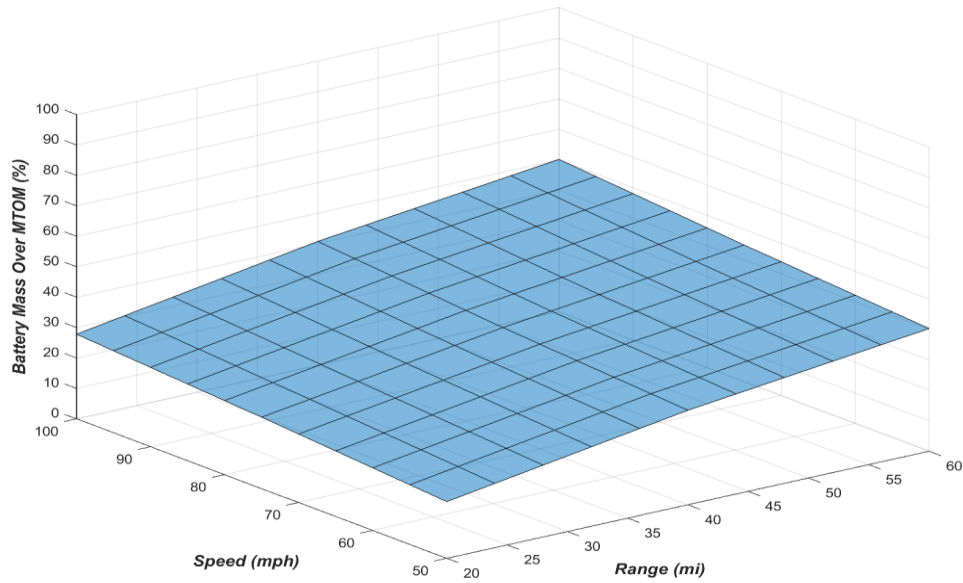


Figure 7-27 Battery mass over MTOM of Multicopter Configurations: Six-Passenger, 900 Wh/kg Battery

Figure 7-28 to Figure 7-30 show the energy consumption for six-passenger, Multicopter configurations from 300 Wh/kg battery to 900 Wh/kg battery.

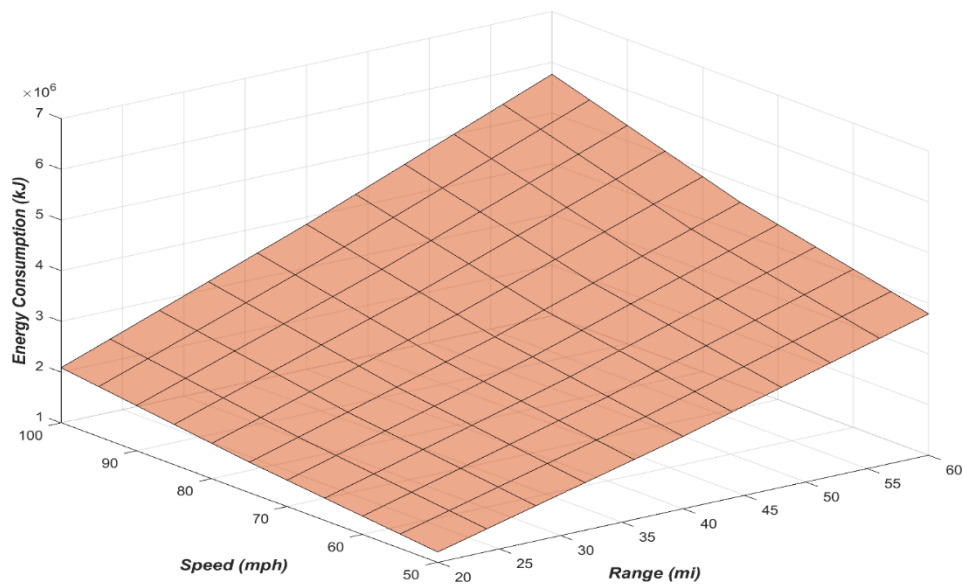


Figure 7-28 Energy consumption of Multicopter Configurations: Six-Passenger, 300 Wh/kg Battery

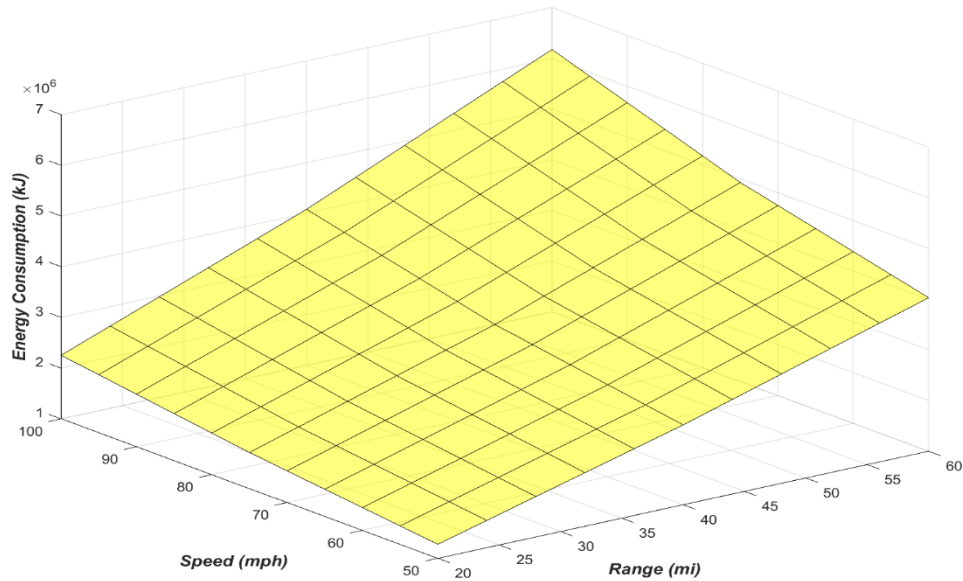


Figure 7-29 Energy consumption of Multicopter Configurations: Six-Passenger, 600 Wh/kg Battery

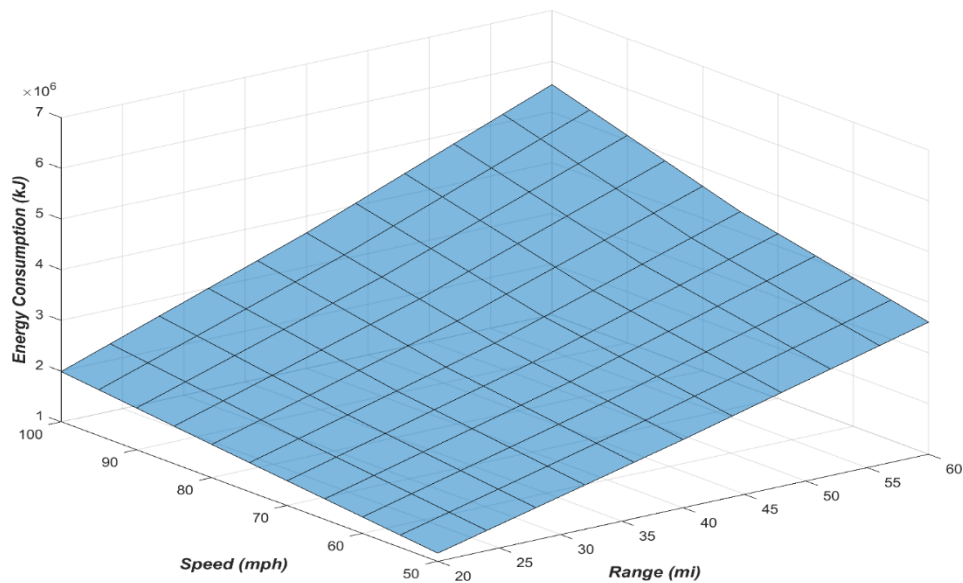


Figure 7-30 Energy consumption of Multicopter Configurations: Six-Passenger, 900 Wh/kg Battery

7.1.4 Conclusion

Multicopter eVTOL configurations demonstrate distinct limitations and advantages based on their inherent design features. Primarily influenced by disk loading and propeller efficiency, Multicopters are best suited for short-range and low-speed applications. This is not necessarily a drawback; on the contrary, they

outperform winged eVTOLs in these specific missions. Winged aircraft often suffer in low-range missions, as the added weight of the wing negates any advantage gained from cruise efficiency over such short distances.

Moreover, the simplicity of the Multicopter's construction and rotor system offers an operational advantage in short-range and low-speed scenarios. However, the absence of wings in the Multicopter design necessitates that all lift and thrust come from its propellers, contributing to generally higher battery mass over MTOM ratios. This has resulted in a substantial number of impractical and unfeasible Multicopter designs, especially when the battery energy density is at lower levels, like 300 Wh/kg.

The observed trends are in line with the current state of the eVTOL industry, where Multicopter designs are generally limited to 1-2 seat configurations, as evident in commercial examples like Ehang116 and Ehang216. However, it is worth noting that as battery technology improves, increasing the energy density, the range of viable Multicopter designs will likely expand due to the potential reduction in the high battery mass over MTOM ratios.

By evaluating these considerations, it becomes evident that while Multicopters may not be universally applicable across all types of eVTOL missions, they do fill a specific niche effectively. Their utilization is expected to grow in parallel with advancements in battery technology, further broadening their applicable range of operations.

8 Design Point Analysis

Figure 8-1 to Figure 8-3 show the gross weight comparison of Vectored Thrust configurations and Lift + Cruise configuration for two-passenger design from 300 Wh/kg battery to 900 Wh/kg battery. The comparison between Lift + Cruise and Vectored Thrust eVTOL configurations for two-passenger design reveals complex but instructive relationships between battery energy density, range, speed, and gross weight. Both configurations exhibit some similarities at lower speeds and shorter ranges when operating with a battery energy density of 300 Wh/kg. However, Lift + Cruise configurations generally have a slightly higher gross weight. This disparity grows notably as the speed and range increase, with Lift + Cruise surpassing Vectored Thrust by as much as 2324.226 kg in certain scenarios. This can be attributed to the different propulsive efficiencies during the cruise phase; Lift + Cruise relies on fewer, larger propellers, which are less efficient and must overcome greater aerodynamic drag due to the higher gross weight, thereby consuming more energy.

However, the dynamics begin to shift as battery energy density rises to 600 Wh/kg and further to 900 Wh/kg. Lift + Cruise configurations outperform Vectored Thrust in short-range missions at speeds between 100 mph and 140 mph. In these scenarios, the cruise phase doesn't dominate the energy expenditure, and the Lift + Cruise configuration benefits from not having the extra energy demands of tilt-wing or tilt-rotor mechanisms, commonly found in Vectored Thrust configurations. This advantage becomes even more pronounced with a battery energy density of 900 Wh/kg; Lift + Cruise shows a lower gross weight than Vectored Thrust for missions ranging from 50 to 100 miles.

To summarize, while Vectored Thrust configurations generally have a gross weight advantage in long-range, high-speed missions, Lift + Cruise configurations can be more efficient in short-range missions, especially as battery energy density improves. This nuanced understanding should inform future eVTOL design decisions, highlighting the critical role that mission profile and technological advancements in battery energy density play in optimizing eVTOL performance.

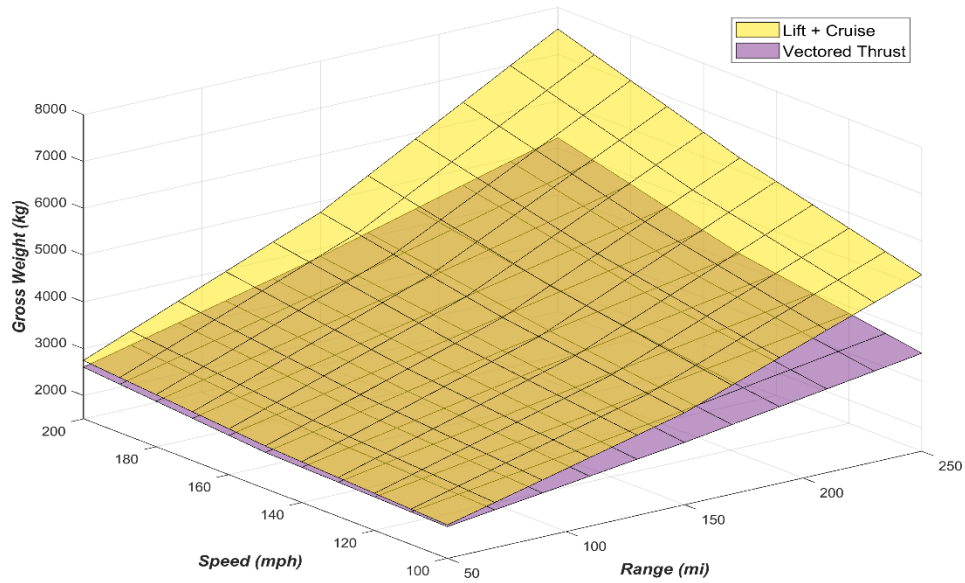


Figure 8-1 Gross weight comparison of Vectored Thrust configurations and Lift + Cruise configurations, two-passenger, 300 Wh/kg battery

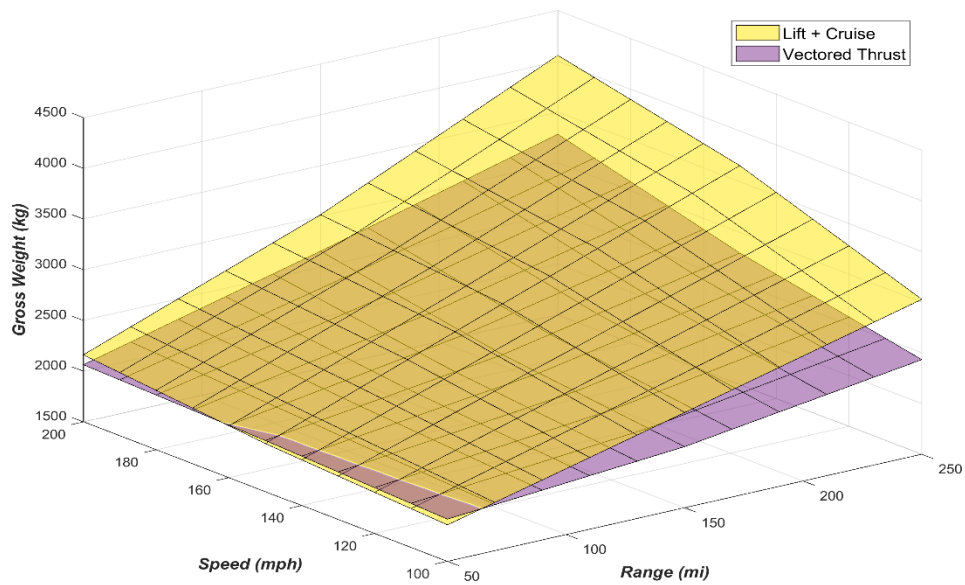


Figure 8-2 Gross weight comparison of Vectored Thrust configurations and Lift + Cruise configurations, two-passenger, 600 Wh/kg battery

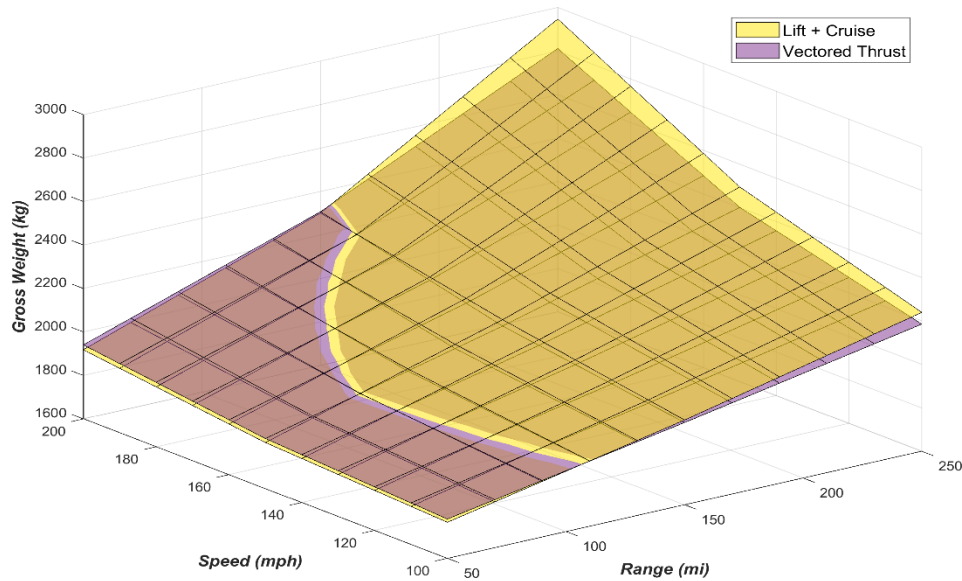


Figure 8-3 Gross weight comparison of Vectored Thrust configurations and Lift + Cruise configurations, two-passenger, 900 Wh/kg battery

Figure 8-4 to Figure 8-6 show the gross weight comparison of Vectored Thrust configurations and Lift + Cruise configuration for four-passenger design from 300 Wh/kg battery to 900 Wh/kg battery. The gross weight trends observed in eight-passenger Lift + Cruise and Vectored Thrust eVTOL configurations share general similarities with those found in their two-passenger counterparts. However, some unique characteristics emerge when analysing the four-passenger designs. Particularly at battery energy densities of 300 Wh/kg and 600 Wh/kg, Lift + Cruise configurations consistently exhibit higher gross weights compared to Vectored Thrust models across the speed and range spectrum.

This difference becomes even more pronounced at higher speeds and ranges. This escalating divergence in gross weight can be attributed to the non-linear increase in aerodynamic drag faced by aircraft as speeds rise. Given that Lift + Cruise configurations employ fewer but larger propellers, they suffer from a more significant drop in propeller efficiency when facing increased drag. As such, these configurations exhibit a noticeably higher gross weight, especially when operating at greater speeds and over longer distances.

However, the picture changes somewhat when the battery energy density increases to 900 Wh/kg. In this case, Lift + Cruise configurations show a slight

advantage over Vectored Thrust configurations, but only in short-range missions conducted at speeds between 100 mph and 120 mph.

In summary, while four-passenger Lift + Cruise configurations generally lag behind their Vectored Thrust counterparts in terms of gross weight, especially at higher speeds and longer ranges, they do show a minor advantage in specific short-range missions when equipped with higher energy-density batteries. This accentuates the role of mission-specific requirements and technological advancements in battery energy density when designing optimal eVTOL configurations.

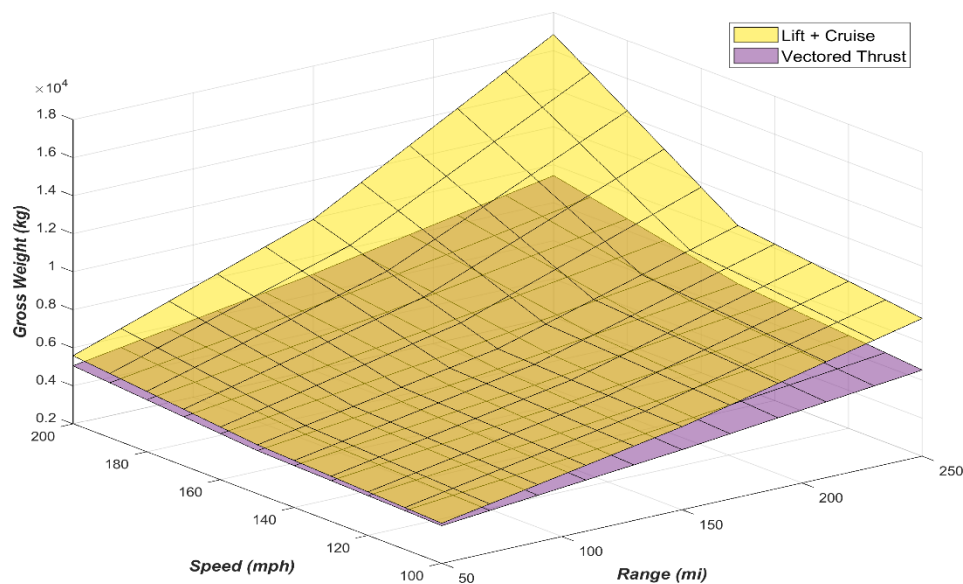


Figure 8-4 Gross weight comparison of Vectored Thrust configurations and Lift + Cruise configurations, eight-passenger, 300 Wh/kg battery

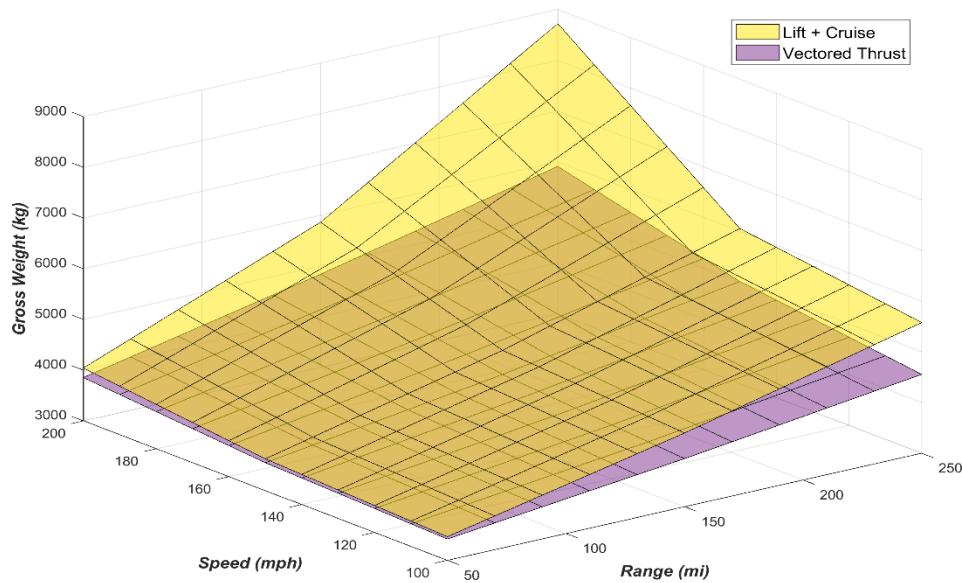


Figure 8-5 Gross weight comparison of Vectored Thrust configurations and Lift + Cruise configurations, eight-passenger, 600 Wh/kg battery

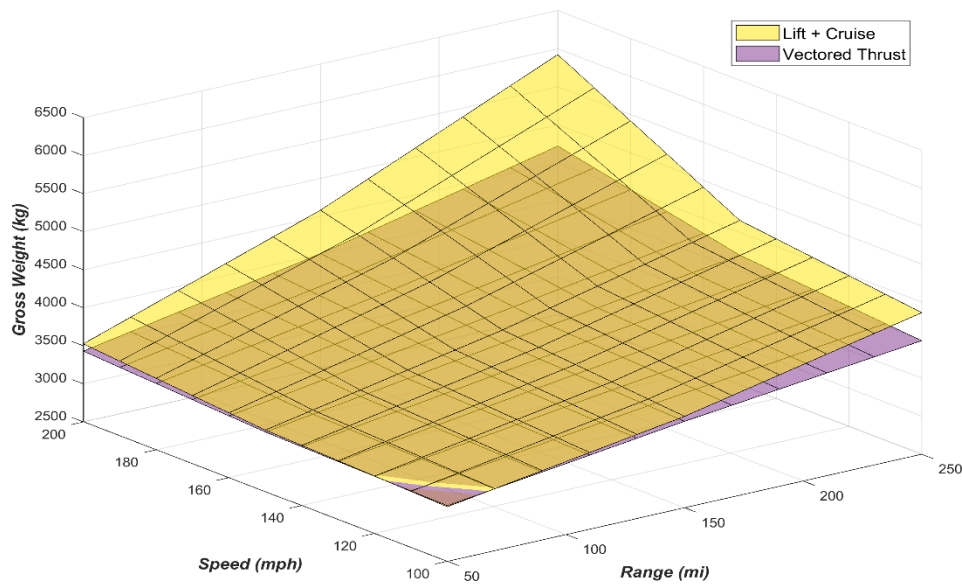


Figure 8-6 Gross weight comparison of Vectored Thrust configurations and Lift + Cruise configurations, eight-passenger, 900 Wh/kg battery

Figure 8-7 to Figure 8-9 show the gross weight comparison of Vectored Thrust configurations and Lift + Cruise configuration for twenty-passenger design from 300 Wh/kg battery to 900 Wh/kg battery. Across the spectrum of evolving battery energy densities—ranging from 300Wh/kg to 900Wh/kg—it is observed that the gross weight of eVTOL aircraft employing Vectored Thrust configurations consistently remains lower than that of their Lift + Cruise counterparts. It

emphasizes the inherent efficiency advantages offered by Vectored Thrust designs in the eVTOL space.

Interestingly, the gap between the gross weights of the two configurations appears to shrink as battery energy density improves, a phenomenon most conspicuous at higher cruising speeds and greater travel ranges. Lift + Cruise configurations demonstrate a heightened sensitivity to improvements in battery energy density compared to Vectored Thrust designs. One reason for this heightened sensitivity is the enhanced propeller efficiency Lift + Cruise configurations experience as their gross weight is reduced. With weight reduction, the power demands during cruising stages diminish more significantly for Lift + Cruise, resulting in a narrowed gross weight gap between the two configurations, particularly evident at higher speeds and longer ranges.

This trend suggests that advancements in battery technology are likely to disproportionately benefit Lift + Cruise configurations, possibly leveling the playing field in future eVTOL designs for larger passenger capacities. Therefore, ongoing improvements in battery energy density may shift the current performance paradigms, making Lift + Cruise configurations increasingly competitive, especially in scenarios demanding higher speeds and greater ranges.

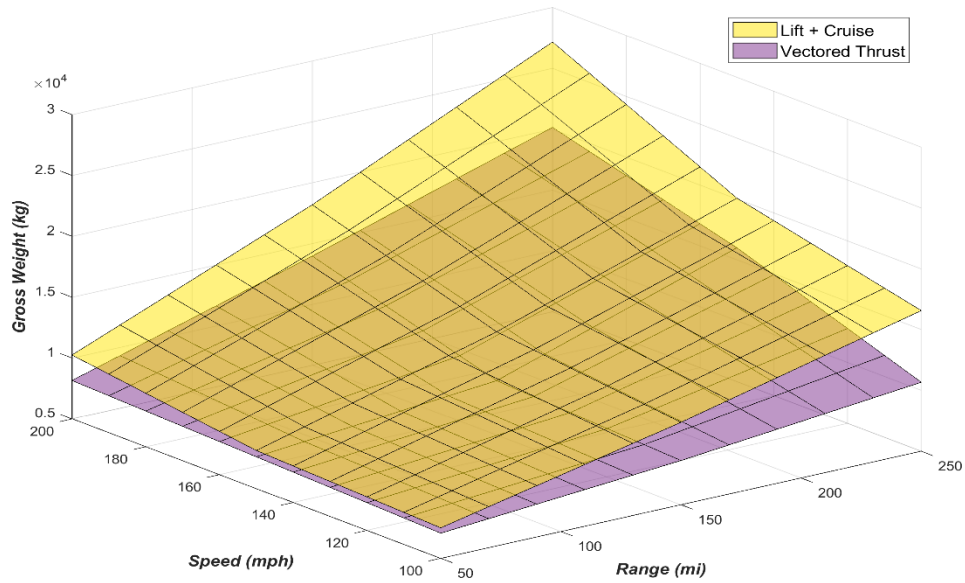


Figure 8-7 Gross weight comparison of Vectored Thrust configurations and Lift + Cruise configurations, twenty-passenger, 300 Wh/kg battery

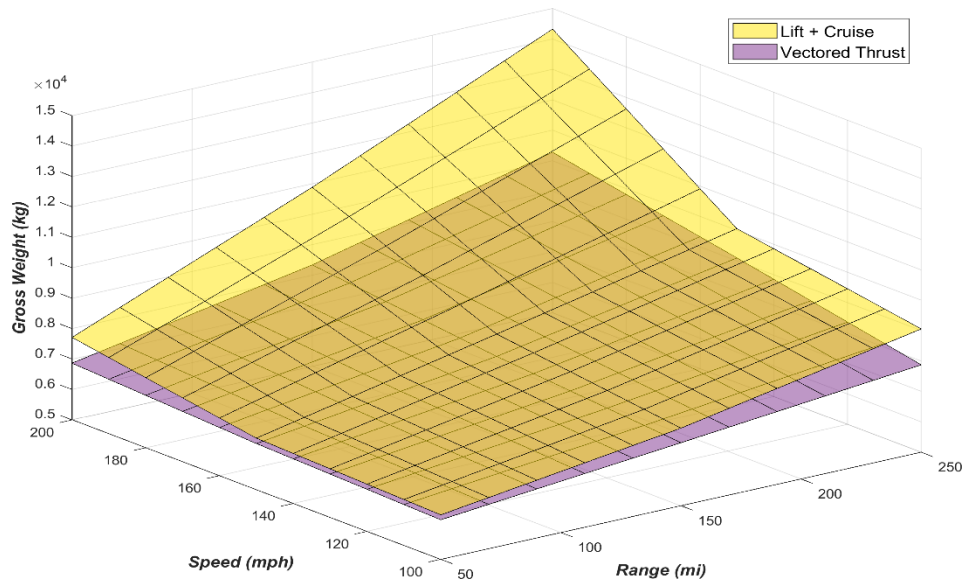


Figure 8-8 Gross weight comparison of Vectored Thrust configurations and Lift + Cruise configurations, twenty-passenger, 600 Wh/kg battery

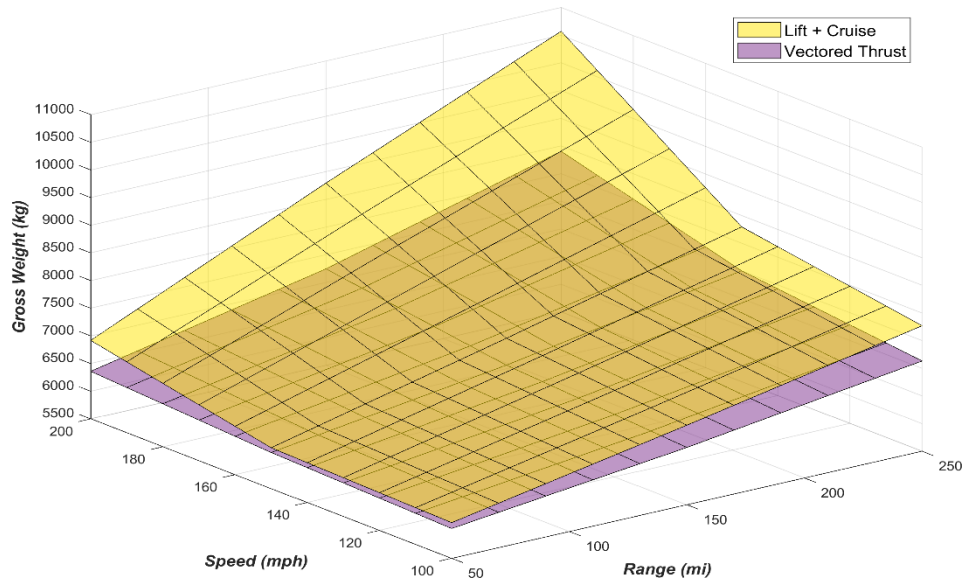


Figure 8-9 Gross weight comparison of Vectored Thrust configurations and Lift + Cruise configurations, twenty-passenger, 900 Wh/kg battery

In the rapidly evolving landscape of electric vertical take-off and landing (eVTOL) aircraft, two configurations have emerged as leading designs: Lift + Cruise and Vectored Thrust. Our analyses across different passenger capacities—two, eight, and twenty—under varying battery energy densities (300Wh/kg to 900Wh/kg) reveal nuanced insights into their comparative performances.

For two-passenger configurations, Vectored Thrust holds a definitive edge in gross weight efficiency at higher speeds and ranges, although Lift + Cruise manages to close the gap in specific short-range scenarios when the battery energy density improves. The trend is consistent in eight-passenger configurations, where Lift + Cruise continues to lag in efficiency at lower battery densities but shows promise in specific scenarios at higher energy densities.

When scaled to twenty-passenger configurations, Vectored Thrust maintains a lower gross weight across all battery densities. However, Lift + Cruise demonstrates a greater sensitivity to battery density improvements, making strides in efficiency and reducing the gross weight gap at higher speeds and ranges. This indicates that Lift + Cruise may become increasingly competitive as battery technology advances, particularly for larger passenger capacities.

In summary, Vectored Thrust configurations offer a decisive advantage in terms of gross weight efficiency for missions requiring high speeds and extensive ranges. Conversely, while Lift + Cruise configurations are generally less efficient in these domains, they display a higher degree of adaptability to technological advancements in battery energy density. As battery technologies continue to advance, Lift + Cruise configurations are expected to expand their envelope of applicability, becoming increasingly competitive, especially for larger eVTOL missions.

9 Conclusions

9.1 Summary

As the frontier of eVTOL aircraft continues to evolve, its potential for disrupting the UAM landscape is increasingly apparent. This technological inflection point demands a departure from traditional, aircraft-centric design paradigms. Instead of relying on empirical models, it necessitates a shift toward physically based, aerodynamic models capable of accounting for the unique challenges eVTOLs face, such as diverse flight modes and novel propulsion systems. The adoption of multidisciplinary design, analysis, and optimization (MDAO) methodologies holds promise for refining the foundational physics, constraining the design space, and minimizing subsequent development costs.

This research has operationalized these principles by integrating a comprehensive eVTOL design model into the established GENUS aircraft conceptual design framework. This expansion not only substantiates the functional accuracy of GENUS but also evaluates the efficacy of various optimization algorithms in handling the intricacies of eVTOL design. To better represent the specialized design elements, new modules for batteries, electric motors, and propellers have been seamlessly incorporated. Furthermore, a distinct segments module has been added to address the diverging flight modes unique to eVTOL aircraft, thus enriching the GENUS framework.

In summary, our comparative analysis of Lift + Cruise, Vectored Thrust, and multicopter configurations across varying passenger capacities and battery energy densities provides an in-depth understanding of the trade-offs involved in eVTOL design. Vectored Thrust configurations demonstrate a clear advantage in high-speed, long-range scenarios, offering lower gross weight compared to Lift + Cruise. On the other hand, Lift + Cruise systems display increased sensitivity to improvements in battery technology, extending their suitability to a broader range of applications as energy densities rise. Multicopter configurations, while simpler to construct and maintain, exhibit inherent limitations in disk loading and propeller efficiency. This restricts them primarily to short-range and low-speed missions,

where they can outperform Lift + Cruise and Vectored Thrust configurations in certain aspects, due to the added weight and complexity of wings in the latter types. The performance considerations are also not uniform across passenger capacities within the same eVTOL type, suggesting that scalability adds another layer of complexity to eVTOL design decisions. Although the general trends observed are valid and in line with engineering expectations, the numerical accuracy of the output variables can be negatively affected by input approximations and possible modelling limitations within the Genus modules.

9.2 Contributions to Knowledge

This research offers significant contribution to knowledge by:

1. The conducted review offers a comprehensive examination of contemporary technological progress within the eVTOL ecosystem, thereby advancing our understanding of its current state. It systematizes extant eVTOL architectures in the commercial sector and critically engages with a spectrum of technical challenges including safety protocols, aeroacoustic management, and advancements in energy storage technologies. Moreover, this inquiry enriches the discourse by identifying and dissecting the contributions of pivotal aerospace institutions and design agencies that are shaping this rapidly evolving landscape. The development of a multidisciplinary design analysis and optimization framework for eVTOL models empowers users to swiftly navigate the design space of eVTOLs across diverse mission profiles.
2. This research introduces a novel Multidisciplinary Design, Analysis, and Optimization (MDAO) framework tailored for eVTOL applications, offering a robust computational toolset. The developed framework allows for efficient traversal of the eVTOL design space across a multitude of mission profiles, thereby enabling designers to meet a broad range of performance criteria and constraints. The inclusion of this framework within the GENUS aircraft conceptual design environment not only validates its functional efficacy but also elucidates the synergies among multiple subsystems and optimization algorithms.

3. Employing a comparative methodology, this study explores the nuanced design implications of eVTOL aircraft configured for different payload capacities and mission requirements. Just a position of these optimization outcomes illuminates the strategic considerations underlying the design of various eVTOL configurations. In doing so, it produces an empirical foundation upon which to evaluate the relative merits and limitations of different eVTOL architectures. This forms a valuable asset for the aerospace community by offering data-driven insights that can serve as referential benchmarks for future design initiatives.

9.3 Future Work

While this study constitutes a significant step in the advancement of eVTOL modeling within the GENUS environment, it also delineates avenues for further research and refinement. The following dimensions offer potential for scholarly inquiry and technological enhancement:

1. The geometric representation within GENUS warrants an expansion to capture a more diverse array of topological configurations, thereby enriching the design choices and increasing the framework's applicability.
2. A deeper integration of physics-driven methodologies for weight estimation is vital to move beyond the limitations of existing empirical formulations, thus enhancing the fidelity of mass prediction in the eVTOL designs.
3. The adaptation of battery models that consider mass variability promises to elevate the realism of the framework, harmonizing its outcomes with empirical scenarios more coherently.
4. The integration of Computational Fluid Dynamics (CFD) techniques with heightened fidelity is indispensable for executing more granular aerodynamic analyses, thus potentially illuminating new optimization pathways.
5. Given the plethora of emergent technological factors intrinsic to eVTOL design, the formulation of a more systematic approach for the optimization of propellers and electric motors remains crucial.

6. Future work should also encompass the integration of additional performance metrics into the GENUS module, including factors such as noise levels, safety measures, and cost considerations, to facilitate a more comprehensive analysis of eVTOL designs.

REFERENCES

- [1] B.J. Holmes, R.A. Parker, A vision and opportunity for transformation of on-demand air mobility, in: 16th AIAA Aviat. Technol. Integr. Oper. Conf., 2016: pp. 1–9. <https://doi.org/10.2514/6.2016-3465>.
- [2] V.C. Nneji, A. Stimpson, M.M. Cummings, K.H. Goodrich, Exploring concepts of operations for on-demand passenger air transportation, in: 17th AIAA Aviat. Technol. Integr. Oper. Conf. 2017, 2017: pp. 1–12. <https://doi.org/10.2514/6.2017-3085>.
- [3] M. Narkus-Kramer, On-demand mobility (ODM): A discussion of concepts and required research, in: 2013 Aviat. Technol. Integr. Oper. Conf., 2013: pp. 1–10. <https://doi.org/10.2514/6.2013-4294>.
- [4] M.D. Moore, Misconceptions of Electric Aircraft and their Emerging Aviation Markets, in: 52nd Aerosp. Sci. Meet., 2014: pp. 1–17. <https://doi.org/10.2514/6.2014-0535>.
- [5] L.A. Garrow, M. Ilbeigi, Z. Chen, Forecasting demand for on demand mobility, in: 17th AIAA Aviat. Technol. Integr. Oper. Conf. 2017, 2017: pp. 1–7. <https://doi.org/10.2514/6.2017-3280>.
- [6] J.C. Smith, J.K. Viken, N.M. Guerreiro, S.M. Dollyhigh, J.W. Fenbert, C.L. Hartman, T.S. Kwa, M.D. Moore, Projected demand and potential impacts to the National Airspace System of autonomous, electric, on-demand small aircraft, in: 12th AIAA Aviat. Technol. Integr. Oper. Conf. 14th AIAA/ISSMO Multidiscip. Anal. Optim. Conf., 2012. <https://doi.org/10.2514/6.2012-5595>.
- [7] M.D. Patterson, K.R. Antcliff, L.W. Kohlman, A proposed approach to studying urban air mobility missions including an initial exploration of mission requirements, Annu. Forum Proc. - AHS Int. 2018-May (2018).
- [8] National Institute of Aerospace, (n.d.). <http://www.nianet.org/ODM/roadmap.htm> (accessed 2021).
- [9] K.R. Antcliff, M.D. Moore, K.H. Goodrich, Silicon valley as an early adopter

for on-demand civil VTOL operations, in: 16th AIAA Aviat. Technol. Integr. Oper. Conf., 2016: pp. 1–17. <https://doi.org/10.2514/6.2016-3466>.

- [10] Vahana, (n.d.). www.vahana.aero (accessed 2021).
- [11] Lilium Jet, (n.d.). <https://lilium.com/the-jet> (accessed 2021).
- [12] Kitty Hawk Cora, (n.d.). <https://kittyhawk.aero/> (accessed 2021).
- [13] Aurora Pegasus Passenger Air Vehicle, (n.d.). <https://www.aurora.aero/> (accessed 2021).
- [14] Prades GyroBike, (n.d.). <https://www.gyrobiketurismodeaventura.com/> (accessed 2021).
- [15] Piasecki PA-890, (n.d.). <https://www.piasecki.com/> (accessed 2021).
- [16] Vinati F-Helix, (n.d.). www.f-helix.com (accessed 2021).
- [17] eVTOL Timeline, (n.d.). <https://evtol.news/resources/evtol-timeline> (accessed 2021).
- [18] AgustaWestland Project Zero, (n.d.). <https://evtol.news/agustawestland-project-zero/> (accessed 2021).
- [19] Project Zero, (n.d.). <https://evtol.news/news/project-zero/> (accessed 2021).
- [20] Volocopter VC1, (n.d.). <https://evtol.news/volocopter-vc1-vc2/> (accessed 2021).
- [21] Opener BlackFly, (n.d.). <https://evtol.news/opener-blackfly/> (accessed 2021).
- [22] AHS International Leads Transformative Vertical Flight Initiative, (n.d.). <https://evtol.news/news/ahs-international-leads-transformative-vertical-flight-initiative> (accessed 2021).
- [23] Sikorsky Firefly, (n.d.). <https://evtol.news/sikorsky-firefly/> (accessed 2021).
- [24] Ehang 184, (n.d.). <https://evtol.news/ehang/> (accessed 2021).

- [25] F.H.S. W. Z. Stepniewski, Noise Implications for VTOL Development, SAE Transa, 1970.
- [26] D.C.D. Martin D. Maisel, Demo J. Giulianetti, The History of the XV-15 Tilt Rotor Research Aircraft From Concept to Flight, 2001.
- [27] M. Filipenko, Back to the Future: A rough comparison of 70's VTOL concepts to current eVTOL designs, (2020). <https://medium.com/@mykhaylo.filipenko/back-to-the-future-a-rough-comparison-of-70s-vtol-concepts-to-current-evtol-designs-c34b87ab480f>.
- [28] E. Botero, J.J. Alonso, Conceptual design and optimization of small transitioning UAVs using SUAVE, 18th AIAA/ISSMO Multidiscip. Anal. Optim. Conf. 2017. (2017) 1–15. <https://doi.org/10.2514/6.2017-4149>.
- [29] ACS Aviation Z-300, (n.d.). <https://www.acs-solutions.com.br/> (accessed 2021).
- [30] Dufour aEro 2, (n.d.). www.dufour.aero (accessed 2021).
- [31] SBX eVTOL, (n.d.). <https://www.gruggroup.com/> (accessed 2021).
- [32] Uber Elevate eCRM-003, (n.d.). <https://evtol.news/uber-elevate-ecrm-003/> (accessed 2021).
- [33] Zuri, (n.d.). <https://zuri.com/> (accessed 2021).
- [34] Hoversurf Formula, (n.d.). <https://www.hoversurf.com/> (accessed 2021).
- [35] Urban Aeronautics CityHawk, (n.d.). <http://www.urbanaero.com/> (accessed 2021).
- [36] Pipistrel 801 eVTOL, (n.d.). <https://www.pipistrel-aircraft.com/> (accessed 2021).
- [37] Airbus CityAirbus, (n.d.). <https://www.airbus.com/innovation/zero-emission/urban-air-mobility/cityairbus.html> (accessed 2021).
- [38] Davinci ZeroG, (n.d.). <http://da-vinci.us/> (accessed 2021).

- [39] Ehang 216, (n.d.). <https://evtol.news/ehang-216/> (accessed 2021).
- [40] A. Bacchini, E. Cestino, Electric VTOL configurations comparison, *Aerospace*. 6 (2019). <https://doi.org/10.3390/aerospace6030026>.
- [41] A.R. Kadhiresan, M.J. Duffy, Conceptual Design and Mission Analysis for eVTOL Urban Air Mobility Flight Vehicle Configurations, in: *AIAA Aviat. 2019 Forum*, 2019: pp. 1–19. <https://doi.org/10.2514/6.2019-2873>.
- [42] J. Xu, Design Perspectives on Delivery Drones, *Des. Perspect. Deliv. Drones*. (2017). <https://doi.org/10.7249/rr1718.2>.
- [43] ICAO, Annex 19 Timeline, 2020. <https://www.icao.int/safety/safetymanagement/Pages/default.aspx>.
- [44] O. Čokorilo, Risk Management Implementation In Aircraft Accident Cost Analysis, in: *Proc. 12nd Annu. World Conf. Air Transp. Res. Soc. World Conf.*, Athens, Greece, 2008: pp. 1–16.
- [45] R. Van Eekeren, S. Wright, O. Čokorilo, Early Cost Safety Analysis of Runway Events, *Int. J. Traffic Transp. Eng.* 8 (2018) 261–270. [https://doi.org/10.7708/ijtte.2018.8\(3\).01](https://doi.org/10.7708/ijtte.2018.8(3).01).
- [46] I. Čavka, O. Čokorilo, L. Vasov, Energy efficiency in aircraft cabin environment: Safety and design, *Energy Build.* 115 (2016) 63–68. <https://doi.org/10.1016/j.enbuild.2015.01.015>.
- [47] L. Moretti, P. Di Mascio, S. Nichele, O. Cokorilo, Runway veer-off accidents: Quantitative risk assessment and risk reduction measures, *Saf. Sci.* 104 (2018) 157–163. <https://doi.org/10.1016/j.ssci.2018.01.010>.
- [48] O. Čokorilo, G. Dell’Acqua, Aviation Hazards Identification Using Safety Management System (SMS) Techniques, in: *16th Int. Conf. Transp. Sci. (ICTS 2013)*, 2013: pp. 66–73. <http://dx.doi.org/10.1080/13669877.2013.879493>.
- [49] O. Cokorilo, Urban Air Mobility: Safety Challenges, in: *AIIT 2nd Int. Congr. Transp. Infrastruct. Syst. a Chang. World (TIS ROMA 2019)*, Elsevier B.V.,

- 2020: pp. 21–29. <https://doi.org/10.1016/j.trpro.2020.02.058>.
- [50] Airbus S.A.S., A Statistical Analysis of Commercial Aviation Accidents 1958-2019, 2020. <https://accidentstats.airbus.com/>.
- [51] A.S. Gohardani, A synergistic glance at the prospects of distributed propulsion technology and the electric aircraft concept for future unmanned air vehicles and commercial/military aviation, *Prog. Aerosp. Sci.* 57 (2013) 25–70. <https://doi.org/10.1016/j.paerosci.2012.08.001>.
- [52] A.M. Stoll, J. Ben Bevirt, P.P. Pei, E. V. Stilson, Conceptual design of the joby S2 electric VTOL PAV, in: *AIAA Aviat. 2014 -14th AIAA Aviat. Technol. Integr. Oper. Conf.*, 2014: pp. 16–20. <https://doi.org/10.2514/6.2014-2407>.
- [53] H.D. Kim, A.T. Perry, P.J. Ansell, A Review of Distributed Electric Propulsion Concepts for Air Vehicle Technology, in: *2018 AIAA/IEEE Electr. Aircr. Technol. Symp. EATS 2018*, 2018: pp. 1–21. <https://doi.org/10.2514/6.2018-4998>.
- [54] European Organisation for the Safety of Air Navigation, Environmental issues for aviation, (n.d.). <http://www.eurocontrol.int/articles/environmental-issues-aviation> (accessed 2021).
- [55] K.A., O. Zaporozhets, V. Tokarev, *Aircraft Noise: Assessment, Prediction and Control*, NY: Spon Press, New York, 2011.
- [56] Southern California Association of Governments. (2020). Los Angeles helicopter noise initiative. Retrieved from https://scag.ca.gov/sites/main/files/file-attachments/atac022714_lahelicopternoise.pdf?1602480559(accessed 2024).
- [57] New York City Economic Development Corporation, NYCEDC and Helicopter Tourism & Jobs Council Announce New Measures to Reduce Helicopter Noise and Impacts Across New York City, (n.d.). <http://www.nycedc.com> (accessed 2021).

- [58] J. Barron, The Citizens of East Hampton v. Its Airport, (n.d.). <https://www.nytimes.com/2017/07/04/nyregion/east-hampton-airport-noise-regulations.html> (accessed 2021).
- [59] M.J.T. Smith, Aircraft noise prediction, *Prog. Aerosp. Sci.* (2014) 227–245. <https://doi.org/10.1017/cbo9780511584527.008>.
- [60] P.D. Vascik, R.J. Hansman, Scaling Constraints for Urban Air Mobility Operations:, MIT Int. Cent. Air Transp. (2018).
- [61] J.L. Felder, H.D. Kim, G. V. Brown, Turboelectric distributed propulsion engine cycle analysis for hybrid-wing-body aircraft, in: 47th AIAA Aerosp. Sci. Meet. Incl. New Horizons Forum Aerosp. Expo., 2009: pp. 1–25. <https://doi.org/10.2514/6.2009-1132>.
- [62] D. Liu, C., Si, X., Teng, J., and Ihiabe, Method to Explore the Design Space of a Turbo-Electric Distributed Propulsion System, *J. Aerosp. Eng. Vol. 29* (2016).
- [63] J. Luo, B. Du, W. Song, Preliminary Design of Vtol Personal Flying Machine – Dereamwings, in: Asian Work. Aircr. Des. Educ., 2016.
- [64] A.R. Kadhiresan, M.J. Duffy, Conceptual design and mission analysis for evtol urban air mobility flight vehicle configurations, in: AIAA Aviat. 2019 Forum, 2019: pp. 1–19. <https://doi.org/10.2514/6.2019-2873>.
- [65] H. Martin, Electric Flight - Potential and Limitations, in: AVT-209 Work. Lisbon, 2012: pp. 1–30.
- [66] A. Datta, Commercial Intra-City On-demand Electric-VTOL, 2018. <https://vtol.org/files/dmfile/TVF.WG2.YR2017draft.pdf>.
- [67] Commercial aircraft propulsion and energy systems research: Reducing global carbon emissions, National Academies Press, Washington, D.C, 2016. <https://doi.org/10.17226/23490>.
- [68] C. Rheume, Jonathan M and Lents, Energy storage for commercial hybrid electric aircraft, *SAE Tech. Pap.* (2016). <https://doi.org/10.4271/2016-01->

2014.

- [69] R.H. Jansen, C. Bowman, A. Jankovsky, R. Dyson, J. Felder, Overview of NASA electrified aircraft propulsion research for large subsonic transports, in: 53rd AIAA/SAE/ASEE Jt. Propuls. Conf. 2017, 2017: pp. 1–20. <https://doi.org/10.2514/6.2017-4701>.
- [70] A.R. Gnadt, R.L. Speth, J.S. Sabnis, S.R.H. Barrett, Technical and environmental assessment of all-electric 180-passenger commercial aircraft, *Prog. Aerosp. Sci.* 105 (2019) 1–30. <https://doi.org/10.1016/j.paerosci.2018.11.002>.
- [71] P.G. Bruce, S.A. Freunberger, L.J. Hardwick, J.M. Tarascon, LiO₂ and LiS batteries with high energy storage, *Nat. Mater.* 11 (2012) 19–29. <https://doi.org/10.1038/nmat3191>.
- [72] C.P. Yang, Y.X. Yin, Y.G. Guo, Elemental Selenium for Electrochemical Energy Storage, *J. Phys. Chem. Lett.* 6 (2015) 256–266. <https://doi.org/10.1021/jz502405h>.
- [73] L. Grande, E. Paillard, J. Hassoun, J.B. Park, Y.J. Lee, Y.K. Sun, S. Passerini, B. Scrosati, The lithium/air battery: Still an emerging system or a practical reality?, *Adv. Mater.* 27 (2015) 784–800. <https://doi.org/10.1002/adma.201403064>.
- [74] I. Muralidharan, N., Self, E. C., Dixit, M., Du, Z., Essehli, R., Amin, R., Nanda, J., Belharouak, Next-Generation Cobalt-Free Cathodes – A Prospective Solution to the Battery Industry’s Cobalt Problem, *Adv. Energy Mater.* 12 (2022).
- [75] W. Yu, N. Deng, K. Cheng, J. Yan, B. Cheng, W. Kang, Advances in preparation methods and mechanism analysis of layered double hydroxide for lithium-ion batteries and lithium-sulfur batteries, *J. Energy Chem.* 58 (2021) 472–499. <https://doi.org/10.1016/j.jechem.2020.10.031>.
- [76] C.K. Chan, H. Peng, G. Liu, K. McIlwrath, X.F. Zhang, R.A. Huggins, Y. Cui, High-performance lithium battery anodes using silicon nanowires, *Nat.*

- Nanotechnol. 3 (2008) 31–35. <https://doi.org/10.1038/nnano.2007.411>.
- [77] Q. Huang, M.J. Loveridge, R. Genieser, M.J. Lain, R. Bhagat, Electrochemical Evaluation and Phase-related Impedance Studies on Silicon-Few Layer Graphene (FLG) Composite Electrode Systems, *Sci. Rep.* 8 (2018) 1–9. <https://doi.org/10.1038/s41598-018-19929-3>.
- [78] B. Markovsky, F. Amalraj, H.E. Gottlieb, Y. Gofer, S.K. Martha, D. Aurbach, On the Electrochemical Behavior of Aluminum Electrodes in Nonaqueous Electrolyte Solutions of Lithium Salts, *J. Electrochem. Soc.* 157 (2010) A423. <https://doi.org/10.1149/1.3294774>.
- [79] V. Etacheri, R. Marom, R. Elazari, G. Salitra, D. Aurbach, Challenges in the development of advanced Li-ion batteries: A review, *Energy Environ. Sci.* 4 (2011) 3243–3262. <https://doi.org/10.1039/c1ee01598b>.
- [80] M.S. Whittingham, Lithium batteries and cathode materials, *Chem. Rev.* 104 (2004) 4271–4301. <https://doi.org/10.1021/cr020731c>.
- [81] J.E. D. Yaakov, I. C. Halalay and D. Aurbach, On the Study of Electrolyte Solutions for Li-Ion Batteries That Can Work Over a Wide Temperature Range, *J. Electrochem. Soc.* 157 (2010).
- [82] B. Kang, G. Ceder, Battery materials for ultrafast charging and discharging, *Nature*. 458 (2009) 190–193. <https://doi.org/10.1038/nature07853>.
- [83] Battery University, BU-212: Future Batteries, (n.d.). https://batteryuniversity.com/learn/article/experimental_rechargeable_batteries (accessed 2021).
- [84] N. Jayaprakash, J. Shen, S.S. Moganty, A. Corona, L.A. Archer, Porous hollow carbon@sulfur composites for high-power lithium-sulfur batteries, *Angew. Chemie - Int. Ed.* 50 (2011) 5904–5908. <https://doi.org/10.1002/anie.201100637>.
- [85] Y.X. Yin, S. Xin, Y.G. Guo, L.J. Wan, Lithium-sulfur batteries: Electrochemistry, materials, and prospects, *Angew. Chemie - Int. Ed.* 52

- (2013) 13186–13200. <https://doi.org/10.1002/anie.201304762>.
- [86] M. Balaish, A. Kraytsberg, Y. Ein-Eli, A critical review on lithium-air battery electrolytes, *Phys. Chem. Chem. Phys.* 16 (2014) 2801–2822. <https://doi.org/10.1039/c3cp54165g>.
 - [87] Committee on Propulsion and Energy Systems to Reduce Commercial Aviation Carbon Emissions, in: *Commer. Aircr. Propuls. Energy Syst. Res.*, National Academies Press, Washington, D.C, 2016.
 - [88] et al. Darecki M, Edelstenne C, Enders T, Flightpath 2050 Europe's Vision for Aviation, 2011. <https://doi.org/10.2777/50266>.
 - [89] NASA, NASA Aeronautics: Strategic Implementation Plan-2017 Update, 2015. www.lternet.edu/sip.pdf.
 - [90] N.K.M. G.J. Follen, R. Del Rosario, R.A. Wahls, NASA's fundamental aeronautics subsonic fixed wing project: generation N+3 technology portfolio, in: *SAE 2011 AeroTech Congr. Exhib.*, 2011. <https://doi.org/https://www.researchgate.net/deref/http%3A%2F%2Fdx.doi.org%2F10.4271%2F2011-01-2521>.
 - [91] N. Polaczyk, S. Joby, S. Joby, K.H. Cora, A Review of Current Technology and Research in Urban On-Demand Air Mobility Applications, (2019). http://www.aere.iastate.edu/~pwei/proceedings/vfs19_nick.pdf.
 - [92] C.E.D. Riboldi, F. Gualdoni, An integrated approach to the preliminary weight sizing of small electric aircraft, *Aerosp. Sci. Technol.* 58 (2016) 134–149. <https://doi.org/10.1016/j.ast.2016.07.014>.
 - [93] M.D. Patterson, B.J. German, M.D. Moore, Performance analysis and design of on-demand electric aircraft concepts, in: *12th AIAA Aviat. Technol. Integr. Oper. Conf. 14th AIAA/ISSMO Multidiscip. Anal. Optim. Conf.*, 2012: pp. 1–28. <https://doi.org/10.2514/6.2012-5474>.
 - [94] C.C. Chan, The State of the Art of Electric, Hybrid, and Fuel Cell Vehicles With their superior fuel economy and performance, hybrid vehicles will

likely increase in popularity in coming years; further development of control theory for hybrids is essential for their, in: Proc. IEEE, 2007: pp. 704–718. <https://www.eee.hku.hk/doc/ccchan/TheStateoftheArtofElectric,Hybrid,andFuelCellVehicles.pdf>.

- [95] A.T. Isikveren, S. Kaiser, C. Pornet, P.C. Vratny, Pre-design strategies and sizing techniques for dual-energy aircraft, *Aircr. Eng. Aerosp. Technol.* 86 (2014) 525–542. <https://doi.org/10.1108/AEAT-08-2014-0122>.
- [96] B.J. Brelje, J.R.R.A. Martins, Electric, hybrid, and turboelectric fixed-wing aircraft: A review of concepts, models, and design approaches, *Prog. Aerosp. Sci.* 104 (2019) 1–19. <https://doi.org/10.1016/j.paerosci.2018.06.004>.
- [97] M.M. Mi C, Hybrid electric vehicles: Principles and applications with practical perspectives., Chichester: John Wiley & Sons, 2017.
- [98] Y. XIE, SAVVARISAL, T. ANTONIOS, Z. DAN, G. JASON, Review of hybrid electric powered aircraft, its conceptual design and energy management methodologies, *Chinese J. Aeronaut.* (2020). <https://doi.org/10.1016/j.cja.2020.07.017>.
- [99] M.K. Bradley, T.J. Allen, C.K. Droney, Subsonic Ultra Green Aircraft Research: Phase II - Volume III - Truss Braced Wing Design Exploration, 2015.
- [100] J.K. Ausserer, F.G. Harmon, Integration, validation, and testing of a hybrid-electric propulsion system for a small remotely-piloted aircraft, in: 10th Annu. Int. Energy Convers. Eng. Conf. IECEC 2012, 2012: pp. 1–11. <https://doi.org/10.2514/6.2012-4239>.
- [101] L.K. Shailendra Jain, Fundamentals of Power Electronics Controlled Electric Propulsion, in: M.H. Rashid (Ed.), *Power Electron. Handb.* (Fourth Ed., Butterworth-Heinemann, 2018: pp. 1023–1065. <https://doi.org/https://doi.org/10.1016/B978-0-12-811407-0.00035-0>.
- [102] G.A. Hill, R.H. Thomas, Challenges and Opportunities for Noise Reduction

Through Advanced Aircraft Propulsion Airframe Integration and Configurations, in: 8th CEAS Work. Aeroacoustics New Aircr. Engine Config., 2004: pp. 1–13.

- [103] L.T. Leifsson, A. Ko, W.H. Mason, J. a. Schetz, R.T. Haftka, B. Grossman, Multidisciplinary Design Optimization for a Blended Wing Body Transport Aircraft with Distributed Propulsion, 2005. http://128.173.188.87/~mason/Mason_f/MAD050501.pdf.
- [104] H. Smith, College of Aeronautics Blended Wing Body Development Programme, Congr. Int. Counc. Aeronaut. Sci. (2000) 114.1-114.10.
- [105] G.A. Hill, S.A. Brown, K.A. Geiselhart, C.M. Burg, Integration of propulsion-airframe-aeroacoustic technologies and design concepts for a quiet blended-wing-body transport, in: Collect. Tech. Pap. - AIAA 4th Aviat. Technol. Integr. Oper. Forum, ATIO, 2004: pp. 703–722. <https://doi.org/10.2514/6.2004-6403>.
- [106] B.G. A. Ko, L. Leifsson, W. Mason, J. Schetz, MDO of a Blended-Wing-Body Transport Aircraft with Distributed Propulsion, in: AIAA's 3rd Annu. Aviat. Technol. Integr. Oper. Tech. Forum, 2003: pp. 1–11.
- [107] M.D. Moore, Distributed Electric Propulsion (DEP) Aircraft, in: 5th Symp. Collab. Aircr. Des. Naples Naples, 2016: pp. 299–305. <https://doi.org/10.1093/eurpub/cks052>.
- [108] M.D. Moore, Aviation frontiers: On-demand aircraft, in: 10th AIAA Aviat. Technol. Integr. Oper. Conf. 2010, ATIO 2010, 2010: pp. 1–12. <https://doi.org/10.2514/6.2010-9343>.
- [109] N. Putra, B. Ariantara, Electric motor thermal management system using L-shaped flat heat pipes, Appl. Therm. Eng. 126 (2017) 1156–1163. <https://doi.org/10.1016/j.applthermaleng.2017.01.090>.
- [110] S. Stückl, Methods for the Design and Evaluation of Future Aircraft Concepts Utilizing Electric Propulsion Systems, 2016. <https://d-nb.info/1107543258/34>.

- [111] S.I.O. Michael Z. Hauschild, Ralph K. Rosenbaum, Theory and Practice, in: Life Cycle Assess., Cham: Springer International, 2018: pp. 17–30.
- [112] K. Khavarian, P.D. Candidate, Life-cycle Analysis of Electric Vertical Take-Off and Landing Vehicles, in: Bridg. Transp. Res. Conf., Bridging Transportation Researchers Conference 7-8, 2020.
- [113] F. Cerdas, S. Thiede, C. Herrmann, Integrated Computational Life Cycle Engineering — Application to the case of electric vehicles, CIRP Ann. 67 (2018) 25–28. <https://doi.org/10.1016/j.cirp.2018.04.052>.
- [114] S.P. Melo, F. Cerdas, A. Barke, C. Thies, T.S. Spengler, C. Herrmann, Life cycle engineering of future aircraft systems: The case of eVTOL vehicles, Procedia CIRP. 90 (2020) 297–302. <https://doi.org/10.1016/j.procir.2020.01.060>.
- [115] N. André, M. Hajek, Robust Environmental Life Cycle Assessment of Electric VTOL Concepts for Urban Air Mobility, in: AIAA Aviat. 2019 Forum Robust, 2019. <https://doi.org/10.2514/6.2019-3473>.
- [116] EASA, ANSI/EASA Standard AR100-2020: Recommended Practice for the Repair of Rotating Electrical Apparatus, (2020). <https://easa.com/resources/resource-library/ansieasa-standard-ar100-2020-recommended-practice-for-the-repair-of-rotating-electrical-apparatus> (accessed 2021).
- [117] Electrical Apparatus Service Association, Failures in Three-Phase Stator Windings, (n.d.). <https://easa.com/resources/failures-in-three-phase-stator-windings> (accessed 2021).
- [118] R.P. Naru, B.J. German, Maintenance considerations for electric aircraft and feedback from aircraft maintenance technicians, in: 2018 Aviat. Technol. Integr. Oper. Conf., 2018: pp. 1–6. <https://doi.org/10.2514/6.2018-3053>.
- [119] Y. Liu, M. Kreimeier, E. Stumpf, Y. Zhou, H. Liu, Overview of recent endeavors on personal aerial vehicles: A focus on the US and Europe led

- research activities, *Prog. Aerosp. Sci.* 91 (2017) 53–66. <https://doi.org/10.1016/j.paerosci.2017.03.001>.
- [120] R.J. Hansman, P.D. Vascik, Operational Aspects of Aircraft-Based On-Demand Mobility, 2016. https://www.faa.gov/about/office_org/headquarters_offices/ang/offices/tc/library/jup/april2016/MIT/MIT_ICAT_Parker_Vascik.pdf.
- [121] P.D. Vascik, R. John Hansman, Evaluation of key operational constraints affecting on demand mobility for aviation in the Los Angeles basin: Ground infrastructure, air traffic control and noise, in: 17th AIAA Aviat. Technol. Integr. Oper. Conf. 2017, 2017: pp. 1–20. <https://doi.org/10.2514/6.2017-3084>.
- [122] ehang white paper, 2020. [https://doi.org/10.1016/0013-4694\(85\)91127-7](https://doi.org/10.1016/0013-4694(85)91127-7).
- [123] M.D. Patterson, K.R. Antcliff, L.W. Kohlman, A proposed approach to studying urban air mobility missions including an initial exploration of mission requirements, in: AHS Int. 74th Annu. Forum Technol. Disp., 2018.
- [124] N. Syed, On Demand Mobility Commuter Aircraft Demand Estimation, 2017. https://vtechworks.lib.vt.edu/bitstream/handle/10919/78879/Syed_NU_T_2017.pdf?sequence=1.
- [125] P.D. Vascik, Systems-Level Analysis of On Demand Mobility for Aviation, 2017. http://seari.mit.edu/documents/theses/SM_VASCIK.pdf.
- [126] J. Melton, D. Kontinos, S. Grabbe, J. Alonso, J. Sinsay, B. Tracey, Combined electric aircraft and airspace management design for metro-regional public transportation, 2014.
- [127] B.I. Schuchardt, P. Lehmann, F. Nieuwenhuizen, P. Perfect, Final list of desirable features / options for the PAV and supporting systems, 2015.
- [128] C.-D. STĂNESCU, Single European Sky – the Solution for an Air Traffic Management Adapted To the Challenges of This Century, *Rev. Air Force Acad.* 15 (2017) 137–148. <https://doi.org/10.19062/1842->

9238.2017.15.1.18.

- [129] F.J.S. Nieto, Introduction to the SESAR WPE Research Network: HALA! (Higher Automation Levels in ATM), in: ENRI Int. Work. ATM/CNS, Tokyo, 2010.
- [130] SESAR Consortium, SESAR definition phase D3: The ATM target concept, 2007.
- [131] Geister, Dagi, DLR Blueprint Concept for Urban Airspace Integration Integrating UAS into the future aviation system, in: 2017. http://www.dlr.de/fl/desktopdefault.aspx/tabid-11763/20624_read-48305/.
- [132] E. Mueller, P. Kopardekar, K. Goodrich, Enabling airspace integration for high-density on-demand mobility operations, 17th AIAA Aviat. Technol. Integr. Oper. Conf. 2017. (2017) 1–24. <https://doi.org/10.2514/6.2017-3086>.
- [133] A. Straubinger, R. Rothfeld, M. Shamiyeh, K.D. Büchter, J. Kaiser, K.O. Plötner, An overview of current research and developments in urban air mobility – Setting the scene for UAM introduction, J. Air Transp. Manag. 87 (2020). <https://doi.org/10.1016/j.jairtraman.2020.101852>.
- [134] P. Pradeep, P. Wei, Energy-efficient arrival with RTA constraint for multirotor EVToL in urban air mobility, in: J. Aerosp. Inf. Syst., 2019: pp. 263–277. <https://doi.org/10.2514/1.1010710>.
- [135] K. Krishnakumar, P. Kopardekar, C. Ippolito, J.E. Melton, V. Stepanyan, S. Sankararaman, B. Nikaido, Safe autonomous flight environment (SAFE50) for the notional last “50 ft” of operation of “55 lb” class of UAS, in: AIAA Inf. Syst. Infotech Aerospace, 2017, 2017: pp. 1–7. <https://doi.org/10.2514/6.2017-0445>.
- [136] H. Ullah, N. Gopalakrishnan Nair, A. Moore, C. Nugent, P. Muschamp, M. Cuevas, 5G communication: An overview of vehicle-to-everything, drones, and healthcare use-cases, IEEE Access. 7 (2019) 37251–37268. <https://doi.org/10.1109/ACCESS.2019.2905347>.

- [137] 5G Americas, New Services & Applications with 5G Ultra-reliable Low Latency Communications, (2018). https://doi.org/10.1587/essfr.13.1_1.
- [138] S.C. Mohleji, A.R. Lacher, P.A. Ostwald, CNS/ATM system architecture concepts and future vision of nas operations in 2020 timeframe, in: AIAA's 3rd Annu. Aviat. Technol. Integr. Oper. Forum, 2003: pp. 1–10.
- [139] Lilium Jet, Lilium eVTOL Jet app, (n.d.). <https://lilium.com/> (accessed 2021).
- [140] Evtol News, Vahana, (n.d.). <https://evtol.news/a3-by-airbus> (accessed 2021).
- [141] G.C.B. Giovanni Droandi, Monica Syal, Tiltwing Multi-Rotor Aerodynamic Modeling in Hover, Transition and Cruise Flight Conditions, in: AHS Int. 74th Annu. Forum Technol. Disp., Phoenix, Arizona, USA, 2018.
- [142] Z. Lovering, Step Inside Alpha Two, (2019). <https://acubed.airbus.com/blog/vahana/step-inside-alpha-two/> (accessed 2021).
- [143] Evtol News, Joby S4, (n.d.). <https://evtol.news/joby-s4> (accessed, 2021).
- [144] Joby Aviation, Joby S4, (n.d.). <http://www.jobyaviation.com/> (accessed 2021).
- [145] Ehang, Ehang 216, (n.d.). www.ehang.com (accessed 2021).
- [146] Evtol News, Ehang 216, (n.d.). <https://evtol.news/ehang-216/> (accessed 2021).
- [147] VTK - The Visualization Toolkit, (2016). <https://vtk.org/>.
- [148] D. Howe, Aircraft Conceptual Design Synthesis, Professional Engineering Publishing, 2000.
- [149] D. Raymer, Aircraft Design: A Conceptual Approach, Fifth Edit, Reston, VA: AIAA, 2012.
- [150] E. Torenbeek, E. Jesse, M. Laban, Conceptual design and analysis of a Mach 1.6 airliner, in: Collect. Tech. Pap. - 10th AIAA/ISSMO Multidiscip.

- Anal. Optim. Conf., 2004: pp. 2631–2648. <https://doi.org/10.2514/6.2004-4541>.
- [151] J.T. Smart, J.J. Alonso, Primary Weight Estimation for eVTOLs via Explicit Analysis and Surrogate Regression, (2019) 1–12. <https://doi.org/10.2514/6.2019-3679>.
- [152] B. Basgall, W. Liu, T. Cassady, W.A. Anemaat, Aircraft design weight methods comparison and improvement, in: AIAA Scitech 2020 Forum, 2020: pp. 1–15. <https://doi.org/10.2514/6.2020-1259>.
- [153] Dr. Jan Roskam, Airplane Design Part V: Component Weight Estimation, Kindle Edi, 2018.
- [154] E. Torenbeek, Synthesis of Subsonic Airplane Design, Delft University Press, Delft, The Netherlands, 1982.
- [155] J.M. Vegh, E. Botero, M. Clark, J. Smart, J.J. Alonso, Current capabilities and challenges of ndarc and suave for evtol aircraft design and analysis, in: AIAA Propuls. Energy Forum Expo. 2019, 2019: pp. 1–19. <https://doi.org/10.2514/6.2019-4505>.
- [156] R.D. Finck, USAF (United States Air Force) Stability and Control DATCOM (Data Compendium), 1978.
- [157] W.M.B. L. R. Miranda, R. D. Elliot, A generalized vortex lattice method for subsonic and supersonic flow applications, 1977.
- [158] T.D. and K.W. Sidwell, PANAIR summary document (version 1.0), 1982.
- [159] W.R. Gentry, Arvel E. Smyth, Douglas N. Oliver, The Mark IV Supersonic-Hypersonic Arbitrary-Body Program. Volume I. User's Manual, 1973.
- [160] O. Gur, W.H. Mason, J.A. Schetz, Full-configuration drag estimation, J. Aircr. 47 (2010) 1356–1367. <https://doi.org/10.2514/1.47557>.
- [161] P. Cebeci, T.; Bradshaw, Momentum transfer in boundary layers, Washington, D.C., Hemisphere Publishing Corp.; New York, McGraw-Hill Book Co., 1977.

- [162] F. M. White, J. Majdalani, *Viscous fluid flow*, 3th ed., McGraw-Hill New York, 2006.
- [163] E.J. Hopkins, *Charts for Predicting Turbulent Skin Friction from the Van Driest Method (II)*, 1972.
- [164] O. Gur, A. Rosen, Optimizing electric propulsion systems for UAV's, in: 12th AIAA/ISSMO Multidiscip. Anal. Optim. Conf. MAO, 2008. <https://doi.org/10.2514/6.2008-5916>.
- [165] M. Drela, *QPROP Formulation Flowfield velocities*, 2006.
- [166] and M.S.S. John B. Brandt, Robert W. Deters, Gavin K. Ananda, Or D. Dantsker, UIUC propeller data site, (n.d.). <https://m-selig.ae.illinois.edu/props/propDB.html>.
- [167] AirCar, (n.d.). <https://www.aircar.aero/> (accessed 2024).
- [168] DaVinci, (n.d.). <https://www.da-vinci.us/> (accessed 2024).

