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A PERFORMANCE BENCHMARK OF RECENT PERSONAL AIR VEHICLE CONCEPTS FOR URBAN AIR MOBILITY

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Abstract

The prospect of a future Urban Air Mobility scenario brought up a vast number of according vehicle programs. Due to a novel design space enabled by distributed electric propulsion, fundamentally different vertical take-off and landing aircraft concepts are developed. To further concretize the vision of an urban air transportation system, it is important to know the characteristics of the various vehicle technologies and to understand the effects on an overall system. This technical paper evaluates two recent aircraft concepts: an 18-rotor multicopter and a configuration with separate propulsion systems for vertical take-off and landing and fixed-wing cruise flight (lift+cruise). Starting from a base configuration, several versions of the aircraft are derived to investigate sizing effects and trade-offs between VTOL and cruise efficiency. Mission performance calculations for a defined design mission and off-design missions are conducted. Finally, a demonstration scenario simulation is presented, which will allow future investigations regarding the transport performance of a vehicle within a complete urban air transportation system.

Nomenclature

Symbols

H_0	Take-off/landing altitude [m]
H_{Cruise}	Cruise altitude [m]
L/D	Lift-to-drag ratio [-]
$P_{Cruise, MaxRange}$	Cruise power at maximum range cruise speed [kW]
$P_{Cruise, Installed}$	Installed power of the cruise propulsion system [kW]
P_{Hover}	Hover power [kW]
$P_{VTOL, Installed}$	Installed power of the VTOL propulsion system [kW]
RoC	Rate of climb [m/s]
RoD	Rate of descent [m/s]
$t_{Landing}$	Hover time landing [s]
$t_{Take-Off}$	Hover time take-off [s]
V_{Cruise}	Vehicle cruise speed [km/h]
$V_{MaxRange}$	Vehicle cruise speed for maximum range [km/h]
$V_{Tip, Max}$	Maximum rotor tip speed [Ma]
ζ	C-Rate [1/h]

Abbreviations

DEP	Distributed Electric Propulsion
eVTOL	Electric Vertical Take-off and Landing (Vehicle)
L+C	Lift + Cruise
MC	Multicopter
MTOW	Maximum Take-off Weight
OWE	Operating Weight Empty
PAV	Personal Air Vehicle
PMAD	(Electric) Power Management and Distribution Unit
UAM	Urban Air Mobility
VTOL	Vertical Take-off and Landing

1 Introduction

The vision of Urban Air Mobility (UAM) is currently attracting a tremendous amount of attention. As a possible solution for capacity bottlenecks and/or attractive mobility alternative to ground transportation in urban areas, UAM is a promising future market. Potential stakeholders from different industries initiate a series of versatile activities to make the vision become reality.

Among these activities, the design and development of a suitable aircraft is of central importance.

The new attractive technology options arising with nearly scale-free [1] distributed electric propulsion (DEP) open up a large vehicle design space. On one hand, DEP reduces effort and complexity of vertical take-off and landing (VTOL) aircraft to a manageable level. On the other hand, new standards in safety and reliability are predicted in connection therewith. Strong improvements are also expected in terms of operating costs [2] and aircraft noise emissions.

The technical possibilities face diverse and new requirements of UAM. Strict emission, noise and safety regulations can lead to a new weighting of the classic aircraft design drivers. Thus, for example, the aviation industry has to deal with scenarios of mass production on the scale of automobile manufacturers. Despite the publication of comprehensive UAM studies and whitepapers, e.g. [3] [4], detailed boundary conditions for a target-oriented vehicle design are not yet in place. Even classical aircraft requirements like range, cruise speed or seat capacity remain unclear. In the absence of precise performance targets, a variety of fundamentally different aircraft concepts referred to as electric vertical take-off and landing vehicle (eVTOL), air taxi or personal air vehicle (PAV) were presented in the past years [5]. A two-step classification scheme depicted in Fig. 1 clusters the variety of aircraft concepts according to lift production during cruise and the mechanism to enable VTOL. The aim is to obtain aircraft clusters with comparable performance data and characteristics.

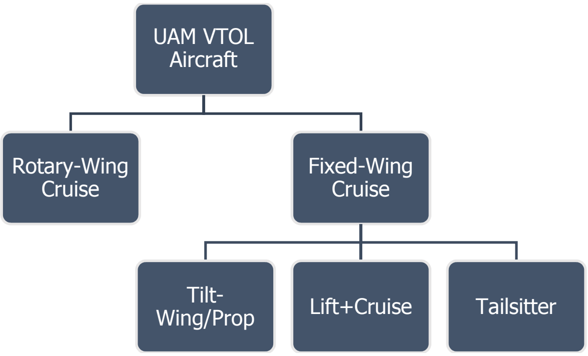

Fig. 1: Vehicle morphologies for VTOL aircraft [5].

For the further development and specification of possible UAM scenarios, it is essential to know fundamental characteristics such as performance potential, design limits or technology sensitivities of the vehicle morphologies. In addition, these aspects are the basis for an evaluation of the vehicle performance in an UAM overall system. It is important to understand how certain aircraft characteristics such as hover efficiency, cruise efficiency, cruise speed, range, maintenance effort and vehicle complexity, physical dimensions or charging times affect a potential urban aerial transport system.

This technical paper addresses two recent vehicle concepts: An 18-rotor multicopter (MC) configuration of the rotary-wing group based on the *Volocopter 2X* [6] and a lift+cruise (L+C) configuration published by Aurora Flight Sciences [7]. Lift+cruise aircraft have two separate drive groups: a vertically oriented VTOL group and a horizontally oriented cruise group providing thrust for fixed-wing cruise. Referring to the wheel of *V/STOL Aircraft and Propulsion Concepts* [8], this vehicle class is in accordance to the *Lift+Cruise* category there.

Both concepts are designed according to published data using conceptual design methods and homogeneous underlying technology assumptions. Subsequently, several configurations of varying size are derived to illustrate sizing options and effects. In an off-design study the transport energy efficiency of all configurations for different mission profiles is investigated. Finally, an initial demonstration case of a system-wide transport analysis is presented. A fictive UAM scenario for a small town in the United States, Sioux Falls, is simulated.

2 Methods, Modelling and Assumptions

Vehicle design and mission performance are based on a combination of common conceptual aircraft design methods. In the following subsection a compact overview of applied methods, implemented models and underlying assumptions are presented.

2.1 Aerodynamics

A blade element method with included tip loss factor is used for VTOL rotors [9]. Cruise propellers are designed with a method published by Adkins [10]. All rotors and propellers are calculated with underlying 2D aerodynamic polars of a CLARKY profile.
Lift, drag and moment coefficients of fixed wings are calculated with an adapted version of the lifting line theory [11], allowing the integration of 2D profile polars. Parasitic drag is considered by equivalent flat plate areas [9].

2.2 Electric Power Train

The electric power train model consists of electric motors, a central power management and distribution unit (PMAD) and battery packs. For component weights and efficiencies, constant values are assumed, see Table 1.

Table 1: Power train component characteristics.

Component	Specific Energy/ Specific Power	Efficiency
Battery	250 Wh/kg	97 %
PMAD	7.0 kW/kg	95 %
El. Motor	5.0 kW/kg	96 %

In addition to the battery efficiency, which considers battery management, for discharge characteristics a runtime model of batteries is included [12]. Fig. 2 depicts the modelled discharge characteristics of a single battery cell. Discharging the battery with higher C-rates, ζ, reduces the extractable amount of energy of the battery significantly.

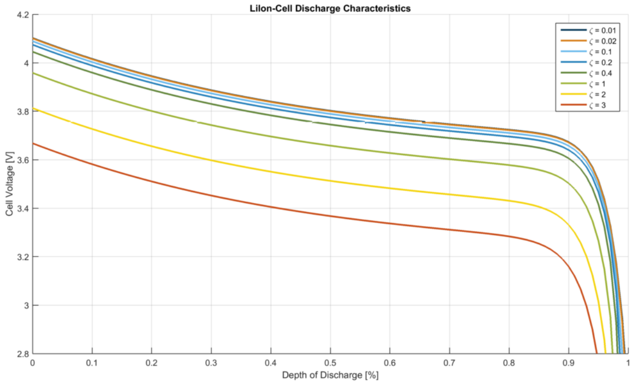

Fig. 2: Modelled discharge characteristics of a single battery cell for varying C-rate.

The representation of these effects is essential, since especially during hover and vertical flight high C-rates may occur.

2.3 Mission Profile and Design Mission

Mission performance analysis is based on a simplified five-segment mission profile. Hover segments with a defined duration, $t_{\text{Take-Off}}$ and t_{Landing}, represent take-off and landing. Climb and descent are performed vertically from an initial altitude, H_0, to cruise altitude, H_{Cruise}, and vice versa with a rate of climb, RoC, and a rate of descent, RoD. The cruise segment consists of a horizontal flight at cruise altitude with constant cruise design speed of the respective vehicle. Fig. 3 shows the complete mission profile in overview.

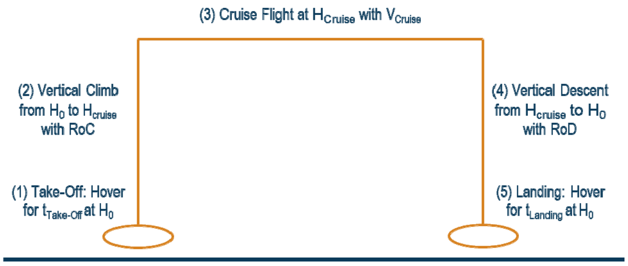

Fig. 3: Five-segment UAM mission profile.

Based on the mission profile, an UAM design mission is defined with the parameters listed in Table 2.

Table 2: Design mission parameters.

Parameter	Value	Unit
$t_{\text{Take-Off}}$	30	s
t_{Landing}	30	s
H_0	0	m
H_{Cruise}	300	m
RoC	2.5	m/s
RoD	2.5	m/s

Transition and acceleration/deceleration phases were neglected in the subsequent studies. Also neglected were climb and descent segments with forward speed. While the presented studies still provide meaningful results with the simplified mission profile, the more detailed flight phases mentioned must be considered in future investigations.

3 UAM Aircraft Platforms

For the studies presented below, both configurations, the multicopter and the lift+cruise concept are modelled according to published data. In addition, derived versions of both vehicles are designed to evaluate sizing effects and scalability.

3.1 Multicopter Configurations

The considered multicopter design has 18 rotors aligned in two concentric circles; see Fig. 4. With total dimensions of 9.15m by 9.15m, the footprint is relatively large compared to other UAM aircraft. However, the very large disc area leads to excellent hover efficiency with low rotor tip speeds at the same time. As a result, rotor noise can be kept to a minimum.

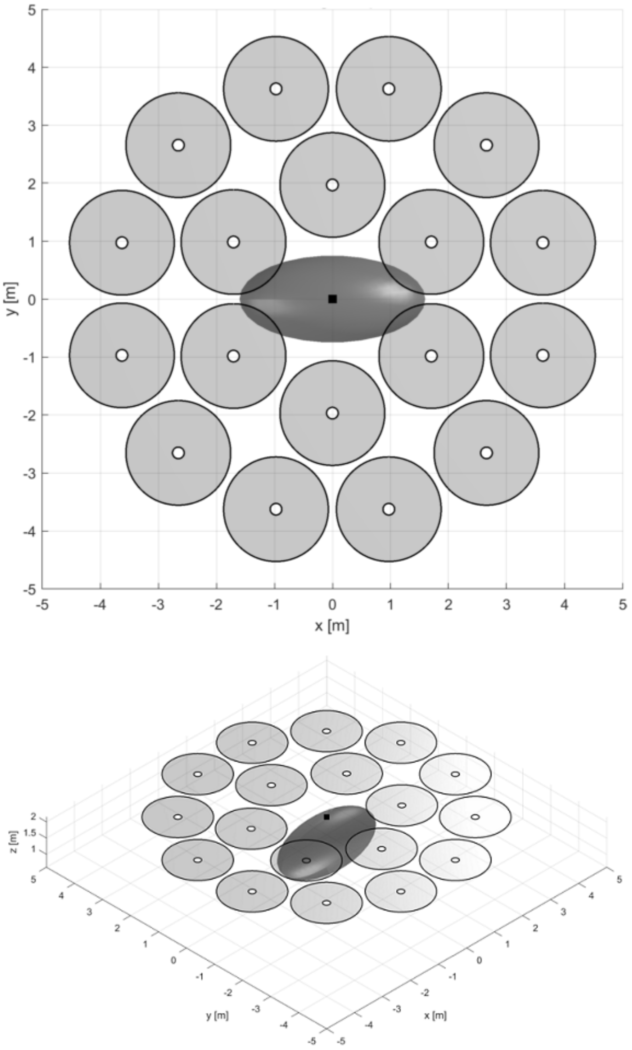

Fig. 4: Top-view and isometric view of the multicopter concepts.

The original design (hereinafter referred to as MC Ultralight) has a maximum take-off weight (MTOW) of 450kg with a maximum payload of 160kg. The two-seater is certified as German ultralight in the class of light sport multicopter [6].

Based on the original configuration, two modified versions are derived: on one hand a slightly larger variant with 225kg payload (MC Light) and on the other hand a four-seater version featuring 450kg maximum payload (MC Heavy). All configurations have the same design mission.

Considering disc loading as an indicator for hover efficiency, the two-seater versions have slight advantages compared to conventional helicopters. The light utility and training helicopter Robinson R22 Beta II [13] has with 13.46 a 13% increased disc loading compared to the MC Light. Comparing the Robinson R44 Raven II [14] (four-seater) to the MC Heavy, the helicopter has the clearly lower disc loading (13.6, -38%). However, the main rotor of the R44 is with a diameter of 10.1m slightly larger than the multicopter configuration. Furthermore, the MTOW of the four-seater configurations is the same, while the MC Light is significantly lighter than its conventional counterpart. This effect is due to the strong increase in battery weight with increasing MTOW of the multicopter concept.

3.2 Lift+Cruise Configurations

The selected lift+cruise concept (L+C Light Small), depicted in Fig. 5, has a VTOL system with eight rotors arranged in two parallel lines aligned in flight direction. Two booms hold the according electric motors and connect three aerodynamic surfaces. A forward swept canard, a forward swept main wing and a u-tail in the rear provide lift and trim forces during forward flight. The rotors are located between the wings to avoid blocking losses. A small propeller in pusher configuration located in the rear of the fuselage produces thrust for cruise flight. The complete aircraft fits into an 8m by 8m box and has a MTOW of 800kg with 225kg payload. Compared to the multicopter, the VTOL propulsion system has a significantly reduced disc area. This leads to less effective hover flight and much higher rotor tip speeds. However, due to the fixed-wing based forward flight the aircraft has a significantly better cruise efficiency compared to the multicopter.

Table 3: Compiled attributes of considered vehicles.

Configuration		**MC Ultralight**	**MC Light**	**MC Heavy**	**L+C Heavy Large**	**L+C Light Large**	**L+C Light Small**
PAX	[-]	2	2	4	4	2	2
Weights:							
MTOW	[kg]	450	546	1005	1383	780	800
OWE	[kg]	290	321	555	933	555	575
Payload	[kg]	160	225	450	450	225	225
Battery	[kg]	77	91	215	395	223	233
Cruise Propulsion Group (Rotors + El. Motors)	[kg]				20	14	13
Miscellaneous	[kg]	45	48	78	93	59	60
PMAD	[kg]	13	16	40	113	52	62
Structure	[kg]	123	130	153	178	147	136
VTOL Propulsion Group (Rotors + El. Motors)	[kg]	32	37	69	133	61	71
Physical Dimensions:							
Width/Span	[m]	9.15	9.15	9.15	9.15	9.15	8.00
Length	[m]	9.15	9.15	9.15	9.15	9.15	8.00
Height	[m]	2.15	2.15	2.15	1.80	1.80	1.80
VTOL System Data:							
Number of Rotors	[-]	18	18	18	8	8	8
No. of Blades per Rotor	[-]	2	2	2	2	2	2
Rotor Diameter	[m]	1.8	1.8	1.8	1.8	1.8	1.5
Disc Area Total	[m²]	46.0	46.0	46.0	20.3	20.3	14.1
$V_{Tip, Max}$	[Ma]	0.40	0.40	0.52	0.80	0.62	0.74
Disc Loading (Hover)	[kg/m²]	9.8	11.9	21.8	68.1	38.4	56.9
P_{Hover}	[kW]	39.5	50.4	124.5	301.5	127.7	160.2
$P_{VTOL, Installed}$	[kW]	75.6	96.9	239.3	583.2	245.0	309.1
Cruise System Data:							
$P_{Cruise, MaxRange}$	[kW]	25.2	29.5	68.4	92.4	62.8	58.8
$P_{Cruise, Installed}$	[kW]				96.8	65.7	61.6
L/D (Cruise)	[-]	3.4	3.5	2.8	12.8	9.8	10.7
Battery:							
Specific Energy	[Wh/kg]	250	250	250	250	250	250
Energy Total	[kWh]	19.2	22.8	53.9	98.8	55.8	58.5
Energy Usable	[kWh]	15.4	18.2	43.1	79.0	44.6	46.8
ζ_{Hover}	[1/h]	2.38	2.59	2.71	3.65	2.84	4.02
$\zeta_{Cruise, MaxRange}$	[1/h]	1.57	1.56	1.54	1.20	1.24	1.06
Design Mission:							
Max. Range	[km]	25.7	25.7	25.7	79.5	79.5	79.5
$V_{MaxRange}$	[km/h]	70	70	70	180	180	180
Energy / PAX / Km	[Wh]	299.4	355.1	420.0	248.5	280.6	294.3
Block Time	[min]	27.0	27.0	27.0	31.5	31.5	31.5

Again, two versions are derived from the original configuration.

First, the physical dimensions of the aircraft are increased. Span and length of the vehicle (L+C Light Large) are stretched to 9.15m each. This corresponds to the box of the multicopter and allows slightly larger, more efficient VTOL rotors. The aim is to investigate in detail the trade-off effects between cruising and hovering efficiency, which is essential for these configurations.

Second, a four-seater version (L+C Heavy Large) with 450kg payload of the aircraft is designed, again fitting in a 9.15m by 9.15m box. The design mission remains the same for all configurations.

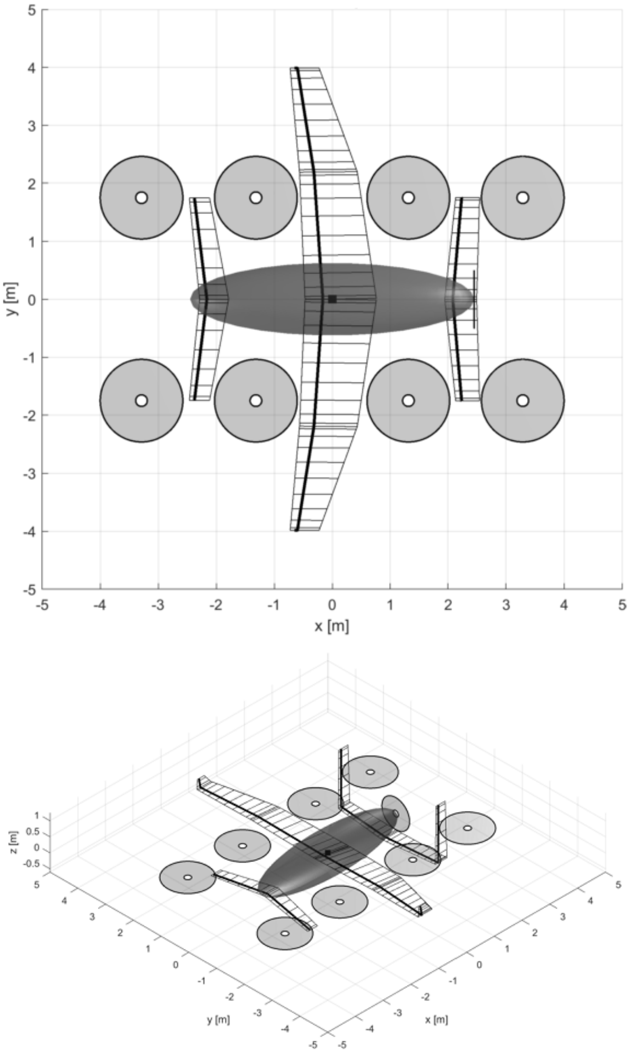

Fig. 5: Top-view and isometric view of the L+C Light Small configuration.

4 Vehicle Characteristics and Mission Performance

This chapter discusses some of the UAM relevant characteristics as well as mission performance of the presented eVTOLs. Table 3 contains compiled aircraft characteristics of all considered vehicle versions.

For the given design mission, the multicopter configuration MC Ultralight provides a range of 25.7km. The variants with higher payload have a MTOW increase of 96kg (MC Light) and 555kg (MC Heavy) for the same mission. Due to higher disc loadings, the amount of energy required per passenger kilometer is increasing significantly with increasing MTOW.

The L+C configurations are capable of a 79.5km cruise range. The improved VTOL system of the L+C Light Large has positive effects for the given mission profile. The almost 45% increase in rotor area reduces the required installed power of the VTOL system by 20%. The resulting weight savings of the VTOL power train predominate the slightly increased structural weight. The larger configuration also has increased parasitic drag, which reduces the lift-to-drag ratio during cruise flight. However, considering all effects, the design mission can be accomplished with a 20kg lighter overall configuration, which in turn increases transport energy efficiency. Of course, the described effects are valid only for mission profiles with a relatively large fraction of hover and vertical flight. A permitted mission segment with steady climb during forward flight may lead to different results.

In contrast to the multicopter concepts, the increased payload version L+C Heavy Large outperforms its lighter version regarding transport energy efficiency. The energy amount per passenger kilometer reduces by 11.4% to 248.5Wh with full vehicle occupancy.

When considering noise emissions of eVTOLs, the rotors are the dominant source of noise. Designing rotors with low blade tip speed, $V_{Tip, Max}$, is a crucial for noise reduction. Due to the large disc area, very low blade tip speeds of Ma 0.4 (MC Ultralight, MC Light) to Ma 0.52 (MC Heavy) can be achieved with the multicopter configuration. This is not possible for the presented L+C configurations. In order to ensure sufficient thrust, significantly higher rotational speeds must be implemented. With the given rotor geometries this leads to tip speeds of Ma 0.62 for the L+C Light Large and Ma 0.80 for the L+C Heavy Large.

Besides the blade tip speed, other influencing factors such as the number of rotors, the detailed rotor design or shielding mechanisms are of great importance. Since low noise emissions may be a crucial criterion for operation within urban areas, noise must be considered early in the design process as a major design driver.

4.1 Off-Design Performance

Considering an UAM scenario with on-demand transportation and several or many vertiports distributed over the city area and the region around it, off-design performance of the vehicles is of great importance. The actual missions flown may be considerably shorter than the design range. Fig. 6 shows the energy per passenger kilometer for various cruise distances. During cruise flight, the configurations fly with their design cruise speed.

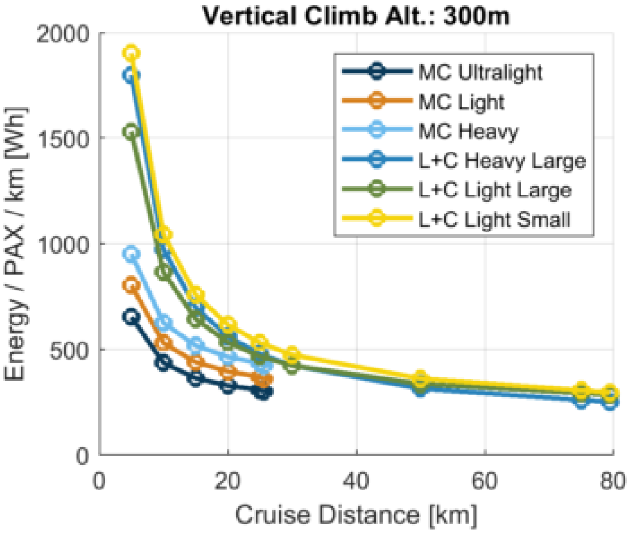

Fig. 6: Transport energy efficiency of UAM vehicles for varying mission ranges and a vertical climb altitude of 300m.

Since the relative amount of energy required for hovering and climbing to cruise altitude rises with decreasing mission ranges, the transport energy efficiency reduces significantly for shorter missions. This affects L+C configurations more strongly, since their less efficient hover performance outweighs the high cruise efficiency.

Considering the flyable missions of the multicopters, they are always more energy efficient than the L+C concepts. The L+C Light Large and L+C Heavy Large configurations only achieve better efficiencies from ranges above 26km.

The mission time, depicted in Fig. 7, has a significant influence on the transport performance. Faster transportation times mean more trips per hour and therefore potentially more revenue. Due to the significantly higher cruise speed, the L+C configurations have a clear advantage.

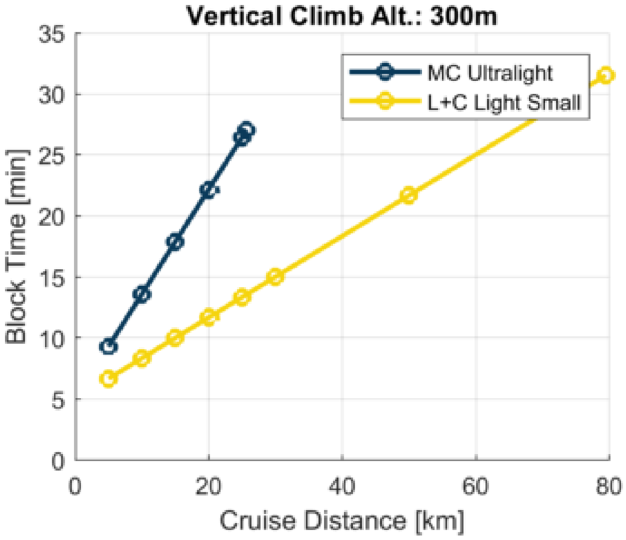

Fig. 7: Mission time of UAM vehicles for varying mission ranges and a vertical climb altitude of 300m.

If the multicopters, for example, fly missions with distances close to their design range, L+C vehicles can fly this trip twice in the same time. The effects of these substantial differences will have to be investigated in overall transport system analyses like the one presented below.

4.2 Variation of the Vertical Climb Altitude

Since the vertical climb altitude has major impact on the vehicle performance, studies at varying altitudes have been conducted. Fig. 8 shows the energy per passenger kilometer for varying flight distances and a vertical climb altitude of 50m.

Here, efficiency in hovering and vertical flight are less important, which leads to significant shifts in transport energy efficiency. L+C vehicles supersede the multicopter concepts from distances of 10-15km as the more efficient aircraft.

Even if the actual profile of an UAM mission may not look like the presented simplified one, the trends described above will still be of relevance. For noise and safety reasons, quite considerable vertical climb segments may be required. Therefore, the balance between efficient hovering or vertical flight and cruise flight is of great importance during the early design phase, since a decision can have major configurational implications.

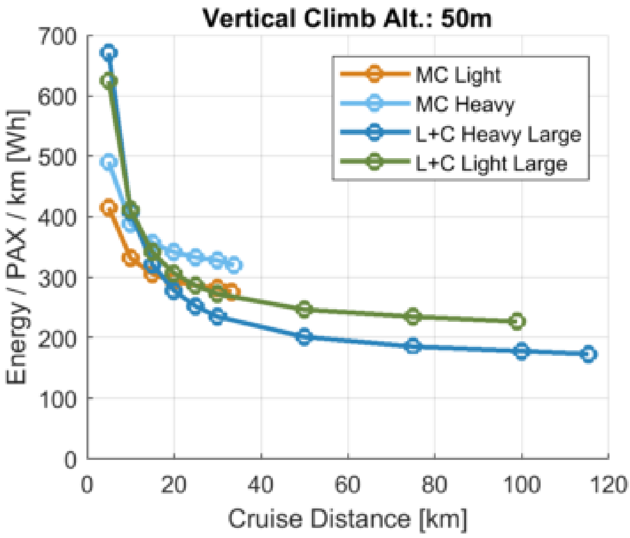

Fig. 8: Transport energy efficiency of UAM vehicles for varying mission ranges and a vertical climb altitude of 50m.

6 A Demonstration Scenario for Transport Performance Analysis

Once the vehicle characteristics are available, their impact within a complete urban air transportation system have to be understood. Urban boundary conditions such as the number and distance of vertiports, the available infrastructure, the potential number of passengers, etc. are essential for the respective mission requirements. In addition, there are other requirements regarding safety or noise that have not been defined yet.

To investigate the interplay between vehicle designs and transport system properties, a simulation of a complete city transportation system is required. Therefore, the transport simulation framework MATSim [15] has been extended by an UAM module [16]. The module adds the capability to model and simulate aerial passenger transport besides ground-based transport modes, and was used to simulate the VTOL vehicles performance in the MATSim scenario of Sioux Falls, US, with a population of 84,110 agents (48% sample) [17].

This Sioux Falls scenario, which has been modified from its original version, created by Hörl [18], in order to accommodate dedicated VTOL infrastructure and aerial routes to be used by VTOL vehicles, provides a prototyping use case for analyzing potential aerial transport demand as presented in an earlier study [17]. The VTOL vehicle within the simulation provide the on-demand transport mode of urban air mobility to the existing ground-based modes of driving one's car, using the bus-based public transport service, bicycling, or walking.

Table 4: Simulated vehicle characteristics.

Config. Name	MC Light	MC Heavy	L+C Light Large	L+C Heavy Large
PAX [-]	2	4	2	4
Range [km] (300m Cruise Altitude)	25.7	25.7	79.5	79.5
V_{Cruise} [km/h]	70	70	180	180
RoC/RoD [m/s]	2.5	2.5	2.5	2.5

The Sioux Falls scenario has been chosen for this demonstration to maintain comparability with previous studies, knowing that the scenario has limitations due to the study area's size, as the Sioux Falls scenario does not provide sufficiently long flight distances for the range to be a limiting factor for any of the listed VTOL vehicles. The flight distances within the scenario range from 2.2 to 11.7 km. In addition, refueling/recharging is assumed to be performed after each landing. Further, for all VTOL vehicles, the same process times of 2.5 minutes, seat-load-factor-independent passenger cost of three times the cost of car-usage [c.f. 16], and a cruise flight altitude of 300 meters have been assumed. Further, for this initial analysis, it is assumed that no redistribution of vehicles is necessary, thus, no empty flights occur as sufficiently large number of vehicles has been provided within the scenario.

Fig. 9 illustrates the transport performance of each simulated VTOL vehicle/concept in terms of passengers transported, number of flights, and total distance flown in km throughout a 24-hour simulation period. Each VTOL vehicle/concept was simulated on its own, i.e. with a homogenous fleet of VTOL vehicles. Due to their increased capacity, all 4-seater vehicles, i.e. the L+C Heavy, and the MC Heavy, outperform the two-seater concepts in terms of passengers transported. In number of flights, however, the faster-cruising L+C vehicles surpass the slower-cruising multicopters. The distance flown correlates strongly with the number of flights, as the distribution of flight distances, i.e. routes, do not differ greatly between the various VTOL concepts, as shown in Fig. 10.

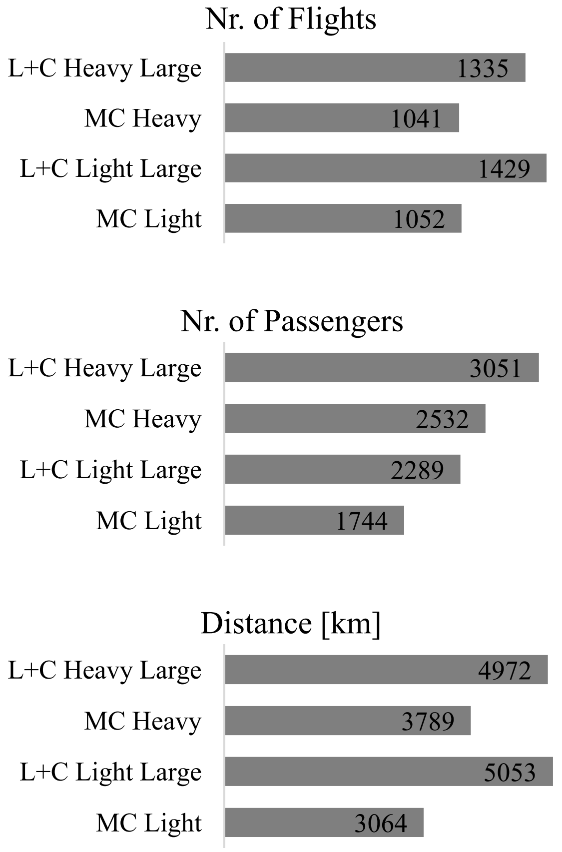

Fig. 9: Transport performance comparison between various VTOL vehicle scenarios.

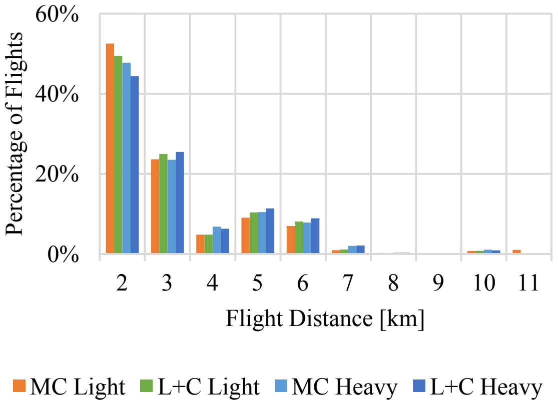

Fig. 10: Distribution of flight distances per vehicle

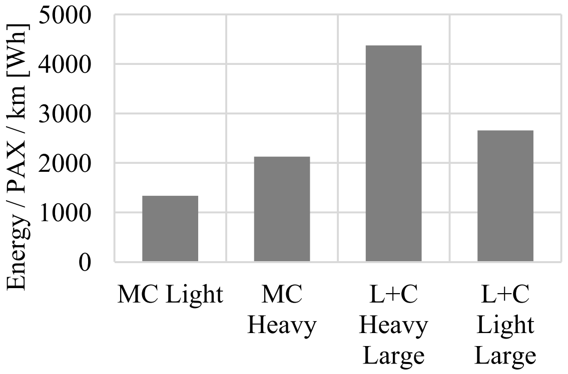

Fig. 11: Actual transport energy efficiency of the vehicles in the Sioux Falls UAM scenario.

Considering the actual transport energy of the vehicles for the scenario, plotted in Fig. 11, the multicopter vehicles perform significantly better. Due to the short mission ranges, the better efficiency during cruise of the L+C VTOLs do not have a strong effect. Further, both two-seater aircraft perform more efficient than their heavier derivatives. This is the result of a better seat load factor under the given scenario conditions.

7 Conclusions and Outlook

Characteristics and mission performance of two fundamentally different VTOL configurations were investigated. A multicopter configuration with a very large disc area and a lift+cruise configuration capable of fixed-wing cruise equipped with a separate VTOL propulsion system were modelled and evaluated based on a simplified mission profile. Starting from two published base configurations, derived configurations with increased payload and an improved VTOL system were sized and evaluated.

Considering a design mission with a required vertical climb altitude of 300m, the multicopter configurations designed for a range of 25.7km provide a higher transport energy efficiency at the flyable ranges compared to the L+C eVTOLs. The L+C configurations, designed for ranges of up to 79.5km, achieve comparable or better efficiency levels only at cruise distances greater than 26km. If the required vertical climb height is reduced, the less efficient VTOL system of the L+C concept has less impact. At a required vertical climb altitude of 50m, the presented multicopter concepts have efficiency disadvantages starting at ranges of 10-15km compared to the L+C vehicles. The significantly higher cruise speed and the resulting shorter trip times of the L+C configuration provide better transport performance, especially on longer distances.

Considering noise emissions, the multicopters have a clear configurational advantage. Due to the large disc area, significantly lower blade tip speeds are achievable in comparison to the L+C VTOL system.

On basis of a simulated UAM demonstration scenario in Sioux Falls, studies of the transport performance of the individual eVTOL concepts in an overall system were shown. Evaluations of transport performance, actual missions flown or energy efficiency under assumed urban boundary conditions are important to develop an understanding of the requirements for UAM aircraft.

After the basic functionality of an UAM simulation has been shown, scenarios for more representative cities will be created. The implemented models for e.g. other transport modes, fares, resident behavior or airspace restrictions will be refined to enable reliable statements on possible future UAM scenarios. These scenarios in turn, have to be simulated with different aircraft designs to understand the impact of vehicle characteristics within the overall system. Moreover, the simulations will help to develop a potential UAM fleet mix for different urban structures.

To this end, the methodology for technical modelling of eVTOLs will also be refined and extended. Besides additional configuration types, additional aspects such as operating costs shall be included in future studies. To enable vehicle design according to defined noise boundary conditions, noise prediction methods will be integrated in the design process. The considered mission profiles will be extended by more detailed segments, such as transition phases or vehicle acceleration and deceleration.

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